UNIVERSITY OF BELGRADE

FACULTY OF MECHANICAL ENGINEERING

ABDO-ALMONAИM A. M. ALGHLAM

NUMERICAL SIMULATION OF NATURAL GAS PIPELINE TRANSIENTS

DOCTORAL DISSERTATION

BELGRADE, 2020
УНИВЕРЗИТЕТ У БЕОГРАДУ
МАШИНСКИ ФАКУЛТЕТ

АВДО-АЛМОНАИМ С. М. АЛГХЛАМ

НУМЕРИЧКА СИМУЛАЦИЈА ПРЕЛАЗНИХ ПРОЦЕСА У ГАСОВОДИМА

Докторска дисертација

Београд, 2020
Mentor of Doctoral Dissertation

Dr. Vladimir Stevanovic, full professor
University of Belgrade, Faculty of Mechanical Engineering

Members of the Committee

Dr. Milos Banjac, full professor
University of Belgrade, Faculty of Mechanical Engineering

Dr. Aleksandar Cocic, associate professor
University of Belgrade, Faculty of Mechanical Engineering

Dr. Sanja Milivojevic, assistant professor
University of Belgrade, Faculty of Mechanical Engineering

Dr. Milica Ilic, research associate
University of Belgrade, Innovation Center of the Faculty of Mechanical Engineering

Date of Defence:
Ментор докторске дисертације
др Владимир Стевановић, редовни професор
Универзитет у Београду, Машински факултет

Članovi komisije
др Милош Бањац, редовни професор
Универзитет у Београду, Машински факултет
др Александар Ћоћић, ванредни професор
Универзитет у Београду, Машински факултет
др Сања Миливојевић, доцент
Универзитет у Београду, Машински факултет
др Милица Илић, научни сарадник
Универзитет у Београду, Иновациони центар Машинског факултета у Београду

Датум одбране:
Dedication

This thesis is dedicated to who taught me that it is never too late to change careers to pursue your true passion and that context is everything.

To my beloved, mother, wife, children, brothers, and sisters

Also in memory of my father

all with love and appreciation

To whom I respect, my supervisor Prof. Vladimir Stevanovic,

with sincere appreciation and thankful
ACKNOWLEDGEMENT

First and foremost, I would like to deeply thank my dissertation supervisor Prof. Vladimir Stevanovic for his invaluable guidance, encouragement and endless support through my Ph.D. study.

My sincere appreciations also extend to all my colleagues and others who have provided assistance on various occasions. Their views and tips are useful indeed. I also wish to express my warm and sincere thanks and appreciation to all staff of the Faculty of Mechanical Engineering – University of Belgrade for their continuous help during the completion of this dissertation.

I give my deepest gratitude to my beloved mother, wife, brothers, and sisters, for their supporting.

Above all praise and thank “Allah” who helped me to perform this work, and I hope to be satisfied with me.
Simulations and analyses of natural gas pipeline transients provide insights into behavior of natural gas pipeline network and transmission pipelines during the action of various disturbances, as well as control and safety systems. The results of these simulations are a support to the design of safe, reliable and efficient natural gas systems operation. Knowing all deviations of operational parameters from the prescribed values are very essential in order to control these parameter changes within acceptable spans that are determined by upper and lower setpoints, as well as to plan and schedule a maintenance with the aim of sustaining a gas supply to consumers in cases of various disturbances. Therefore, a numerical model and a computer code have been developed for the simulation and analyses of natural gas pipeline transients, as those that typically occur in high-pressure gas transmission pipelines. The developed model is based on the mass and momentum balance equations that describe one-dimensional, compressible, frictional natural gas transient flow, as well as on boundary conditions that enable simulation of gas flows in complex pipeline networks. The developed model is solved with the numerical procedures of the method of characteristics and implemented into the Gas Transient Analysis (GTA) computer code.

The developed model and the GTA code are validated by simulations of several test cases which are available in open literature. The simulated transients are caused by variable gas consumptions from gas pipelines of different lengths and networks, as well as by a pressure pulse at the pipeline inlet. The comparison between the obtained numerical results and the previously measured or calculated data from the literature, shows a good agreement. Afterwards, the code is applied to the simulation and analyses of transients in a real natural gas transmission pipeline in Libya with the length of over 500 km. The simulated scenarios cover common operating conditions, as well as abrupt disturbances of the gas parameters at the inlet gas manifold in the gas source fields and trips of gas delivery to consumers, with the aim of getting insight into the supply capacity of the gas transmission pipeline under abnormal conditions. The comparison between results obtained with the GTA code and measured data for normal real conditions shows good agreement as well, while the calculated results for the abnormal conditions show a significant accumulation and inertia of the gas within the long distance transmission pipeline, which allow gas accumulation and consumers supply during a half-day time period. Since the GTA code results are obtained under isothermal gas transient conditions, an analytical method is derived for the evaluation of differences between isothermal and non-isothermal transient flow predictions of pressure and non-isothermal temperature change. It is shown that non-isothermal transient effects can be neglected in engineering predictions of natural gas packing and discharging transient in long distance transmission pipelines.
transmission pipelines during hourly time periods. In addition, the prescribed isothermal temperature should be a few degrees K higher than the soil temperature as a result of the heat generation by friction on the pipelines wall and heat transfer from the gas to the surrounding soil. The GTA code simulations are robust and numerically stable, while the gas network and boundary conditions can be simply defined by specification of code input parameters.

Key words: natural gas, pipelines, transients, numerical simulations, non-isothermal flow, heat transfer, wall friction.
АПСТРАКТ

Симулације и анализе прелазних процеса у гасоводима омогућавају увид у понашање гасних мрежа и магистралних гасовода током деловања различитих поремећаја, као и током деловања управљачких и сигурносних система. Резултати ових симулација су подршка пројектовању сигурног, поузданог и ефикасног погон система са природним гасом. Познавање свих одступања погонских параметара од прописаних вредности је веома битно за управљање и одржавање ових параметара у прелазним границама дефинисаним доњим и горњим граничним вредностима, као и за планирање и временско усклађивање одржавања са циљем обезбеђења снабдевања потрошача гасом током дејства различитих поремећаја. Узимајући у обзир значај ових резултата, развијени су нумерички модели и компјутерски програм за симулације и анализе прелазних процеса у гасоводима са природним гасом, као што су типични прелазни процеси у магистралним гасоводима на великим притисцима. Развијени модели је заснован на билансним једначинама масе и количине кретања које описују једнодимензионално, стишљиво, нестационарно струјање природног гаса са трењем, као и на граничним условима који омогућавају симулацију струјања у сложеним гасним мрежама. Развијени модели се решава нумеричким поступком методе карактеристика и применен је у комјутерском програму за анализе прелазних процеса у гасоводима („Gas Transient Analysis – GTA“ програм).

Развијени модели и GTA програм су валидирани симулацијама неколико тест примера који су располаживи у литератури. Симулирани прелазни услови су изазвани променљивом потрошњом гаса из гасовода са различитим мрежама и дужинама цевовода, као и импулсом притиска на улазу у гасовод. Поређење добијених нумеричких резултата са претходним измереним или срачунатим вредностима из литературе даје добро слагање. Након тога програм је применен за симулације и анализе прелазних процеса у реалном магистралном гасоводу у Либији дужине преко 500 km. Симулиран сценарији обухватају обичајене погонске услове, као и нагле поремећаје у извору напајања гасом и престанак испоруке потрошачима, са циљем одређивања капацитета испоруке и акумулације гаса у овим поремећеним условима. Поређење резултата добијених GTA програмом и измерених вредности током нормалних стварних услова погона показује добро слагање. Резултати добијени за поремећене услове рада показују значајну акумулациону способност магистралног гасовода велике дужине и инерцију масе гаса, што омогућава акумулацију гаса и снабдевање потрошача у периодима од око 12 часова. Пошто су резултати са GTA
програмом добијени за изотермске услове, развијен је аналитички поступак за одређивање разлике у резултатима који се добијају изотермским и неизотермским моделом. Показује се да се неизотермски ефекти прелазних процеса могу занемарити током вишечасовних процеса акумулације и пражњења магистралних гасовода велике дужине. Такође, вредност изотермске температуре гаса треба да буде пар степени К виша од температуре околне услед генерације топлоте услед трења на зидовима гасовода и пролаза топлоте са гаса на околну. Програм GTA је поздан и нумерички стабилен, при чему се гасоводна мрежа и гранични услови једноставно задају преко улазних параметара.

Кључне речи: природни гас, гасоводи, прелазни процеси, нумеричке симулације.
# TABLE OF CONTENTS

| CHAPTER No. | TITLE | PAGE |
|-------------|-------|------|
| DEDICATION |       | iii  |
| Mentor of Doctoral Dissertation |       | iv   |
| Members of the Committee |       | iv   |
| Ментор докторске дисертације |       | v    |
| Članovi komisije |       | v    |
| ACKNOWLEDGEMENT |       | vi   |
| ABSTRACT |       | vii  |
| ЈУСТРАКТ |       | ix   |
| TABLE OF CONTENTS |       | xi   |
| LIST OF FIGURES |       | xv   |
| LIST OF TABLES |       | xvii |
| NOMENCLATURE |       | xviii|

## 1 INTRODUCTION

1.1 General | 1

1.2 Natural Gas and its Transmission: History and Present | 2

1.3 Natural Gas Origin and Composition | 5

1.4 Demand for Natural Gas | 5

1.5 Transportation of Natural Gas | 11

1.5.1 Liquefied Natural Gas (LNG) | 11

1.5.2 Gas to liquid products | 12

1.5.3 Natural Gas Transportation via Pipelines | 12

1.6 Mathematical flow modelling of gas pipelines | 13

1.7 Problem Background | 15

1.8 Problem statement | 16

1.9 Objective | 16

1.10 Scope of research | 17

1.11 Thesis organization | 17

1.12 Major Contribution | 18
2 LITERATURE REVIEW 19
2.1 Introduction 19
2.2 Steady-state models 20
2.3 Transient models 24
2.4 Concluding Remarks 33

3 FORMULATION OF NATURAL GAS FLOW IN PIPELINES BACKGROUND 36
3.1 Introduction 36
3.2 Gas Properties 36
  3.2.1 Density of Gas 36
  3.2.2 Specific Gravity 37
  3.2.3 Viscosity 38
  3.2.4 Ideal Gas law 39
  3.2.5 Real Gas properties 40
  3.2.6 Natural Gas composition and pseudo-critical properties 40
  3.2.7 Compressibility Factor 42
3.3 Flow Regimes 44
3.4 Friction factor calculation 45
  • Colebrook-White correlation 47
  • Modified Colebrook-White correlation 48
  • American Gas Association (AGA) correlation 48
  • Friction factor from Weymouth equation 48
  • Friction factor from Panhandle A equation 49
  • Friction factor from Panhandle B Equation 49
3.5 Velocity of natural gas in pipeline 50
  3.5.1 Erosional Velocity 51
3.6 Heat Transfer Consideration of Gas Flow in Pipeline 51
3.7 Mathematical modelling of natural gas one-dimensional unsteady compressible flow in pipelines 52
  3.7.1 Governing Equations 53
    • Conservation of mass: continuity equation 53
    • Momentum balance: Newton’s second law of motion 54
• Transformation of the balance equations 55

3.7.2 Solution methods 56
  3.7.2.1 Method of characteristics 56
  3.7.2.2 Finite element method 56
  3.7.2.3 Explicit finite difference methods 57
  3.7.2.4 Implicit finite difference methods 57
  3.7.2.5 Central difference method 57
  3.7.2.6 Crank-Nicolson method 57
  3.7.2.7 Fully implicit method 58

MODEL FORMULATION AND SOLUTION

4 ALGORITHM 59
4.1 Application of the Method of Characteristics for the Simulation of Natural Gas Pipeline Transients 59
4.2 Boundary Conditions 65
4.3 Flowchart of the calculation process 67

5 CODE VALIDATION 69
5.1 Case 1 69
5.2 Case 2 71
5.3 Case 3 73
5.4 Case 4 75
5.5 Conclusion remarks 78

6 TRANSIENT BEHAVIOR OF A LONG TRANSMISSION GAS PIPELINE 80
6.1 Analyses of transient behaviour of gas pipeline of the Western Libya Gas Project 80
  6.1.1 Scenario 1 83
  6.1.2 Scenario 2 84
  6.1.3 Scenario 3 86
6.2 Thermal effects in long transmission natural gas pipeline 88
  6.2.1 The influence of temperature change along the gas pipeline on the pressure drop 88
  6.2.2 The influence of thermal effects on pressure transient in the long transmission gas pipeline 92
REFERENCES

APPENDIX A-1  FLOW GOVERNING EQUATIONS  113
APPENDIX A-2  DETERMINING THE SPEED OF SOUND  117
APPENDIX A-3  DETERMINING THE CONSTANT C1  119
APPENDIX A-4  DETERMINING THE CONSTANT C2  120
APPENDIX B  CASES OF STUDY CALCULATION RESULTS  121

AUTHOR BIOGRAPHY

ИЗЈАВА О АУТОРСТВУ
ИЗЈАВА О ИСТОВЕТНОСТИ ШТАМПАНЕ И ЕЛЕКТРОНСКЕ ВЕРЗИЈЕ ДОКТОРСКОГ РАДА
ИЗЈАВА О КОРИШЋЕЊУ
# LIST OF FIGURES

| FIGURE NO. | TITLE |
|------------|-------|
| 1.1        | Planned and under construction pipelines worldwide, 2017 |
| 1.2        | Historic demand for natural gas |
| 1.3        | World-wide energy consumption with projections to 2050 |
| 1.4        | World natural gas consumption with projections to 2050 |
| 1.5        | World-wide primary energy consumption by fuel (sources), 2018 |
| 1.6        | World energy production and demand by natural gas and coal |
| 3.1        | Compressibility factor chart for natural gas |
| 3.2        | Laminar and Turbulent Pipe Flow |
| 3.3        | Moody diagram |
| 3.4        | Demonstration of all forces acting on a gas particle moving in a pipeline |
| 3.5        | Control volume for continuity equation |
| 3.6        | Control volume for momentum equation |
| 4.1        | Spatial-temporal plane |
| 4.2        | Pipes in a junction |
| 4.5        | Flowchart of the calculation procedure |
| 5.1        | Specified volume flow rate at the pipeline outlet (Case 1) |
| 5.2        | Calculated volume flow rates at the pipeline inlet (Case 1) |
| 5.3        | Specified daily change of the mass flow rate at the pipeline outlet (Case 2) |
| 5.4        | Calculated pressure at the pipeline outlet (Case 2) |
| 5.5        | Gas pipeline network (Case 3) |
| 5.6        | Gas demand versus time for nodes 2 and 3 of the simulated network (Case 3) |
| 5.7        | Calculated pressure in node 2 of the network (Case 3) |
| 5.8        | Calculated pressure in node 3 of the network (Case 3) |
| 5.9        | Boundary conditions and geometry of the pipeline in |
| Section | Description |
|---------|-------------|
| 5.10    | Pressure history at the outlet of the pipeline (Case 4) |
| 5.11    | Pressure history at the inlet of the pipeline (Case 4) |
| 5.12    | Gas volume flow rate at the pipeline midpoint (Case 4) |
| 5.13    | Pressure history at the pipeline closed end obtained with different number of numerical nodes (grid refinement test for Case 4) |
| 6.1     | Main gas pipeline of the Western Libya Gas Project |
| 6.2     | Measured pressure at the main gas pipeline inlet in the Wafa Desert Plant |
| 6.3     | Measured volume flow rates at the delivery outlets in the Mellitah Complex and in the Ar Ruways Gecol TPP |
| 6.4     | Measured and calculated pressure at the transmission pipeline outlet in the Mellitah Complex |
| 6.5     | Flow rate behaviour in the gas pipeline of the Western Libya Gas Project during the gas supply trip |
| 6.6     | Pressure history in the gas pipeline of the Western Libya Gas Project during the gas supply trip |
| 6.7     | Flow rate behaviour in the gas pipeline of the Western Libya Gas Project during the trip of gas delivery to the Mellitah Complex |
| 6.8     | Pressure history behavior in the gas pipeline of the Western Libya Gas Project during the trip of gas delivery to the Mellitah Complex |
| 6.9     | Flow rate behavior in the gas pipeline of the Western Libya Gas Project during the trip of total gas delivery |
| 6.10    | Pressure behavior in the gas pipeline of the Western Libya Gas Project during the trip of total gas delivery |
| 6.11    | Velocity change along the pipeline at the initial steady-state and 5 and 11 hours after the trip of total gas delivery |
| 6.12    | Pipeline buried in the ground at the depth x |
| 6.13    | Temperature change along the entrance part of the long transmission gas pipeline for two heat conduction coefficient values |
| 6.14    | Gas control volume in the pipeline |
## LIST OF TABLES

| TABLES NO. | TITLE                                                                 | PAGE |
|------------|-----------------------------------------------------------------------|------|
| 1.1        | Typical Composition of Natural Gas                                   | 6    |
| 2.1        | Summarizing of the literature                                        | 33   |
| 3.1        | Molecular weights and critical properties of several hydrocarbon gases| 38   |
| 3.2        | List of common gases viscosity                                       | 39   |
| 3.3        | Typical values of absolute roughness of pipe walls                   | 47   |
| 3.4        | Summary of friction factor correlations                              | 50   |
| 5.1        | Dimensions of the pipelines in the gas network (Case 3)               | 73   |
NOMENCLATURE

A indicator of the pipe inlet (A = 1) or outlet (A=2)
C₁, C₂ imperial constants.
C⁺, C⁻ corresponding characteristics paths
c sonic velocity, m/s
cₚ specific heat capacity at constant pressure, J/kgK
D diameter, m or mm
e absolute or internal pipe wall roughness, mm
E internal energy per unit mass, J/kg. Eq. (A-5)
E pipeline efficiency
f friction coefficient
G=ρₕ/ρₛ specific gravity (gas and air densities under standard conditions)
G(A,J) indicator of the pipe boundary type
g acceleration of gravity, m/s²
H total enthalpy, J
h specific enthalpy, J/kg
k heat transfer coefficient, W/m²K
L length, m
M₉ Molecular weight of gas, g/mole
Mₐir Molecular weight of air, g/mole
Mᵢ Molecular weight of natural gas component i, g/mole
m mass, kg
ṁ mass flow rate, kg/s
n maximum number of nodes, number of moles in Eq. (3-7)
p pressure, Pa
pₐve average pressure, Pa
pₖ gas critical pressure, Pa
pₚₖ pseudo-critical pressure, Pa
pseudo-reduced pressure of gas mixture

reduced pressure of gas (dimensionless)

pressure change, Pa

heat power, W

heat power per unit length of pipe, W/m

Reynolds number, \( \left( \frac{u \rho D}{\mu} \right) \)

gas constant, J/mol K

temperature, K

gas critical temperature, K

pseudo-critical temperature, K

pseudo-reduced temperature of gas mixture

reduced temperature of gas

The temperature of pipeline surrounding (soil), K

time step of integration, s

velocity, m/s

volume, m³

Volume flow rate, m³/s

spatial coordinate, depth, m

spatial step of integration, m

frictional force per unit length of pipe, N/m

Mole fraction or percent of natural gas component i, %

compressibility factor of natural gas

thermal conductivity, W/mK

dynamic viscosity, kg/ms

dynamic viscosity of natural gas component i, kg/ms

pipeline angle of upward inclination from the horizontal, rad

shear stress between the fluid and pipe wall, Pa
\( \rho \) 
density, kg/m\(^3\)

Indices
0 initial value
H hydraulic parameter
I\(_j\) pipe that transports gas from the junction, Eq. (20)
in inlet
J counter of pipes
J\(_i\) pipe that transports gas towards the junction, Eq. (19)
out outlet
s soil

Abbreviation
GTA Gas Transients Analysis
MASL meters above sea level
TPP thermal power plant
CHAPTER 1

Introduction

1.1 General

Over the past couple of centuries, fossil fuels, as primary energy sources, have been essential for global economic growth. During the industrial revolution in Europe in the 19th century, coal played a key role in supporting technological progress in agriculture, manufacturing and transport. Since then, petroleum has superseded the position of coal, and is an essential factor in sustaining our very expensive and ‘dangerous’ lifestyle.

Nowadays, however, the need for the cleaner fuels usage with lower content of carbon, as well as proven sufficient reserves and more stable prices than in case of oil market prices lead to the strong increase of the natural gas usage. The exploitable reserves of the natural gas are enough for the consumption in longer future time period, the carbon emission during the combustion of natural gas is approximately half of the emission by coal combustion and its price is more stable than in case of oil [1].

The natural gas is used in various sectors of industry, both as a fuel and as a raw material. As a fuel it is used in boilers and furnaces to generate steam, heat water or to provide heat for technological purposes. It is a raw material in petrochemical manufacturing, in polymer manufacturing and used to produce hydrogen, sulphur, carbon black, ammonia, and ethylene. In domestic sector natural gas is a fuel for district and individual building heating, for cooking and sanitary water preparation.

In contrast to petroleum or coal, natural gas can be used directly as a source of primary energy that causes less carbon dioxide and nitrogen oxide emissions (greenhouse gases). Besides substantially lower carbon dioxide emissions in comparison to usage of coal and oil, the combustion of natural gas leads to negligible emissions of sulfur dioxide, as well as lower nitrous oxide emissions. All these characteristics provide benefits such as elimination of acid rains, and reduced
ozone layer depletion and effects of the greenhouse gasses in the atmosphere. In addition, it can be safely transported, stored and used [2].

Hence, the current position of natural gas as a primary non-renewable energy source (second to oil in OECD\textsuperscript{1} countries) leads to the conclusion that the analysis, design and improvement of its processes, including transportation, play a significant role for both private and public sectors while offering a number of challenges to the scientific research community [1].

1.2 Natural gas and its transmission: history and present

The natural gas is known to humans since ancient times in the Middle East. At the beginning people had been aware of burning springs of natural gas. In Persia, Greece, or India, temples were built around these eternal flames for religious practices [2]. There is also historical evidence from the ancient times that people had started to harness natural gas springs with the aim of providing their living needs. Some 900 years B.C. the drilling of the ground was applied in China with the aim of obtaining springs of gas and that gas was used as a fuel for efficient provision of their living needs. Namely, the seawater was evaporated by natural gas combustion in order to obtain salt and drinkable water. In addition, by the first century, the Chinese had developed “an advanced techniques for tapping underground reservoirs of natural gas, which allowed them to drill wells as deep as 1,460 m in soft soil; they used metal drilling bits inserted through sections of hollowed-out bamboo pipes to reach the gas and bring it to the surface” [2].

The Romans were also aware about natural gas existence. It is supposed that Julius Caesar saw a "burning spring" near Grenoble in France. Also, there is evidence that religious temples in early Russia were built around burning sources of natural gas in the ground, which represented some kind of "eternal flames" [3].

The natural gas was discovered in Great Britain in 1659, but its commercial usage started more than a century later in 1790. A source of natural gas was discovered in Fredonia in United States US in 1821, as bubbles that rose to the surface from a creek. The first natural gas well in North America was dug by William Hart, who is called as “America’s father of natural gas” [2]. He applied hollowed logs for the transport of gas from the well to a nearby building and the gas was burned for illumination. In 1865, the Fredonia Gas, Light, and Waterworks Company became the first natural gas company in the United States. The first transmission natural gas pipeline was built in 1872. It was some 40 km long and it supplied gas from the wells to the city of Rochester in New

\textsuperscript{1} Organization for Economic Cooperation and Development
York. This pipeline was also built of hollowed logs. In 1885 Robert Bunsen developed so called “Bunsen burner”, which enabled the usage of natural gas for heating and cooking, besides its use for lighting. Certainly, at the beginning of these commercial natural gas consumptions, an obstacle of its wider usage was the lack of pipeline infrastructure for natural gas transport and distribution. In addition, a need for facilities for gas storage was encountered [2].

Further development of technology related to natural gas usage led to the exploitation of a high-pressure gas deposit in central Indiana, which started in 1891. This gas was transported for consumption to Chicago in Illinois and a 192 km long pipeline was built for that purpose. Natural gas is also extracted together with oil from the oil wells, but during the early period of oil exploitation it was observed as burden. Hence, natural gas was leaked directly to the atmosphere at the oil fields or it was burnt and the flame illuminated the oil fields day and night. Oil companies realized that this is an unreasonable practice and they started to develop gas transmission pipelines and pipeline networks for gas distribution to the consumers in large cities. This activity was an additional source of profit for them. The technological progress after the World War II boosted the natural gas consumption, for example in pipeline manufacturing, metallurgy and welding. Gas transport companies started building and expanding their pipeline systems. The fast and steady growth of gas industry finally entailed the construction of various gas facilities, including processing and storage plants, as well as a number of sustainable projects around the world since the late 20th century. In this way natural gas became an attractive alternative to electricity and coal [1].

Despite periodic economic and international crises, new oil and gas pipelines are being planned and built. Pipeline and Gas Journal’s worldwide survey (January 2017) [4] figures indicate 134866 kilometres of pipelines are planned and under construction. Of these, 61783 kilometres represent projects in the engineering and design phase (planned) while 73083 kilometres reflect pipelines in various stages of construction. Next figure 1.1 identifies regions by levels of new and planned pipeline kilometres in seven basic country groupings in the report: North America 51200 kilometres; South/Central America and Caribbean 7532 kilometres; Africa 6412 kilometres; Asia Pacific Region 31926 kilometres; Former Soviet Union and Eastern Europe 20448 kilometres; Middle East 14833 kilometres; and Western Europe and European Union 2515 kilometres [4].
Primary energy consumption growth averaged 2.2% in 2017, up from 1.2% in 2016 and the fastest since 2013. This compares with the 10-year average of 1.7% per year. By fuel, natural gas accounted for the largest increment in energy consumption, followed by renewables and then oil. Natural gas consumption rose by 96 billion cubic metres (bcm), or 3%, the fastest since 2010. This consumption growth was driven by China (31 bcm), the Middle East (28 bcm) and Europe (26 bcm) [5].

Global natural gas production increased by 131 bcm, or 4%, almost double the 10-year average growth rate. Russian growth was the largest at 46 bcm, followed by Iran (21 bcm). Gas trade expanded by 63 bcm, or 6.2%, with growth in LNG outpacing growth in pipeline trade. The increase in gas exports was driven largely by Australian and US LNG (up by 17 and 13 bcm respectively), and Russian pipeline exports (15 bcm) [5].

2017 was a bumper year for natural gas, with consumption (3.0%, 96 bcm) and production (4.0%, 131 bcm) both increasing at their fastest rates since the immediate aftermath of the financial crises. The growth in consumption was led by Asia, with particularly strong growth in China (15.1%, 31 bcm), supported by increases in the Middle East (Iran 6.8%, 13 bcm) and Europe. The growth in consumption was more than matched by increasing production, particularly in Russia (8.2%, 46 bcm), supported by Iran (10.5%, 21 bcm), Australia (18%, 17 bcm) and China (8.5%, 11 bcm) [5].
Natural gas is foreseen as the fuel source with the highest increase in consumption in the near future. Huge projects of transmission pipelines are planned and conducted with the aim of transporting gas from distant gas fields with great reserves to industrial areas and big cities. Natural gas is transported through long distance pipelines by work of a series of compressor stations.

1.3 Natural gas origin and composition

“Natural gas exists in nature under pressure in rock reservoirs in the Earth’s crust, either in conjunction with and dissolved in heavier hydrocarbons and water or by itself” [2]. It is exploited alone from the natural cavities or porous sediments or together with crude oil. “Natural gas has been formed by the degradation of organic matter accumulate in the past millions of years. Two mechanisms (biogenic and thermogenic) are responsible for this degradation” [2].

Natural gas is composed mainly of methane. Other ingredients are paraffinic hydrocarbons such as ethane, propane, and butane. Natural gas contains nitrogen as well as carbon dioxide and hydrogen sulfide [2]. A minor amount of argon, hydrogen, and helium may exist in it. Natural gas from geographically separated areas can have substantially different composition. Table (1.1) illustrates the typical composition of natural gas. Hydrocarbons C5+ can be also included and it can be separated as a light gasoline. Some toxic substances might be present in small quantities, such as benzene, toluene, and xylenes, as well as some acid contaminants like mercaptans R-SH, carbonyl sulfide (COS), and carbon disulfide (CS2). Mercury can also be present either as a metal in vapor phase or as an organometallic compound in liquid fractions [2].

Typical composition of natural gas is presented in Table 1.1. It should be emphasise that the gas composition can vary substantially from the values presented in Table 1.1. Standard test methods were developed for the determination of the natural gas composition and description of these methods is available elsewhere [2].

1.4 Demand for natural gas

The demand for natural gas has been steadily increasing over the last several years as shown in figure (1.2). The world consumption of natural gas in the year 2018 was 3.85 trillion cubic meters (Tm³) (on the left vertical axis the consumption is presented in trillion cubic feets - TCF) [6, 7]. The projected demand up to 2030 is also illustrated in the same figure.
It is difficult to predict the increase in natural gas demand in the future since it depends on several socioeconomic factors. Starting with worldwide energy demand, figure (1.3), the energy demand is expected to grow from $5.71 \times 10^5$ PJ (petajoule (PJ) = 1015 J) in 2010 to $9.54 \times 10^5$ PJ in 2050 for about 67% total increasing.

**Table 1.1: Typical Composition of Natural Gas [2]**

| Name            | Formula | Volume (%) |
|-----------------|---------|------------|
| Methane         | CH$_4$  | >85        |
| Ethane          | C$_2$H$_6$ | 3-8      |
| Propane         | C$_3$H$_8$ | 1-2      |
| Butane          | C$_4$H$_{10}$ | <1       |
| Pentane         | C$_5$H$_{12}$ | <1       |
| Carbon dioxide  | CO$_2$  | 1-2       |
| Hydrogen sulfide | H$_2$S | <1        |
| Nitrogen        | N$_2$   | 1-5       |
| Helium          | He      | <0.5      |

**Figure 1.2: Historic demand for natural gas [6]**
Figure 1.3 shows that the greatest increase in energy consumption occurs in non-OECD countries, “where strong economic growth, increased access to marketed energy, and rapid population growth lead to rising energy consumption. On the other hand, in OECD countries, growth in energy consumption is slower as a result of relatively slower population and economic growth, improvements in energy efficiency, and less growth in energy-intensive industries. Energy consumption in non-OECD countries increases nearly 70% between 2018 and 2050 in contrast to about 15% increase in OECD countries” [8].

In figure (1.3), the energy demand increase is uneven across the world. In developing countries, the increase in demand is a lot higher (22% over last eight years), whereas, for industrialized countries the increase is slower (4% over last ten years). The shift in demand can have significant consequences on the demand for natural gas since transportation of gas is an important bottleneck in satisfying the demand for natural gas [8].

According to the U.S. Energy Information Administration (EIA) report (September 2019) [8] the world natural gas consumption demand will increase more than 60% from 2010 to 2050, from about $1.3 \times 10^5$ PJ to $2.1 \times 10^5$ PJ over forty years. “Natural gas use accelerates the most in countries outside of the Organization of Economic Cooperation and Development (OECD) to meet demand from increased industrial activity, natural gas-fired electricity generation, and transportation fueled by liquefied natural gas (LNG).”
Natural gas consumption in non-OECD countries will grow from about $74\times10^3$ PJ in 2018 to around $126.5\times10^3$ PJ in 2050, a 71% increase. It is projected that the natural gas consumption during this time in the OECD countries will increase 17% between 2018 and 2050.

Also, the projected demand of natural gas is shown in figure (1.4). This is the most likely demand based on an assumption that fuel cell technology will not have significant contribution to transportation power. If fuel cell technology indeed becomes viable, the demand for natural gas can be even higher than predicted in figure.

![World natural gas consumption with projections to 2050](image)

**Figure 1.4**: World natural gas consumption with projections to 2050 [8]

Even more interesting to examine is the percentage of world energy provided by natural gas compared with the other sources of energy. As in figure (1.5), the primary energy consumption by different types of fuel (sources) in the year of 2018 is illustrated where the natural gas occupies the third place preceded by oil and coal. In this review, primary energy comprises commercially-traded fuels, including modern renewables used to generate electricity [7].
In figure (1.6), energy produced from the natural gas and its projected demand is show and compared with the energy provided from coal for the period of forty years. In 2010, the energy produced from coal was more than the energy from natural gas by about $3.6 \times 10^3$ PJ. For three years after, both fuels keep to increase. In 2013 coal shows decline in energy production and the production of natural gas continues to increase. The 2028 is the year where both coal and natural gas production is about $1.5 \times 10^5$ PJ. After this, the energy provided by natural gas will be more than the energy produced by coal. For about five years after 2028 the energy provided by coal is expected to remain constant and then start to slightly increase up to 2050. The energy produced from natural gas is expected to show a gradual increase and reach $2.1 \times 10^5$ PJ in 2050 that is about $0.2 \times 10^5$ PJ more than the energy provided by coal [8]. Hence, it is concluded that the outlook of the future natural gas roll in the primary energy mix in the World shows that its consumption, production and reserves will continue to increase for the foreseeable future [8].

![Pie chart showing energy consumption by fuel](image)

**Figure 1.5:** World-wide primary energy consumption by fuel (sources), 2018
The natural gas supply to the consumers is based on the following chain of technical and technological processes and activities [9].

- **“Exploration: In this stage, the issue of how natural gas is found and how companies decide where to drill wells for it is addressed.**
- **Extraction: This stage deals with the drilling process, and how natural gas is brought from its underground reservoirs to the surface.**
- **Production: In this stage the processing of natural gas once is brought out from the underground takes place.**
- **Transport: The natural gas is transported from the processing plant to local distribution companies across a pipeline network in this stage.**
- **Storage: This stage accounts for the storage of natural gas.**
- **Distribution: In this stage, natural gas is delivered from the major pipelines to the end users.**
- **Marketing: This stage involves the buying/selling activity from the natural gas marketers.”**

The reliable and efficient transportation of natural gas from production to consumption areas needs a developed transportation system. In the majority of cases the distance between the natural gas wells and consumers in industry or domestic sector is long over thousands of kilometres. Therefore, long distance transmission pipelines are being built, accompanied with the development of complex distribution systems in urban and industrial areas with the aim of gas supply to final consumers. The supply of the natural gas is closely linked with its storage. The roll of the gas

**Figure 1.6: World energy production demand by natural gas and coal [6]**
storage is to adjust mainly constant gas extraction from the natural wells with variable seasonal or
daily gas consumption by the final consumers. In winter periods natural gas consumption increases
due to heating. Hence, the gas is accumulated in summer period usually in huge natural
underground cavities, and discharged from them and consumed in winter period. On the daily level,
during the reduced consumption periods, natural gas can be packed in long transmission pipelines,
distribution networks and built gas storage facilities, while in later periods the gas is discharged
from these storage units in order to cover peaks of increased consumption.

The whole transportation path, from the gas wells to the final consumers consists of three major
types of pipelines: “the gathering system, the interstate pipeline system, and the distribution system.
The gathering system consists of low pressure, small diameter pipelines that transport raw natural
gas from the wellhead to the processing plant. Natural gas from a particular well might have high
sulfur and carbon dioxide contents (sour gas), a specialized sour gas gathering pipe must be
installed. Sour gas is corrosive, thus its transportation from the wellhead to the sweetening plant
must be done carefully” [9].

1.5 Transportation of natural gas

Natural gas is often found in places where there is no local market, such as in the many
offshore fields or onshore fields in the deserts around the world. For natural gas to be available to
the market it must be collected, processed, and transported.

Natural gas, as a result of the storage difficulties, needs to be transported immediately to its
destination after production and processing from a reservoir. There are a number of options for
transporting natural gas energy from oil and gas fields to market. These include pipelines, LNG
(liquefied natural gas), MLG (medium conditioned liquefied gas), or CNG (compressed natural gas)
[2].

1.5.1 Liquefied natural gas (LNG)

Liquefied natural gas (LNG) technology has proven to be effective over the last 30 years. In
2005, about 0.2 Tm³ or 5.6% of natural gas was transported using LNG technology. By 2020, the
worldwide demand for gas transported through LNG is expected to be 0.49 Tm³. The LNG was
exported from eight countries (Indonesia, Malaysia, Algeria, Australia, Brunei, United Arab
Emirates, United States, and Libya) and was imported by eight countries (United States, Japan, South Korea, Taiwan, Belgium, France, Spain, and Turkey).

1.5.2 Gas to liquid products

Gas to liquid (GTL) technology refers to the conversion of natural gas into synthetic hydrocarbon liquids, particularly middle distillates. By some estimates, 25.5 Tm$^3$ of natural gas are stranded too far from markets to be produced or transported profitably. This is sufficient to justify about 200 gas-to-liquid plants.

The technology of converting natural gas to liquids is not new. In the first step, natural gas is reformed and converted to hydrogen and CO. The mixture is called synthetic gas or syngas. This is the same process for converting natural gas to hydrogen, which can be used as a fuel in a fuel cell. This step is the most expensive and consumes about 50% of the total GTL costs. In the second step, in a slurry reactor the syngas is blown over a catalyst at about 232°C and is converted to liquids. This is called Fischer-Tropsch synthesis. These liquids can be converted to other desirable products, such as synthetic fuels, using the cracking process.

1.5.3 Natural gas transportation via pipelines

Transportation of natural gas from gas fields with wells to consumers’ areas is very important and crucial activity regarding reliability and economics of gas supply to the consumers. Natural gas can be transported by different technological solutions, but the most economically acceptable method to transport large quantities of natural gas is by pipelines. This method of gas transport by pipelines has been boosted by metallurgical and welding techniques improvements. Hence, there is a fast increase of pipeline networks deployment during the last decades all over the world, which enables economic gas transportation.

Pipelines can be installed both offshore and onshore, but there is an substantial difference in terms of security and construction prices. “Building pipeline systems under the sea is highly costly and technically demanding, a lot more than onshore” [9].

Transportation pipelines can be divided into three types: gathering pipelines, transmission pipelines, and distribution pipelines. Raw natural gas is transported from the production wells to the gas processing plant by gathering pipelines. Transmission pipelines transport natural gas from the gas processing plants towards storage facilities and distribution systems, while these distances can
be of the order of hundred or even thousands of kilometres. The transmission pipelines are under high pressure and the pressure is reduced at connections with the distribution network pipeline systems. Distribution pipeline systems can be found in communities and distribute natural gas to homes and businesses.

At the end, the natural gas pressure is further reduced in devices called regulators, which decrease the pressure to a level that is safe to enter homes or other facilities [10].

The main differences among these systems are the physical properties of the pipelines used, such as diameter, stiffness, material, etc., and the specifications of the maximum and minimum upstream and downstream pressures.

The major transportation of natural gas is carried through cross-border pipelines. Throughout the world, major efforts are under way to increase the gathering, transmission, and distribution capacity in order to promote and support projected growth of natural gas demand [6].

The natural gas cross-border transmission pipeline infrastructure in the U.S. represents one of the largest and most complex mechanical systems in the world. This system of natural gas pipeline network is a highly integrated network that moves natural gas throughout the continental United States. More than 210 natural gas pipeline systems have about 490850 kilometres of interstate and intrastate transmission pipelines that link natural gas production areas and storage facilities with consumers. In 2017, this natural gas transportation network delivered about 0.708 trillion cubic meter (Tm$^3$) of natural gas to 75 million customers. These pipelines systems are driven by more than 1,400 compressor stations that maintain pressure on the natural gas pipeline network and assure continuous forward movement of supplies.

This system has been developed over the last 60 years, and is controlled at a very low level of sophistication [6]. Quite often, collected natural gas (raw gas) must be transported over a substantial distance in pipelines of different sizes. These pipelines vary in length between hundreds of meters to hundreds of kilometres, across undulating terrain commonly occurs because of the multicomponent nature of transmitted natural gas and its associated phase behaviour to the inevitable temperature and pressure changes that occur along the pipeline [2].

1.6 Mathematical flow modelling of gas pipelines

Optimal design of the gas transmission pipeline diameter for steady-state operational conditions is determined by the minimal overall exploitation costs. The major parts of these costs
are investment cost in the pipeline and operational cost of fuel that energizes compressors. The greater pipe diameter means higher investment costs, but lower gas velocity, lower pressure drop and lower compressors’ power and fuel consumption, and vice versa, the lower diameter reduces investments but increases fuel expenditures. But, the gas consumption has transient character and it also influence the optimal design of gas pipeline diameter. A design according to the maximum gas flow rate, without taking into account the possibility of gas accumulation, would lead to an uneconomical solution. Hence, there is a need for accurate prediction of operational parameters (mainly flow rates, velocities and pressure drops) of natural gas transmission pipelines both in steady-state and transient conditions. Such an engineering need has led to the development of various types of mathematical models for the prediction of gas transport. “Isothermal steady-state and transient pressure drop or flow rate calculation methods for single-phase dry gas pipelines are the most widely used and the most basic relationships in the engineering of gas delivery systems. They also form the basis of other more complex transient flow calculations and network designs” [2].

There are several purposes that shape the demand of having precise and accurate pipeline mathematical flow models, mainly serving for pipeline balance, pressure monitoring, and deliverability. There are two types of mathematical models for lengthy pipeline flow; the steady-state and the transient models. The core difference between the two types of flow models lies in the equation of motion. In the transient flow models, there are terms that represent the change of transport parameters with time. When these terms are set to zero, the steady-state representation of the flow equation is obtained. Consequently, and due to this fundamental difference between the two types of models, the functionality of each of them differs. For purposes such as pressure monitoring and leak localization, in which the change of transport parameters with time is vital, transient flow models become a necessity. For other purposes such as pipeline design, sizing, line capacity estimations and line packing, where the changes of transport parameters with time are of no significance, steady-state models become ideal. Both of the two types are approximations of the actual conditions of the pipeline.

The prediction of the pressure drop due to gas friction on the inner pipeline wall is one of the most important tasks in the design of the gas transmission and network distribution systems. On the basis of this prediction the capacity and operational characteristics of compressor stations should be determined [11].

A mathematical modelling for the simulation of gas transport parameters is especially important for the transmission systems of large capacity due to its overall influence on the whole energy systems of regions and countries. Researchers have simulated and optimized gas pipeline
networks and equipment for both steady-state and transient conditions with varying degrees of success. In Chapter 2 of this dissertation a literature review of previous research results are presented. “Historically, most of the efforts have been focused on steady-state flow conditions, but researchers have also identified the need for transient flow simulation” [12].

Fluid dynamicists and mechanical engineers are devising robust mathematical and numerical models to serve the gas transmission related purposes. Material engineers and scientists are developing advanced materials for the pipeline insulation and protection. Electric, control, and telecommunications engineers are developing sophisticated SCADA (Supervisory Control and Data Acquisition) systems in order to gain full control over the millions kilometres of gas pipelines worldwide.

A range of numerical schemes have been applied for the simulation of natural gas flow in pipelines, such as the method of characteristics, finite element methods, and explicit and implicit finite difference methods. The choice of the method is influenced more or less on the individual requirements of the system under investigation.

1.7 Problem background

In general, a mathematical model to simulate pipeline system operation, as well as the impact of design changes and equipment enhancements is urgently needed for this huge system to adjust the operation conditions. Simulation allows us to predict the behaviour of natural gas pipelines under different conditions.

Such predictions can then be used to guide decisions regarding the design and operation of the real system. The control of natural gas pipelines system also requires simulation in order to obtain information about the pressure and flow rates at given points of the pipeline [13].

Natural gas driven by pressure is transported through pipeline for a hundreds or thousands of kilometres or miles (cross-border). As it flows over long distances through pipelines, energy and so pressure is lost due to both the friction of pipelines and heat transfer between the natural gas and its environment [14]. This lost pressure of the natural gas is added or recovered at the compressor stations which are installed along the route of the natural gas pipelines which consume un-neglected amount of money.

Many pipelines systems use online pressure and flow monitoring to detect leaks. In these systems, a computer algorithm compares actual pipeline operating conditions to calculated
conditions. Discrepancies beyond a certain threshold are potential leaks. Numerical simulations have been used for solving these problems; these simulations are based on either transient or steady-state models of pipelines [14].

1.8 Problem statement

Simulations and analyses of natural gas pipeline transients provide an insight into flow parameters changes and a pipeline capacity to deliver gas to consumers or accumulate gas from the source wells under various abnormal conditions. This information is important in order to control gas pressure changes within acceptable minimum and maximum setpoints and to plan repairs in timely manner with the aim of sustaining gas accumulation and supply to consumers in cases of various disturbances.

The major concern of the present thesis is to devise a mathematical model and a proper solution algorithm for modelling compressible, frictional natural gas transient flow in complex pipelines to predict natural gas flow properties. The considered area of application of such model is natural gas flow in cross-border and network pipelines.

Therefore, a numerical model and a computer code have been developed for the simulation and analyses of natural gas transients, such as those typically found in high-pressure gas transmission pipelines. The model is based on the mass and momentum balance equations that describe one-dimensional, compressible, frictional natural gas transient flow, as well as on boundary conditions that enable simulation of gas flows in complex pipeline networks. The developed model is solved with the numerical procedure of the method of characteristics and implemented into the gas transient analysis (GTA) computer code.

1.9 Objective

The objective of this study is to develop a numerical model and a computer code for the simulation and analyses of one-dimensional, compressible, frictional natural gas transient flow in lengthy and shortened pipelines that are able to predict natural gas flow properties in normal and abnormal operation conditions under isothermal or non-isothermal conditions.
1.10 Scope of research

This research involves both mathematical modelling and numerical simulation of one-dimensional, compressible, frictional natural gas transient flow, such as those typically found in high-pressure gas transmission pipelines to predict the behaviour of flow under different operation conditions.

The developed model and the Gas Transient Analysis - GTA code are validated by simulations of several test cases that are available in open literature. Afterwards, the code is applied to the simulation and analyses of transients in a real, several hundred kilometres long natural gas pipeline in Libya.

1.11 Thesis organization

The present thesis proposes a novel mathematical model and a computational algorithm to model the transmission of natural gas in (length/short) pipelines. A predictive numerical scheme is proposed to encapsulate the model equations and solve them consecutively to provide flow rate, pressure, temperature, density, and other profiles for such class of pipelines. The thesis comprises seven chapters; the second and third chapters respectively deal with the literature and discuss the properties and flow dynamics of natural gas, as well as the mathematical modelling of natural gas flow in pipeline systems is highlighted in these chapters. Also, methods of computing natural gas properties and flow field variables (density, velocity, mass flow rate, and etc.) are briefly described in chapter three. The model development, the applied numerical procedure and the outline of the GTA (Gas Transient Analysis) code are presented in Chapter 4. In the fifth chapter, the developed model and the corresponding GTA code for the simulation and analyses of gas pipeline transients are validated by simulation of several test cases that are available in the open literature. Numerical results of gas pipeline transient simulations are also illustrated in this chapter.

The natural gas transients in the long gas pipeline of the Western Libya Gas Project are presented and discussed in Chapter 6 for three scenarios related to (i) disruption of gas supply from the gas source wells to the pipeline inlet point and (ii) stopping of gas delivery to a thermal power plant and a terminal for further off-shore gas transport at transmission pipeline outlet points. The method for the evaluation of thermal effects during these gas accumulation and discharging transients are presented in this chapter, together with the comparison of pressure changes obtained with isothermal and non-isothermal model evaluations.

Chapter seven provides detailed conclusions for this thesis. The appendix section contains the derivation of formulas for mathematical modelling of natural gas one-dimensional unsteady
compressible flow in pipelines based on the governing equations of one-dimensional, compressible, frictional natural gas transient flow in pipelines.

1.12 Major contribution

The major contributions of this thesis are as following:

1. Presenting chronological and technical reviews of the mathematical modelling of natural gas in pipelines.
2. Devising a novel algorithm based on numerical model and a computer code for the simulation and analyses of natural gas transients, such as those typically found in high-pressure gas transmission pipelines. The developed model is solved with the numerical procedure of the method of characteristics and implemented into the gas transient analysis (GTA) computer code.
3. Providing evidences of code validation and stability using several case studies.
4. Contributes to observed deviations between modelled and measured flow parameters in the natural gas transmission.
5. Analysis of long transmission gas pipeline transients caused by disturbances of gas supply and delivery. The main aim of the performed simulations is to show the pipeline gas accumulation capacity, i.e. to accumulate gas during the disturbance at the gas delivery to consumers and to supply the consumers during disturbance in gas supply at the source.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Natural gas pipelines systems are becoming more complex as the use of this energy source increases. Mathematical modelling is one of the most important tools used in both design and operation of natural gas pipelines. Plentiful efforts have been spent and continue to be spent on steady-state and transient mathematical models.

In recent decades, world consumption of natural gas has grown and it is now one of the most commonly used primary energy source worldwide, accounting for 24% of total primary energy supply, behind coal and oil (33.5% and 27%) respectively [7], and it is the second energy source in power generation by 23.2%, behind coal (IEA, 2019) [15]. Natural gas is becoming a larger portion of the petroleum sector and is considered to play a more important role in the future of environmental friendly energy supply. Transmission pipelines have been developed in order to supply natural gas from source wells to power stations, distribution networks and industries. Numerical simulations of transmission pipeline transients are applied with the aim of predicting their capacity and dynamic behaviour under various normal operational conditions, such as pipeline start-ups and shut-downs, variations of gas consumption, etc., as well as under abnormal conditions caused by various equipment failures and disturbances. Results of the gas pipeline transient simulations are a support to the design of pipelines and its safety and control systems, as well as to the specifications of operational procedures and guidelines.

Numerous researches are available in the open literature on numerical simulations of natural gas pipeline transients. A brief overview of some results is presented in order to illustrate the variety of engineering applications

Simulations and analyses of natural gas pipeline transients provide an insight into flow parameters changes and a pipeline capacity to deliver gas to consumers or accumulate gas from the source wells under various abnormal conditions. This information is important in order to control gas pressure changes within acceptable minimum and maximum setpoints and to plan repairs in timely manner with the aim of sustaining gas accumulation and supply to consumers in cases of
various disturbances. Therefore, a numerical models and a computer codes have been developed for the simulation and analyses of natural gas transients, such as those typically found in high-pressure gas transmission pipelines. It is noteworthy to mention that many operation conditions problems can be solved by transient flow modelling.

The most notable efforts dealing with the problem of mathematical modelling of natural gas pipelines are reported in this chapter.

2.2 Steady-state models

Steady-state gas flows have been studied in numerous research papers and theses. Steady-state flows of natural gas through pipelines are simulated in order to investigate and analyse the behaviour of gas flow in both operational and design conditions. In some researches, the investigators as Stoner [16], Mohitpour et al [17], Costa et al [18], etc., developed models which describe isothermal gas flow, and some others applied models that analyse non-isothermal gas flow as what Borujerdi and Rad [19] have done - they analysed the gas flow in pipelines subjected to wall friction and heat transfer. A few researchers presented comparisons between isothermal and non-isothermal pipelines gas flow models, as it was done by Alghlam [20]. On the other hand, some models are developed analytically such as those solved by Cameron [21], Szoplik [22], and Zhou and Adewumi [23] and the others are solved numerically as done by Mohitpour et al. [17] and some other investigators by using a various of numerical methods such as the method of characteristics, the implicit finite difference method, the explicit finite difference method, the finite elements method; the choice depends upon the particular requirements of the system under studying.

In addition, in this subsection, in order to provide some reading structure, it would be useful to find some other common characteristics among these research papers and thesis, such as solving the gas flow models with taking into account or neglecting the term of kinetic energy in the energy equation, studying the gas flow in pipelines systems as a single-phase flow and two-phase flow, and investigate the non-isothermal gas flow with and without consideration of gas wall friction, etc.

The most commonly used equations for the prediction of pressure drop due to wall friction in natural gas pipelines under steady-state calculations are the Weymouth equation, the Panhandle equations, Colebrook-White equation and AGA equation. Governing equations of the compressible fluids flow through the pipes were described by some researcher as Ouyang and Aziz [24], Rhoads [25] and Schroeder [26].
Abbaspour establishes general flow equations of simple form as a principle of the pressure loss calculations due to friction, elevation and kinetic energy [13]. Stoner had developed a new methodology for getting a steady-state solution of an integrated gas system model comprising of pipelines, compressors, control valves and storage fields. He utilized Newton-Raphson method for solving nonlinear algebraic equations [16, 27].

Berard et al. developed a simulation based on computer software to perform a steady-state gas transmission network utilizing the Newton-Raphson method for solving nonlinear equations. The simulated computer software has several features that facilitate efficient, accurate simulation of large nodal systems, including 1) optimal number of nodes, 2) implicit compressor fuel gas consumption calculation, 3) the ability to prorate gas volumes entering the network system, and 4) gas temperature distribution calculation [28].

Hoeven and Gasunie[29 ] used a linearization method to describe some mathematical aspects of gas network simulation. Tian and Adewumi [30] used a one-dimensional compressible fluid flow equation without neglecting the kinetic energy term to evaluate the flow of natural gas through a pipeline network. This equation includes a functional relationship between the gas flow levels along with a given segment of the pipe's inlet and outlet pressure. This then defines the steady-state compressible gas flow, assuming constant temperature and compressibility factor.

Costa et al. [18] presented a simulation of a steady – state gas pipeline. This simulation selects the pipeline and the compressors as the building components of a compressible flow network. However, this model uses the one-dimensional compressible flow equation to describe the relationship between the pressure and temperature along the pipe, as well as the flow rate through the pipe. To explore the variations between isothermal, adiabatic and polytropic flow conditions, the flow equation and the conservation of energy equation are both solved in a coupled way. The compressors are modelled simply by using a functional relationship between the increase in pressure and the rate of gas mass flow through the compressor.

A hybrid network model (HY-PIPENET) that uses a minimum cost spanning tree was presented by Sung et al. [31]. In their simulation a parametric study was achieved to comprehend the role of each individual parameter such as the source of pressure, flow rate and pipeline diameter on the optimized pipeline network. The authors distinguish that there is an optimal relationship between pipe diameter and the source pressure.

Rios-Mercado et al. [32] proposed a reduction strategy to solve problems related to the optimization of the natural gas transmission pipeline network. Such findings are valid for compressible steady state flow through a pipeline network. The decision variables are the rate of the
mass flow through each arc (segment of the pipeline), and the degree of the gas pressure at each node.

Martinez-Romero et al. [33] have defined the compressible steady-state flow through a pipeline. For the most appropriate flow equations, they provided a sensitivity analysis describing the main parameters in the optimization process. The software package “Gas Net” has been used by them based on Stoner’s method with some enhancements to solve the system equations. The essential mathematical model assumed a two element gas network: nodes and connectors of nodes. The connectors are components with different inlet and outlet pressures, such as pipes compressors, valves, and regulators.

Cameron [21] introduced TFlow using a steady-state and transient simulation model based on Excel. TFlow contains a user interface written in Microsoft Excel’s Visual Basic for Applications (VBA) and a dynamic linked library (DLL) written in C++. All information required to model a pipeline system is contained in an Excel workbook, which also displays the simulation result. The robustness for general applications, however, is not readily apparent.

Doonan et al. [34] simulated a pipeline network using SimulinkTM. The simulation was used to analyse the safety parameters of an alternate control a considerable distance downstream from the main pressure regulating station. The elements that were used in this model were extremely limited. SimulinkTM has very limited knowledge on operation and reliability of pipelines. Fauer [35] proposed a general equation and contributed to making precise predictions for every variable. In order to provide reliable predictions the model must include many descriptions explaining not only the pipeline network but also the fluid it carries and the environment in which it operates. He used two steps to reach a useful model, 1) getting the appropriate level of detail in the model and 2) tuning the model to real world results that include steady-state tuning, steady-state tuning with transient factors, transient tuning and on-line tuning.

The well-known Patankar process "SIMPLE algorithm" (Patankar, 1980), known in Computational Fluid Dynamics (CFD), was used by Greyvenstein and Laurie to solve pipe network problems. The solution of the pressure correction equation, the consistency of the algorithm, the sensitivity to initial conditions and the convergence parameters are given particular attention [36].

Mohitpour et al. [17] addressed the significance of a dynamic simulation on pipeline transmission systems design and optimisation. The authors demonstrate in this paper that steady-state simulations are enough to optimize a pipeline when supply / demand conditions are relatively stable. In general, steady-state simulations should give a reasonable degree of confidence to the designer when the system is not subject to radical changes in mass flow rates on operating
conditions. The mass flow rate varies in practice, so the most practical and general simulation is one that allows for transient behaviour.

Zhou and Adewumi [23] presented a new analytical equation which was derived based on the continuity and momentum equation for gas flow in pipelines, without neglecting any terms in the momentum equation. The equation provides a functional relationship among inlet and outlet gas density, gas mass flux, length, internal diameter and wall friction. It can handle any pipeline configuration, including horizontal, vertical and inclined pipelines. Ouyang and Aziz [24] developed a new flow equation to compensate for the drop in pressure due to changes in friction, elevation and kinetic energy. Simplified forms are also provided for new gas flow equations in pipelines or wells in which the term of kinetic energy can be ignored. Such new general flow equations and their simplified forms are compared to the previously used AGA equations and evaluated using field data. Results show that the new equations make excellent estimates of flow rates or drops in pressure, and are valid over a much wider range of gas types and gas flow rates than the AGA equation and old simplified flow equations. Furthermore, various empirical explicit correlations for the Fanning friction factor are compared.

Schroeder outlined equations that control compressible fluid flow through pipes. Particular emphasis has been placed on those used in the natural gas industry, in the hope that engineers in that industry will make informed decisions on how to model pipes. All practical equations were developed to solve extreme numerical problems, and the development in computing technology had made them absolute. It discussed further a new flow formula proposed by the research project GERG * [26].

Borujerdi and Rad [19] analysed the gas flow in high pressure buried pipelines treated with wall friction and heat transfer. The governing equations for one-dimensional compressible pipe flow are derived and solved numerically. This examines the effects of friction, heat transfer from the pipeline wall and inlet temperature on several parameters such as gas pressure, temperature and mass flow rate. By using some previous numerical experiments and available experimental data, the numerical scheme and numerical solution was verified.

Zhou and Adewumi [37] presented a mathematical model describing steady-state gas flow in pipeline. The model was reduced to a second-order ODE (Ordinary Differential equations) system of first order initial-value problem with gas pressure and temperature as the two dependent variables. The fourth-order Runge-Kutta method was used to solve this ODE system.
2.3 Transient models

Some researchers developed or presented natural gas models for prediction of pressure transients, temperature transients, leakages, etc. Numerical simulations of gas pipeline network of transient flow were conducted by Osiadacz [38] to predict the gas pressure and flow rate distribution and time change within the network, with the aim of minimization of compressors’ operational costs. Osiadacz used the theory of hierarchical systems to explain the dynamic optimisation of high-pressure gas networks. The author explains that mathematically the transient optimization is more complicated than the steady state simulation, but the advantage of using a dynamic simulation is that the operator can achieve greater savings. He further states that it is of great importance to be able to optimize large-scale systems represented by partial differential equations as fast as possible in order to achieve real time optimization.

Gas pressure and flow rate changes in the long transmission pipeline network under the partial reduction of the gas supply at the inlet point were predicted by Pambour et al. [39]. They applied the approach with the isothermal gas flow model, also in an investigation of long transmission pipeline transients. According to these authors, a prediction of the influence of thermal effects on the gas flow would require a good knowledge of the thermal resistance of the ground and the distribution of ground temperature, which is typically difficult to estimate. Moreover, due to the slow dynamics in transport pipelines (with gas velocity lower than 15 m/s) the flowing gas typically has sufficient time to exchange heat with the ground and adapt its temperature to ground temperature. Thus, it is reasonable to neglect the temperature changes and assume a constant temperature equal to the ground temperature, as it is done by many authors in the literature.

Also, Mohitpour et al. [17] showed that the natural gas transmission pipelines should be designed by taking into account the transient pressure changes and compressible gas accumulation in the volume of pipelines, which are caused by the daily changes of gas consumption by consumers. A calculation of the transmission pipeline diameter on the basis of an average daily gas consumption and the minimum pressure setpoint would lead to an under design of the supply capacity. A calculation of the pipeline diameter on the basis of the maximum gas consumption, but without taking into account the transient accumulation of the gas within the transmission pipelines would lead to an over design of the pipeline and increased construction costs. Zuo et al. [40] investigated gas pipeline transients as a support to the prediction of setpoints for the action of automatic line-break control valves closure, which are used to prevent the gas release in the event of a pipeline rupture accident.
On the other hand, for the temperature profile of buried gas pipelines prediction, M. Edalat [41] developed a new analytic technique based on the corresponding states principle. This new technique can predict temperature profile quite accurately without using any additional chart or table. It can also be used for predication of gas mixture temperature profile flowing in a buried pipeline. Also, Oosterkamp et al. [42] developed a model of one-dimensional gas flow inside pipe. For comparison the developed model is coupled to three different external heat transfer models (1D steady state, 1D radial unsteady and 2D unsteady description of pipe wall layer and soil) of the ambient domain (pipe wall layers and soil). Both conduction and convection heat transfer in the soil layers were investigated. The effect of transient boundary conditions on heat transfer rates and flow parameter calculations were quantified.

A natural gas leakage and transient gas dynamic forces, which act on the pipeline structure and supports during gas pipeline blowdown accidents were numerically simulated by Stevanovic [43]. Yuan et al. performed natural gas transient calculations with the aim of detecting partial and extended blockages inside the pipelines [44].

As same as the steady-state flow models of natural gas pipelines, some transient models are based on isothermal flow, and the rest on non-isothermal flow. But a few of these models made a comparison between the two types of flow as was done by Osiadacz and Chaczyskowski [11]. They used constant friction and compressibility factors, while neglecting the convective term to compare the transient models of isothermal and non-isothermal conditions for gas pipelines. They showed that there is a considerable difference within the pressure profile along the pipeline between the cases of isothermal and non-isothermal conditions, and this distinction increases with the gas density increase. Also, Thorley and Tilley [45] developed conservation laws for unsteady one-dimensional, non-isothermal compressible flow. They also surveyed several popular methods of solution for transient pipeline analysis, such as characteristics method, explicit and implicit method of finite difference, and finite-element method. The paper has an excellent review of the literature for these solution approaches.

Meanwhile, some investigators developed, presented, and solved the transient flow models numerically based on different mathematical methods. A number of numerical schemes and methods developed for the solution of differential equations were applied in numerical simulations of transient gas flows. For instance, Heath and Blunt [46] solved the mass and momentum conservation equations for slow isothermal gas transient flow by using the Crank-Nicolson semi-implicit numerical method. In case of nonlinear problems, this method is not stable according to the large time-step Neumann stability analysis; hence, this is the main disadvantage of the method. Osiadacz and Yedroudj [47] compared the application of the finite difference and the finite element
methods for the simulation of gas pipeline transients. It was found that for the same level of accuracy, the finite difference method provides less computational time. Deen and Reintsema developed a technique that reduces energy equation to one single parameter in the mass equation without isothermal or isentropic flow assumption. They used the characteristics approach in combination with a finite difference method with a second-order truncation error [48]. Again, the method of characteristics was also used by Abott [49], Mekebel and Loraud [50], and Osiadacz [51] for the simulation of natural gas transient flow. It was also applied by Yow [52] and Wylie et al. [53] with an inertia multiplier modification to the equation of motion to move forward its computational capabilities for analysing natural gas pipeline flow.

Wylie et al. [53] compared the method of characteristics with an implicit finite difference method which uses central differences. The finding was that the explicit technique of the method of characteristics avoids the difficulty of simultaneous solving of a large matrix of equations, which is pertinent to the implicit methods, and therefore can generally be used on smaller computers. The drawback of the method of characteristics is the restriction of the time step of integration by the distance between adjacent nodes, as defined by the Courant criteria.

Herran-Gonzales et al. [54] prepared S-functions and used MATLAB-Simulink for unsteady flow simulation of gas networks. They derived two simplified models based on the method of characteristics and Cranke-Nicolson algorithm. While, Reddy et al. [55] used the transfer functions in Laplace domain to present an effective transient flow simulation for gas pipelines and networks. The equivalent transfer functions have been derived for the governing equations, and afterwards, the convolution theorem has been used in order to obtain the output series form in the time domain. On the other hand, Alamian et al. [56] analysed the natural gas transient flow in pipelines based on the state space equations with different boundary conditions. The state space model was applied for a large and complex network and the accuracy and computational efficiency of the proposed simulation were verified by comparing the results with those of the conventional finite difference schemes. The results showed that the proposed simulation with the state space model of the unsteady gas flow is more computationally efficient than other finite difference methods. Based on the finite volume technique and transfer function models an efficient simulation of transient flow for gas pipelines and networks has been performed by Wang et al. [57]. For different boundary conditions, the equivalent transfer functions of the nonlinear governing equations have been derived to verify the accuracy of the proposed simulation and obtained results were compared with experimental results. In this simulation, the effect of the flow inertia is considered with discretization by TVD scheme.
In addition, a significant number of analysts investigated and analysed the behaviour of natural gas flow in pipelines systems as one-dimensional flow, though, rare investigators applied two-dimensional flow. As an example, Noorbehesht and Ghaseminejad [58] utilized two-dimensional computational fluid dynamic (CFD) simulations in cylindrical coordinates to investigate the dynamic behaviour of natural gas flow in transmission pipelines. The applied modelling approach was based on the continuity, momentum and energy balance equations, a modified k-ε turbulence model and the ideal gas law. They discretized the coupled partial differential equations with the finite volume method and compared results with the experimental field data. Errors of approximately 4 to 4.5% were achieved. In addition, to simulate a 2-D natural gas transient flow phenomena a numerical procedure was developed by Ibraheem and Adewumi [59]. They used a special Runge-Kutta based method to model accurate evolution of flow characteristics. Therefore, the Total Variation Diminishing (TVD) strategy can be utilized with higher-order accuracy in order to resolve sharp discontinuous fronts.

An alternative approach for simulating the dynamics of natural gas pipelines was presented by Dorao and Fernandino [60]. They described a time-space least squares spectral method using a C^1 type p-version hierarchical interpolations in space and time. In their formulation, both time and property space are coupled in the least squares minimization procedure. Farzaneh-Gord and Rahbari [61] developed an analytical approach to study and analyse natural gas pipeline network under transients based on the Kirchhoff’s laws.

Different levels of modelling accuracy were applied in the description of transient gas flows. Issa and Spalding [62], Thorley and Tiley [45] and Price et al. [63] evolved the basic equations for one-dimensional, transient, compressible flow, comprising the effects of wall friction and heat transfer. Some previous researchers had neglected the convective term in the momentum equation, which resulted in a loss of accuracy in results of natural gas transient flow in pipelines. Hence, Zhou and Adewumi [23] solved one-dimensional natural gas transient flow in a horizontal pipeline, and they took into account all terms in the momentum conservation equation.

Price et al. [63] calculated the effective friction factor and the overall heat transfer coefficient for a high pressure natural gas pipeline under fully transient flow conditions. For pipeline boundary state, they used time-varying SCADA (Supervisory Control and Data Acquisition) measurements and implicit finite difference approximations for solving partial differential equations. This transient flow model was based on one-dimensional transient flow equations (continuity, momentum and energy) numerical solution. Tentis et al. [64] simulated the unsteady gas flow in pipelines utilizing the Adaptive Method of Lines.
Rachford et al. [65] used a Galerkin finite element method to model the isothermal transient gas flow by considering two dimensional elements in space-time. Maddox and Zhou [66] applied steady-state friction loss determination techniques to assess the unsteady state behavior of pipeline systems from pressure drop and material balance relationships in real time.

Kiuchi [67] defined a method for solving isothermal unsteady compressible flow by a fully implicit finite difference. A Von Neumann stability analysis on the finite difference equations of a pipe (after neglecting the inertia term in the momentum equation) showed that the equations are unconditionally stable. He contrasted this method with other methods such as the characteristics method, the Lax-Wendroff method, the Guys method and the Crank-Nicolson method and showed that fully implicit methods are very reliable for a small number of sections and a large time step, which is very useful for industrial gas pipelines due to the savings in calculation time. Likewise, Beam and Warming [68] developed an implicit finite difference scheme in conversation-law form for the effective numeric solution of nonlinear hyperbolic systems. The algorithm results in a second order time-accurate, two-level, non-iterative solution using a spatially factored form.

Luongo [69] presented an isothermal solution for gas pipelines using the Crank-Nicolson method for solving equations. He developed a simulation code with both linearized and nonlinearized form of governing equations. By using an implicit finite difference scheme, the numerical solution is accomplished and then used to simulate transients in real pipeline networks. The results showed that 25% of the computational time is often saved by utilization of the linearized version without a serious sacrifice in accuracy.

Tao and Ti [70] extended the electric analogy method by combining resistance and capacitance, which resulted in a first order ordinary differential equation instead of partial differential equation for the solving of transient gas flow problems. It was found that the results obtained are akin to those obtained with the common techniques for solving partial differential equations.

A variety of hydraulic and thermal models and numerical methods were applied to the transient gas flow simulations. Osiadacz [71] characterized various transient flow models and assorted numerical methods which are utilized to resolve unsteady flow equations. For a given mathematical model, the challenge is to identify the numerical strategy that provides a high level of accuracy without requiring noteworthy computational resources. He used the Runge-Kutta Chebyshev (RKC) methods to solve ordinary differential equations resulting from the line approach applied to parabolic-type partial differential equations. Lewandowski [72] presented an application of an object-oriented methodology to model a network for the transmission of natural gas. For
organized modeling and sensitivity analysis of dynamic systems, this approach was applied using a library of C++ classes. The model of a gas pipeline network can be formulated as a directed graph. Each arc of this graph represents a segment of the pipeline and has associated a partial differential equation which describes the gas flow through this segment. Graph nodes corresponding to gas pipeline nodes may be categorized as: source nodes, sink nodes, passive nodes, and active nodes.

A focusing on another characteristic of the natural gas flow in pipelines can be posed, such as solving of governing flow equations of state for single-phase and two-phase transient flow. It could be clearly noted that many researchers solved and developed the transient models of gas flow of state for single-phase and few investigators analyzed the flow of state for two-phase as same as Modisette [73] and Abbaspour [74].

Modisette [73] investigated the influence of the thermal model on the overall pipeline model accuracy for both gas and liquid. He coupled this model with a transient ground thermal model. The first effort to simulate the non-isothermal, one-dimensional, transient homogenous two-phase flow gas pipeline system using two-fluid conservation equations was done by Abbaspour et al. [74]. He used the modified Peng–Robinson equation of state to calculate the vapor–liquid equilibrium in multi-component natural gas to find the vapor and liquid compressibility factors. The fully implicit finite difference was the technique of solutions. This approach is robust when a large time step for gas pipeline simulations is used and thus minimizes the calculation time. The algorithm used to solve the non-linear thermo-fluid differential equations for two-phase flow through a pipe is based on the Newton–Raphson method. In the equation of momentum conservation, the inertia term is not neglected.

Most previous researchers ignored the term inertia in the momentum equation when they simulated transient flow of single-phase natural gas in pipelines. This makes the consequent set of partial differential equations linear. Formerly, numerical methods utilized to solve this system of partial differential equations such as the method of characteristics and a set of explicit and implicit finite difference schemes. Neglecting the inertia term in the momentum equation will definitely result in a loss of accuracy of the simulation results.

Dufont and Rachford described the effect of thermal changes induced by transients in gas flow and examined three different environments around the pipe and illustrated the effect of these conditions on temperature distribution [75].

Gato and Henriques [76] presented a numerical modelling of the dynamic behaviour of high-pressure natural-gas flow in pipelines. They performed numerical simulations by solving the conservation equations for one-dimensional compressible flow, using the Runge–Kutta and
discontinuous Galerkin method, with third-order approximation in space and time. Chaczykowski [77] investigated the consequences gas state equation selection for the model of pipeline gas flow. He studied a non-isothermal transient gas flow model with AGA-8 and SGERG-88 equations of state. Models with Soave-Redlich-Kwong and Benedict-Webb-Rubin equations of state were solved to illustrate the overall gas flow model inaccuracies. The effect of the selection of different equations of state on the flow parameters is demonstrated and discussed.

Also, Chaczykowski [78] simulated the fast and slow fluid transients, like those normally found in high-pressure gas transmission pipelines by solving non-isothermal, one-dimensional gas flow model. Results of this simulation were applied to see the effect of different pipeline thermal models on the pressure, flow rate and temperature in the pipeline. Coelho and Pinho [79] discussed the particularities of the pressure drop equations being used in the design of natural gas pipelines. Several versions are presented according to the different flow regimes under consideration and through the presentation of these equations the basic physical support for each one was discussed as well as their feasibility.

Zhou and Adewumi [80] simulated eight field examples of engineering interest to provide some understanding of the behaviour of gas pipeline transient under operational scenarios. They solved one-dimensional natural gas transient flow in a horizontal pipeline, and they took into account all terms in the momentum conservation equation.

Abbaspour and Chapman [81] solved the continuity, momentum, and energy balance equations by using the fully implicit finite-difference technique to simulate and analyse non-isothermal, one-dimensional unsteady gas flow in pipelines. Their work results show that the effect of treating the gas in a non-isothermal manner is extremely necessary for pipeline flow calculation accuracies, especially for rapid transient process.

Adeosun et al. [82] took into account all terms in the momentum equation to present unsteady-state Weymouth Equations for flow of natural gas in long pipelines. The new Weymouth Equations yield results close to steady-state flow and is able to account for the initial transient in gas volumetric flow rate.

A reduced-order modelling approach has been proposed by Behbahani-Nejad and Shekari [83]. They considered the Euler equations as the governing equations and used the method of implicit Steger-Warming flux vector splitting (FSM). Linearized form of the Euler equations has been derived and the corresponding eigensystem was obtained. Then, they used a few dominant flow eigenmodes to construct an efficient reduced-order model.
Helgaker et al. [84] utilized an implicit finite difference method to solve the governing equations for one-dimensional compressible flow, and they investigated the influence of different physical parameters which enter into the model.

Helgaker et al. [85] predicted a gas temperature change in a long transmission gas pipeline during a several days transient. The pipeline is buried in the ground and the heat transfer from the gas to the soil was predicted with and without the heat accumulation in the soil. A better agreement between calculated and measured outlet gas temperatures was obtained by taking the heat accumulation in the ground. The model with the steady-state heat transfer from the gas to the soil showed greater divergences from the measured data during periods with more intensive transient operational conditions. Nevertheless, the variation of the presented measured gas temperature at the long pipeline outlet was within 3°C during the 4 days of the transient with the initial mass flow rate change of about 40 % and the gas pressure change variation between 150 bar and 180 bar. At the same time, there were no practical differences in the pressure predictions obtained by inclusion of thermal model with and without heat accumulation in the ground. But, regarding these presented results, no conclusions could be drawn about the uncertainty of the transient prediction that would be introduced by the assumption of the isothermal gas flow model.

Santos [86] also analysed the influence of the transient gas consumption on the optimal design and capital investments for the case of a long transmission gas pipeline. In addition, he showed the importance of the simulation and analyses of gas pipeline transients in cases of compressors’ trips in the early stage of the system design. It was found that parallel arrangements of compressors would increase a reliability of gas supply. Finch and Ko [87] provided detailed information in three different areas in flow equation usage. First, a step by step development of the fundamental flow equation is included, followed by a discussion of various friction factor equations and their relation to the Moody diagram. This included the diameter dependence, the Reynolds number dependence and the recently developed explicit friction factor equation. The last area discussed the practical considerations of using the fundamental flow equation. Applicable variable ranges, sensitivity, and efficiency factor usage are included.

Gas pipeline transients caused by the time-varying consumers demand was simulated by Zhang et al. [88], with the aim of applying optimization of operational control, which should provide a minimum of energy consumption by compressor stations. Zhang [89] numerically simulated the performance of the surge avoidance system in a natural gas compression station and validated the results against experimental measurements during the emergency shutdown of compressor in an experimental piping network. Recently, Chaczykowski et al. [90] simulated natural gas pipeline transients with the tracking of gas composition propagation, which are caused
by the injection of gases from unconventional sources, such as hydrogen and biomethane. Natural gas network of transient flow caused by the ambient temperature variations are numerically simulated by Farzaneh-Gord and Rahbari [61].

Table 2.1 shows the summary of the literature where it can be noted that the most of the previous investigators who studied natural gas flow in pipeline neglected the effect of heat transfer and considered that the temperature of gas remains constant. On the other hand, the most of researchers who take into account the change in temperature of natural gas flow in pipeline in their studies consider that the flow is transient; however, almost all of them neglected the heat generation due to the friction between the flowing gas and the inner surface of pipe. In addition, most of previous researches have not analysed or investigated the natural gas transmission pipeline behaviour during operational disturbances that are likely to happen during the gas pipeline exploitation.
Table 2.1: summary of the literature

| Researcher               | Research                                                                 | Highlight               | Flow mode  | Solving Method                                                                 |
|--------------------------|--------------------------------------------------------------------------|-------------------------|------------|--------------------------------------------------------------------------------|
| Stoner [16]              | new method for obtaining a steady-state solution of gas system model of   | Isoth. flow             | Steady-state| New technique based on Newton-Raphson method                                  |
|                          | pipelines                                                                 |                         |            |                                                                                |
| Ouyang and Aziz [24]     | account for the pressure drop due to friction, elevation and kinetic energy change | Isoth. flow             | Steady-state| new general flow equations and compared with AGA equations                     |
| Tian and Adewumi [30]    | determine the flow of natural gas through a pipeline system              | Isoth. flow             | Steady-state| Deriving analytical equation based on mass and momentum balance                |
| Costa et al [18]         | provided a steady-state gas pipeline simulation                          | Isoth. flow             | Steady-state| Model based on flow equation associated with the energy equation               |
| Borujerdi and Rad [19]   | analysed the gas flow in high pressure buried pipelines subjected to wall friction and heat transfer. | Non-isoth.              | Steady-state| governing equations for 1D compressible pipe flow are derived and solved numerically |
| Zhou and Adewumi [37]    | Predicting N-G flow Temp. & Press. with heat transfer with surrounding and Joule-Thompson effect | Non-isoth.              | Steady-state| fourth-order Runge-Kutta method to solve ODE system                           |
| Dufont & Rachford [75]   | explained the effect of thermal changes induced by transients in gas flow | Non-isoth.              | Transient   |                                                                                |
| Edalat & Mansoori [41]   | developed a new analytic technique for the prediction of temperature profile | Non-isoth.              | Transient   | new analytic technique based on the corresponding states principle            |
| Kiuchi [67]              | solving isothermal unsteady compressible flow                            | Isoth. flow             | Transient   | fully implicit finite difference method                                        |
| Price et al. [63]        | determined the effective friction factor and overall heat transfer a high pressure, natural gas pipeline | Non-isoth.              | Transient   | implicit finite difference approximations for solving PDE                    |
| Zhou & Adewumi [23]      | provide a functional relationship among inlet and outlet gas density, gas mass flux, length, internal diameter and wall friction | Isoth. flow             | Transient   | new analytical equation based on the continuity and momentum equation for gas flow in pipelines |
| Osiadacz & Chaczykowski [11] | compared isothermal and non-isothermal transient models for gas pipelines | Isoth. & non-isoth.     | Transient   | Flow equations are derived from motion, continuity, energy and state equations |
| Issa and Spalding [62]   | numerical procedure to solve 1D, unsteady, compressible, frictional gas flows with heat transfer | Non-isoth.              | Transient   | procedure is based on the Hartree ‘hybrid’ method which                       |

2.4 Concluding remarks

The above literature review leads to the following conclusions:

- Most of the researchers focused on isothermal conditions where they neglected the effect of heat transfer from and to the gas flow in pipelines.
- Most of researchers have studied the natural gas problems in terms of steady-state and transient flow of one-phase of transported natural gas, also, in one-dimensional flow.
Most of researchers who focused on the non-isothermal flow conditions did not take into account the heat generation due to the friction between pipe wall and the gas flows in the pipeline.

Researchers have developed numerical schemes for a flow dynamics of natural gas pipelines using different methods such as the implicit finite difference method, the explicit finite difference method, the finite elements method, and the method of characteristics.

The presented literature survey shows that there is limited information about the natural gas transmission pipelines behaviour during operational disturbances. Some of these disturbances are likely to happen during the gas pipeline exploitation, such as: (a) the stoppage of gas delivery from gas source (wells) to consumers or storage, or (b) disruption of gas consumption while the gas input from the source is available. In such cases, it is worth to know the accumulation capacity of the long transmission pipelines or a time period during which the gas pipeline accumulation capacity can satisfy consumers’ needs without disruption. Regarding a need for the insight into these transient operational characteristics under likely disturbances, the topic of research of the present PhD thesis is stated.

In addition, the literature survey shows that there is a lack of a simple method for the prediction of uncertainty that is introduced by the isothermal gas flow assumption into transient gas pipeline simulations. Hence, a derivation of an original analytical method is a topic of research in the presented thesis.

The motivation of the present research is to investigate the capacity of the long natural gas transmission pipelines to deliver gas to consumers in a case of abrupt disturbance of gas supply at the inlet point. A time period is determined from the trip of the gas supply to the instance of reaching a low pressure level at the delivery points at consumers. Also, an accumulation capacity of the transmission pipeline is evaluated in cases of cease of gas delivery to consumers under sustained gas pressure at the pipeline inlet point. The results should support the operation procedures and guidelines in cases of abnormal condition operations. In order to numerically simulate the gas transmission pipeline transients, the code GTA (Gas Transient Analysis) is developed, based on the model of one-dimensional, compressible and transient natural gas flow. The model mass and momentum balance governing equations are solved with the method of characteristics, which has the potential to produce the most accurate results (Wulff, [91]). Its high accuracy originates from the fact that it reduces partial differential equations to ordinary differential equations, as well as being the only method that accurately tracks the propagation of discontinuities in first-order derivatives. The characteristic coordinates are Lagrangian coordinates for such discontinuities. An analytical method for the evaluation of the difference between isothermal and non-isothermal transient pressure predictions and non-isothermal temperature change is derived. It supports the
application of the isothermal simulations by the GTA code of transient gas accumulation and discharging of the long transmission pipeline within time periods of several hours. The motivation for the evaluation of the influence of thermal effects on the pressure changes in gas transmission pipelines was also initiated by the ambiguity of previously published results.
CHAPTER 3

FORMULATION OF NATURAL GAS FLOW IN PIPELINES - BACKGROUND

3.1 Introduction

The main goal of this research is to develop a numerical model and a code for the simulation of transient natural gas pipeline flows and to apply the developed method to analyses of natural gas transmission pipelines under different operational conditions. Hence, a numerical model and a computer code have been developed for the simulation and analyses of natural gas transients, such as those typically found in high-pressure gas transmission pipelines. The research deals with one-dimensional, compressible, frictional natural gas transient flow in pipelines. The derivation of the mathematical model is based on corresponding mass and momentum balance equations.

In this chapter, physical properties and flow dynamic parameters of natural gas, which is treated as mixture of non-ideal gases are discussed. Then the mathematical modelling of natural gas flow in pipeline systems is presented. Finally, numerical methods for computing of these natural gas flows are described.

3.2 Gas properties

In this section the properties of natural gas that influence gas flow through a pipeline are discussed. The relationship of pressure, volume, and temperature of a natural gas is presented and how the gas properties such as density, viscosity, and compressibility change with a variation of temperature and pressure.

3.2.1 Density of Gas

Density ($\rho$) is the ratio of the mass ($m$) of gas and the volume ($V$) that the gas occupies. Therefore, it is measured in units of mass per volume [92].
\[ \rho = \frac{m}{V} \]  
(3-1)

Density is expressed in kg/m\(^3\) in SI units.

### 3.2.2 Specific Gravity

Specific gravity (G) is a measure of how heavy the gas is compared to air at a particular temperature. Sometimes it is called gravity or relative density.

\[ G = \frac{\rho_g}{\rho_{air}} \]  
(3-2)

where, \(\rho_g\): density of gas.

\(\rho_{air}\): density of air.

It is noted that \(\rho_{air}\) is the density of dry air at the temperature of 20 °C and the pressure of 101.325 kPa. In terms of the molecular weight \((M)\), gravity of gas can be calculated as following:

\[ G = \frac{M_g}{M_{air}} = \frac{M_g}{28.9625} \approx \frac{M_g}{29} \]  
(3-3)

where, \(M_g\): molecular weight of gas.

\(M_{air}\): molecular weight of air.

Table 3.1 lists the molecular weights and other properties of several hydrocarbon gases [92].

Because natural gas is formed of a mixture of several gasses (methane, ethane, etc.), molecular weight \(M_g\) in equation (3-3) is referred to as the gas mixture apparent molecular weight.

\[ M_g = \sum M_i y_i \]  
(3-4)

where, \(M_i\): molecular weight of natural gas component \(i\), g/mol.

\(y_i\): mole fraction of natural gas component \(i\), %
Table 3.1: Molecular weights and critical properties of several hydrocarbon gases [92]

| Compound                  | Molecular weight (g/mol) | Critical Temperature K | Critical Pressure MPa |
|---------------------------|--------------------------|------------------------|-----------------------|
| Methane CH₄               | 16.043                   | 191                    | 4.60                  |
| Ethane C₂H₆               | 30.070                   | 305                    | 4.88                  |
| Propane C₃H₈              | 44.097                   | 370                    | 4.25                  |
| Iso-butane C₄H₁₀          | 58.124                   | 408                    | 3.65                  |
| n-butane C₄H₁₀            | 58.124                   | 425                    | 3.80                  |
| Iso-pentane C₅H₁₂         | 72.151                   | 460                    | 3.39                  |
| n-pentane C₅H₁₂           | 72.151                   | 470                    | 3.37                  |
| n-hexane C₆H₁₄            | 86.178                   | 507                    | 3.01                  |
| n-Heptane C₇H₁₆           | 100.205                  | 540                    | 2.74                  |
| n-octane C₈H₁₈            | 114.232                  | 569                    | 2.49                  |
| n-Nonane C₉H₂₀            | 128.259                  | 595                    | 2.29                  |
| n-Decane C₁₀H₂₂           | 142.286                  | 618                    | 2.10                  |
| Nitrogen N₂               | 28.016                   | 126                    | 3.40                  |
| Carbon dioxide CO₂        | 44.010                   | 304                    | 7.38                  |
| Hydrogen sulphide H₂S     | 34.076                   | 373                    | 8.96                  |
| Oxygen O₂                 | 32.000                   | 155                    | 5.04                  |
| Hydrogen H₂               | 2.016                    | 33                     | 1.30                  |
| Water H₂O                 | 18.015                   | 647                    | 22.06                 |
| Air                       | 28.960                   | 132                    | 3.77                  |
| Helium He                 | 4.000                    | 5                      | 0.23                  |

3.2.3 Viscosity

The viscosity of fluid (gas or liquid) represents its resistance to flow. It depends on fluid temperature and pressure. Table 3.2 gives the viscosity of common components of natural gas [93].

Since natural gas is a mixture of pure non-ideal gases such as methane and ethane, the following formula key rule is used to calculate the viscosity from the viscosities of component gases:

\[
\mu = \frac{\sum (\mu_i y_i \sqrt{M_i})}{\sum (y_i \sqrt{M_i})}
\]  

(3-5)

Where, \(\mu_i\) is a dynamic viscosity of natural gas component \(i\) (kg/ms), \(M_i\) is a molecular weight of natural gas component \(i\) (g/mol), and \(y_i\) is a mole fraction of natural gas component.
A related quantity to the dynamic viscosity $\mu$ is the kinematic viscosity ($\nu$):

$$\nu = \frac{\mu}{\rho} \quad (3-6)$$

**Table 3.2: List of common gases viscosity [93]**

| Gas         | Viscosity (cP) | Viscosity (kg/m.s) |
|-------------|----------------|--------------------|
| Methane     | 0.0107         | 1.07×10^{-5}       |
| Ethane      | 0.0089         | 0.89×10^{-5}       |
| Propane     | 0.0075         | 0.75×10^{-5}       |
| i-Butane    | 0.0071         | 0.71×10^{-5}       |
| n-Butane    | 0.0073         | 0.73×10^{-5}       |
| i-Pentane   | 0.0066         | 0.66×10^{-5}       |
| n-Pentane   | 0.0066         | 0.66×10^{-5}       |
| Hexane      | 0.0063         | 0.63×10^{-5}       |
| Heptane     | 0.0059         | 0.59×10^{-5}       |
| Octane      | 0.0050         | 0.50×10^{-5}       |
| Nonane      | 0.0048         | 0.48×10^{-5}       |
| Decane      | 0.0045         | 0.45×10^{-5}       |
| Ethylene    | 0.0098         | 0.98×10^{-5}       |
| Carbon Monoxide | 0.0184     | 1.84×10^{-5}       |
| Carbon Dioxide | 0.0147     | 1.47×10^{-5}       |
| Hydrogen Sulphide | 0.0122 | 1.22×10^{-5}       |
| Air         | 0.0178         | 1.78×10^{-5}       |
| Nitrogen    | 0.0173         | 1.73×10^{-5}       |
| Helium      | 0.0193         | 1.93×10^{-5}       |

### 3.2.4 Ideal gas law

The ideal gas law sometimes referred to as the perfect gas equation, states that the pressure, volume, and temperature of the gas are related as following:

$$pV = nRT \quad (3-7)$$

where, $p$ stands for pressure, $T$ represents temperature, $R$ is the ideal gas constant (8.314 J/mol K), and $n$ is a number of moles which can be calculated as:

$$n = \frac{m}{M} \quad (3-8)$$
3.2.5 Real gas properties

The ideal gas equation presented in section (3.2.4) can be applied when dealing with real gases, and get adequately accurate results when the pressure levels are similar or close to the atmospheric pressure. For most real gases, the ideal gas equation will not be appropriate if the pressure values are considerably higher. To achieve reasonably accurate results, ideal gas equation should be modified.

It is necessary to define two terms which are called critical temperature and critical pressure. A real gas critical temperature is defined as the temperature above which a gas cannot be compressed to form a liquid, whatever the pressure. The critical pressure is known as the minimum pressure required for the compression of gas into a liquid at the critical temperature [92].

Real gases can be treated with a modified form of the ideal gas law described in section (3.2.4), if the modifying factor, known as the compressibility factor \( z \) is included. This factor is also called the deviation factor. It is dimensionless number less than 1 and varies with gas temperature, pressure, and gas composition.

Including the compressibility factor \( z \), the ideal gas equation gets the following form:

\[
pV = znRT
\]

The ratio of the gas temperature \( (T) \) to its critical temperature \( (T_c) \) is called the reduced temperature and is defined as:

\[
T_r = \frac{T}{T_c}
\]

The reduced pressure is the ratio of gas pressure \( (p) \) to its critical pressure \( (p_c) \) and is given by:

\[
p_r = \frac{p}{p_c}
\]

3.2.6 Natural gas composition and pseudo-critical properties

In reality, natural gas is a mixture of several gaseous components. The critical temperature and critical pressure can be found for each pure component that constitutes this mixture of gases. However, the critical values of temperature and pressure of the gas mixture, which are called
respectively the pseudo-reduced temperature \( T_{pr} \) and pseudo-reduced pressure \( p_{pr} \) need to be calculated as follows [92]:

\[
T_{pr} = \frac{T}{T_{pc}} \\
p_{pr} = \frac{p}{p_{pc}}
\]  

(3-12)  

(3-13)

where, \( T_{pc} \) and \( p_{pc} \) represent pseudo-critical temperature and pseudo-critical pressure. These quantities are determined in an analogous way to one used to calculate the molecular weight.

Therefore, the apparent molecular weight is defined in equation (3-4) as following:

\[
M_g = \sum M_i y_i
\]

In an analogous fashion, Kay’s rule can be used as following to calculate the average pseudo-critical temperature \( T_{pc} \) and pseudo-critical pressure \( p_{pc} \) of the gas mixture:

\[
T_{pc} = \sum y_i T_{ci} \\
p_{pc} = \sum y_i p_{ci}
\]  

(3-14)  

(3-15)

For the given mole fractions \( y_i \) of gas components.

In equations (3-14) and (3-15) \( T_{ci} \) and \( p_{ci} \) represent the critical temperature and critical pressure of a pure component \( i \) within the gas mixture.

For the case that the composition of gas mixture is not exactly known, i.e. the mole fractions of the various components in the natural gas mixture are not available, the pseudo-critical properties of the gas mixture can be computed if the specific gravity \( G \) of gas is known in the following approximate way [2]:

\[
T_{pc} = 170.491 + 307.344G \\
p_{pc} = 709.604 - 58.718G
\]  

(3-16)  

(3-17)
3.2.7 Compressibility factor

As introduced in section 3.2.5, the compressibility factor is a measure of how similar real gas is to the ideal gas. The compressibility factor $z$ is defined as the ratio of the volume of gas at a given pressure and temperature to the volume of the gas would occupy at the same temperature and pressure if it were an ideal gas. The factor $z$ is a dimensionless number close to 1 and its value depends on the gas gravity, gas temperature, gas pressure, and the critical gas properties.

Generalized plots showing the variation of $z$ with pseudo reduced temperature ($T_{pr}$) and pseudo reduced pressure ($p_{pr}$) can be used for most gases for calculating the compressibility factor, as shown in Figure 3.1 [92].

Besides using the chart, the compressibility factor $z$ can also be computed. The methods for the calculation of the compressibility factor $z$ are presented in the following.

![Figure 3.1: Compressibility factor chart for natural gas [93]](image-url)
The available methods to calculate the compressibility factor are the Standing-Katz method, the Dranchuk, Purvis, and Robinson method, the American Gas Association (AGA) method, and the California Natural Gas Association (CNGA) method (Menon, 2005) [92].

Although the Standing-Katz method is the most common, it is not suitable for the application in a code as it is based on the use of a graph designed for binary mixtures and saturated hydrocarbon vapour. Also, the American Gas Association (AGA) method is not suitable for use in a computer code as it is based on complex mathematical algorithm, which necessitates an individual computer program of significant complexity. For the above reasons, in the present thesis the approach of California Natural Gas Association (CNGA) is used to calculate the compressibility factor of natural gas flow in pipelines because of its simplicity to be applied mathematically in the algorithm (Mohitpour et. al., 2007) [93].

Therefore, according to CNGA method, the compressibility factor is computed from the following relation when the gas gravity (G), average temperature ($T_{ave}$), and average pressure ($p_{ave}$) are known [92].

$$z_{ave} = \left[ \frac{1}{1 + \left( \frac{p_{ave} c_1 (10)^{1.745G}}{T_{ave}^{3.825}} \right)} \right]^{10}$$

(3-18)

where, $C_1 = 5260$. For $C_1$ value derivation see Appendix A-3. Further, $p_{ave}$ and $T_{ave}$ represent the average pressure and temperature at any location on the pipeline. Therefore, for two points along the pipeline at pressure $p_1$ and $p_2$ the average pressure is $(p_1 + p_2)/2$ and average temperature $(T_1 + T_2)/2$. For more accurate evaluation of average pressure the following formula can be used.

$$p_{avg} = \frac{2}{3} \left[ p_1 + p_2 - \frac{p_1 p_2}{p_1 + p_2} \right]$$

(3-19)

In addition, at any particular point along the pipeline; the compressibility factor is determined as follows:

$$z = \left[ \frac{1}{1 + \left( \frac{p c_1 (10)^{1.785 G}}{T^{3.825}} \right)} \right]^{1.75}$$

(3-20)
where, $p$ is a gauge pressure of gas in kPa and $T$ is in K.

### 3.3 Flow regimes

In high-pressure gas transmission lines with moderate to high flow rates, two types of flow regimes are normally observed, which are turbulent flow and laminar flow. A determination of whether a given flow in pipe is laminar or turbulent is necessary, since the two different flow regimes often need different methods to analyse the flow behaviour.

The laminar flow occurs in conditions with low fluid velocity and high fluid viscosity. In the case of laminar flow, all trajectories of fluid particles are parallel to the flow direction. On the other side, turbulent flow is characterized by flow mixing due to development of eddies of different size. The vectors of point velocity are in all directions but the overall flow is one-way in the direction of flow. Opposite to the laminar flow, turbulent flow appears in flow situations with high fluid velocity and low fluid viscosity.

![Figure 3.2 laminar and turbulent Pipe Flow](image)

The regime of flow is defined by the Reynolds number, which is a dimensionless expression, which represents the ratio between the momentum forces of the flow to the viscous forces of the fluid:

$$
Re = \frac{\rho D u}{\mu}
$$

(3-21)

where, $Re$: Reynolds number.
ρ: density of gas.

D: inner diameter of pipe.

u: gas flow velocity.

μ: dynamic viscosity of gas.

Reynolds number is used to characterize the type of flow in a pipe, such as laminar, transitional, or turbulent flow. It is also used to calculate the friction factor in the pipe flow. For Reynolds numbers less than 2100 the flow in pipes is normally laminar or stable. Turbulent flow in pipes occurs when the Reynolds number is greater than 4000. For the so-called the transition region (2100 < Re < 4000) the flow may be either laminar or turbulent, depending upon factors like the entrance conditions into the pipe and the roughness of the pipe surface. In general transition region conditions should be avoided in designing piping systems. In natural gas transmission the Reynolds number is much greater than 4000 [92]. Therefore, transport of natural gas in a pipeline is typically turbulent flow.

### 3.4 Friction factor calculation

When gas flows in a pipeline, friction occurs between the flow stream and pipeline walls and causes pressure losses. This pressure loss is computed by introducing friction factor. The friction factor is a dimensionless parameter depending on the Reynolds number of flow and roughness of pipe walls. In engineering literature, there are two formulation of friction factor; Darcy friction factor and Fanning friction factor. The relationship between the both factors is given by:

\[
f_f = \frac{f_d}{4}
\]  

where, \(f_d\) is a Darcy friction factor, and \(f_f\) is a fanning friction factor.

Darcy friction factor is more general and will be used in this study. For the sake of simplicity, the Darcy friction factor hereafter will be denoted by the symbol \(f\).
The friction factor for laminar flow depends only on Reynolds number:

\[ f = \frac{64}{Re} \]  \hspace{1cm} (3-23)

The friction factor for turbulent flow is a function of the Reynolds number and relative roughness of pipe walls (defined as the ratio of absolute wall roughness \( e \) and inside pipe diameter \( D \)). This dependence is graphically presented by Moody diagram in Figure 3.3. As shown in Figure 3.3, turbulent flow in pipes (\( Re > 4000 \)) is divided into three zones; turbulent flow in smooth pipes, turbulent flow in rough pipes, and transition flow between smooth pipes and rough pipes.

The friction factor \( f \) only depends on Reynolds number for turbulent flow in smooth pipes. For fully rough pipes, \( f \) is more dependent on relative roughness of pipe walls \( (e/D) \). The value of friction factor depends on both the roughness of pipe wall, and Reynolds number in the transition zone.

![Figure 3.3: Moody diagram [93]](image)

As shown above the roughness plays an important role in determination of friction factor. For that reason, in Table 3.3 typical values of absolute pipe roughness \( (e) \) are given.
Table 3.3 Typical values of absolute roughness of pipe walls [92]

| Pipe Material            | Roughness, (in.) | Roughness, (mm) |
|--------------------------|------------------|-----------------|
| Riveted steel            | 0.0354 to 0.354  | 0.9 to 9.0      |
| Commercial steel/welded  | 0.0018           | 0.045           |
| iron                     | 0.0102           | 0.26            |
| Galvanized iron          | 0.0059           | 0.15            |
| Asphaltered cast iron    | 0.0047           | 0.12            |
| Wrought iron             | 0.0018           | 0.045           |
| PVC, drawn tubing, glass | 0.000059         | 0.0015          |
| Concrete                 | 0.0118 to 0.118  | 0.3 to 3.0      |

There are many correlations for calculating the friction factor. The most widely used ones for evaluation of friction factor in the gas flow in pipelines are presented below.

- **Colebrook-White correlation**

  The Colebrook-White correlation relates the friction factor and the Reynolds number, pipe roughness, and inside diameter of pipe. It is the most popular equation for general gas industry transmission pipelines which combines both partially and fully turbulent flow regimes and is most suitable for cases where the pipeline is operating in transition zone (White, 1999) [94]. The following form of the Colebrook correlation is used to calculate the friction factor in gas pipelines in turbulent flow:

  \[
  \frac{1}{\sqrt{f}} = -2 \log_{10} \left( \frac{e}{3.7D} + \frac{2.51}{\text{Re} \sqrt{f}} \right) \tag{3-24}
  \]

  In order to calculate the friction factor \( f \) from equation (3-24) one must use a trial and error approach.
• Modified Colebrook-White correlation

The modified Colebrook-White correlation form was introduced in 1956. The main difference to Colebrook-White correlation is that it gives a higher friction factor. Because of this, conservative value of flow rate is obtained. The modified version of the Colebrook-White turbulent flow correlation reads as follows:

$$\frac{1}{\sqrt{f}} = -2 \log_{10}\left(\frac{e}{3.7D} + \frac{2.825}{\text{Re} \sqrt{f}}\right)$$

(3-25)

• American Gas Association (AGA) correlation

American Gas Association (AGA) correlation is derived as a result of a study which dealt with determination of the transmission factor for gas pipelines. The transmission factor $F$ is related to the friction factor $f$ in the following way:

$$F = \frac{2}{\sqrt{f}}$$

(3-26)

The transmission factor $F$ is determined using the method of two separate equations. First, $F$ is calculated for the zone of turbulent flow in rough pipe. Next, $F$ is determined for the zone of turbulent flow in smooth pipe. Finally, the smaller of the two values of the transmission factor is used for pressure drop calculation.

Based on these investigations, AGA suggests using the following formula for $F$ for the fully turbulent region, based on relative roughness $e/D$ and independent on the Reynolds number.

$$F = \frac{2}{\sqrt{f}} = 4 \log_{10}\left(\frac{3.7 D}{e}\right)$$

(3-27)

• Friction factor from Weymouth equation

Weymouth equation was developed for evaluation of flow for high pressure, high flow rate, and large diameter gas gathering systems. In this method, the transmission factor $F$ is determined by [92]:
\[ F = 6.521 \ (D)^{1/6} \]  

Hence, the friction factor derived from this equation is of the following form:

\[ \frac{1}{\sqrt{f}} = \frac{6.521}{2} D^{1/6} \]  

**Friction factor from Panhandle A equation**

The Panhandle A equation was developed for evaluation of flow rate in natural gas pipelines for Reynolds numbers in the range of 5 to 11 million. The roughness of the pipe is not accounted for. The friction factor extracted from this equation is given in the following form:

\[ \frac{1}{\sqrt{f}} = \frac{11.85 \ E}{2} \left( \frac{\sqrt{\nu \ G}}{D} \right)^{0.07365} \]  

where, \( \nu \) is the volume flow rate of the natural gas, and \( E \) is pipeline efficiency.

**Friction factor from Panhandle B equation**

The Panhandle B equation, is used for evaluation of flow rate in transmission lines with large diameters, high pressure and for fully turbulent flows with Reynolds number values in the range of 4 to 40 million. The friction factor devised from this following equation has the form:

\[ \frac{1}{\sqrt{f}} = \frac{19.08 \ E}{2} \left( \frac{\sqrt{\nu \ G}}{D} \right)^{0.01961} \]  

Summary of various correlations for friction factor used in the gas pipeline industry is presented in Table 3.4.
Table 3.4 Summary of friction factor correlations [92]

| Equation                      | Application                                                                 |
|-------------------------------|-----------------------------------------------------------------------------|
| Colebrook-White               | Friction factor calculated for pipe roughness and Reynolds number; most popular correlation for general gas transmission pipelines |
| Modified Colebrook-White      | Modified correlation based on U. S. Bureau of Mines experiments; gives higher pressure drop compared to the original Colebrook correlation |
| AGA                           | Transmission factor calculated for partially and fully turbulent flow considering roughness and Reynolds number |
| Panhandle A & B               | Panhandle equations do not consider pipe roughness; instead, an efficiency factor is used; less conservative than Colebrook or AGA |
| Weymouth                      | Does not consider pipe roughness. Used for high-pressure gas gathering systems; most conservative equation that gives highest pressure drop for given flow rate |

In the present thesis, for a code, it is more complicated to write all flow equations in their different forms; so, friction factor is calculated individually then substituted as an input in a code for flow calculations.

3.5 Velocity of natural gas in pipeline

Unlike a liquid pipeline, the natural gas velocity depends upon the pressure and, hence, will vary along the pipeline even if the pipeline diameter is constant, that is due to the change in compressibility of gas. In addition, if the flow is non-isothermal, the gas velocity is affected by the variation of gas flow temperature, because of its impact on the natural gas compressibility.

The highest gas velocity will be where the pressure is least and that is at the downstream end. On the opposite, the lowest value of velocity of gas will be at the upstream end, where the pressure is the highest.

Mathematically, the calculation of the velocity of the one-dimensional, compressible, frictional natural gas transient flow could be done numerically by the combination of the mass balance and momentum balance. The derivation of pressure and velocity of the natural gas transient flow in pipe will be described in detail in Chapter 4.
3.5.1 Erosional velocity

The velocity of natural gas flows in a pipeline is directly related to the pressure. The gas velocity increases as the flow pressure decreases. With the velocity increase, the vibration and noise occur. Another problematic issue is that higher velocities cause erosion of the pipeline during long period of time. If the gas velocity exceeds the erosional velocity calculated for the pipeline, the erosion of the wall is increased to rates that can significantly reduce the life of the pipeline. Therefore, it is necessary to control gas velocity in natural gas transmission lines to prevent it from rising above this limit. The upper limit of the gas velocity is usually calculated approximately from the following equation [92]:

\[ u_{\text{max}} = \frac{C_2}{\sqrt{\rho}} \]  

(3-32)

where, \(C_2\) is an empirical constant (\(C_2 = 122\) for continuous service as per API 14E\(^2\)) [95]

The recommended value for \(C_2\) in natural gas transmission pipelines is 122 in SI units. The derivation of this constant is illustrated in Appendix A-4.

From the equation of state of gas: 

\[ \rho = \frac{p}{zRT} \]

\[ u_{\text{max}} = C_2 \sqrt{\frac{zRT}{29 Gp}} \]  

(3-33)

Usually, the acceptable operational velocity \((u_{\text{acc}})\) in natural gas transmission pipelines is 50% from the maximum velocity [92].

\[ u_{\text{acc}} = 0.5 \ u_{\text{max}} \]  

(3-34)

3.6 Heat transfer consideration of gas flow in pipeline

Generally, in some applications, where pipelines are relatively short and at low pressure, an isothermal (i.e. constant temperature) assumption for the gas flow is fairly sufficient. There are certain characteristics of lengthy pipelines (e.g. cross-border pipelines) that make the implementation of an isothermal flow model inadequate. The majority of these pipelines transport massive amount of gas every day, which requires the line to be at high pressure values all along its

\(^2\) The American Petroleum Institute recommended practice 14E.
route. The energy loss due to pressure drop is mostly caused by friction, this lost energy is transformed into heat that is dissipated in the ground. In some cases, when the pipeline routes from north to south or from east to west and vice versa, the climatic changes along the year create relatively large difference in soil temperature, which can pump the heat out from the gas reducing its pressure. For all these reasons, it is useful to include in some studied cases a heat transfer model that takes into consideration the heat transfers between gas and its surrounding (Osiadacz and Chaczykowski, 2001) [11].

Natural gas temperature in a pipeline is affected by the conductive and convective transfer of heat in a radial direction, by the accumulation of heat in the surrounding soil, and by the Joule-Thomson effect.

3.7 Mathematical modelling of natural gas one-dimensional unsteady compressible flow in pipelines

There are several factors that control the precise and accurate pipeline mathematical flow models, mainly serving for pipeline balance, pressure monitoring, and deliverability. There are two types of mathematical models for lengthy pipelines and networks flow; the steady-state and the transient models. The core difference between the two types of flow models lies in the equation of motion. In the transient flow models, there are terms that represent the change of transport parameters with time. When these terms are set to zero, the steady-state representation of the flow equation is obtained. Consequently, and due to this fundamental difference between the two types of models, the functionality of each of them differs. For the purposes such as pressure monitoring and leak localization, in which the change of transport parameters with time is vital, transient flow models become ideal. For other purposes such as pipeline design, sizing, line capacity estimations and line packing, where the changes of transport parameters with time are of no significance, steady-state models become ideal. The transient models are more difficult to implement compared to steady-state models.

Modelling the flow of natural gas in pipelines requires consideration of the physical processes that govern the flow. In this section, the physical laws governing the processes that take place during natural gas transportation are applied in the derivation of mathematical expressions to model natural gas flows.
3.7.1 Governing equations

The flow of natural gas in pipelines is governed by the time-dependent continuity and momentum for isothermal flow and continuity, momentum, and energy equations for non-isothermal flow and an equation of state for homogenous, geometrically one-dimensional flow. By solving these equations, the behaviour of gas parameters can be obtained along the pipe network [2]. Some of investigators developed the basic equations for one-dimensional unsteady compressible flow that include the effects of wall friction and heat transfer.

A one-dimensional unsteady flow of a homogeneous fluid in a tube with constant cross section is depicted in figure 3.4 [93], and the balance equations are as follows:

![Figure 3.4 Demonstration of all forces acting on a gas particle moving in a pipeline](image)

- **Conservation of mass: continuity equation**
  The conservation of mass for the control volume shown in Figure 3.5 can be expressed in the form as follows:
  \[
  \frac{D\rho}{Dt} + \rho \frac{\partial u}{\partial x} = 0 \quad ;
  \]  
  \[ (3-35) \]
where, $\rho$ is the density of gas, $u$ is the flow velocity. Operator $D/Dt = \partial / \partial t + u \partial / \partial x$ is the material derivative. The derivation of Eq. (3-35) is presented in Appendix A-1.

**Momentum balance: Newton’s second law of motion**

The momentum equation can be written for the control volume shown in figure 3.6 using the following force component summation:

$$\frac{Du}{Dt} + \frac{1}{\rho} \frac{\partial \rho u}{\partial x} + \frac{fu |u|}{2H_{\mu}} + g \sin \theta = 0 \quad ;$$

(3-36)

where $g$ is the acceleration of gravity, $f$ is the friction coefficient, and $\theta$ is the angle between the horizon and the direction $x$. The last two terms on the left hand side of equation (3-36) represent consequently the momentum drop due to friction on the pipeline wall and its change due to gravity. The derivation of Eq. (3-36) is presented in Appendix A-1.
Transformation of the balance equations

The applied equation of state for gas under isenthalpic flow is written as

\[ \rho = \rho(p) \]  

(3-37)

The equation of state is differentiated by time \( t \) and by spatial coordinates \( x \)

\[ \frac{\partial \rho}{\partial t} = \frac{d \rho}{dp} \frac{\partial p}{\partial t} \]  

(3-38)

\[ \frac{\partial \rho}{\partial x} = \frac{d \rho}{dp} \frac{\partial p}{\partial x} \]  

(3-39)

The mass balance equation (3-35) is transformed by the introduction of derivatives (3-38) and (3-39) and the following form is obtained with the pressure material derivatives

\[ \frac{Dp}{Dt} + c^2 \rho \frac{\partial u}{\partial x} = 0 \]  

(3-40)

where the speed of sound is expressed as

\[ c = (dp/d\rho)^{1/2} \]  

(3-41)

Determination of the speed of sound is presented in Appendix A-2.

Equations (3-40) and (3-36) present a set of two partial differential equations of the hyperbolic type as follows

\[ \frac{\partial p}{\partial t} + u \frac{\partial p}{\partial x} + c^2 \rho \frac{\partial u}{\partial x} = 0 \]  

(3-42)

\[ \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + \frac{1}{\rho} \frac{\partial p}{\partial x} = Y \]  

(3-43)

where

\[ Y = -\frac{fu|u|}{2D_u} - g \sin \theta \]  

(3-44)

In this system of equations dependent variables are the pressure and velocity of fluid, and the independent variables are the time and space coordinate. In order to solve the above system of equations it is necessary to specify the appropriate initial and boundary conditions. The initial conditions are defined with flow parameters of the fluid at the initial time prior to disturbance. Boundary conditions are defined on the basis of the state of the fluid at the inlet and outlet of the
pipeline segment. The analytical solution of this system cannot be obtained, so a numerical method is applied to determine the particular integral.

3.7.2 Solution methods

Various numerical schemes have been developed for the solving of the mass, momentum and energy balance equations for one-dimensional transient pipeline flow, such as the method of characteristics, the finite elements method, the explicit finite difference method, and the implicit finite difference method. The choice depends partly upon the particular requirement of the system under investigation.

3.7.2.1 Method of characteristics

The method of characteristics is a technique for solving hyperbolic partial differential equations (PDE). Typically the method applies to first-order equations, although it is valid for any hyperbolic-type PDEs. The method involves the determination of special curves, called characteristics curves, along which the PDE becomes a family of ordinary differential equations (ODE). Therefore, it can be used to transform the partial differential of the continuity, momentum and energy equations into ordinary differential equations [27]. The resulting characteristics equations are solved numerically either on a grid of characteristics or on a rectangular coordinate grid. This method has the potential to produce the most accurate results (Wulff, 1987) [91]. Its high accuracy originates from the fact that it reduces partial differential equations to ordinary differential equations, as well as being the only method that accurately tracks the propagation of discontinuities in first-order derivatives. The method of characteristics was also used for the simulation of natural gas transients by Abott (1966) [49], Mekebel and Loraud (1985) [50], Osiadacz (1987) [51], and Herran-Gonzales et al. (2009) [54].

3.7.2.2 Finite element method

This method can handle some boundary conditions better than finite difference methods. On the other hand, the method has not been commonly used for gas transient flow modelling because computing time and the storage requirement are high. The element size, shape, and distribution are relatively flexible, so that nonuniform internal distribution of nodal points is possible. This method was compared with the application of the finite difference for the simulation of gas pipeline transients by Osiadacz and Yedroudj (1989) [47].
3.7.2.3 Explicit finite difference methods

There are several explicit methods of finite difference such as first-order and second-order approximations. A first-order approximation is typically not sufficiently accurate to model gas transients in a pipeline and therefore attention is focused on second-order methods [45]. The main drawback of the second-order approximation is that these techniques require a greater amount of computer time and are therefore not ideal for examining large systems or analysing unsteady flows over long periods of time.

3.7.2.4 Implicit finite difference methods

The main advantage of using an implicit method over the explicit method is that some sort of implicit method is unconditionally consistent and does not enforce any limitations on the maximum allowable time stage. Nonetheless, the approach will produce unsatisfactory results for the strong transients. In addition, some implicit methods have been known to produce erratic results during the imposition of some types of boundary conditions [45]. This method was used by Luongo (1986) [69], Abbaspour et al. (2010) [74], Helgaker et al (2014) [84], and etc.

3.7.2.5 Central difference method

In this method, the partial derivatives are approximated for sections of the pipeline rather than node points. It was used by Wiley at al. [53] to solve for the transient isothermal flow field gas pipeline network. For the non-linear equations, the Newton- Raphson method was used, and sparse matrix algebra reduced the solution time for the simultaneous equations. Although this method requires a large amount of computer storage to handle the coefficient matrix and lengthy execution times, these major disadvantages can be overcome by using a sparse matrix method.

3.7.2.6 Crank-Nicolson method

This method is a central difference solution of high-order accuracy. It was utilized by Heath and Blunt (1969) [46] to solve the conservation of mass and momentum equations for slow transients in isothermal gas flow. The main advantage of this method is that it does always give a stable solution according to the Neumann stability analysis of large time step for nonlinear problems.
3.7.2.7 Fully implicit method

Whereas the explicit finite difference methods are forward difference methods, the fully implicit method is a backward method. This method mostly is unconditionally stable. It is very robust for the gas pipeline industry because of relatively slow transient. The implicit method guarantees stability for a large time step, but requires a numerical method such as the Newton-Raphson method to solve a set of nonlinear simultaneous equations at each time step.
CHAPTER 4

MODEL FORMULATION AND SOLUTION ALGORITHM

In this chapter the procedure for the computation of natural gas properties and flow field variables (pressure and velocity) is presented. The newly proposed model is based on the method of characteristics.

4.1 Application of the method of characteristics for the simulation of natural gas pipeline transients

The transient one-dimensional natural gas flow in pipelines is described with the mass and momentum balance equations. These equations are partial differential equations of the hyperbolic type. In this research, the method of characteristics is used for the numerical solution of the system of partial differential equations of hyperbolic type. This method can solve the system of two quasilinear partial differential equations (3-42) to (3-43), with the two dependent variables (pressure and velocity) and the two independent variables (time and space coordinate).

The method of characteristics converts the quasilinear system of partial differential equations (3-42) and (3-43) into a system of differential equations with the total differential, wherein the family of curves is determined in the space-time coordinate system along which the derived transformation apply. Total differentials are then replaced by finite differences, thus obtaining two difference equations. Solving these algebraic equations by the dependent variable obtained are values of the fluid flow parameters along the pipeline during the transient.

The family of curves in the space-time coordinate system represent a physical propagation of pressure waves in the flow field. The time step of integration is determined by the Courant criterion. The Courant criterion links spatial and temporal integration step. The numerical grid for the solving of the difference equations is formed with the uniform spatial step of integration.

Multiplying equation (3-42) by $\lambda_1$ coefficient and equation (3-43) by $\lambda_2$ coefficient, and then adding the resulting equations, the following equation is obtained:
\[
\lambda_1 \frac{\partial p}{\partial t} + \lambda_2 \frac{\partial u}{\partial t} + \left( \lambda_1 u + \frac{\lambda_2}{\rho} \right) \frac{\partial p}{\partial x} + (\lambda_1 c^2 \rho + \lambda_2 u) \frac{\partial u}{\partial x} = \lambda_2 Y
\]  
(4-1)

The dependant variables are marked as a general function \( f \in (p, u) \) and their total derivatives are

\[
df = \left( \frac{\partial f}{\partial t} \right)_x dt + \left( \frac{\partial f}{\partial x} \right) dx.
\]  
(4-2)

By substituting corresponding equation (4-2) for each dependant flow parameter into (4-1) the following equation is obtained

\[
\left[ \lambda_1 - \left( \lambda_1 u + \frac{\lambda_2}{\rho} \right) \frac{dt}{dx} \right] \frac{\partial p}{\partial t} + \left( \lambda_1 u + \frac{\lambda_2}{\rho} \right) \frac{dp}{dx} + \\
+ \left[ \lambda_2 - (\lambda_1 c^2 \rho + \lambda_2 u) \frac{dt}{dx} \right] \frac{\partial u}{\partial t} + (\lambda_1 c^2 \rho + \lambda_2 u) \frac{du}{dx} = \lambda_2 Y
\]  
(4-3)

where coefficients \( \lambda_1 \) and \( \lambda_2 \) are determined from the condition that the expressions in equation (4-3) that multiply the partial derivatives of dependant variables \( p \) and \( u \) with respect to time \( t \) are zero. Hence, a system of two linear homogeneous equations is obtained

\[
\begin{align*}
(1-u \frac{dt}{dx}) \lambda_1 - \frac{dt}{\rho \ dx} \lambda_2 &= 0 \\
-c^2 \rho \frac{dt}{dx} \lambda_1 + \left(1-u \frac{dt}{dx}\right) \lambda_2 &= 0
\end{align*}
\]  
(4-4)

Solutions of this system will be nontrivial if and only if the determinant of the system is equal to zero

\[
\left|\begin{array}{cc}
1 - u \frac{dt}{dx} & - \frac{1}{\rho \ dx} \\
- c^2 \rho \frac{dt}{dx} & 1 - u \frac{dt}{dx}
\end{array}\right| = 0
\]  
(4-5)

Solutions by derivative \( \frac{dt}{dx} \) represent the characteristic directions, i.e., characteristic equation

\[
\frac{dt}{dx} = \left\{ \frac{1}{u+c}, \frac{1}{u-c} \right\}.
\]  
(4-6)
Replacement $\frac{dt}{dx} = \frac{1}{u+c}$ in equation (4-4) gives

$$\frac{\dot{\lambda}_1}{\dot{\lambda}_2} = \frac{1}{\rho c} \quad (4-7)$$

and $\frac{dt}{dx} = \frac{1}{u-c}$ in equation (4-4) gives

$$\frac{\dot{\lambda}_1}{\dot{\lambda}_2} = -\frac{1}{\rho c} \quad (4-8)$$

Substitution of equations (4-7) and (4-8) into equation (4-3) removes the partial derivatives of dependant variables and a system of ordinary differential equations is obtained as follows

for $\frac{dt}{dx} = \frac{1}{u+c}$, $C^+$ characteristic

$$\left(\frac{u}{\rho c} + \frac{1}{\rho}\right) \frac{dp}{dx} + (c+u) \frac{du}{dx} = Y. \quad (4-9)$$

for $\frac{dt}{dx} = \frac{1}{u-c}$, $C^-$ characteristic

$$\left(-\frac{u}{\rho c} + \frac{1}{\rho}\right) \frac{dp}{dx} + (-c+u) \frac{du}{dx} = Y. \quad (4-10)$$

By substituting corresponding equation (4-6) in equations (4-9), and (4-10) it is obtained

for $\frac{dt}{dx} = \frac{1}{u+c}$, $C^+$ characteristic

$$dp + \rho cdu = \rho cYdt \quad (4-11)$$

for $\frac{dt}{dx} = \frac{1}{u-c}$, $C^-$ characteristic

$$dp - \rho cdu = -\rho cYdt. \quad (4-12)$$

Equations (4-11) and (4-12) are related to the propagation of the pressure waves. The laws of conservation of mass and momentum are resolved along $C^+$ and $C^-$ characteristics.

The differentials in equations (4-11) and (4-12) are approximated by finite differences. The finite differences are taken along the typical straight lines. In this way a system of difference equations is obtained. The coefficients in equations (4-11) and (4-12) are considered to be constant during the integration time step, and their values are obtained by linear interpolation of the result of the previous calculation steps. The presentation of the calculation procedure follows.
Figure 4.1 shows a time instant $t$, which represents the initial or previous time instant, and the next time moment $t+\Delta t$. Points A, B and C are optionally selected three consecutive nodes, in the observed flow field, in which the count value depends on the variables at time $t$. Point D is the place in which pressure waves reaches during $\Delta t$ from points L and R. Hence, at node D the two characteristic lines intersect: $C^+$ passing through point R and $C^-$ passing through point L. Consequently, the point D represents a condition in a current area which is formed in the following point in time $t+\Delta t$ as a result of propagation of disturbances occurring at time $t$. Time step is determined from the Courant's stability criterion according to which a disturbance that starts from point R, moving with speed $u + c$, and a disturbance that starts from point L, moving with speed $u - c$, should not exceed the point D because this would cause instability solutions. The distance along the x-axis between the nodes A and B, and B and C are identical to each other and constant over time, ie. $\overline{AB}=\overline{BC}$. Depending on variables known in all nodes in the time $t$, their values are calculated at the moment $t+\Delta t$.

By approximating the total differentials in equations (4-11) and (4-12) with finite differences along the characteristic directions, the following system of algebraic equations is obtained,

$$\frac{\Delta t}{\Delta x} = \frac{1}{u_R + c_R} C^+ \text{ characteristic } (p_D - p_R) + \frac{c_L}{v_R} (u_D - u_R) = \frac{c_R}{v_R} Y_R \Delta t,$$

(4-13)

$$\frac{\Delta t}{\Delta x} = \frac{1}{u_L - c_L} C^- \text{ characteristic } (p_D - p_L) - \frac{c_L}{v_L} (u_D - u_L) = -\frac{c_L}{v_L} Y_L \Delta t,$$

(4-14)
where, $v = \frac{1}{\rho}$ is specific volume.

Solving of algebraic equations (4-13) and (4-14) provides expressions for the calculation of $p_D$ and $u_D$

$$p_D = \frac{\alpha \delta + \beta \gamma}{\alpha + \beta},$$

(4-15)

$$u_D = \frac{\gamma - \delta}{\alpha + \beta},$$

(4-16)

where

$$\alpha = \frac{c_R}{v_R},$$

(4-17)

$$\gamma = p_R + \alpha u_R + \alpha Y_R \Delta t,$$

(4-18)

$$\beta = \frac{c_L}{v_L},$$

(4-19)

$$\delta = p_L - \beta u_L - \beta Y_L \Delta t.$$  

(4-20)

Equations (4-15) and (4-16) provide the values of dependant variables at time $t + \Delta t$ in node $D$ as functions of the initial values of dependant variables at time $t$ in nodes $R$ and $L$. The initial values of the dependant variables are determined by linear interpolation as follows

**Item R**

$$\frac{x_B - x_R}{x_B - x_A} = \frac{u_B - u_R}{u_B - u_A},$$

(4-21)

$$\frac{x_B - x_R}{x_B - x_A} = \frac{c_B - c_R}{c_B - c_A},$$

(4-22)

$$\frac{x_B - x_R}{x_B - x_A} = \frac{p_B - p_R}{p_B - p_A},$$

(4-23)

$$\frac{\Delta t}{x_B - x_R} = \frac{1}{u_R + c_R}.$$  

(4-24)
Solving equations (4-21) to (4-24) by \( u_R, c_R \) and \( p_R \) it is obtained

\[ u_R = \frac{(1+b)u_B - ac_B}{1+a+b}, \]  
(4-25)

\[ c_R = \frac{(1+a)c_B - bu_B}{1+a+b}, \]  
(4-26)

\[ p_R = p_B - \frac{u_B + c_B}{1+a+b} (p_B - p_A) \frac{\Delta t}{\Delta x}, \]  
(4-27)

and

\[ v_B = v_B - \frac{u_B + c_B}{1+a+b} (v_B - v_A) \frac{\Delta t}{\Delta x}, \]  
(4-28)

where

\[ a = (u_B - u_A) \frac{\Delta t}{\Delta x}, \quad b = (c_B - c_A) \frac{\Delta t}{\Delta x}. \]  
(4-29)

Item L

\[ \frac{x_B - x_L}{x_B - x_C} = \frac{u_B - u_L}{u_B - u_C}, \]  
(4-30)

\[ \frac{x_B - x_L}{x_B - x_C} = \frac{c_B - c_L}{c_B - c_C}, \]  
(4-31)

\[ \frac{x_B - x_L}{x_B - x_C} = \frac{p_B - p_L}{p_B - p_C}, \]  
(4-32)

\[ \frac{\Delta t}{x_B - x_L} = \frac{1}{u_L - c_L}. \]  
(4-33)

Solving the equations (4-30) to (4-33) by \( u_L, c_L \) and \( p_L \) is obtained

\[ u_L = \frac{(1+d)u_B - ec_B}{1-e+d}, \]  
(4-34)

\[ c_L = \frac{(1-e)c_B + du_B}{1-e+d}, \]  
(4-35)
\[ p_L = p_B + \frac{u_B - c_B}{1 - e + d} \left( p_B - p_C \right) \frac{\Delta t}{\Delta x}, \]  

(4-36)

and

\[ v_L = v_B + \frac{u_B - c_B}{1 - e + d} \left( v_B - v_C \right) \frac{\Delta t}{\Delta x}, \]  

(4-37)

where

\[ e = (u_B - u_C) \frac{\Delta t}{\Delta x}, \quad d = (c_B - c_C) \frac{\Delta t}{\Delta x}. \]  

(4-38)

Calculation of all dependent variables \((p, u)\), as well as specific volume \(v\), in the nodes of R and L enables the prediction of pressure and velocity in the node D according to equations (4-15) and (4-16). Specific volume of fluid in the node D is determined from the equation of state, and the local speed of sound in the fluid can be determined from the appropriate theoretical expressions or an empirical correlation for the speed of sound.

In the presented method, the spatial step, i.e. the distance between nodes, is constant. The time steps is determined by Courant criterion that provides the stability of numerical solutions

\[ \Delta t \leq \min \left( \frac{\Delta x}{c_J + |u_J|} \right), \quad J = 1, 2, \ldots, n, \]  

(4-39)

wherein the minimum time step, for a given value of spatial step \(\Delta x\), is determined by the maximum value of the sum of the speed of sound and the absolute value of the fluid velocity.

### 4.2 Boundary conditions

Boundary conditions are defined for the pipe inlet and outlet. In case of the pipe inlet the \(C^+\) characteristic path in (Fig. 4.1) and corresponding characteristic equation (4-13) are not defined, while in case of the pipe outlet \(C^-\) characteristic path (Fig. 4.1) and equation (4-14) are not defined. These undefined characteristic equations are replaced by time functions \(u = u(t)\) or \(p = p(t)\), which should be derived from hydraulic conditions that define the transient flow problem. These hydraulic conditions might be related to gas inlet and/or outlet mass flow rates, a valve opening or closing, a leakage to the atmosphere in case of a break, a junction to the compressor, etc. A boundary condition inside a pipe network is a junction of two or more pipes (Fig. 4.2) and it is derived as follows. The pipes that transport fluid towards the junction node \(D\) in (Fig. 4.2) are denoted with \(J_i\),
while the pipes that transport fluid from the node $D$ are denoted with $I_j$. The characteristic equations in $I_j$ pipes can be written for $C^+$ paths from point $R$ to node $D$ (Fig. 4.1) as follows

$$p_D + \alpha_{R,I_j} u_{D,I_j} = \gamma_{R,I_j}, \; i = 1, 2, \ldots, n$$

(4-40)

The characteristic equations in $I_j$ pipes can be written for $C^-$ paths from point $L$ to node $D$ (Fig. 1) in the following form

$$p_D - \beta_{L,I_j} u_{D,I_j} = \gamma_{L,I_j}, \; j = 1, 2, \ldots, m$$

(4-41)

The mass balance equation is added for the node $D$

$$\sum_{i=1}^{n} \rho_{D} u_{D,I_i} A_{I_i} = \sum_{j=1}^{m} \rho_{D} u_{D,I_j} A_{I_j}$$

(4-42)

The velocities $u_{D,I_i}$ and $u_{D,I_j}$ are expressed from equations (4-40) and (4-41)

$$u_{D,I_i} = \frac{\gamma_{R,I_i} - p_D}{\alpha_{R,I_i}}$$

(4-43)

$$u_{D,I_j} = \frac{p_D - \delta_{L,I_j}}{\beta_{L,I_j}}$$

(4-44)

Finally, equations (4-43) and (4-44) are introduced into equation (4-42) and the explicit expression is obtained for the calculation of pressure in node $D$

$$p_D = \left( \frac{\sum_{i=1}^{n} \rho_{D} A_{I_i}}{\alpha_{R,I_i}} + \sum_{j=1}^{m} \rho_{D} A_{I_j}}{\beta_{L,I_j}} \right)^{-1}$$

(4-45)

After calculating the pressure in the junction node $D$ with equation (4-45), the velocities in cross sections at pipe ends towards the junction node $D$ are calculated with equations (4-43) and (4-44). The density in the node $D$ in the new time $t + \Delta t$ is approximated with the density at the same location but from the initial time $t$, i.e. $\rho_D \approx \rho_B$, in order to avoid iteration in calculation process.
4.3 Flowchart of the calculation process

The calculation flowchart of the GTA code is developed in a way to enable defining the pipe network and appropriate boundary conditions by input parameters. The flowchart is shown in Figure 4.3. The inlet and outlet pipe boundary conditions are defined by G(A,J) matrix, where A=1,2 denotes the pipe inlet and outlet respectively and J=1,2,…n denotes the pipe number. The value of matrix element G(A,J) denotes a type of the predefined boundary condition. The solution procedure is shown in figure 4.3.
Figure 4.3 Flowchart of the calculation procedure
CHAPTER 5

CODE VALIDATION

In this chapter, the developed model and the GTA code for the simulation and analyses of gas pipeline transients are validated. Four cases are applied from the open literature as the benchmark experiments for the validation of the developed model and code GTA. Here presented results are published in [96].

5.1 Case 1

A natural gas transient in a single pipeline of 8000 m length and with 0.406 m diameter is numerically simulated. The pipeline has the upward elevation of 1 m in the flow direction. The natural gas temperature is 300 K, the specific gravity is 0.675 and the viscosity is $10^{-5}$ kg/(ms). The pipeline wall roughness is 0.046 mm. The gas flow rate varies at the pipeline’s outlet due to the consumer’s demand with a period of 6000s, as depicted in figure 5.1. The volumetric flow rate in figure 5.1 is presented in million metric standard cubic meters per day (MMSCmD). The gas pressure at the pipeline’s inlet is constant during the transient and its value is 6 MPa.

The transient is simulated with the presently developed Gas Transients Analysis (GTA) code. In order to investigate the numerical calculation sensitivity on the numerical grid refinement, the pipe length is discretized with a small number of 9 nodes, as well as with a much greater number of 161 nodes, i.e. the simulations were performed with uniform distances between two adjacent numerical nodes of 1000 m and 50 m respectively.
The obtained results are shown in figure 5.2 and compared with the previously reported numerical results of Reddy et al. (2006) [55] and Alamian et al. (2012) [56]. The calculated inlet flow rate in figure 5.2 shows the same trend and values as the prescribed outlet flow rate in figure 5.1. These results indicate that during this long lasting transient the gas flow rate along the pipeline, from the inlet to the outlet, is nearly constant in every time instant, although, as shown, it changes with time. A very good agreement of GTA code results with the results of Reddy et al. (2006) [55] and Alamian et al. (2012) [56] is achieved.

A grid refinement tests were performed and the pipeline length was discretized with 9, 41, 81 and 161 nodes. Practically the same results are obtained in all these tests. The results obtained with the minimum number of 9 nodes and the maximum 161 nodes are presented in figure 5.2. It is shown that a coarse numerical grid with the distance of 1000 m between two adjacent nodes is sufficient for an accurate calculation. Such an accurate calculation with a coarse grid is possible due to the relatively short distance of the pipeline and the low gas velocity. The gas velocity along the pipeline is approximately 2.4 m/s and the pressure drop along the pipeline is lower than 0.05 MPa. Due to the low pressure change there is no influence of the gas compressibility, there is no nonlinearity caused by the gas density change, and the accurate simulation is obtained by applying the coarse grid. The time step of numerical integration is calculated according to the Courant criterion equation (4-39) and its value is approximately 2.56 s in the case with the spatial discretization with 9 nodes.
5.2 Case 2

This transient was previously numerically simulated by Taylor et al. (1962) [45], Zhou and Adewumi (1997) [37], Tentis et al. (2003) [64], Behbahani-Nejad and Bagheri (2008) [97] and Alamian et al. (2012) [56]. A single pipeline with the length of 72,259.5 m, the diameter of 0.2 m and the pipeline wall roughness of 0.617 mm transports natural gas. The gas pressure at the pipeline inlet is constant at 4.205 MPa. The flow is isothermal at 283 K. The specific gravity of gas is 0.675, the viscosity is $1.1831 \times 10^{-5}$ kg/(ms) and the isothermal speed of sound is equal to 367.9 m/s. At the pipeline outlet the mass flow rate varies within a 24-h cycle according to consumer’s daily demand changes, as shown in figure 5.3. The mass flow rate shown in figure 5.3 specifies the boundary condition at the pipeline outlet and it is the input into the simulation.

The transient was simulated with the GTA code that is developed in this presented thesis. The pipeline was discretized with 371 nodes. Further grid refinement by increasing the number of nodes provided practically the same results.
The calculated pressure at the pipeline outlet is shown in figure 5.4. As presented, the GTA code results are in agreement with the previously published results. The flow rate decrease in the period from 1.4 h to 6.8 h (Fig. 5.3) leads to the pressure increase at the pipeline outlet (Fig. 5.4), where the maximum pressure is reached after 8 hours. This delay of the maximum pressure occurrence compared to the time of minimum flow rate at the pipeline outlet for approximately 1.2 hours indicates an accumulation of gas and an inertia effect of the accumulated gas mass along the pipeline during the period of decreased gas flow rate from the pipeline. A similar delay is observed for the period of gas flow rate increase at the pipeline outlet.

The maximum gas flow rate at the pipeline outlet is reached after 13 hours, while the minimum pressure is reached after 15 hours. Again, the delay of minimum pressure occurrence after the maximum flow rate at the pipeline outlet is attributed to the gas accumulation in the pipeline and inertia of the gas mass along the pipeline. After 18.7 hours the gas flow rate at the pipeline outlet remains constant (Fig. 5.3). A certain discrepancy between measured and calculated data is shown.

The measured maximum pressure is higher for approximately 0.1 MPa than the calculated values after 8 hours (Fig. 5.4). The measured pressure at the outlet is nearly constant after 16 hours as shown in figure 5.4, while numerical results show transient behaviour in this period. These discrepancies are attributed to the uncertainty in the specification of the pipeline boundary flow in figure 5.3 (it might be questioned whether the gas flow rate is constant for the last five hours (in the period from 19 till 24 hours) or there is a certain decrease of the flow rate).
5.3 Case 3

The ability of the GTA code to predict transients in gas pipeline networks is validated by a simulation of transient in the gas network shown in figure 5.5:

Dimensions of three pipelines that form the network are presented in Table 5.1. The gas specific gravity is 0.6, the operational temperature is 278 K, and the friction factor is considered to be constant and equal to 0.003.

Table 5.1: Dimensions of the pipelines in the gas network (Case 3)

| Gas Pipe | Diameter (m) | Length (km) |
|----------|--------------|-------------|
| 1        | 0.6          | 80          |
| 2        | 0.6          | 90          |
| 3        | 0.6          | 100         |
Gas flows into the network at node 1 with the constant pressure of 5 MPa. Gas outflows from the network at nodes 2 and 3 with flow rates specified by figure 5.6.

The GTA code results are compared in figures 5.7 and 5.8 with numerical results obtained by Osiadcz (1987) [51], Ke and Ti (1999) [98], Behbahani-Nejad and Bagheri (2008) [97] and Alamian et al. (2012) [56].
As shown in figures 5.7 and 5.8, the GTA code results are in agreement with the results of other researchers.

In the periods of increased gas demands from nodes 2 and 3 the pressure in these nodes decreases, while in the periods of decreased gas demands from nodes 2 and 3 the pressure in these nodes increases as illustrated in figures 5.7 and 5.8 respectively. The time instants when the maximum and minimum pressures are reached in nodes 2 and 3, as shown in figures 5.7 and 5.8, are delayed for about 0.3 hours to 0.5 hours compared to time instants of outlet gas flow rates changes from nodes 2 and 3 at 4 hours, 12 hours and 20 hours from the beginning of transient, as shown in figure 5.6. This effect is attributed to the accumulation and inertia of gas mass in long pipelines 1, 2 and 3. The GTA code results are obtained with the uniform distance of 2000 m between the numerical nodes along all three pipelines, i.e. the number of numerical nodes is 41, 46 and 51 in gas pipelines 1, 2 and 3 respectively.

The time step of integration is approximately 5.2 s, as predicted with equation (4-39).

Figure 5.7: Calculated pressure in node 2 of the network (Case 3)
A gas transient takes place in a gas pipeline with a length of 91.44 m and an inner diameter of 0.61 m. The initial gas pressure in the pipeline is 4.136 MPa, the sonic wave speed is 348.1 m/sec, and the friction factor is 0.03. The gas specific gravity is 0.67. The downstream pipeline end is closed during the whole transient, while the upstream inflow begins to increase linearly from zero and reaches 17 MMSCMD (millions of standard meter cubic per day) at 0.145 s, then decreases again linearly and reaches zero at 0.29 s. Figure 5.9 shows schematically this study case along with its boundary conditions.

Figure 5.8: Calculated pressure in node 3 of the network (Case 3)

Figure 5.9: Boundary conditions and geometry of the pipeline in Case 4
Numerical results of previous simulations of this case were reported Zhou and Adewumi (1996) [80] and Behbahani-Nejad and Shekari (2010) [83], and presently by the usage of the GTA code.

Measured and calculated pressure changes at the closed end of the pipeline are shown in figure 5.10. The pressure change has the same shape as the inlet flow rate change. The pressure pulse reaches the closed end after approximately 0.26 s. This time period is determined by the sonic velocity of the gas and the pipeline length (91.44 [m]/348.1 [m/s] = 0.26 [s]).

![Figure 5.10: Pressure history at the outlet of the pipeline (Case 4)](image)

The pressure change at the pipeline inlet is shown in figure 5.11. The inlet pressure increases with the gas inlet flow rate increase, and decreases with the inlet flow rate decrease. The inlet pressure increases for approximately 0.2 MPa. This amplitude is approximate to the value determined by the Joukowsky equation

$$\Delta p = \rho c \Delta u$$  \hspace{1cm} (5-1)

where change of pressure $\Delta p$ is equal to the product of density $\rho$, speed of sound $c$, and change of velocity $\Delta u$. Namely, the inlet gas velocity increases from zero to 16.2 m/s, the gas density at 4.15 MPa is 28 kg/m3, and taking into account the above reported sonic velocity of 348.1 m/s, the pressure pulse of 0.16 MPa is obtained. The amplitude of the pressure increase at the closed pipe end is approximately 0.4 MPa, which is two times greater than the amplitude at the pipeline inlet due to the pressure wave rarefaction at the rigid pipeline closed end. This greater pressure amplitude reaches later on the pipeline inlet at 0.65 s.
The gas flow rate change at the half length of the pipeline is shown in figure 5.12, and it is determined by the compression pressure wave propagation along the pipeline. The presented GTA code results are obtained with 101 numerical nodes along the pipeline, while the influence of the number of numerical nodes is presented in figure 5.13. As shown, there is no practical difference between results obtained with 51 and 101 nodes.

The time step of integration in case with 101 nodes is approximately 0.0025 s according to equation (4-39).
5.5 Conclusion remarks

The GTA code is validated by computer simulations of transient cases reported in the literature. The simulated cases include transients caused by the variable gas consumption and boundary pressure pulses.

It is shown that the calculation procedure is numerically stable and the good agreement is obtained between the GTA code results and the previous published results. The presented model derivation and analysis of validation results show that the applied method is relatively easily implemented in the computer code, the calculation procedure is robust and the reliable simulations are obtained for both slow and fast gas pipeline transients.
CHAPTER 6

TRANSIENT BEHAVIOR OF A LONG TRANSMISSION GAS PIPELINE

The GTA code was used to analyse the behaviour of natural gas transient flow in long transmission pipeline. Real natural gas transmission pipeline in Libya was taken for studying, and some scenarios were assumed and simulated to predict the gas flow parameters to investigate its behaviour. Also here, the presented results are published in reference [96].

6.1 Analyses of transient behaviour of gas pipeline of the Western Libya Gas Project

The developed GTA code was applied to the analysis of transients in the onshore gas transmission pipeline of the Western Libya Gas Project shown in figure 6.1 below [99].

Figure 6.1 Main gas pipeline of the Western Libya Gas Project

The gas inlet to the main transmission gas pipeline is at the Wafa Desert Plant with gas wells, which is located at the 329 meters above the sea level (MASL). The pipeline extends to the Mellitah Complex at the sea coast. The pipeline length from Wafa to Mellitah is 525 km and the diameter is 0.8128 m (32 in). At the distance of 370 km from the gas inlet at Wafa, there is junction
with a branch line (depicted as the junction D in Fig. 6.1) that is 5 km long and has the diameter of 0.4064 m (16 in). This branch transport gas to the Ar Ruways Gecol Thermal Power Plant (TPP) at 245 MASL. The highest elevation of the pipeline of 632 MASL is near the Nalut city. From Nalut to Mellitah at the sea level the pipeline elevation steadily decreases. The maximum total delivery of the pipeline from Wafa Desert Plant is about 530,000 Sm$^3$/h of gas. The design delivery to the Ar Ruways Gecol$^3$ TPP is 212,520 Sm$^3$/h, which is based on the maximum TPP capacity [99]. Based on the field data, the gas pressure and temperature at the pipeline inlet at Wafa are 6.4 MPa and 315 K. The gas viscosity is 1.71×10^{-5} kg/(ms) and the specific gravity is 0.67. The gas temperature at the outlet in the Mellitah Complex is about 300 K.

Gas Transient Analysis code simulations results are first compared to the real plant data for the period of 12 hours operation on the 31$^{st}$ of July 2017. In the presented simulation the pipeline from Wafa Desert Plant to the junction with the branch towards the TPP is denoted as pipeline 1, from the junction to the Mellitah Complex as pipeline 2 and the branch towards the TPP as pipeline 3. The inlet pressure at Wafa and outlet volume flow rates at the Mellitah Complex and the TPP are specified according to the measured data presented in figures 6.2 and 6.3.

![Figure 6.2 Measured pressure at the main gas pipeline inlet in the Wafa Desert Plant](image)

---

$^3$ GECOL: General Electricity Company of Libya.
The calculated pressure at the Mellitah Complex is compared with measured values in figure 6.4. The calculated values show the increase of pressure during the first hour, which is the result of the measured gas flow rate decrease at the pipeline outlet in the Mellitah Complex that is shown in figure 6.3 (Pipe 2 out). The measured pressure shows a decrease during the first hour in figure 6.4.

This discrepancy between calculated and measured data is attributed to the permanent weak fluctuations of the gas pressure and flow rate during long transmission pipeline operation, which is not taken into account by the prediction of the initial condition of the pipeline (the initial condition
is calculated as the steady-state condition, since the actual distribution of pressure and flow rate along the pipeline is not recorded).

In the later period between 1 and 8 hours both calculated and measured values show the pressure decrease. In the period between 8 and 9 hours the gas flow rate decreases at the outlet in the Mellitah Complex (Fig.6.3) and both measured and calculated values show the pressure increase (Fig.6.4) due to this gas flow rate change. In the period between 10 and 11 hours the gas flow rate at the outlet in the Mellitah Complex increases (Fig.6.3) and this leads to the pressure decrease as shown in Fig.6.4 by both measured and calculated values. The maximum difference between these values is lower than 0.02 MPa and the calculated pressure transient behaviour is in the complete agreement with measured behaviour in the period when the influence of the uncertainty of the initial condition is diminished.

Further work was directed towards investigation of gas pipeline transport capacity in transients caused by a trip of gas source at Wafa Desert Plant and by a trip of gas delivery at the TPP and the Mellitah Complex.

6.1.1 Scenario 1

The trip of the gas supply in Wafa Desert Plant is assumed. As presented in figure 6.5 the gas supply in Wafa Desert Plant is constant for 2 hours and then suddenly stops. The gas delivery in the Mellitah Complex and to the TPP is kept constant at the initial level that corresponds to the nominal operation. These flow rates are specified boundary conditions for this simulation.

![Flow rate behaviour in the gas pipeline of the Western Libya Gas Project during the gas supply trip](image)

**Figure 6.5** Flow rate behaviour in the gas pipeline of the Western Libya Gas Project during the gas supply trip
Calculated pressure values are shown in figure 6.6. The pressure at the main pipeline inlet at Wafa Desert Plant is denoted as (Pipe 1in) as in figure 6.6. The pressure in the junction D (Fig.6.1) equals the pressure at the outlet of Pipe 1 and inlets of Pipe 2 and Pipe 3, as presented in figure 6.6 (Pipe1out = Pipe2in = Pipe3in). The pressures at the outlet in the Mellitah Complex and at the outlet in the TPP are denoted as (Pipe 2out and Pipe 3out) in figure 6.6. All these pressure values are constant for the first 2 hours till the gas supply trip.

![Figure 6.6 Pressure history in the gas pipeline of the Western Libya Gas Project during the gas supply trip](image)

Later on, the pressure level in the whole pipeline system decreases, but during the whole simulated transient the pressure is the highest at the inlet in Wafa Desert Plant and gradually decreases along the pipeline to the junction D (Fig.6.1). The pressure also drops from the junction D towards the TPP and the Mellitah Complex. Although there is a pressure drop along the transmission pipeline, the required delivery flow rates at the TPP and at the Mellitah Complex are sustained for a period even longer than 24 hours, which is a result of the gas accumulation in the large volume of the main gas pipeline.

### 6.1.2 Scenario 2

In the second simulated scenario the gas delivery stops at the Mellitah Complex after one hour, while the gas pressure at the pipeline inlet in Wafa desert plant and the gas delivery to the TPP are kept constant at the initial value. The mass flow rates in the pipeline system are presented in figure 6.7. All flow rates are constant during the first hour. Later on, the mass flow rate at the transmission pipeline inlet in the Wafa Desert Plant gradually decreases (denoted as (Pipe1in) as in Fig.6.7). Although the delivery flow rate in the Mellitah Complex is stopped after 1 hour, the
decreasing flow rate at the inlet of pipeline 2 (denoted as (Pipe2in) as in Fig.6.7) still exists in the long period of 11 hours after the outlet flow stoppage due to the pressure increase and the gas accumulation.

Figure 6.7 Flow rate behaviour in the gas pipeline of the Western Libya Gas Project during the trip of gas delivery to the Mellitah Complex

The pressure history during the transient is shown in figure 6.8. The gas pressure at the pipeline inlet in the Wafa Desert Plant is kept constant at 6.4 MPa. Within one hour after the trip of the gas delivery in the Mellitah Complex the gas pressure from the junction D (Fig.6.1) towards the Mellitah Complex is practically equal. The pressure drop from the junction D towards the TPP exists due to the gas delivery to the TPP and this pressure drop is practically constant because of the constant mass flow rate. The pressure increase within the whole pipeline system indicates gas accumulation.
6.1.3 Scenario 3

A trip of gas delivery both in the Mellitah Complex and in the TPP is assumed in the third simulated scenario. The flow rate change within the pipeline system is shown in figure 6.9.

It is shown that although the whole gas delivery is stopped, there is still a gas inflow at the inlet point of the transmission pipeline at the Wafa Desert Plant due to the gas packing and pressure increase, as shown in figure 6.10. Due to the short length of the pipeline branch towards the TPP of 5 km, compared to the length of the main pipeline of 525 km, the flow in the branch almost instantaneously stops with the delivery trip at the TPP.

The pressure history during the transient in figure 6.10 shows that the pressure values at the junction D (Fig.6.1) with the branch towards the TPP and at the pipeline outlet in the Mellitah Complex become practically equal about five hours after the trip of gas delivery, while in the pipeline branch towards the TPP, inlet and outlet pressure values are momentary equal and governed by the pressure in the junction D.

Although the pressure within the whole pipeline system reaches the main pipeline inlet pressure in the Wafa Desert Plant after 12 hours, the inlet flow rate at the Mellitah Complex still exists after this period due to the inertia of the gas mass within the long distance main pipeline of large volume.
The calculated velocity change along the pipeline from the inlet at the Wafa plant to the outlet at the Mellitah Complex is shown in figure 6.11 at the initial steady-state and 5 and 11 hours after the stop of gas outflows. As shown, prior to the transient, the gas velocity increases along the pipeline due to the pressure drop and corresponding density decrease. At the distance of 370 km from the inlet there is a drop of velocity since a part of the gas flow rate from the main transmission pipeline is directed towards the TPP, while the main pipeline diameter is unchanged. The velocity
decreases after the stop of gas delivery at pipeline ends in the Mellitah Complex and in the TPP. At the transmission pipeline end at 525 km the velocity is zero during the transient, while along the pipeline the compressible gas still flows due to the inertia of the large gas mass and gas packing in the long pipeline. Hence, the pressure gradually increases and the velocity decreases along the pipeline.

Figure 6.11 Velocity change along the pipeline at the initial steady-state and 5 and 11 hours after the trip of total gas delivery

6.2 Thermal effects in long transmission natural gas pipeline

6.2.1 The influence of temperature change along the gas pipeline on the pressure drop

The following presentation is related to the influence of the heat transfer from the gas pipeline to the surrounding medium and the heat generation due to friction between the flowing gas and the inner pipeline wall on the pressure drop in the case of the long transmission pipeline of the Western Libya Gas Project. The main transmission gas pipeline of the Western Libya Gas Project is buried in the ground with the pipeline centreline depth of approximately 1.5 m as shown in figure (6.12). The carbon steel pipeline is coated with 3.2 mm thick polyethylene. The following steady-state operating parameters are considered: the inlet gas mass flow rate is 78 kg/s and the inlet gas temperature is 315 K at Wafa plant. The mean soil temperature of 295 K is adopted at the depth of 1.5 m. The soil thermal conductivity varies between 0.64 W/(mK) for silty sand and 1.28 W/(mK) for limestone. The lower value of 0.64 W/(mK) leads to a more conservative conditions with a higher temperature and pressure increase. [96]
The temperature change along the main gas pipeline is predicted by solving the energy equation in the following form

\[
\frac{d(\rho u c_p T)}{dx} = f \frac{\rho u^3}{2D} - \frac{4k}{D} (T - T_s)
\]

(6-1)

where the product of specific heat capacity at constant pressure \( c_p \) and temperature \( T \) represents enthalpy and \( k \) is the heat transfer coefficient from the gas to the surrounding soil at temperature \( T_s \). The first term on the right hand side of equation (6-1) represents the heat generation due to the friction between the flowing gas and the inner pipeline wall. It is noted that the heat generation due to the wall friction is of the order of MW in long transmission gas pipelines. In case of the Western Libya Gas Project \( f \rho u^3 V/(2D) \approx 4 \text{ MW} \). The second term is the heat transfer rate from the gas stream to the surrounding. Differential equation (6-1) is solved analytically by applying the following relations and assumptions:

a) The product of density and velocity \( \rho u \) is constant under a steady-state condition.

b) The heat transfer coefficient is determined by the heat conduction from the pipeline outer surface through the soil.

The heat transfer rate per unit length of the buried pipeline is calculated as [100].
\[ q_L = \lambda \left( T - T_i \right) \frac{2\pi}{\cosh^{-1} \left( \frac{2x}{D} \right)} \]  

(6-2)

which holds for \( x \approx 2D \), where \( x \) is the depth from the ground surface to the centerline of the buried pipeline. The soil temperature in the massive of the ground is \( T_s \), \( T \) is the gas temperature in the pipeline and \( \lambda \) is the soil thermal conductivity. The relation between surface and linear heat flux is 

\[ q_L = \pi D q_A \] 

Since \( q_A = k(T - T_i) \) and introducing equation (6-2), it follows

\[ k = \frac{\lambda}{D} \frac{2}{\cosh^{-1} \left( \frac{2x}{D} \right)} \]  

(6-3)

c) The gas velocity changes along the pipeline due to the pressure, temperature and consecutive density change.

d) The soil temperature depends on the ground surface temperature change, which is determined by the seasonal and day-night period changes, and on the soil conductivity. The soil conductivity changes along the pipeline, especially in cases of hundreds of kilometres long pipelines. The precise information about the soil characteristic is usually not available. Further, the soil temperature at some distance from the ground surface changes slowly with time and usually it can be assumed constant during a 24 hours day period [101]. According to the above presented analyses, the parameters \( (\rho u, u, c_p, f, k \text{ and } T_s) \) are approximated fairly well with constant values. Therefore, Eq. (6-1) is solved analytically in the following form

\[ T = \left( \frac{f \rho u^3}{8k} + T_i \right) \left[ 1 - \exp \left( -\frac{4k}{\rho u c_p D} x \right) \right] + T_s \exp \left( -\frac{4k}{\rho u c_p D} x \right) \]  

(6-4)

Friction factor and compressibility factor were calculated respectively with Colebrook-White equation and California Natural Gas Association (CNGA) method [14].

The thermal effect is evaluated first by the introduction of the above defined parameters and the value of the heat conduction coefficient \( \lambda = 0.64 \text{ W/(mK)} \) into equation (6-4) which leads to

\[ T = 25.8 \left[ 1 - \exp \left( -1.046 \cdot 10^{-5} x \right) \right] + 42 \exp \left( -1.046 \cdot 10^{-5} x \right) \]  

(6-5)

while for \( \lambda = 1.28 \text{ W/(mK)} \) it leads to

\[ T = 23.9 \left[ 1 - \exp \left( -2.092 \cdot 10^{-5} x \right) \right] + 42 \exp \left( -2.092 \cdot 10^{-5} x \right) \]  

(6-6)
The calculation of natural gas temperature changes along the pipeline with equations (6-5) and (6-6) according to equation (6-4) are presented in figure 6.13 for the heat conduction coefficient values $\lambda = 0.64 \ \text{W/(mK)}$ and $1.28 \ \text{W/(mK)}$. As shown, the gas temperature decreases within the first hundred kilometres even with the low value of the heat conduction coefficient related to the dry send. For higher values of $\lambda$, which are most common, the natural gas temperature decrease at the pipeline inlet part will be more intensive. The difference between gas temperatures calculated with $\lambda = 0.64 \ \text{W/(mK)}$ and $1.28 \ \text{W/(mK)}$ is 2.3 K at the distance of 370 km from the pipeline inlet figure (6.13). [96]

![Figure 6.13](image)

**Figure 6.13** Temperature change along the entrance part of the long transmission gas pipeline for two heat conduction coefficient values

The temperature change in figure (6.13) is presented till 370 km since at that distance the gas mass flow rate is reduced in the main transmission pipeline due to the branch towards the TPP, which leads to the further decrease of difference between gas and soil temperatures. It is also noted that after 200 km the gas temperature is practically constant in case of $\lambda = 1.28 \ \text{W/(mK)}$.

According to these results, the conclusion can be derived that the difference in the pressure change calculation with an isothermal and a non-isothermal model is small, as follows. Since the natural gas density change is about 5% with the temperature change form 315 K to 299 K (the density change with temperature is related to $(315/299 = 1.05)$, the difference in the pressure drop calculated with the non-isothermal and isothermal models is lower than 5% (assuming that the adopted isothermal gas temperature is between the maximum value of 315 K and the minimum value of 299 K, and according to the well-known Darcy relation that $\Delta p = \frac{fm^2}{(2\rho A^2)\cdot L/D}$). This
uncertainty is of the same order as the change of pressure drop that is introduced by the change of the pipe wall roughness by 0.01 mm. The friction coefficient values calculated with Colebrook-White correlation which is the most popular equation for general gas industry transmission pipelines equation (3-24) are 0.01004 and 0.01054 for wall roughness 0.02 mm and 0.03 mm respectively and corresponding parameters: Re=7·10^6, D=0.8128 m (which shows the pressure drop change by 5%). According to data presented in Jia et al. (2014) [102], the change of wall roughness within a long transmission pipeline is in the span of 0.01 mm. Therefore, it is concluded that the assumption of the isothermal gas condition leads to an uncertainty of the pressure drop calculation that is of the same order as the uncertainty of the friction pressure drop calculation due to the uncertainty of the wall surface roughness prediction.

6.2.2 The influence of thermal effects on pressure transient in the long transmission gas pipeline

Scenario 3 presented in Section 6.1.3 is used for the analyses of natural gas temperature change during a long pipeline transient. It shows the greatest time rate of pressure change among presented Scenarios 1, 2 and 3 from Section 6.1 and consequently the greatest temperature change and the most intensive influence of thermal effects on the pressure change are expected during this scenario (even higher rate of pressure change can occur in case of pipeline rupture and blowdown, but this unlikely accident scenario is not considered in here presented research).

The gas temperature change during the transient of gas packing in Scenario 3 is evaluated with a model derived from the mass, energy and volume balances of the fluid control volume presented in figure (6.14).

![Figure 6.14 Gas control volume in the pipeline](image-url)
Mass Balance
\[
\frac{dm}{dt} = m_{in} - m_{out}
\]

Energy Balance
\[
\frac{dH}{dt} = (m \dot{h})_{in} - (m \dot{h})_{out} + Q + V \frac{dp}{dt}
\]

Volume of Pipeline
\[
V = \frac{M}{\rho}
\]

Total enthalpy \( H \) is expressed as
\[
H = m \ h
\]

Where
\[
h = c_p \ T
\]
\[
m = \rho \ V
\]

The total enthalpy \( H \) in Eq. (6-8) is replaced with the product of fluid mass \( M \) and specific enthalpy \( h \) and the specific enthalpy is expressed as the product of the specific heat capacity \( c_p \) and temperature \( T \). After derivation of the left hand side term in Eq. (6-8), by taking into account the mass balance Eq. (6-7) and by assuming that the change of the specific heat capacity by pressure and temperature is negligible \((c_p=\text{const.})\) in the range of pressure and temperature change during the analysed transients) the following expression is obtained for the temperature change.

\[
\frac{dT}{dt} = \frac{1}{\rho V} \left[ m_{in} (T_{in} - T) - m_{out} (T_{out} - T) + \dot{Q} + V \frac{dp}{dt} \right]
\]

Differentiation of equation (6-9) gives,

\[
\frac{dV}{dt} = 0 = \frac{1}{\rho} \frac{dm}{dt} - \frac{m \, d\rho}{\rho^2} \frac{dt}{dt} = \frac{1}{\rho} \frac{dm}{dt} - \frac{m}{\rho^2} \left[ \frac{\partial \rho}{\partial p} \right]_{T} \frac{dp}{dt} + \left[ \frac{\partial \rho}{\partial T} \right]_{p} \frac{dT}{dt}
\]

and from equation (6-14) is derived
\[
\frac{dp}{dt} = \frac{\rho}{m} \left( \frac{\partial p}{\partial \rho} \right)_T \frac{dm}{dt} - \left( \frac{\partial \rho}{\partial T} \right)_p \left( \frac{\partial p}{\partial \rho} \right)_T \frac{dT}{dt} \tag{6-15}
\]

Substitution of equations (6-7) and (6-13) into equation (6-15) gives

\[
\frac{dp}{dt} = \left( \frac{\partial p}{\partial \rho} \right)_T \rho + T \left( \frac{\partial p}{\partial T} \right)_p \left( \dot{m}_m - \dot{m}_{out} \right) - \left( \frac{\partial \rho}{\partial T} \right)_p \left( \frac{\partial p}{\partial \rho} \right)_T \left[ (\dot{m}T)_m - (\dot{m}T)_{out} + \frac{\dot{Q}}{c_p} \right] \]
\[
\rho V \left[ 1 + \frac{1}{c_p \rho} \left( \frac{\partial \rho}{\partial T} \right)_p \left( \frac{\partial p}{\partial \rho} \right)_T \right] \tag{6-16}
\]

The heat rate \( \dot{Q} \) is determined as

\[
\dot{Q} = f \frac{\rho u^2}{2D} V - \dot{q}_L L \tag{6-17}
\]

The first term on the right hand side represents the heat generation due to the gas friction on the pipeline wall, while the second term is the heat transfer rate from the gas stream to the surrounding and the linear heat transfer rate is determined with Eq. (6-2).

As an assumption, in case of the trip of gas delivery the gas flow rate at the pipeline outlet is zero \( \dot{m}_{out} = 0 \); hence, equations (6-13) and (6-16) are reduced to

\[
\frac{dT}{dt} = \frac{1}{\rho V} \left[ \dot{m}_m (T_m - T) + \frac{\dot{Q}}{c_p} + \frac{V}{c_p} \frac{dp}{dt} \right] \tag{6-18}
\]

\[
\frac{dp}{dt} = \rho \left( \frac{\partial p}{\partial \rho} \right)_T \dot{m}_m - \left( \frac{\partial \rho}{\partial T} \right)_p \left( \frac{\partial p}{\partial \rho} \right)_T \left[ \dot{m}_m (T_m - T) + \frac{\dot{Q}}{c_p} \right] \]
\[
\rho V \left[ 1 + \frac{1}{c_p \rho} \left( \frac{\partial \rho}{\partial T} \right)_p \left( \frac{\partial p}{\partial \rho} \right)_T \right] \tag{6-19}
\]

For isothermal flow, where \( \left( \frac{\partial \rho}{\partial T} \right)_p = 0 \), equation (6-19) is reduced to

\[
\frac{dp}{dt} = \frac{1}{V} \frac{\partial p}{\partial \rho} \dot{m}_m \tag{6-20}
\]

Partial derivatives \( \left( \frac{\partial p}{\partial \rho} \right)_T \) and \( \left( \frac{\partial \rho}{\partial T} \right)_p \) in Eq. (6-19) are obtained by the differentiation of the ideal gas law as follows. The ideal gas law is written as
\[ p = z \rho R_g T \]  

(6-21)

From this equation,

\[
\left(\frac{\partial p}{\partial \rho}\right)_T = R_g T \left(\frac{\partial}{\partial \rho}(z\rho)\right)_T = R_g T \left[ \rho \left(\frac{\partial z}{\partial \rho}\right)_T + z \right]
\]

(6-22)

The compressibility factor \( z \) is function of \( p \) and \( T \) and its derivative is

\[ dz = \left(\frac{\partial z}{\partial p}\right)_T dp + \left(\frac{\partial z}{\partial T}\right)_p dT \]

(6-23)

Dividing the above equation with \( d\rho \) and assuming the isothermal conditions, i.e. \( dT = 0 \), the following expression is obtained

\[
\left(\frac{\partial z}{\partial \rho}\right)_T = \left(\frac{\partial z}{\partial p}\right)_T \left(\frac{\partial p}{\partial \rho}\right)_T
\]

(6-24)

Introduction of Eq. (6-24) into Eq. (6-22) leads to

\[
\left(\frac{\partial p}{\partial \rho}\right)_T = \frac{z R_g T}{1 - R_g T \rho \left(\frac{\partial z}{\partial \rho}\right)_T}
\]

(6-25)

By expressing the ideal gas law in the form

\[ \rho = \frac{p}{z R_g T} \]

(6-26)

and differentiation by temperature for isobaric conditions leads to

\[
\left(\frac{\partial \rho}{\partial T}\right)_p = \frac{p}{R_g} \left[ \frac{\partial}{\partial T} \left(\frac{1}{z T}\right) \right]
\]

(6-27)

\[
\left(\frac{\partial \rho}{\partial T}\right)_p = - \frac{p}{z R_g T} \left[ \frac{\partial z}{\partial T}\right)_p + \frac{1}{T} \right]
\]

(6-28)
Finally, Eq. (6-19) is written as

\[
\frac{dp}{dt} = a_1 + b_1 T
\]  

(6-29)

where

\[
a_i = \frac{\left( \frac{\partial}{\partial \rho} \right)_T \rho \dot{m}_{in} - \left( \frac{\partial}{\partial \rho} \right)_T c_p \left[ \frac{2\pi \lambda L}{c_p \cosh^{-1}(2x/D)} T_s + \rho \frac{\dot{u}^3}{2D c_p} V \right]}{\rho V \left[ 1 + \frac{1}{c_p \rho} \left( \frac{\partial}{\partial \rho} \right)_T \left( \frac{\partial}{\partial T} \right)_T \right]} 
\]

(6-30)

\[
b_i = \frac{\left( \frac{\partial}{\partial \rho} \right)_T \left( \frac{\partial}{\partial T} \right)_p \dot{m}_{in} + \frac{2\pi \lambda L}{c_p \cosh^{-1}(2x/D)}}{\rho V \left[ 1 + \frac{1}{c_p \rho} \left( \frac{\partial}{\partial \rho} \right)_T \left( \frac{\partial}{\partial T} \right)_T \right]} 
\]

(6-31)

Substitution of Eq. (6-29) into Eq. (6-18) leads to

\[
\frac{dT}{dt} = a_2 - b_2 T 
\]

(6-32)

where

\[
a_2 = \frac{1}{\rho V} \left[ \dot{m}_{in} T_{in} + \frac{2\pi \lambda L}{c_p \cosh^{-1}(2x/D)} T_s + \rho \dot{m}_{in} - \left( \frac{\partial}{\partial \rho} \right)_T \left( \frac{\partial}{\partial T} \right)_T \dot{m}_{in} T_{in} + \frac{2\pi \lambda L}{c_p \cosh^{-1}(2x/D)} T_s + \rho \frac{\dot{u}^3}{2D c_p} V \right] \left( \frac{\partial}{\partial \rho} \right)_T \left( \frac{\partial}{\partial T} \right)_T \right] 
\]

(6-33)

\[
b_2 = \frac{1}{\rho V} \left[ \dot{m}_{in} + \frac{2\pi \lambda L}{c_p \cosh^{-1}(2x/D)} + \rho \dot{m}_{in} + \frac{2\pi \lambda L}{c_p \cosh^{-1}(2x/D)} \right] \left( \frac{\partial}{\partial \rho} \right)_T \left( \frac{\partial}{\partial T} \right)_T \right] 
\]

(6-34)

Parameters on the right hand side of Eqs. (6-30,6-31) and (6-33,6-34) are taken as constant for a certain range of gas pressure and temperature change and gas packing with the constant gas inlet mass flow rate and temperature. This assumption enables an analytical solving of the differential equations (6-29) and (6-32). Equation (6-32) is solved as
Substitution of Eq. (6-35) into Eq. (6-29) leads to the following solution

\[ p = p_0 + \left( a_i + \frac{a_2 b_i}{b_2} \right) t + \frac{b_i}{b_2} \left( \frac{a_2}{b_2} T_0 \right) e^{-b_i t} \]  

(6-36)

In order to evaluate the temperature and pressure change during the gas packing of Scenario 3, the stated balance equations (6-7) and (6-8) and derived equations (6-35) and (6-36) are applied to the whole length of the transmission pipeline. Therefore, the pressure \( p \) and temperature \( T \) in equations (6-35) and (6-36) represent the mean values for the whole gas volume. The temperature distribution along the pipeline presented in figure (6.13) shows that approximately after one third of the pipeline length the temperature is nearly constant and the assumption of the gas mean temperature for the whole pipeline has a sense. The pressure change from the inlet to the outlet of the long transmission pipeline is about 2.5 MPa (the difference between initial inlet and outlet values in figure (6.10) and approximation of the gas pressure along the pipeline with the mean pressure seems to be rather crude. But, during the gas packing the difference between the inlet and outlet values is reduced and becomes zero at the end of transient, which diminishes the pressure change along the pipeline. Further, results of the evaluation of the mean pressure change during the gas packing, as it is presented in this section below, show that the predicted mean pressure change is in accordance with the pressure change presented in figure (6.10).

The initial mean temperature of the gas along the pipeline \( T_0 \), prior to the gas delivery trip, is expressed explicitly from equation (6-13) by taking into account that the time derivatives are equal to zero in the steady-state operation and with the introduction of relation for the heat transfer rate Eq. (6-17)

\[ T_0 = T_s + \frac{\dot{m}_c p (T_{in} - T_{out}) + f \frac{Dm^2}{2D} V}{2\pi\lambda} - \frac{\tanh^{-1}(2x/D) L}{2} \]  

(6-37)

The following values of the operational parameters are taken in order to evaluate the pressure and temperature change during the gas packing: the inlet mass flow rate is assumed to be constant and \( \dot{m}_c \) = 78 kg/s, the initial mean gas pressure is \( p_0 = 53 \) bar, the solution of equation (6-37) provides the initial mean temperature \( T_0 = 301.5 \) K, the soil massive temperature is constant along the pipeline with a value \( T_s = 295 \) K, the gas inlet temperature is \( T_{in} = 315 \) K, the natural gas
constant is $R_g = 500 \ J/\text{kgK}$, the mean gas density value is $\rho = 37.6 \ \text{kg/m}^3$ (it is determined from the assumption that the gas mean velocity along the pipeline is $u = 4 \ \text{m/s}$ and the gas mass flux is $\rho u = \dot{m}/(3.14 \cdot D^2 / 4) = 150.4 \ \text{kg/}(\text{m}^2 \cdot \text{s})$), the gas specific heat capacity is $c_p = 2500 \ J/\text{kgK}$, the compressibility factor is $z = 0.89$, the partial derivatives are $(\partial p/\partial \rho)_T = 120000 \ J/\text{kg}$ and $(\partial p/\partial T)_T = -0.189 \ \text{kg/}\text{m}^3 \text{K}$, the soil thermal conductivity is $\lambda = 0.64 \ W/\text{mK}$, pipeline inner diameter is $D = 0.8 \ \text{m}$ and the length of the pipeline $L = 525 \cdot 10^3 \ \text{m}$.

Introduction of these parameters into equations (6-35) and (6-36) leads to

$$T - T_0 = 4.8 \left( 1 - e^{-6.489 \cdot 10^{-9} t} \right)$$

(6-38)

$$(p - p_0)_{\text{nonisothermal}} = 37.93t - 108943 \left( e^{-6.489 \cdot 10^{-9} t} - 1 \right)$$

(6-39)

According to equation (6-38) the mean temperature rise is 4.4 K during the gas packing for 11 hours (the same time period of gas packing as shown in figure (6.10)). Equation (6-39) provides the mean pressure increase during the gas packing under this non-isothermal condition, while the following integral of equation (6-20) provides the pressure change under the assumption of the isothermal gas packing

$$(p - p_0)_{\text{isothermal}} = 34.38t$$

(6-40)

The difference between the pressure rise during the gas packing for 11 hours and under non-isothermal and isothermal conditions is calculated with equation (6-39) and (6-40) as following

$$(p - p_0)_{\text{nonisothermal}} - (p - p_0)_{\text{isothermal}} = 1.499 - 1.361 = 0.138 \ \text{MPa}$$

(6-41)

where the value of 0.138 MPa is the relative difference of 9.2% in comparison to the non-isothermal pressure change.

The above calculation is performed with the assumption that during the whole gas packing transient the gas velocity is constant and has the initial value of 4 m/s. According to figure (6.11) the gas velocity decreases during the transient. The heat generation due to friction is related to the third power of velocity; hence, the heat generation due to friction rapidly decreases with the velocity decrease during the gas packing transient. So, if the heat generation due to gas friction on the pipeline wall is neglected, the term $f \rho u^3 V/(2D)$ is removed from equation (6-17), as well as
the term $f \rho u^2 V / (2Dc_p)$ from equation (6-30) and (6-33). In this case the temperature and pressure rises during the gas packing with the constant inlet flow rate are calculated as

$$T - T_0 = 4.0 \left(1 - e^{-6.489 \times 10^{-7} t}\right)$$  \hspace{1cm} (6-42)

$$\left(p - p_0\right)_{\text{nonisothermal}} = 34.36 t - 91464 \left(e^{-6.489 \times 10^{-7} t} - 1\right)$$  \hspace{1cm} (6-43)

According to equations (6-42) and (6-43) the temperature and pressure rises during the gas packing with the constant inlet flow rate is 3.7 K and 1.445 MPa. The difference between the pressure rises under non-isothermal and isothermal conditions is 0.084 MPa, obtained as next,

$$\left(p - p_0\right)_{\text{nonisothermal}} - \left(p - p_0\right)_{\text{isothermal}} = 1.445 - 1.361 = 0.084 \text{ bar}$$  \hspace{1cm} (6-44)

which is the relative difference of 5.8% in comparison to the non-isothermal pressure change.

The presented differences between calculated temperature and pressure changes under non-isothermal and isothermal conditions in the intervals from 3.7 K and 4.4 K and 0.084 MPa and 0.138 MPa are in the range of uncertainty caused by the unknown local soil thermal conductivity and ambient temperature along the whole long pipeline. Therefore, the prediction of the pressure change during the long lasting pressure packing transient is acceptable with isothermal model and the temperature change does not have significant influence on the gas properties.

The same is concluded for the case when the gas inflow is stopped ($\dot{m}_{in} = 0$) and its delivery to the consumers is continued with unchanged flow rate, such as in Scenario 1 applied to the Western Libya Gas Project in Section 6.1. In this case the temperature and pressure change differential equations (6-13) and (6-16) have the form

$$\frac{dT}{dt} = \frac{1}{\rho V} \left[\dot{m}_{out} (T - T_{out}) + \frac{\dot{Q}}{c_p} + \frac{V \frac{dp}{dt}}{c_p dt}\right]$$  \hspace{1cm} (6-45)

$$\frac{dp}{dt} = \frac{\left(\frac{\partial p}{\partial \rho}\right)_T}{\rho V} \left\{ -\rho \dot{m}_{out} \left[\frac{\partial p}{\partial T}\right] + \left[\frac{\dot{Q}}{c_p}\right] \left[\dot{m}_{out} (T - T_{out}) + \frac{\dot{Q}}{c_p}\right]\right\}$$  \hspace{1cm} (6-46)
During the pipeline discharge transient the gas outlet temperature $T_{out}$ is not constant. Therefore, in the above equations the outlet temperature is approximated with the mean gas temperature. It should be noted that this approximation leads to an even more conservative approach to the estimation of the temperature and pressure change. Namely, the term $m_{out}(T - T_{out})$ is positive and it reduces the temperature drop calculated by equation (6-45) in case of the gas discharging transient. The same holds for the pressure drop. The partial derivative $\left(\frac{\partial p}{\partial T}\right)_p$ has a negative value and the term $\left(\frac{\partial p}{\partial T}\right)_p \left(\frac{\partial T}{\partial T}\right)_p m_{out}(T - T_{out})$ in the numerator of equation (6-46) reduces the pressure drop during the gas discharging from the pipeline. The solution of equations (6-45) and (6-46) is also in the form of equations (6-35) and (6-36). The related coefficients in these equations are

$$a_i = \frac{\left(\frac{\partial p}{\partial \rho}ight)_T}{\rho} \left\{-\rho m_{out} - \left(\frac{\partial p}{\partial T}\right)_T \left[\frac{2\pi \lambda L}{c_p \cosh^{-1}(2x/D)} T_s + f \frac{\rho u^3}{2Dc_p} \right]\right\}$$

$$b_i = \frac{\left(\frac{\partial p}{\partial \rho}ight)_T}{\rho} \left(\frac{\partial p}{\partial T}\right)_p \frac{2\pi \lambda L}{c_p \cosh^{-1}(2x/D)}$$

$$a_2 = \frac{1}{\rho} \left[\frac{2\pi \lambda L}{c_p \cosh^{-1}(2x/D)} T_s + \left(\frac{\partial p}{\partial \rho}\right)_T \left\{-\rho m_{out} - \left(\frac{\partial p}{\partial T}\right)_T \left[\frac{2\pi \lambda L}{c_p \cosh^{-1}(2x/D)} T_s + f \frac{\rho u^3}{2Dc_p} \right]\right\} \right]$$

$$b_2 = \frac{1}{\rho} \left[\frac{2\pi \lambda L}{c_p \cosh^{-1}(2x/D)} \left(\frac{\partial p}{\partial \rho}\right)_T \left(\frac{\partial p}{\partial T}\right)_p \frac{2\pi \lambda L}{c_p \cosh^{-1}(2x/D)} \right]$$
The differences of mean temperature and pressure changes under non-isothermal and isothermal conditions, in case of the pipeline emptying Scenario 1 in Section 6.1, when the gas supply at the Wafa plant is stopped and the gas delivery is continued with the value of the initial flow rate, are respectively -0.8 K and 0.17 MPa (this pressure difference is 11% of the calculated pressure change under non-isothermal conditions).

6.3 Conclusions

The GTA code is used for the simulation of transient behaviour of the 525 kilometres long distance pipeline of the Western Libya Gas Project. First, the results of simulated operational condition are compared with the available measured data and an acceptable agreement is obtained. Afterwards, simulated are transients caused by hypothetical scenarios of abrupt disturbances in gas inflow at the gas source form the wells field and trips of gas delivery to the consumers. In addition, The GTA code predictions are obtained under isothermal flow conditions, while the influence of the heat generation due to friction on the inner pipeline wall and the heat transfer to the surrounding soil is determined by the application of adequate thermal energy balance equations. The main findings are discussed in the next Chapter 7.
CHAPTER 7

CONCLUSIONS

For the prediction of transient natural gas flows in transmission pipelines and pipe networks, the numerical model and computer code GTA (Gas Transient Analysis) are developed based on one-dimensional compressible gas flow in pipeline of constant diameter. Using the method of characteristics the mass and momentum governing equations are solved numerically. The intersection of several pipes and prescribed transient mass flow rates and pressure data at inlet and outlet of pipeline are considered as boundary conditions of a model, which enable modelling of gas networks of diverse configurations.

The GTA code is validated by computer simulations of transient cases reported in the literature. Four cases are simulated to validate the code, which include transients caused by the variable gas consumption and boundary pressure pulses. Results of simulations show that the procedure of calculation is numerically stable, also the good agreement between the previous published results and the GTA results is achieved.

In addition, the gas transient analysis code is applied for the simulation of transient behavior of the several hundred kilometers long distance pipeline of the Western Libya Gas Project. The results of simulated operational condition are firstly compared with available measured data and acceptable agreement is obtained. Thereafter, transients are simulated for different suppositional scenarios of sudden disturbances in gas inflow at the gas source wells fields and trips of gas delivery to the consumers. The main findings are as following:

- In spite of the trip of the natural gas delivery to the inlet point of the pipeline from the source wells and the decreasing of corresponding pressure and flow rate along the pipeline from the Wafa Desert Plant towards the Mellitah Complex and in the branch towards the TPP, scenario 1 shows that the required delivery flow rates at the TPP and at the Mellitah Complex are maintained for a period even longer than 24 hours, due to the gas accumulation in the large volume of the gas transmission pipeline.

- Scenario 2 shows that even though the delivery flow rate in the Mellitah Complex is stopped after 1 hour, the decreasing flow rate at the inlet of the long pipeline towards Mellitah Complex still exists in the long period of 11 hours after the outlet flow stoppage due to the corresponding pressure increase and the gas accumulation. After one hour of the trip of gas delivery in the
Mellitah Complex, the pressure along the several hundred kilometers long pipeline towards the Mellitah Complex is practically constant. The pressure increase within the whole pipeline system indicates gas accumulation.

- Scenario 3 shows that although the whole gas delivery to consumers (Mellitah Complex and TPP) is stopped, there is still a gas inflow at the main pipeline inlet point for a period about 11 hours, due to the gas accumulation and corresponding pressure increase. Because of its relatively short length of 5 km, the flow rate in the branch towards the TPP practically immediately stops. The flow rate sustains for a time period longer than 11 hours in the main transmission pipeline due to its long length of 525 km.

- Furthermore, the GTA code predictions are obtained under isothermal flow conditions. In order to evaluate the error introduced by this assumption in the simulation of long transmission pipeline transients of the Western Libya Gas Project, the analytical expressions are derived based on the solving of mass, volume and energy balance equations of the pipeline gas volume. These equations provide differences between isothermal and non-isothermal mean gas pressure changes in the pipeline during the gas packing and during the gas discharge from the pipeline under the trip of gas supply, as well as the temperature changes during these transients. The results show that the mean temperature change is a few degrees Celsius and the relative difference between isothermal and non-isothermal pressure change is not greater than 9.2% in case of gas packing and up to 11% in case of pipeline discharging. These differences are in the range that can be introduced with the uncertainties of the soil thermal conductivity and ambient temperature along the long transmission pipeline. In addition, the thermal effects under steady-state conditions are analytically evaluated and their influence on the prediction of pressure change along the long transmission pipeline is within 3%. This error is in the range of the uncertainty of friction pressure drop calculation due to the uncertainty of the wall roughness prediction in the span of 0.01 mm. Therefore, these estimations of maximum errors that are introduced by the application of the isothermal gas flow model are in favor of the isothermal model application in engineering calculations, when other important conditions, such as the soil thermal conductivity, the ambient temperature or the wall surface roughness might introduce uncertainty of even higher values.

- The gas temperature in steady-state condition is determined by the heat generation due to the gas friction on the pipeline’s wall and by the heat transfer from the pipeline to the surrounding ambient, as presented by equation (6-37). The heat generation by friction in the long transmission pipelines is of the order of MW and according to equation (6-37) there is a difference of the gas and soil temperatures by a few Celsius degrees. This difference should be taken into account also in case of isothermal calculations (in Subsection 6.2.1 the adopted soil
temperature is 295 K, the gas inlet temperature is 315 K and the calculated mean gas temperature in steady-state operation is 301.5 K). Hence, the assumption that in the long pipeline the gas temperature is equal to the surrounding soil temperature is not adequate. The gas temperature is a few degrees higher and, as explained, it is determined by the heat generation by friction and its transfer from the gas to the surrounding soil.

The developed GTA code and presented results are a support to planning and specification of operational and repair procedures and guidelines in cases of abnormal conditions.
REFERENCES

1. Borraz-Sanchez, C. 2010. Optimization Methods for Pipeline Transportation of Natural Gas. PhD dissertation. University of Bergen, Norway.

2. Mokhatab, M., Poe, W. A., Speight, J. G., 2006. Handbook of Natural Gas Transmission and Processing, Gulf Professional Publishing, Elsevier. USA.

3. How products are made. http://www.madehow.com/Volume-6/Natural-Gas.html. 2010

4. Pipeline and Gas Journal’s 2017 Worldwide Pipeline Construction Report. January 2017, Vol. 244, No.1.

5. BP Statistical Review of World Energy. June 2018. 67th edition. UK.

6. Kelkar, M., 2008. Natural Gas: Production Engineering. Copyright by Penn Well Corporation, USA.

7. BP Statistical Review of World Energy. June 2019. 68th edition. UK.

8. International Energy Outlook 2019 with projections to 2050, the U.S. Energy Information Administration (EIA), 24 Sep. 2019. USA.

9. Rios-Mercado, R. Z., Borraz-Sa´nchez, C., 2014, “Optimization Problems in Natural Gas Transportation Systems: A State-of-the-Art Review”, University Autònoma de Nuevo León (UANL), Report number: PISIS-2014-04.

10. Government of Alberta, Energy. http://www.energy.alberta.ca/NaturalGas/. 2011

11. Osiadacz, A. J., and Chaczykowski, M., 2001. Comparison of Isothermal and Non-Isothermal Pipeline Gas Flow Models. Chem. Eng. J. 81(1-3), pp. 41–51.

12. Chapman, K. S., Krishniswami, P., Wallentine, V., Abbaspour, M., Ranganathan, R., Addanki, R., Sengupta, J., Chen, L., 2005. Final Technical Report: Virtual Pipeline System Testbed to Optimize the U.S. Natural Gas Transmission Pipeline System. DE-FC26-02NT41322, USA.

13. Abbaspour, M., 2005. Simulation and Optimization of Non-Isothermal, One-Dimensional Single / Two-Phase Flow in Natural Gas Pipeline. PhD, Kansas State University, USA.

14. Wu, S., 1998. Steady State Simulation and Fuel Cost Minimization of Gas Pipeline Networks. PhD, University of Houston, USA.

15. Key World Energy Statistics, International Energy Agency (IEA), 2019.

16. Stoner, M. A., 1972. Sensitivity Analysis Applied to a Steady-State Model of Natural Gas Transportation systems. SPE 45th Annual Fall Meeting, Houston, USA.
17. Mohitpour, M., William, T., Asante, B., 1996. The Importance of Dynamic Simulation on the Design and Optimization of pipeline transmission systems. International Pipeline Conference — Vol. 2, ASME 1996

18. A.L.H. Costa, J.L. de Medeiros and F.L.P. Pessoa. 1998. Steady-State Modeling and Simulation of Pipeline Networks for Compressible Fluids. Brazilian Journal of Chemical Engineering, vol. 15 n. 4.

http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0104-66321998000400004&lng=en&tlng=en

19. Nouri-Borujerdi, A., Ziaei-Rad, M., 2009. Simulation of compressible flow in high pressure buried gas pipelines. International Journal of Heat and Mass Transfer 52, 5751–5758

20. Alghlam, A.S. 2012. Numerical Scheme for Modeling Natural Gas Flow in Cross-Border Pipelines. ME thesis, University of technology Malaysia.

21. Cameron, I. 1999 Using an Excel-Based Model for Steady State and Transient Simulation. TransCanada Transmission. Alberta, Canada.

22. Szoplik, J., 2010. The Steady-State Simulations for Gas Flow in a Pipeline Network. Chemical Engineering Transactions, Vol. 21, 1459-1464.

23. J. Zhou, M. A. Adewumi. The Development and Testing of a New Flow Equation. Pipeline Simulation Interest Group Annual Meeting, PSIG-9504, US.

24. Ouyang, L., Aziz, K., 1995. Steady-state gas flow in pipes. Journal of Petroleum Science and Engineering, Vol. 14, pp 137-158.

25. Rhoads, G. A., 1983. Which Flow Equation- Does It Matter?. Pipeline Simulation in Interset Group. PSIG Annual Meeting, Michigan, USA.

26. Schroeder, Jr. D. W., 2001. A Tutorial on Pipe Flow Equations. Carlisle Pennsylvania 17013-0086, pp. 1-18.

27. Stoner, M. A., 1969. Steady-state Analysis of Gas Production, Transmission and Distribution Systems. No. SPE 2554, Society of Petroleum Engineers of AIME, Texas, USA.

28. Berard, G. P., Eliason, B. G., 1978. An Improved Gas Transmission System Simulator. Society of Petroleum Engineers of AIME. No. SPE 6872, 52ND Annual Fall Technical Conference Exhibition, Denver, USA.

29. Hoeven, T. V., Gasunie, N. V.N., 1992. Some Mathematical Aspects of Gas Network Simulation. Gasunie Netherlands.

30. Tian, S., Adewumi, M. A., 1994. Development of Analytical Design Equation for Gas Pipelines. Society of Petroleum Engineers, SPE Production & Facilities, pp 100-106.
31. Sung, W., Huh, D., Lee, J., Kwon, O., 1998. Optimization of Pipeline Networks with a Hybrid MCST-CD Networking Model. SPE Production & Facilities, pp 213-219.

32. Rios-Mercado, Roger Z. A, Suming Wu, Ridgway S. L., S., Boyd, E. A., 2001. A Reduction Technique for Natural Gas Transmission. Network Optimization Problems.

33. Martínez-Romero, N., Osorio-Peralta, O., Santamaria-Vite, I., 2002. Natural Gas Network Optimization and Sensibility Analysis. Society of Petroleum Engineers, SPE 74384. International Petroleum Conference and Exhibition, Mexico.

34. Doonan, A.F., Fletcher, I. Cox, C.S., Arden W.J.B, 1998. Evaluation of a Remote Boundary Pressure Control Strategy Using SIMULINKTM. UKACC International Conference on Control. Publication No. 455, pp 129-134.

35. Fauer, D., 2002. The Making of a Useful Pipeline Simulation Model. Southern Natural Gas.

36. Greyvenstein, G. P., Laurie, D. P., 1994. A Segregated CFD Approach to Pipe Network Analysis. International Journal for Numerical Methods in Engineering, Vol. 37, pp 3685-3705.

37. Zhou, J., Adewumi, M. A., 1997. Predicting Gas Flowing Temperature and Pressure Profiles in Buried Pipelines. Society of Petroleum Engineers, SPE 38460.

38. Osiadacz, A. J., 1994. Dynamic Optimization of High Pressure Gas Networks Using Hierarchica System Theory. State Committee for Scientific Research, No. 80565.

39. Pambour, K.A., Bolado-Lavin, R., Dijkema, G.P.J. 2016. An integrated transient model for simulating the operation of natural gas transport systems. Journal of Natural Gas Science and Engineering 28. 672-690.

40. Zuo, L., Jiang, F., Jin, B., Zhang, L., Xue, T., 2015. Value settings for the rate of pressure drop of automatic line-break control valves in natural gas pipelines. Journal of Natural Gas Science and Engineering 26. 803-809.

41. Edalat, M., Mansoori, G. A., 1988. Buried Gas Transmission Pipelines: Temperature Profile Prediction Through the Corresponding States Principle. Energy Sources, Vol. 10, 247-252

42. Oosterkamp, A., 2016. Modelling and Measuring Transient Flow in Natural Gas Pipelines, Effect of Ambient Heat Transfer Models. Norwegian University of Science and Technology.

43. Stevanovic, V. 2008. Security of gas pipelines. Proceedings of the NATO Advanced Research Workshop on Security and Reliability of Damaged Structures and Defective Materials, Portoroz, Slovenia, Springer, pp. 253-256.
Yuan, Z., Deng, Z., Jiang, M., Xie, Y., Wu, Y., 2015. A modeling and analytical solution for transient flow in natural gas pipelines with extended partial blockage. Journal of Natural Gas Science and Engineering 22. 141-149.

Thorley, A.R.T., Tiley, C.H. 1987. Unsteady and transient flow of compressible fluids in pipelines—a review of theoretical and some experimental studies. Thermo-Fluids Engineering Research Centre, the City University of London, UK. International Journal of Heat and Fluid Flow, volume 8, issue 1, March 1987, pages 3-15.

Heath, M. J., Blunt J. C. 1968. Dynamic Simulation Applied to the Design and Control of a Pipeline Network. Volume 149 of Research communication, Gas Council.

Osiadacz, A.J., Yedrouj, M. 1989. A comparison of a finite element method and a finite difference method for transient simulation of a gas pipeline. Applied Mathematical Modelling, vol. 13.

Van Deen, J.K., Reintsema, S.R., 1983. Modelling of high-pressure gas transmission lines. Applied Mathematical Modelling, Vol. 7, pp 268-273.

Abott, M.B. 1966. An Introduction to the Method of Characteristics. (Book) New York, American Elsevier.

Mekebel, S., Loraud, J.C. 1985. Study of a variable flow in natural gas pipelines. International Chemical Engineering, vol.:25:2.

Osiadacz, A. J., 1987. Ke Simulation and Analysis of Gas Networks. Gulf Publishing Company, Houston.

Yow, W., 1971, Analysis and Control of Transient Flow in Natural Gas Piping Systems. Ph.D. dissertation, U. of Michigan.

Wylie, E. B., Streeter, V. L., Stoner, M. A., 1974. Unsteady-State Natural-Gas Calculations in Complex Pipe Systems. Society of Petroleum Engineers Journal, SPE 4004

Herran-Gonzalez, A., De La Cruz, J.M., De Andres-Toro, B., Risco-Martín, J.L. 2009. Modeling and simulation of a gas distribution pipeline network. Applied Mathematical Modelling 33, (1584-1600).

Reddy, H.P., Narasimhan, S., Bhallamudi, S.M. 2006. Simulation and State Estimation of Transient Flow in Gas Pipeline Networks Using a Transfer Function Model. Industrial & Engineering Chemistry Research 45(11).

Alamian, R., Behbahani-Nejad, M., Ghanbarzadeh, A., 2012. A state space model for transient flow simulation in natural gas pipelines. Journal of Natural Gas Science and Engineering 9, 51-59.

Wang, H., Liu, X., L., Zhou, W. 2011. Transient flow simulation of municipal gas pipelines and networks using semi implicit finite volume method. SREE
Conference on Engineering Modelling and Simulation (CEMS 2011), Procedia Engineering 12, 217–223.

58. Noorbehesht N., Ghaseminejad P., 2013. Numerical Simulation of the Transient Flow in Natural Gas Transmission Lines Using a Computational Fluid Dynamic Method. American Journal of Applied Sciences, 10 (1): 24-34, 2013. ISSN: 1546-9239.

59. Ibraheem, S. O., Adewumi, M. A., 1996. Higher-Resolution Numerical Solution for 2-D Transient Natural Gas Pipeline Flows. Society of Petroleum Engineers, SPE 35626.

60. Dorao, C.A., Fernandino, M. 2011. Simulation of transients in natural gas pipelines. Journal of Natural Gas Science and Engineering 3, pp 349-355.

61. Farzaneh-Gord, M., Rahbari, H.R. 2016. Unsteady natural gas flow within pipeline network, an analytical approach. Journal of Natural Gas Science and Engineering 28, 397-409.

62. Issa, R. I., and Spalding, D. B., 1972, “Unsteady One-Dimensional Compressible Frictional Flow with Heat Transfer”, Journal of Mechanical Engineering Science, 14 (6), pp. 365-369.

63. Price, G. R., McBrien, R. K., Rizopoulos S. N., Golshan, H., 1999. Evaluating the Effective Friction Factor and Overall Heat Transfer Coefficient During Unsteady Pipeline Operation. Journal of offshore Mechanics and Arctic Engineering, Vol. 121, ASME.

64. Tentis, E., Margaris, D., Papanikas, D. 2003. Transient gas flow simulation using an Adaptive Method of Lines. C. R. Mecanique, 331, pp 481–487.

65. Rachford, Jr. H. H., Rice U, Dupont T., 1974. A Fast Highly Accurate Means of Modeling Transient Flow in Gas Pipeline Systems by Variational Methods. SPE-AIME 47th Annual Fall Meeting, SPE 4005A, pp 165-178

66. Maddox, R. N., Zhou, P., 1983. Use of Steady State Equations for Transient Flow Calculations. Pipeline Simulation in Interest Group.

67. T. Kiuchi. An Implicit Method for Transient Gas Flow in Pipe Networks. 1994

68. Beam, R. M., Warming, R. F., 1976. An Implicit Finite-Difference Algorithm for Hyperbolic Systems in Conservation-Low Form. Journal of Computational Physics 22, pp 87-110.

69. Luongo, C. A., 1986. An Efficient Program for Transient Flow Simulation In Natural Gas Pipelines. Pipeline Simulation in Interest Group, PSIG Annual Meeting.

70. Tao, W. Q., Ti, H. C., 1998. Transient Analysis of Natural Gas Network. Chemical Engineering Journal 69, pp 47-52

71. Osiadacz, A. J., 1996, “Different Transient Models- Limitations, Advantages
and Disadvantages”, Proceedings of the Pipeline Simulation Interest Group, PSIG Annual Meeting, 23-25 October, San Francisco, California.

72. Lewandowski, A., 1995. New Numerical Methods for Transient Modeling of Gas Pipeline Networks. Pipeline Simulation Interest Group. PSIG-9510.

73. Modisette, J., 2002. Pipeline Thermal Models, PhD. Energy Solutions International.

74. Abbaspour, M., Chapman, K.S., Glasgow, L.A. 2010. Transient modeling of non-isothermal dispersed two-phase flow in natural gas pipelines. Applied Mathematical Modelling 34, 495–507.

75. Dufont, T., Rachford. Jr. H. H., The Effect of Thermal Changes Induced by Transients in Gas Flow. University of Chicago and Dupont-Rachford Engineering Mathematics Company. 1980

76. Gato, L.M.C., Henriques, J.C.C. 2005. Dynamic behavior of high-pressure natural-gas flow in pipelines. International Journal of Heat and Fluid Flow 26, 817–825.

77. Chaczykowski, M., 2009. Sensitivity of pipeline gas flow model to the selection of the equation of sate. Journal of chemical engineering research and design 87, 1596–1603.

78. Chaczykowski, M., 2010. Transient flow in natural gas pipeline – The effect of pipeline thermal model. Applied Mathematical Modelling 34, pp 1051–1067

79. Coelho, P. M., Pinho, C., 2007. Considerations about Equations for Steady State Flow in Natural Gas Pipelines. J. of the Braz. Soc. of Mech. Sci. & Eng., Vol. XXIX, No. 3, pp 262-273.

80. Zhou, J., Adewumi, M.A., 1996. Simulation of transient flow in natural gas pipelines, the Pennsylvania State University. Petroleum and Natural Gas Engineering. GRIPA 16802.

81. Abbaspour, M., Chapman, K. S., 2008. Non-isothermal Transient Flow in Natural Gas Pipeline. Journal of Applied Mechanics, ASME, Vol. 75.

82. Adeosun, T. A., Olatunde, O. A., Aderohunmu, J. O., Ogunjare, T. O., 2009. Development of unsteady-state Weymouth equations for gas volumetric flow rate in horizontal and inclined pipes. Journal of Natural Gas Science and Engineering 1, pp 113–117.

83. Behbahani-Nejad, M., Shekari, Y., 2010. The accuracy and efficiency of a reduced-order model for transient flow analysis in gas pipelines. Journal of Petroleum Science and Engineering 73 (1-2), 13-19.

84. Helgaker, J. F., Muller, B., Ytrehus, T., 2014. Transient Flow in Natural Gas Pipelines Using Implicit Finite Difference Schemes. Journal of Offshore Mechanics and Arctic Engineering. ASME, vol. 136

110
85. Helgaker, J. F., Oosterkamp, A., Langelandvik, L.I., Ytrehus, T. 2014. Validation of 1D flow model for high pressure offshore natural gas pipelines. Journal of Natural Gas Science and Engineering 16. 44-56

86. Santos, S.P., 1997. Transient Analysis, a Must in Gas Pipeline Design. Pipeline Simulation Interest Group, Engineering Service of Petrobras - SEGEN

87. Finch, J. F., Ko, D. W., 1988. Tutorial: Fluid Flow Formula. Pipeline Simulation Interest Group

88. Zhang, X., Wu, C., Zuo, L., 2016. Minimizing fuel consumption of a gas pipeline in transient states by dynamic programming. Journal of Natural Gas Science and Engineering 28. 193-203.

89. Zhang, L., 2016. Simulation of the transient flow in a natural gas compression system using a high-order upwind scheme considering the real-gas behaviors. Journal of Natural Gas Science and Engineering 28. 479-490.

90. Chaczykowski, M., Sund, F., Zarodkiewicz, P., Hope, S.M., 2018. Gas composition tracking in transient pipeline flow. Journal of Natural Gas Science and Engineering 55, 321-330.

91. Wulff, W., 1987. Computational Methods for Multiphase Flow. Proceedings of the Second International Workshop on Two-phase Flow Fundamentals, New York, USA, Rensselaer Polytechnic Institute.

92. Menon, E. S., 2005. Gas pipeline hydraulics. Taylor & Francis Group, LLC.

93. Mohitpour, M., Golshan, H., Murray, A., 2007. Pipeline Design and Construction: A Practical Approach. 2nd Edition.

94. White, F. M., 1999, Viscous Fluid Flow, McGraw-Hill, NY.

95. Sani, F. M., Huiainga, S., Esaklul, K. A., Nestic, S., 2019. Review of the API RP 14E erosional velocity equation: Origin, applications, misuses, limitations and alternatives. An International Journal on the Science and Technology of Friction, Lubrication and Wear, 426–427 (2019) 620–636.

96. Alghlam, A. S., Stevanovic, V. D., Elgazdori, E. A., Banjac, M., 2019. Numerical Simulation of Natural Gas Pipeline Transients. Journal of Energy Resources Technology, ASME, Vol. 141, article No. 102002, pp. 1-14.

97. Behbahani-Nejad, M., Bagheri, A. 2008. A MATLAB Simulink Library for Transient Flow Simulation of Gas Networks. World Academy of Science, International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering Vol. 2, No:7.

98. Ke, S.L., Ti, H.C., 2000. Transient analysis of isothermal gas flow in pipeline network. Chemical Engineering Journal 76, 169-177.

99. Eni Gas B.V., 2007, Western Libya Gas Project, Onshore Pipelines, Ar
100. Rohsenow, W. M., and Hartnett, J. P., 1998, Handbook of Heat Transfer, Y.I. Cho. 3rd ed., McGraw-Hill.

101. Badache, M., Eslami-Nejad, P., Ouzzane, M., Aidoun, Z., and Lamarche, L., 2016. A new modeling approach for improved ground temperature profile determination. Renewable Energy, 85, pp. 436-444.

102. Jia, W, Li, C., and Wu, X., 2014. Internal Surface Absolute Roughness for Large-Diameter Natural Gas Transmission Pipelines. Oil Gas European Magazine, 4, pp. 1-3.
APPENDIX A-1

FLOW GOVERNING EQUATIONS

- Continuity Equation

In figure A1 below, the control volume of the continuity is shown, where the conservation of mass can be written as follows:

Figure A1 Control volume of continuity equation

\[
\rho Au - \rho Au - \frac{\partial}{\partial x} (\rho Au) dx = \frac{\partial}{\partial t} (\rho Adx)
\]

\[
\frac{\partial}{\partial x} (\rho Au) dx + \frac{\partial}{\partial t} (\rho Adx) = 0
\]

\[
\frac{\partial}{\partial x} (\rho u) dx + \frac{\partial}{\partial t} (\rho dx) = 0
\]

\[
\left[ u \frac{\partial \rho}{\partial x} + \rho \frac{\partial u}{\partial x} \right] dx + \frac{\partial \rho}{\partial t} dx = 0 \]

\[
u \frac{\partial \rho}{\partial x} + \rho \frac{\partial u}{\partial x} + \frac{\partial \rho}{\partial t} = 0
\]

\[
\frac{D\rho}{Dt} + \rho \frac{\partial u}{\partial x} = 0
\]  (A-2)
Momentum Equation

For the control volume illustrated in figure A2, and using the following force component summation, the momentum equation can be written as below:

\[
pA - pAa - \frac{\partial}{\partial x} (pA)dx - \tau \pi Ddx - \rho g A dx \left( \frac{dy}{dx} \right) = (\rho A dx) \left( u \frac{\partial u}{\partial x} + \frac{\partial u}{\partial t} \right)
\]

Dividing by \( dx \) and the cross section area \( A \) leads to

\[
- \frac{\partial p}{\partial x} - \frac{\tau \pi D}{A} - \rho g \frac{dy}{dx} = \rho \left( u \frac{\partial u}{\partial x} + \frac{\partial u}{\partial t} \right)
\]

where: the hydraulic diameter \( D_H \) equals the pipeline inner diameter \( D \) in case of pipe flow;

\( u \) is the absolute value of flow velocity;

\( \tau \) is the shear stress between the fluid and pipe wall which can be obtained by the next equation:

\[
\tau = \frac{f \rho u |u|}{8}
\]

\( f \) is the Darcy friction factor

Introducing \( \left( \frac{dy}{dx} \right) = \sin \theta \) and the cross section area of pipe \( A = \frac{\pi}{4} D_H^2 \) the following equation is obtained

\[
- \frac{\partial p}{\partial x} - \frac{f \rho u |u| \pi D_H}{8 \frac{\pi}{4} D_H^2} - \rho g \sin \theta = \rho \frac{Du}{Dt}
\]
Dividing by $\rho$
\[
-\frac{1}{\rho} \frac{\partial p}{\partial x} - \frac{f u|u|}{2D_{ul}} - g \sin \theta = \frac{Du}{Dt}
\]
and the final form of the momentum equation reads
\[
\frac{Du}{Dt} + \frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{f u|u|}{2D_{ul}} + g \sin \theta = 0 \quad (A-4)
\]

**Conservation of Energy**

The basic form of energy equation is written for the control volume illustrated in figure A3 by applying the first law of thermodynamics

![Figure A3 Control volume of energy equation](image)

\[
\dot{Q} = \dot{q}Adx = \frac{\partial}{\partial t} \left[ \rho Adx \left( e + \frac{u^2}{2} + gy \right) \right] + \frac{\partial}{\partial x} \left[ \rho uA \left( e + \frac{u^2}{2} + gy + \frac{p}{\rho} \right) \right] dx \quad (A-5)
\]

where: $\dot{q}$ is the heat transfer per unit volume, W/m$^3$, $e$ is the internal energy per unit mass in J/kg and $Q$ is the heat transfer in W. The separation of the second term leads to

\[
\dot{Q} = \dot{q}Adx = \rho Adx \left[ \frac{\partial}{\partial t} \left( e + \frac{u^2}{2} + gy \right) + u \frac{\partial}{\partial x} \left( e + \frac{u^2}{2} + gy \right) + \left( e + \frac{u^2}{2} + gy \right) \frac{\partial (\rho A)}{\partial t} + \frac{\partial (\rho uA)}{\partial x} \right] dx + \left[ p \frac{\partial (\rho uA)}{\partial x} + (\rho uA) \frac{\partial (\rho A)}{\partial x} \right] dx
\]

From continuity equation (A-2), the term
\[
\left( \frac{\partial (\rho A)}{\partial t} + \frac{\partial (\rho uA)}{\partial x} \right) = 0
\]

dividing by $\rho Adx$ the energy equation reduces to
\[
\dot{q} = \frac{D}{\rho} \left( e + \frac{u^2}{2} + gy \right) + \frac{p}{\rho A} \frac{\partial (uA)}{\partial x} + \frac{u}{\rho} \frac{\partial p}{\partial x}
\]

From momentum equation (A-4) and multiplying by \( u \) it is obtained
\[
u \frac{\partial u}{\partial t} + u^2 \frac{\partial u}{\partial x} + \frac{u}{\rho} \frac{\partial p}{\partial x} = -\frac{uw}{\rho A} - ug \sin \theta \tag{A-6}\]

where \( w \) is a work of frictional force per unit length of pipe
\[
w = \frac{f \rho u |u|}{8 \pi D_h}
\]

The above equation is written as
\[
u \frac{\partial p}{\partial x} = -u \frac{Du}{Dt} - \frac{wu}{\rho A} - ug \sin \theta
\]

The continuity equation (A-2) is written as
\[
\frac{\partial}{\partial x} (uA) = -\frac{A D \rho}{\rho D_t}
\]

Introduction of the above momentum and continuity equations in the energy equation (A-6) leads to
\[
\dot{q} = \frac{D}{\rho} \left( e + \frac{u^2}{2} + gy \right) - \frac{p}{\rho^2} \frac{D \rho}{D_t} - u \frac{Du}{D_t} - \frac{wu}{\rho A} - ug \sin \theta
\]

On the other hand, it is known that \( \frac{d y}{d x} = \sin \theta \), so, we can consider the following equation:
\[
\frac{D}{D_t} (gy) = g \left( \frac{\partial y}{\partial t} + u \frac{\partial y}{\partial x} \right) = gusin \theta \text{ and } \frac{D}{D_t} \left( \frac{u^2}{2} \right) = u \frac{Du}{D_t}
\]

Introduction of these two relations into energy equation gives
\[
\dot{q} = \frac{D e}{D_t} \frac{p}{\rho D_t} \frac{Du}{\rho A}
\]

Introducing enthalpy as \( h = e + \frac{p}{\rho} \) and its material derivative as
\[
\frac{Dh}{D_t} = \frac{D e}{D_t} + \frac{D}{D_t} \left( \frac{p}{\rho} \right)
\]

the final form of energy equation is obtained as
\[
\frac{Dh}{D_t} - \frac{1}{\rho} \frac{Dp}{D_t} \frac{fu^2 |u|}{2D_h} - \frac{\dot{q}}{\rho} = 0 \tag{A-7}
\]
DETERMINING THE SPEED OF SOUND

The speed of sound is defined under the assumption of an isentropic propagation of infinitesimal mechanical disturbance in an elastic medium, with the following equation

\[ c^2 = \left( \frac{\partial p}{\partial \rho} \right)_s. \quad (A-8) \]

By using the coupling between the density and specific volume, \( \rho = \frac{1}{\nu} \) the velocity of sound can be expressed as a function of the pressure and specific volume as

\[ c^2 = -\nu^2 \left( \frac{\partial p}{\partial \nu} \right)_s. \quad (A-9) \]

For the purposes of the calculation with the GTA code developed in this thesis, the following derivation is introduced.

The equation of state \( \nu=\nu(p,h) \) is derived

\[ dv = \left( \frac{\partial \nu}{\partial p} \right)_h dp + \left( \frac{\partial \nu}{\partial h} \right)_p dh. \quad (A-10) \]

Since the definition of the speed of sound indicates that the square of the speed of sound equals partial derivative of pressure with respect to density at constant entropy, the second law of thermodynamics is taken into account \( ds = \frac{\delta q}{T} \) followed by \( \delta q = 0 \). Further, inclusion of this equality in the first law of thermodynamics \( \delta q = du + pd\nu \), and by using the definition of enthalpy \( dh = du + (p\nu) \), the following equation is derived

\[ dh = vdp. \quad (A-11) \]

Substituting equation (A-11) into equation (A-10) gives

\[ \left( \frac{\partial \nu}{\partial p} \right)_s = \left( \frac{\partial \nu}{\partial p} \right)_h + \nu \left( \frac{\partial \nu}{\partial h} \right)_p, \quad (A-12) \]

which is further introduced into equation (A-9) and we get the equation for the determination of the speed of sound as a function of pressure and enthalpy.
\[ c = \left[ \frac{1}{v^2 \left( \frac{\partial v}{\partial p} \right)_h + 1 \left( \frac{\partial v}{\partial h} \right)_p} \right]^{-1}. \] \tag{A-13}

In case of gas flow Eq. (A-21) can be further simplified by introducing the assumption of applicability of the ideal gas low. The ideal gas law is introduced in the form

\[ v = \frac{R_g T}{p} = \frac{R_g h}{(c_p) p} \] \tag{A-14}

where the gas constant is the ratio of the universal gas constant \( R \) and the molar mass \( M \), i.e. \( R_g = \frac{R}{M} \). Derivative of the specific volume \( v \) by \( p \) under constant \( h \) reads

\[ \left( \frac{\partial v}{\partial p} \right)_h = -\frac{R_g h}{c_p p^2} \] \tag{A-15}

and derivative by \( h \) under constant \( p \) reads

\[ \left( \frac{\partial v}{\partial h} \right)_p = \frac{R_g}{c_p p} \] \tag{A-16}

Introduction of Eqs. (A-15) and (A-16) into (A-13) and application of the relation \( R_g = c_p - c_v \) leads to

\[ c = \sqrt{\kappa R_g T} \] \tag{A-17}

where \( \kappa = \frac{c_p}{c_v} \).
APPENDIX A-3

DETERMINING THE CONSTANT C₁

In many references, C₁ is given only in USCS (United States Customary System) units and it has not been found in SI units. Because the code works in SI units, hence, it is necessary to determine constant C₁ in SI units.

From (Menon, 2005) [92], it is found that in USCS units the compressibility factor of natural gas flow in pipeline is given by the CNGA method, equation (3-20):

\[
z = \frac{1}{1 + \left( \frac{p \times C_1(10)^{1.785G}}{T^{3.825}} \right)}
\]

where in the USCS C₁ = 344400

From the same reference (Menon, 2005) [92] and from example 12 chapter 1:

T = 530 R, G = 0.6 and P = 1200 Psig

So, the calculation of compressibility factor results to, \( Z = 0.844 \)

To determine C₁ in SI units, all variable must be converted to SI units as following:

T = 294.26 K, G = 0.6 and P = 8273.71 kPa.

Substitute these variables in equation (3-20):

\[
0.844 = \frac{1}{1 + \left( \frac{8273.71 \times C_1(10)^{1.785G\times0.6}}{294.26^{3.825}} \right)}
\]

So, in SI units C₁ = 5260
DETERMINING THE CONSTANT C₂

As same in the previous section, the constant C₂ is given only in USCS units in many references and it has been found in SI units. Again, the GTA code works in SI units, hence, constant C₂ must be determined in SI units.

From section 2.7 in reference [92], it is found that in USCS units the maximum velocity of natural gas flow in pipeline is given in equation (3-32):

\[ u_{\text{max}} = \frac{C_2}{\sqrt{\rho}} = C_2 \sqrt{\frac{zRT}{29Gp}} \]

Where in USCS \( C_2 = 100 \)

From the same reference [92] and from example 1 in section 2.7:

\[ Z=0.9, R = 10.73 \text{ psia. ft}^3/\text{lb mol.}^o\text{R}, T = 520 \text{ R}, G = 0.6, \text{ and } P = 1014.7 \text{ Psia} \]

So, the calculated maximum velocity is, \( u_{\text{max}} = 53.33 \text{ ft/sec} \)

To determine \( C_2 \) in SI units, all variables must be converted to SI units as following:

\[ Z = 0.9, R = 8.314 \text{ kPa.m}^3/\text{kmol.K}, T = 288.7 \text{ K}, G = 0.6, \text{ and } P = 6996.1 \text{ kPa} \]

\[ u_{\text{max}}= 16.255 \text{ m/sec.} \]

Substitute these variables in equation (3-34):

\[ 16.255 = C_2 \sqrt{\frac{0.9 \times 8.314 \times 288.7}{29 \times 0.6 \times 6996.1}} \]

So, in SI units \( C_2 = 122 \)
APPENDIX B

CASES OF STUDY CALCULATION RESULTS

Chapter 5: Code Validation

- **Case 1**: (grid independency of Code)
  - 8 segments (9 nodes)

| Time (s) | M (kg/s) | V (MMSCMD) |
|----------|----------|------------|
| 26.2     | 14.497   | 1.521435   |
| 282.7    | 14.497   | 1.521435   |
| 539.2    | 14.497   | 1.521435   |
| 795.7    | 14.497   | 1.521435   |
| 1052.2   | 14.522   | 1.524045   |
| 1308.7   | 14.668   | 1.539287   |
| 1565.1   | 14.938   | 1.567474   |
| 1821.5   | 15.329   | 1.608293   |
| 2077.9   | 15.748   | 1.652035   |
| 2334.2   | 15.867   | 1.664458   |
| 2590.6   | 15.728   | 1.649947   |
| 2847     | 15.4     | 1.615705   |
| 3103.4   | 14.958   | 1.569562   |
| 3359.8   | 14.451   | 1.516633   |
| 3616.4   | 13.935   | 1.462764   |
| 3872.9   | 13.462   | 1.413385   |
| 4129.6   | 13.171   | 1.383006   |
| 4386.2   | 13.262   | 1.392506   |
| 4642.8   | 13.598   | 1.427583   |
| 4899.4   | 13.847   | 1.453578   |
| 5156     | 14.015   | 1.471116   |
| 5412.5   | 14.13    | 1.483122   |
| 5669     | 14.22    | 1.492517   |
| 5925.6   | 14.314   | 1.502331   |
- 160 segments (161 nodes)

| Time (s) | M (kg/s) | V (MMSCMD) |
|----------|----------|------------|
| 0        | 14.504   | 1.522166   |
| 13.1     | 14.505   | 1.52227    |
| 26       | 14.504   | 1.522166   |
| 38.8     | 14.504   | 1.522166   |
| 51.6     | 14.504   | 1.522166   |
| 64.4     | 14.504   | 1.522166   |
| 77.3     | 14.504   | 1.522166   |
| 90.1     | 14.506   | 1.522375   |
| 102.9    | 14.505   | 1.52227    |
| 115.7    | 14.504   | 1.522166   |
| 128.6    | 14.506   | 1.522375   |
| 141.4    | 14.505   | 1.52227    |
| 154.2    | 14.505   | 1.52227    |
| 167      | 14.505   | 1.52227    |
| 179.9    | 14.505   | 1.52227    |
| 192.7    | 14.506   | 1.522375   |
| 205.5    | 14.505   | 1.52227    |
| 218.3    | 14.506   | 1.522375   |
| 231.2    | 14.505   | 1.52227    |
| 244      | 14.505   | 1.52227    |
| 256.8    | 14.506   | 1.522375   |
| 269.6    | 14.504   | 1.522166   |
| 282.5    | 14.505   | 1.52227    |
| 295.3    | 14.505   | 1.52227    |
| 308.1    | 14.506   | 1.522375   |
| 320.9    | 14.505   | 1.52227    |
| 333.7    | 14.505   | 1.52227    |
| 346.6    | 14.505   | 1.52227    |
| 359.4    | 14.505   | 1.52227    |
| 372.2    | 14.506   | 1.522375   |
| 385      | 14.504   | 1.522166   |
| 397.9    | 14.505   | 1.52227    |
| 410.7    | 14.505   | 1.52227    |
| 423.5    | 14.504   | 1.522166   |
| 436.3    | 14.505   | 1.52227    |
| 449.2    | 14.504   | 1.522166   |
| 462      | 14.505   | 1.52227    |
| 474.8    | 14.505   | 1.52227    |
| 487.6    | 14.505   | 1.52227    |
| 500.4    | 14.505   | 1.52227    |
| 513.3    | 14.505   | 1.52227    |
| 526.1    | 14.505   | 1.52227    |
| 538.9    | 14.506   | 1.522375   |
| 551.7    | 14.505   | 1.52227    |
| 564.6    | 14.505   | 1.52227    |
| 577.4    | 14.505   | 1.52227    |
| Value  | 14.504 | 1.522166 |
|--------|--------|----------|
| 590.2  | 14.504 | 1.522166 |
| 603    | 14.504 | 1.522166 |
| 615.9  | 14.505 | 1.52227  |
| 628.7  | 14.506 | 1.522375 |
| 641.5  | 14.505 | 1.52227  |
| 654.3  | 14.505 | 1.52227  |
| 667.2  | 14.504 | 1.522166 |
| 680    | 14.506 | 1.522375 |
| 692.8  | 14.504 | 1.522166 |
| 705.6  | 14.506 | 1.522375 |
| 718.4  | 14.505 | 1.52227  |
| 731.3  | 14.505 | 1.52227  |
| 744.1  | 14.505 | 1.52227  |
| 756.9  | 14.504 | 1.522166 |
| 769.7  | 14.504 | 1.522166 |
| 782.6  | 14.504 | 1.522166 |
| 795.4  | 14.504 | 1.522166 |
| 808.2  | 14.505 | 1.52227  |
| 821    | 14.504 | 1.522166 |
| 833.9  | 14.501 | 1.521853 |
| 846.7  | 14.5    | 1.521748 |
| 859.5  | 14.498 | 1.52154  |
| 872.3  | 14.498 | 1.52154  |
| 885.2  | 14.499 | 1.521644 |
| 898    | 14.5    | 1.521748 |
| 910.8  | 14.5    | 1.521748 |
| 923.6  | 14.502 | 1.521957 |
| 936.4  | 14.505 | 1.52227  |
| 949.3  | 14.506 | 1.522375 |
| 962.1  | 14.507 | 1.522479 |
| 974.9  | 14.51   | 1.522792 |
| 987.7  | 14.513 | 1.523106 |
| 1000.6 | 14.517 | 1.523523 |
| 1013.4 | 14.521 | 1.523941 |
| 1026.2 | 14.524 | 1.524254 |
| 1039   | 14.528 | 1.524672 |
| 1051.9 | 14.532 | 1.525089 |
| 1064.7 | 14.536 | 1.525507 |
| 1077.5 | 14.544 | 1.526342 |
| 1090.4 | 14.546 | 1.526551 |
| 1103.2 | 14.551 | 1.527073 |
| 1116   | 14.557 | 1.527699 |
| 1128.9 | 14.561 | 1.528117 |
| 1141.7 | 14.568 | 1.528847 |
| 1154.5 | 14.573 | 1.529369 |
| 1167.3 | 14.579 | 1.529996 |
| 1180.2 | 14.585 | 1.530622 |
| 1193   | 14.592 | 1.531353 |
| 1205.8  | 14.6  | 1.532188 |
| 1218.7  | 14.608 | 1.533023 |
| 1231.5  | 14.619 | 1.534172 |
| 1244.3  | 14.627 | 1.535007 |
| 1257.1  | 14.639 | 1.53626 |
| 1270    | 14.65  | 1.537408 |
| 1282.8  | 14.66  | 1.538452 |
| 1295.6  | 14.672 | 1.539705 |
| 1308.5  | 14.682 | 1.540749 |
| 1321.3  | 14.693 | 1.541897 |
| 1334.1  | 14.7   | 1.542628 |
| 1346.9  | 14.71  | 1.543672 |
| 1359.8  | 14.721 | 1.54482 |
| 1372.6  | 14.731 | 1.545864 |
| 1385.4  | 14.744 | 1.547221 |
| 1398.2  | 14.757 | 1.548578 |
| 1411    | 14.773 | 1.550249 |
| 1423.8  | 14.789 | 1.551919 |
| 1436.7  | 14.805 | 1.553589 |
| 1449.5  | 14.817 | 1.554842 |
| 1462.3  | 14.83  | 1.556199 |
| 1475.1  | 14.843 | 1.557556 |
| 1487.9  | 14.854 | 1.558705 |
| 1500.7  | 14.868 | 1.560166 |
| 1513.6  | 14.883 | 1.561732 |
| 1526.4  | 14.901 | 1.563611 |
| 1539.2  | 14.92  | 1.565595 |
| 1552    | 14.94  | 1.567683 |
| 1564.8  | 14.957 | 1.569458 |
| 1577.7  | 14.971 | 1.570919 |
| 1590.5  | 14.984 | 1.572276 |
| 1603.3  | 14.999 | 1.573842 |
| 1616.1  | 15.016 | 1.575617 |
| 1628.9  | 15.036 | 1.577705 |
| 1641.7  | 15.059 | 1.580106 |
| 1654.6  | 15.08  | 1.582298 |
| 1667.4  | 15.1   | 1.584386 |
| 1680.2  | 15.117 | 1.586161 |
| 1693    | 15.132 | 1.587727 |
| 1705.8  | 15.149 | 1.589502 |
| 1718.6  | 15.171 | 1.591798 |
| 1731.5  | 15.197 | 1.594513 |
| 1744.3  | 15.219 | 1.59681 |
| 1757.1  | 15.24  | 1.599002 |
| 1769.9  | 15.257 | 1.600777 |
| 1782.7  | 15.276 | 1.60276 |
| 1795.5  | 15.297 | 1.604952 |
| 1808.4  | 15.325 | 1.607876 |
| Year | Latitude | Longitude |
|------|----------|-----------|
| 1821.2 | 15.35 | 1.610485 |
| 1834 | 15.373 | 1.612887 |
| 1846.8 | 15.394 | 1.615079 |
| 1859.6 | 15.414 | 1.617167 |
| 1872.5 | 15.436 | 1.619464 |
| 1885.3 | 15.464 | 1.622387 |
| 1898.1 | 15.492 | 1.62531 |
| 1910.9 | 15.513 | 1.627502 |
| 1923.7 | 15.536 | 1.629903 |
| 1936.5 | 15.558 | 1.6322 |
| 1949.4 | 15.588 | 1.635332 |
| 1962.2 | 15.618 | 1.638464 |
| 1975 | 15.643 | 1.641074 |
| 1987.8 | 15.668 | 1.643684 |
| 2000.6 | 15.69 | 1.64598 |
| 2013.4 | 15.721 | 1.649217 |
| 2026.3 | 15.709 | 1.647964 |
| 2039.1 | 15.725 | 1.649634 |
| 2051.9 | 15.737 | 1.650887 |
| 2064.7 | 15.749 | 1.65214 |
| 2077.5 | 15.767 | 1.654019 |
| 2090.3 | 15.78 | 1.655376 |
| 2103.2 | 15.792 | 1.656629 |
| 2116 | 15.801 | 1.657568 |
| 2128.8 | 15.813 | 1.658821 |
| 2141.6 | 15.822 | 1.659761 |
| 2154.4 | 15.832 | 1.660805 |
| 2167.3 | 15.844 | 1.662057 |
| 2180.1 | 15.853 | 1.662997 |
| 2192.9 | 15.862 | 1.663936 |
| 2205.7 | 15.868 | 1.664563 |
| 2218.5 | 15.873 | 1.665085 |
| 2231.3 | 15.877 | 1.665502 |
| 2244.2 | 15.881 | 1.66592 |
| 2257 | 15.883 | 1.666129 |
| 2269.8 | 15.884 | 1.666233 |
| 2282.6 | 15.885 | 1.666338 |
| 2295.4 | 15.885 | 1.666338 |
| 2308.2 | 15.884 | 1.666233 |
| 2321.1 | 15.885 | 1.666338 |
| 2333.9 | 15.883 | 1.666129 |
| 2346.7 | 15.879 | 1.665711 |
| 2359.5 | 15.875 | 1.665294 |
| 2372.3 | 15.87 | 1.664772 |
| 2385.1 | 15.865 | 1.66425 |
| 2398 | 15.858 | 1.663519 |
| 2410.8 | 15.852 | 1.662892 |
| 2423.6 | 15.844 | 1.662057 |
| Value | Distance | Refractive Index |
|-------|----------|-----------------|
| 2436.4 | 15.834   | 1.661013        |
| 2449.2 | 15.825   | 1.660074        |
| 2462.1 | 15.814   | 1.658925        |
| 2474.9 | 15.802   | 1.657673        |
| 2487.7 | 15.798   | 1.656315        |
| 2500.5 | 15.777   | 1.655063        |
| 2513.3 | 15.764   | 1.653706        |
| 2526.1 | 15.751   | 1.651347        |
| 2539   | 15.738   | 1.649984        |
| 2551.8 | 15.725   | 1.648625        |
| 2564.6 | 15.712   | 1.647266        |
| 2577.4 | 15.699   | 1.645907        |
| 2590.2 | 15.686   | 1.644548        |
| 2603   | 15.673   | 1.643189        |
| 2615.9 | 15.660   | 1.641830        |
| 2628.7 | 15.647   | 1.640471        |
| 2641.5 | 15.634   | 1.639112        |
| 2654.3 | 15.621   | 1.637753        |
| 2667.1 | 15.608   | 1.636394        |
| 2679.9 | 15.595   | 1.635035        |
| 2692.8 | 15.582   | 1.633676        |
| 2705.6 | 15.569   | 1.632317        |
| 2718.4 | 15.556   | 1.630958        |
| 2731.2 | 15.543   | 1.629599        |
| 2744   | 15.530   | 1.628240        |
| 2756.9 | 15.517   | 1.626881        |
| 2769.7 | 15.504   | 1.625522        |
| 2782.5 | 15.491   | 1.624163        |
| 2795.3 | 15.478   | 1.622804        |
| 2808.1 | 15.465   | 1.621445        |
| 2820.9 | 15.452   | 1.620086        |
| 2833.8 | 15.439   | 1.618727        |
| 2846.6 | 15.426   | 1.617368        |
| 2859.4 | 15.413   | 1.615909        |
| 2872.2 | 15.399   | 1.614450        |
| 2885   | 15.386   | 1.613091        |
| 2897.8 | 15.373   | 1.611732        |
| 2910.7 | 15.360   | 1.610373        |
| 2923.5 | 15.347   | 1.609014        |
| 2936.3 | 15.334   | 1.607655        |
| 2949.1 | 15.321   | 1.606296        |
| 2961.9 | 15.308   | 1.604937        |
| 2974.7 | 15.295   | 1.603578        |
| 2987.6 | 15.282   | 1.602219        |
| 3000.4 | 15.269   | 1.599860        |
| 3013.2 | 15.256   | 1.598501        |
| 3026   | 15.243   | 1.597142        |
| 3038.8 | 15.230   | 1.595783        |
| X1      | X2      | X3      |
|---------|---------|---------|
| 3051.7  | 15.052  | 1.579375|
| 3064.5  | 15.029  | 1.576974|
| 3077.3  | 15.006  | 1.574573|
| 3090.1  | 14.981  | 1.571963|
| 3102.9  | 14.955  | 1.569249|
| 3115.7  | 14.93   | 1.566639|
| 3128.6  | 14.907  | 1.564238|
| 3141.4  | 14.884  | 1.561837|
| 3154.2  | 14.86   | 1.559331|
| 3167    | 14.834  | 1.556617|
| 3179.8  | 14.807  | 1.553798|
| 3192.6  | 14.782  | 1.551188|
| 3205.5  | 14.757  | 1.548578|
| 3218.3  | 14.733  | 1.546073|
| 3231.1  | 14.707  | 1.543359|
| 3243.9  | 14.682  | 1.540749|
| 3256.7  | 14.655  | 1.53793 |
| 3269.5  | 14.63   | 1.53532 |
| 3282.4  | 14.606  | 1.532814|
| 3295.2  | 14.579  | 1.529996|
| 3308    | 14.553  | 1.527281|
| 3320.8  | 14.526  | 1.524463|
| 3333.6  | 14.499  | 1.521644|
| 3346.5  | 14.475  | 1.519139|
| 3359.3  | 14.45   | 1.516529|
| 3372.1  | 14.424  | 1.513814|
| 3384.9  | 14.398  | 1.5111  |
| 3397.7  | 14.371  | 1.508281|
| 3410.5  | 14.344  | 1.505463|
| 3423.4  | 14.319  | 1.502853|
| 3436.2  | 14.293  | 1.500138|
| 3449    | 14.268  | 1.497528|
| 3461.8  | 14.242  | 1.494814|
| 3474.6  | 14.215  | 1.491995|
| 3487.4  | 14.188  | 1.489177|
| 3500.3  | 14.163  | 1.486567|
| 3513.1  | 14.138  | 1.483957|
| 3525.9  | 14.112  | 1.481243|
| 3538.7  | 14.086  | 1.478528|
| 3551.5  | 14.062  | 1.476023|
| 3564.3  | 14.035  | 1.473204|
| 3577.2  | 14.009  | 1.47049 |
| 3590    | 13.984  | 1.46788 |
| 3602.8  | 13.96   | 1.465374|
| 3615.6  | 13.935  | 1.462764|
| 3628.4  | 13.909  | 1.46005 |
| 3641.3  | 13.883  | 1.457336|
| 3654.1  | 13.859  | 1.45483 |
|          |    |    |        |
|----------|----|----|--------|
| 3666.9   | 13.836 | 1.452429 |
| 3679.7   | 13.811 | 1.449819 |
| 3692.5   | 13.786 | 1.447209 |
| 3705.3   | 13.761 | 1.444599 |
| 3718.2   | 13.736 | 1.44199 |
| 3731     | 13.711 | 1.43938 |
| 3743.8   | 13.689 | 1.437083 |
| 3756.6   | 13.667 | 1.434786 |
| 3769.4   | 13.643 | 1.432281 |
| 3782.3   | 13.619 | 1.429775 |
| 3795.1   | 13.594 | 1.427165 |
| 3807.9   | 13.571 | 1.424764 |
| 3820.8   | 13.551 | 1.422676 |
| 3833.6   | 13.53  | 1.420484 |
| 3846.5   | 13.51  | 1.418396 |
| 3859.3   | 13.487 | 1.415995 |
| 3872.1   | 13.465 | 1.413698 |
| 3885     | 13.44  | 1.411088 |
| 3897.8   | 13.416 | 1.408583 |
| 3910.7   | 13.397 | 1.406599 |
| 3923.5   | 13.378 | 1.404616 |
| 3936.4   | 13.359 | 1.402632 |
| 3949.2   | 13.339 | 1.400544 |
| 3962     | 13.318 | 1.398352 |
| 3974.9   | 13.297 | 1.39616 |
| 3987.7   | 13.276 | 1.393967 |
| 4000.6   | 13.257 | 1.391984 |
| 4013.4   | 13.24  | 1.390209 |
| 4026.2   | 13.232 | 1.389374 |
| 4039.1   | 13.224 | 1.388539 |
| 4051.9   | 13.217 | 1.387808 |
| 4064.8   | 13.21  | 1.387077 |
| 4077.6   | 13.203 | 1.386346 |
| 4090.5   | 13.195 | 1.385511 |
| 4103.3   | 13.19  | 1.384989 |
| 4116.1   | 13.184 | 1.384363 |
| 4129     | 13.181 | 1.38405 |
| 4141.8   | 13.177 | 1.383632 |
| 4154.7   | 13.176 | 1.383528 |
| 4167.5   | 13.174 | 1.383319 |
| 4180.3   | 13.173 | 1.383214 |
| 4193.2   | 13.175 | 1.383423 |
| 4206     | 13.176 | 1.383528 |
| 4218.9   | 13.178 | 1.383736 |
| 4231.7   | 13.179 | 1.383841 |
| 4244.6   | 13.182 | 1.384154 |
| 4257.4   | 13.187 | 1.384676 |
| 4270.2   | 13.188 | 1.38478 |
| Value      | First Reading | Second Reading |
|------------|---------------|----------------|
| 4283.1     | 13.194        | 1.385407       |
| 4295.9     | 13.202        | 1.386242       |
| 4308.8     | 13.207        | 1.386764       |
| 4321.6     | 13.217        | 1.387808       |
| 4334.4     | 13.222        | 1.38833        |
| 4347.3     | 13.232        | 1.389374       |
| 4360.1     | 13.241        | 1.390313       |
| 4373       | 13.253        | 1.391566       |
| 4385.8     | 13.267        | 1.393028       |
| 4398.7     | 13.283        | 1.394698       |
| 4411.5     | 13.299        | 1.396368       |
| 4424.3     | 13.319        | 1.398456       |
| 4437.2     | 13.337        | 1.400335       |
| 4450       | 13.355        | 1.402215       |
| 4462.9     | 13.368        | 1.403572       |
| 4475.7     | 13.383        | 1.405138       |
| 4488.5     | 13.401        | 1.407017       |
| 4501.4     | 13.423        | 1.409313       |
| 4514.2     | 13.448        | 1.411923       |
| 4527.1     | 13.465        | 1.413698       |
| 4539.9     | 13.485        | 1.415786       |
| 4552.8     | 13.5          | 1.417352       |
| 4565.6     | 13.518        | 1.419231       |
| 4578.4     | 13.529        | 1.42038        |
| 4591.3     | 13.54         | 1.421528       |
| 4604.1     | 13.555        | 1.423094       |
| 4617       | 13.571        | 1.424764       |
| 4629.8     | 13.587        | 1.426435       |
| 4642.7     | 13.605        | 1.428314       |
| 4655.5     | 13.622        | 1.430088       |
| 4668.3     | 13.64         | 1.431968       |
| 4681.2     | 13.657        | 1.433742       |
| 4694       | 13.667        | 1.434786       |
| 4706.9     | 13.678        | 1.435935       |
| 4719.7     | 13.689        | 1.437083       |
| 4732.5     | 13.7          | 1.438231       |
| 4745.4     | 13.712        | 1.439484       |
| 4758.2     | 13.726        | 1.440946       |
| 4771.1     | 13.739        | 1.442303       |
| 4783.9     | 13.755        | 1.443973       |
| 4796.8     | 13.769        | 1.445435       |
| 4809.6     | 13.781        | 1.446687       |
| 4822.4     | 13.795        | 1.448149       |
| 4835.3     | 13.805        | 1.449193       |
| 4848.1     | 13.816        | 1.450341       |
| 4861       | 13.825        | 1.451281       |
| 4873.8     | 13.834        | 1.45222        |
| 4886.6     | 13.841        | 1.452951       |
|      |      |      |
|------|------|------|
| 4899.5 | 13.85 | 1.453891 |
| 4912.3 | 13.859 | 1.45483 |
| 4925.2 | 13.867 | 1.455666 |
| 4938 | 13.88 | 1.457023 |
| 4950.9 | 13.889 | 1.457962 |
| 4963.7 | 13.901 | 1.459215 |
| 4976.5 | 13.912 | 1.460363 |
| 4989.4 | 13.922 | 1.461407 |
| 5002.2 | 13.933 | 1.462556 |
| 5015.1 | 13.942 | 1.463495 |
| 5027.9 | 13.952 | 1.464539 |
| 5040.7 | 13.958 | 1.465166 |
| 5053.6 | 13.966 | 1.466001 |
| 5066.4 | 13.974 | 1.466836 |
| 5079.3 | 13.979 | 1.467358 |
| 5092.1 | 13.985 | 1.467984 |
| 5105 | 13.991 | 1.468611 |
| 5117.8 | 13.996 | 1.469133 |
| 5130.6 | 14.003 | 1.469863 |
| 5143.5 | 14.009 | 1.47049 |
| 5156.3 | 14.015 | 1.471116 |
| 5169.2 | 14.022 | 1.471847 |
| 5182 | 14.029 | 1.472578 |
| 5194.8 | 14.037 | 1.473413 |
| 5207.7 | 14.045 | 1.474248 |
| 5220.5 | 14.052 | 1.474979 |
| 5233.4 | 14.059 | 1.47571 |
| 5246.2 | 14.067 | 1.476545 |
| 5259.1 | 14.074 | 1.477276 |
| 5271.9 | 14.08 | 1.477902 |
| 5284.7 | 14.087 | 1.478633 |
| 5297.6 | 14.092 | 1.479155 |
| 5310.4 | 14.098 | 1.479781 |
| 5323.3 | 14.103 | 1.480303 |
| 5336.1 | 14.108 | 1.480825 |
| 5349 | 14.113 | 1.481347 |
| 5361.8 | 14.117 | 1.481765 |
| 5374.6 | 14.122 | 1.482287 |
| 5387.5 | 14.126 | 1.482704 |
| 5400.3 | 14.131 | 1.483226 |
| 5413.2 | 14.134 | 1.483539 |
| 5426 | 14.138 | 1.483957 |
| 5438.8 | 14.143 | 1.484479 |
| 5451.7 | 14.148 | 1.485001 |
| 5464.5 | 14.151 | 1.485314 |
| 5477.4 | 14.155 | 1.485732 |
| 5490.2 | 14.159 | 1.486149 |
| 5503.1 | 14.163 | 1.486567 |
|       |       |       |
|-------|-------|-------|
| 5515.9| 14.167| 1.486984 |
| 5528.7| 14.173| 1.487611 |
| 5541.6| 14.178| 1.488133 |
| 5554.4| 14.183| 1.488655 |
| 5567.3| 14.188| 1.489177 |
| 5580.1| 14.194| 1.489803 |
| 5592.9| 14.199| 1.490325 |
| 5605.8| 14.205| 1.490952 |
| 5618.6| 14.21  | 1.491474 |
| 5631.5| 14.215| 1.491995 |
| 5644.3| 14.22  | 1.492517 |
| 5657.2| 14.225| 1.493039 |
| 5670   | 14.23  | 1.493561 |
| 5682.8| 14.236| 1.494188 |
| 5695.7| 14.24  | 1.494605 |
| 5708.5| 14.243| 1.494919 |
| 5721.4| 14.248| 1.495441 |
| 5734.2| 14.252| 1.495858 |
| 5747   | 14.256| 1.496276 |
| 5759.9| 14.261| 1.496798 |
| 5772.7| 14.265| 1.497215 |
| 5785.6| 14.269| 1.497633 |
| 5798.4| 14.273| 1.49805  |
| 5811.3| 14.277| 1.498468 |
| 5824.1| 14.28  | 1.498781 |
| 5836.9| 14.284| 1.499199 |
| 5849.8| 14.289| 1.499721 |
| 5862.6| 14.294| 1.500243 |
| 5875.5| 14.297| 1.500556 |
| 5888.3| 14.303| 1.501182 |
| 5901.1| 14.307| 1.5016   |
| 5914   | 14.311| 1.502018 |
| 5926.8| 14.317| 1.502644 |
| 5939.7| 14.323| 1.50327  |
| 5952.5| 14.33  | 1.504001 |
| 5965.4| 14.336| 1.504627 |
| 5978.2| 14.343| 1.505358 |
| 6000   | 14.35  | 1.506089 |

Note: because of the huge number of data, the other results of this calculation of code stability (code validation-case1) for 320 segments (321 nodes) are in the CD.
- **Case 2**: Single pipeline
  - Pressure at the pipeline outlet

| Time (s) | Time (hr) | Pressure (MPa) |
|----------|-----------|----------------|
| 0        | 0         | 2.622          |
| 398.8    | 0.110778  | 2.6227         |
| 656.2    | 0.182278  | 2.6227         |
| 913.6    | 0.253778  | 2.6228         |
| 1171.1   | 0.325306  | 2.6228         |
| 1428.5   | 0.396806  | 2.6229         |
| 1685.9   | 0.468306  | 2.6229         |
| 1943.4   | 0.539833  | 2.623          |
| 2200.8   | 0.611333  | 2.623          |
| 2458.3   | 0.682861  | 2.6231         |
| 2715.7   | 0.754361  | 2.6231         |
| 2973.2   | 0.825889  | 2.6232         |
| 3230.6   | 0.897389  | 2.6232         |
| 3488     | 0.968889  | 2.6232         |
| 3745.5   | 1.040417  | 2.6233         |
| 4002.9   | 1.111917  | 2.6233         |
| 4260.4   | 1.183444  | 2.6234         |
| 4517.8   | 1.254944  | 2.6234         |
| 4775.2   | 1.326444  | 2.6234         |
| 5032.6   | 1.397944  | 2.6234         |
| 5290.1   | 1.469472  | 2.6236         |
| 5547.5   | 1.540972  | 2.6238         |
| 5804.9   | 1.612472  | 2.6241         |
| 6062.3   | 1.683972  | 2.6247         |
| 6319.7   | 1.755472  | 2.6254         |
| 6577.2   | 1.827     | 2.6263         |
| 6834.6   | 1.8985    | 2.6274         |
| 7092     | 1.97      | 2.6287         |
| 7349.4   | 2.0415    | 2.6301         |
| 7606.9   | 2.113028  | 2.6318         |
| 7864.3   | 2.184528  | 2.6336         |
| 8121.7   | 2.256028  | 2.6355         |
| 8379.1   | 2.327528  | 2.6377         |
| 8636.5   | 2.399028  | 2.64           |
| 8894     | 2.470556  | 2.6424         |
| 9151.4   | 2.542056  | 2.645          |
| 9408.8   | 2.613556  | 2.6477         |
| 9666.2   | 2.685056  | 2.6505         |
| 9923.7   | 2.756583  | 2.6534         |
| 10181.1  | 2.828083  | 2.6565         |
| 10438.5  | 2.899893  | 2.6595         |
| 10695.9  | 2.971083  | 2.6627         |
| 10953.3  | 3.042583  | 2.6659         |
| 11210.8  | 3.114111  | 2.6691         |
|       |          |          |
|-------|----------|----------|
| 11468.2 | 3.185611 | 2.6724   |
| 11725.6 | 3.257111 | 2.6756   |
| 11983   | 3.328611 | 2.6788   |
| 12240.4 | 3.400111 | 2.682    |
| 12497.9 | 3.471639 | 2.6851   |
| 12755.3 | 3.543139 | 2.6882   |
| 13012.7 | 3.614639 | 2.6912   |
| 13270.1 | 3.686139 | 2.6941   |
| 13527.6 | 3.757667 | 2.6968   |
| 13785   | 3.829167 | 2.6995   |
| 14042.4 | 3.900667 | 2.702    |
| 14299.8 | 3.972167 | 2.7044   |
| 14557.2 | 4.043667 | 2.7066   |
| 14814.7 | 4.115194 | 2.7086   |
| 15072.1 | 4.186694 | 2.7105   |
| 15329.5 | 4.258194 | 2.7122   |
| 15586.9 | 4.329694 | 2.7149   |
| 15844.4 | 4.401222 | 2.7188   |
| 16101.8 | 4.472722 | 2.7232   |
| 16359.2 | 4.544222 | 2.7278   |
| 16616.6 | 4.615722 | 2.7325   |
| 16874   | 4.687222 | 2.7372   |
| 17131.5 | 4.75875  | 2.742    |
| 17388.9 | 4.83025  | 2.7467   |
| 17646.3 | 4.90175  | 2.7513   |
| 17903.7 | 4.97325  | 2.7558   |
| 18161.2 | 5.044778 | 2.7602   |
| 18418.6 | 5.116278 | 2.7645   |
| 18676   | 5.187778 | 2.7687   |
| 18933.4 | 5.259278 | 2.7728   |
| 19190.8 | 5.330778 | 2.7767   |
| 19448.3 | 5.402306 | 2.7804   |
| 19705.7 | 5.473806 | 2.7841   |
| 19963.1 | 5.545306 | 2.7876   |
| 20220.5 | 5.616806 | 2.7909   |
| 20477.9 | 5.688306 | 2.7942   |
| 20735.4 | 5.759833 | 2.7973   |
| 20992.8 | 5.831333 | 2.8003   |
| 21250.2 | 5.902833 | 2.8032   |
| 21507.6 | 5.974333 | 2.8059   |
| 21765.1 | 6.045861 | 2.8086   |
| 22022.5 | 6.117361 | 2.8111   |
| 22279.9 | 6.188861 | 2.8136   |
| 22537.3 | 6.260361 | 2.8159   |
| 22794.7 | 6.331861 | 2.8182   |
| 23052.2 | 6.403389 | 2.8204   |
| 23309.6 | 6.474889 | 2.8225   |
| 23567   | 6.546389 | 2.8244   |
|                |                |                |
|----------------|----------------|----------------|
| 23824.4        | 6.617889       | 2.8263         |
| 24081.9        | 6.689417       | 2.8281         |
| 24339.3        | 6.760917       | 2.8299         |
| 24596.7        | 6.832417       | 2.8315         |
| 24854.1        | 6.903917       | 2.8330         |
| 25111.5        | 6.975417       | 2.8344         |
| 25369          | 7.046944       | 2.8357         |
| 25626.4        | 7.118444       | 2.8369         |
| 25883.8        | 7.189944       | 2.8379         |
| 26141.2        | 7.261444       | 2.8388         |
| 26398.7        | 7.332972       | 2.8395         |
| 26656.1        | 7.404472       | 2.8401         |
| 26913.5        | 7.475972       | 2.8405         |
| 27170.9        | 7.547472       | 2.8407         |
| 27428.3        | 7.618972       | 2.8407         |
| 27685.8        | 7.6905         | 2.8405         |
| 27943.2        | 7.762          | 2.8400         |
| 28200.6        | 7.8335         | 2.8392         |
| 28458          | 7.905          | 2.8382         |
| 28715.4        | 7.9765         | 2.8368         |
| 28972.9        | 8.048028       | 2.8366         |
| 29230.3        | 8.119528       | 2.8363         |
| 29487.7        | 8.191028       | 2.8359         |
| 29745.1        | 8.262528       | 2.8351         |
| 30002.6        | 8.334056       | 2.8341         |
| 30260          | 8.405556       | 2.8328         |
| 30517.4        | 8.477056       | 2.8311         |
| 30774.8        | 8.548556       | 2.8291         |
| 31032.2        | 8.620056       | 2.8268         |
| 31289.7        | 8.691583       | 2.8241         |
| 31547.1        | 8.763083       | 2.8212         |
| 31804.5        | 8.834583       | 2.8180         |
| 32061.9        | 8.906083       | 2.8145         |
| 32319.4        | 8.977611       | 2.8108         |
| 32576.8        | 9.049111       | 2.8069         |
| 32834.2        | 9.120611       | 2.8028         |
| 33091.6        | 9.192111       | 2.7985         |
| 33349          | 9.263611       | 2.7941         |
| 33606.5        | 9.335139       | 2.7897         |
| 33863.9        | 9.406639       | 2.7851         |
| 34121.3        | 9.478139       | 2.7804         |
| 34378.7        | 9.549639       | 2.7758         |
| 34636.2        | 9.621167       | 2.7711         |
| 34893.6        | 9.692667       | 2.7664         |
| 35151          | 9.764167       | 2.7618         |
| 35408.4        | 9.835667       | 2.7571         |
| 35665.8        | 9.907167       | 2.7526         |
| 35923.3        | 9.978694       | 2.7481         |
| Value   | 1st Column | 2nd Column |
|---------|------------|------------|
| 36180.7 | 10.05019   | 2.7437     |
| 36438.1 | 10.12169   | 2.7393     |
| 36695.5 | 10.19319   | 2.7351     |
| 36952.9 | 10.26469   | 2.7309     |
| 37210.4 | 10.33622   | 2.7269     |
| 37467.8 | 10.40772   | 2.7229     |
| 37725.2 | 10.47922   | 2.7191     |
| 37982.6 | 10.55072   | 2.7154     |
| 38240.1 | 10.62225   | 2.7117     |
| 38497.5 | 10.69375   | 2.7082     |
| 38754.9 | 10.76525   | 2.7047     |
| 39012.3 | 10.83675   | 2.7014     |
| 39269.7 | 10.90825   | 2.6981     |
| 39527.2 | 10.97978   | 2.6949     |
| 39784.6 | 11.05128   | 2.6917     |
| 40042  | 11.12278   | 2.6886     |
| 40299.4 | 11.19428   | 2.6855     |
| 40556.9 | 11.26581   | 2.6824     |
| 40814.3 | 11.33731   | 2.6794     |
| 41071.7 | 11.40881   | 2.6763     |
| 41329.1 | 11.48031   | 2.6732     |
| 41586.5 | 11.55181   | 2.6701     |
| 41844  | 11.62333   | 2.6669     |
| 42101.4 | 11.69483   | 2.6637     |
| 42358.8 | 11.76633   | 2.6604     |
| 42616.2 | 11.83783   | 2.657      |
| 42873.7 | 11.90936   | 2.6535     |
| 43131.1 | 11.98086   | 2.65       |
| 43388.5 | 12.05236   | 2.6449     |
| 43645.9 | 12.12386   | 2.6413     |
| 43903.3 | 12.19536   | 2.6381     |
| 44160.8 | 12.26689   | 2.6351     |
| 44418.2 | 12.33839   | 2.6324     |
| 44675.6 | 12.40989   | 2.6299     |
| 44933  | 12.48139   | 2.6276     |
| 45190.4 | 12.55289   | 2.6254     |
| 45447.9 | 12.62442   | 2.6234     |
| 45705.3 | 12.69592   | 2.6215     |
| 45962.7 | 12.76742   | 2.6197     |
| 46220.1 | 12.83892   | 2.6181     |
| 46477.6 | 12.91044   | 2.6166     |
| 46735  | 12.98194   | 2.6152     |
| 46992.4 | 13.05344   | 2.6139     |
| 47249.8 | 13.12494   | 2.6128     |
| 47507.2 | 13.19644   | 2.6117     |
| 47764.7 | 13.26797   | 2.6107     |
| 48022.1 | 13.33947   | 2.6097     |
| 48279.5 | 13.41097   | 2.6089     |
| Value  | 13.48247 | 2.6054  |
|--------|----------|---------|
| 48536.9| 13.554   | 2.6074  |
| 48794.4| 13.6255  | 2.6068  |
| 49051.8| 13.697   | 2.6063  |
| 49309.2| 13.7685  | 2.6058  |
| 49566.6| 13.84    | 2.6054  |
| 50081.5| 13.91153 | 2.605   |
| 50338.9| 13.98303 | 2.6047  |
| 50596.3| 14.05453 | 2.6044  |
| 50853.7| 14.12603 | 2.6042  |
| 51111.2| 14.19756 | 2.604   |
| 51368.6| 14.26906 | 2.6039  |
| 51626  | 14.34056 | 2.6039  |
| 51883.4| 14.41206 | 2.6038  |
| 52140.8| 14.48356 | 2.6039  |
| 52398.3| 14.55508 | 2.6039  |
| 52655.7| 14.62658 | 2.604   |
| 52913.1| 14.69808 | 2.6041  |
| 53170.5| 14.76958 | 2.6043  |
| 53427.9| 14.84108 | 2.6044  |
| 53685.4| 14.91261 | 2.6046  |
| 53942.8| 14.98411 | 2.6048  |
| 54200.2| 15.05561 | 2.6037  |
| 54457.6| 15.12711 | 2.6036  |
| 54715.1| 15.19864 | 2.6038  |
| 54972.5| 15.27014 | 2.6041  |
| 55229.9| 15.34164 | 2.6045  |
| 55487.3| 15.41314 | 2.6049  |
| 55744.7| 15.48464 | 2.6054  |
| 56002.2| 15.55617 | 2.606   |
| 56259.6| 15.62767 | 2.6066  |
| 56517  | 15.69917 | 2.6073  |
| 56774.4| 15.77067 | 2.608   |
| 57031.9| 15.84219 | 2.6088  |
| 57289.3| 15.91369 | 2.6097  |
| 57546.7| 15.98519 | 2.6106  |
| 57804.1| 16.05669 | 2.6115  |
| 58061.5| 16.12819 | 2.6125  |
| 58319  | 16.19972 | 2.6136  |
| 58576.4| 16.27122 | 2.6147  |
| 58833.8| 16.34272 | 2.6158  |
| 59091.2| 16.41422 | 2.617   |
| 59348.7| 16.48575 | 2.6182  |
| 59606.1| 16.55725 | 2.6194  |
| 59863.5| 16.62875 | 2.6207  |
| 60120.9| 16.70025 | 2.622   |
| 60378.3| 16.77175 | 2.6234  |
| 60635.8| 16.84328 | 2.6248  |
| Value       | First Reading | Second Reading |
|------------|---------------|----------------|
| 60893.2    | 16.91478      | 2.6261         |
| 61150.6    | 16.98628      | 2.6276         |
| 61408      | 17.05778      | 2.629          |
| 61665.4    | 17.12928      | 2.6304         |
| 61922.9    | 17.20081      | 2.6319         |
| 62180.3    | 17.27231      | 2.6333         |
| 62437.7    | 17.34381      | 2.6348         |
| 62695.1    | 17.41531      | 2.6363         |
| 62952.6    | 17.48683      | 2.6377         |
| 63210      | 17.55833      | 2.6391         |
| 63467.4    | 17.62983      | 2.6406         |
| 63724.8    | 17.70133      | 2.642          |
| 63982.2    | 17.77283      | 2.6433         |
| 64239.7    | 17.84436      | 2.6447         |
| 64497.1    | 17.91586      | 2.646          |
| 64754.5    | 17.98736      | 2.6473         |
| 65011.9    | 18.05886      | 2.6485         |
| 65269.4    | 18.13039      | 2.6496         |
| 65526.8    | 18.20189      | 2.6507         |
| 65784.6    | 18.2735       | 2.6518         |
| 66042.4    | 18.34511      | 2.6528         |
| 66300.2    | 18.41672      | 2.6537         |
| 66558      | 18.48833      | 2.6545         |
| 66815.8    | 18.55994      | 2.6552         |
| 67073.6    | 18.63156      | 2.6559         |
| 67331.5    | 18.70319      | 2.6565         |
| 67589.3    | 18.77481      | 2.6573         |
| 67847.1    | 18.84642      | 2.6579         |
| 68104.9    | 18.91803      | 2.6585         |
| 68362.7    | 18.98964      | 2.659          |
| 68620.5    | 19.06125      | 2.6595         |
| 68878.3    | 19.13286      | 2.6599         |
| 69136.1    | 19.20447      | 2.6603         |
| 69394      | 19.27611      | 2.6607         |
| 69651.8    | 19.34772      | 2.6611         |
| 69909.6    | 19.41933      | 2.6615         |
| 70167.4    | 19.49094      | 2.6618         |
| 70425.2    | 19.56256      | 2.6622         |
| 70683      | 19.63417      | 2.6625         |
| 70940.8    | 19.70578      | 2.6628         |
| 71198.6    | 19.77739      | 2.6631         |
| 71456.5    | 19.84903      | 2.6634         |
| 71714.3    | 19.92064      | 2.6636         |
| 71972.1    | 19.99225      | 2.6639         |
| 72229.9    | 20.06386      | 2.6641         |
| 72487.7    | 20.13547      | 2.6644         |
| 72745.5    | 20.20708      | 2.6646         |
| 73003.3    | 20.27869      | 2.6648         |
|      |        |        |
|------|--------|--------|
| 73261.1 | 20.35031 | 2.665  |
| 73519 | 20.42194 | 2.6652 |
| 73776.8 | 20.49356 | 2.6654 |
| 74034.6 | 20.56517 | 2.6656 |
| 74292.4 | 20.63678 | 2.6658 |
| 74550.2 | 20.70839 | 2.6659 |
| 74808 | 20.78 | 2.6661 |
| 75065.8 | 20.85161 | 2.6663 |
| 75323.6 | 20.92322 | 2.6664 |
| 75581.5 | 20.99486 | 2.6666 |
| 75839.3 | 21.06647 | 2.6667 |
| 76097.1 | 21.13808 | 2.6668 |
| 76354.9 | 21.20969 | 2.667 |
| 76612.7 | 21.28131 | 2.6671 |
| 76870.5 | 21.35292 | 2.6672 |
| 77128.3 | 21.42453 | 2.6673 |
| 77386.1 | 21.49614 | 2.6674 |
| 77644 | 21.56778 | 2.6675 |
| 77901.8 | 21.63939 | 2.6676 |
| 78159.6 | 21.711 | 2.6677 |
| 78417.4 | 21.78261 | 2.6678 |
| 78675.2 | 21.85422 | 2.6679 |
| 78933 | 21.92583 | 2.668 |
| 79190.8 | 21.99744 | 2.6681 |
| 79448.6 | 22.06906 | 2.6682 |
| 79706.5 | 22.14069 | 2.6682 |
| 79964.3 | 22.21231 | 2.6683 |
| 80222.1 | 22.28392 | 2.6684 |
| 80479.9 | 22.35553 | 2.6685 |
| 80737.7 | 22.42714 | 2.6685 |
| 80995.5 | 22.49875 | 2.6686 |
| 81253.3 | 22.57036 | 2.6687 |
| 81511.1 | 22.64197 | 2.6687 |
| 81769 | 22.71361 | 2.6688 |
| 82026.8 | 22.78522 | 2.6688 |
| 82284.6 | 22.85683 | 2.6689 |
| 82542.4 | 22.92844 | 2.6689 |
| 82800.2 | 23.00006 | 2.669 |
| 83058 | 23.07167 | 2.669 |
| 83315.8 | 23.14328 | 2.6691 |
| 83573.6 | 23.21489 | 2.6691 |
| 83831.5 | 23.28653 | 2.6691 |
| 84089.3 | 23.35814 | 2.6692 |
| 84347.1 | 23.42975 | 2.6692 |
| 84604.9 | 23.50136 | 2.6693 |
| 84862.7 | 23.57297 | 2.6693 |
| 85120.5 | 23.64458 | 2.6693 |
| 85378.3 | 23.71619 | 2.6694 |
|        |        |        |
|--------|--------|--------|
| 85636.1| 23.78781 | 2.6694 |
| 85894  | 23.85944 | 2.6694 |
| 86400  | 24      | 2.6694 |
Case 3: The ability of the GTA code to predict transients in gas pipeline networks

- Pressure and mass flow rate in the three nodes of the pipeline network.

| Time (hr) | Node 1 | Node 2 | Node 3 |
|----------|--------|--------|--------|
|          | P (Mpa) m (kg/s) | P (Mpa) m (kg/s) | P (Mpa) m (kg/s) |
| 0        | 4.969 48.97 | 4.9058 42.989 | 2.9385 14.735 |
| 0.049917 | 4.969 48.97 | 4.9057 42.989 | 2.9456 14.808 |
| 0.099583 | 4.969 48.969 | 4.9056 42.993 | 2.9538 14.893 |
| 0.151    | 4.969 48.967 | 4.9054 43.008 | 2.9625 14.98 |
| 0.200639 | 4.9689 48.964 | 4.9051 43.035 | 2.9709 15.065 |
| 0.250306 | 4.9689 48.961 | 4.9049 43.073 | 2.9793 15.151 |
| 0.3035   | 4.9688 48.958 | 4.9045 43.128 | 2.9884 15.243 |
| 0.502083 | 4.9683 48.94 | 4.9028 43.424 | 3.0229 15.592 |
| 0.562361 | 4.9682 48.934 | 4.9022 43.537 | 3.0335 15.699 |
| 0.571222 | 4.9681 48.933 | 4.9021 43.554 | 3.0351 15.715 |
| 0.580083 | 4.9681 48.932 | 4.902 43.573 | 3.0365 15.73 |
| 0.590722 | 4.9681 48.931 | 4.9019 43.594 | 3.0384 15.749 |
| 0.601361 | 4.9681 48.93 | 4.9018 43.615 | 3.0403 15.768 |
| 0.60339 | 4.9681 48.93 | 4.9017 43.618 | 3.0406 15.771 |
| 0.604917 | 4.968 48.93 | 4.9017 43.623 | 3.0409 15.773 |
| 0.606994 | 4.968 48.929 | 4.9017 43.626 | 3.0412 15.777 |
| 0.608444 | 4.968 48.929 | 4.9017 43.63 | 3.0416 15.78 |
| 0.610222 | 4.968 48.929 | 4.9017 43.633 | 3.0419 15.783 |
| 0.651    | 4.9679 48.924 | 4.9012 43.72 | 3.049 15.856 |
| 0.700639 | 4.9677 48.919 | 4.9006 43.829 | 3.0578 15.945 |
| 0.750278 | 4.9676 48.913 | 4.9 43.943 | 3.0667 16.034 |
| 0.801694 | 4.9674 48.906 | 4.8994 44.066 | 3.0757 16.126 |
| 0.851333 | 4.9672 48.9 | 4.8988 44.187 | 3.0845 16.216 |
| 0.900972 | 4.967 48.893 | 4.8981 44.313 | 3.0934 16.305 |
| 0.950583 | 4.9668 48.887 | 4.8975 44.441 | 3.1022 16.394 |
| 1.000222 | 4.9666 48.88 | 4.8968 44.572 | 3.1111 16.484 |
| 1.051639 | 4.9664 48.873 | 4.8961 44.71 | 3.1203 16.577 |
| 1.053389 | 4.9664 48.872 | 4.8961 44.715 | 3.1206 16.58 |
| 1.055167 | 4.9664 48.872 | 4.896 44.721 | 3.1209 16.584 |
| 1.056944 | 4.9664 48.872 | 4.896 44.725 | 3.1212 16.586 |
| 1.058722 | 4.9664 48.872 | 4.896 44.73 | 3.1215 16.59 |
| 1.0605   | 4.9664 48.871 | 4.896 44.735 | 3.1218 16.593 |
| 1.06225 | 4.9664 48.871 | 4.8959 44.74 | 3.1222 16.597 |
| 1.064028 | 4.9664 48.871 | 4.8959 44.744 | 3.1225 16.599 |
| 1.065806 | 4.9664 48.871 | 4.8959 44.749 | 3.1229 16.603 |
| 1.067583 | 4.9663 48.871 | 4.8959 44.754 | 3.1231 16.606 |
| 1.069361 | 4.9663 48.87 | 4.8958 44.759 | 3.1234 16.609 |
| 1.071111 | 4.9663 48.87 | 4.8958 44.764 | 3.1237 16.612 |
| 1.072889 | 4.9663 48.87 | 4.8958 44.77 | 3.1241 16.615 |
| 1.074667 | 4.9663 48.869 | 4.8958 44.774 | 3.1245 16.618 |
| 1.076444 | 4.9663 48.869 | 4.8957 44.778 | 3.1247 16.622 |
| 1.078222 | 4.9663 48.869 | 4.8957 44.783 | 3.125 16.625 |
| 1.079972 | 4.9663 48.869 | 4.8957 44.788 | 3.1253 16.628 |
| Value     | 4.9663 | 48.868 | 4.8957 | 44.793 | 3.1257 | 16.631 |
|-----------|--------|--------|--------|--------|--------|--------|
| Value     | 4.9663 | 48.868 | 4.8956 | 44.798 | 3.126  | 16.634 |
| Value     | 4.9663 | 48.868 | 4.8956 | 44.803 | 3.1263 | 16.638 |
| Value     | 4.9663 | 48.868 | 4.8956 | 44.808 | 3.1266 | 16.642 |
| Value     | 4.9663 | 48.867 | 4.8956 | 44.813 | 3.127  | 16.644 |
| Value     | 4.9662 | 48.867 | 4.8955 | 44.818 | 3.1273 | 16.648 |
| Value     | 4.9662 | 48.867 | 4.8955 | 44.822 | 3.1276 | 16.651 |
| Value     | 4.9662 | 48.867 | 4.8955 | 44.827 | 3.1279 | 16.653 |
| Value     | 4.9662 | 48.866 | 4.8955 | 44.832 | 3.1282 | 16.657 |
| Value     | 4.9662 | 48.866 | 4.8954 | 44.837 | 3.1285 | 16.66  |
| Value     | 4.9662 | 48.866 | 4.8954 | 44.842 | 3.1288 | 16.663 |
| Value     | 4.9662 | 48.866 | 4.8954 | 44.847 | 3.1291 | 16.666 |
| Value     | 4.9662 | 48.865 | 4.8954 | 44.852 | 3.1295 | 16.67  |
| Value     | 4.9662 | 48.865 | 4.8953 | 44.857 | 3.1298 | 16.673 |
| Value     | 4.9662 | 48.865 | 4.8953 | 44.862 | 3.1301 | 16.676 |
| Value     | 4.9662 | 48.864 | 4.8953 | 44.867 | 3.1304 | 16.68  |
| Value     | 4.9662 | 48.864 | 4.8953 | 44.871 | 3.1308 | 16.682 |
| Value     | 4.9662 | 48.864 | 4.8952 | 44.876 | 3.131  | 16.686 |
| Value     | 4.9662 | 48.864 | 4.8952 | 44.882 | 3.1314 | 16.689 |
| Value     | 4.9661 | 48.864 | 4.8952 | 44.886 | 3.1317 | 16.692 |
| Value     | 4.9661 | 48.863 | 4.8952 | 44.891 | 3.1321 | 16.695 |
| Value     | 4.9661 | 48.863 | 4.8951 | 44.896 | 3.1324 | 16.699 |
| Value     | 4.9661 | 48.863 | 4.8951 | 44.901 | 3.1326 | 16.702 |
| Value     | 4.9661 | 48.863 | 4.8951 | 44.905 | 3.133  | 16.705 |
| Value     | 4.9661 | 48.862 | 4.8951 | 44.91  | 3.1333 | 16.708 |
| Value     | 4.9661 | 48.862 | 4.895  | 44.916 | 3.1336 | 16.711 |
| Value     | 4.9661 | 48.862 | 4.895  | 44.921 | 3.134  | 16.714 |
| Value     | 4.9661 | 48.862 | 4.895  | 44.926 | 3.1342 | 16.718 |
| Value     | 4.9661 | 48.861 | 4.895  | 44.931 | 3.1345 | 16.722 |
| Value     | 4.9661 | 48.861 | 4.895  | 44.935 | 3.1349 | 16.724 |
| Value     | 4.9661 | 48.861 | 4.8949 | 44.935 | 3.1352 | 16.727 |
| Value     | 4.9661 | 48.861 | 4.8949 | 44.94  | 3.1355 | 16.731 |
| Value     | 4.9661 | 48.861 | 4.8949 | 44.945 | 3.1358 | 16.734 |
| Value     | 4.9661 | 48.861 | 4.8948 | 44.949 | 3.1361 | 16.737 |
| Value     | 4.966   | 48.86  | 4.8948 | 44.95  | 3.1364 | 16.741 |
| Value     | 4.966   | 48.86  | 4.8948 | 44.956 | 3.1367 | 16.743 |
| Value     | 4.966   | 48.86  | 4.8948 | 44.97  | 3.1371 | 16.747 |
| Value     | 4.966   | 48.86  | 4.8947 | 44.974 | 3.1374 | 16.75  |
| Value     | 4.966   | 48.859 | 4.8947 | 44.98  | 3.1377 | 16.753 |
| Value     | 4.966   | 48.859 | 4.8947 | 44.984 | 3.1381 | 16.756 |
| Value     | 4.966   | 48.858 | 4.8947 | 44.99  | 3.1384 | 16.759 |
| Value     | 4.966   | 48.858 | 4.8946 | 44.994 | 3.1386 | 16.762 |
| Value     | 4.966   | 48.858 | 4.8946 | 44.999 | 3.139  | 16.766 |
| Value     | 4.966   | 48.857 | 4.8946 | 45.004 | 3.1394 | 16.769 |
| Value     | 4.966   | 48.857 | 4.8946 | 45.009 | 3.1396 | 16.772 |
| Value     | 4.9659  | 48.857 | 4.8945 | 45.014 | 3.1399 | 16.776 |
| Value     | 4.9659  | 48.857 | 4.8945 | 45.02  | 3.1403 | 16.779 |
| Value     | 4.9659  | 48.856 | 4.8945 | 45.024 | 3.1406 | 16.782 |
| 7.500583 | 4.9629 | 48.79 | 4.888 | 47.011 | 3.0417 | 15.765 |
|----------|--------|-------|-------|-------|--------|-------|
| 8.000222 | 4.9656 | 48.877| 4.8966| 45.277| 2.9503 | 14.843 |
| 8.500083 | 4.9683 | 48.962| 4.9051| 43.517| 2.8588 | 13.921 |
| 9.009056 | 4.9709 | 49.046| 4.9133| 41.705| 2.7655 | 12.98 |
| 9.498694 | 4.9733 | 49.124| 4.9209| 39.946| 2.6758 | 12.076 |
| 10.00106 | 4.9757 | 49.2  | 4.9285| 38.126| 2.5834 | 11.146 |
| 10.51958 | 4.9781 | 49.275| 4.9359| 36.233| 2.4882 | 10.187 |
| 10.99217 | 4.9801 | 49.341| 4.9423| 34.497| 2.4013 | 9.313  |
| 11.5005  | 4.9823 | 49.408| 4.9489| 32.615| 2.3079 | 8.372  |
| 12.00022 | 4.9842 | 49.471| 4.955 | 30.756| 2.2159 | 7.446  |
| 12.52686 | 4.9847 | 49.475| 4.9553| 30.218| 2.2998 | 8.304  |
| 12.98214 | 4.9837 | 49.437| 4.9516| 31.25 | 2.3805 | 9.118  |
| 13.50142 | 4.9819 | 49.38 | 4.9461| 32.842| 2.4744 | 10.064 |
| 14.05061 | 4.9799 | 49.313| 4.9395| 34.638| 2.5742 | 11.069 |
| 15.0595  | 4.9758 | 49.18 | 4.9265| 37.966| 2.7576 | 12.917 |
| 15.49975 | 4.9739 | 49.119| 4.9204| 39.411| 2.8376 | 13.725 |
| 16.06222 | 4.9714 | 49.036| 4.9123| 41.246| 2.9397 | 14.754 |
| 17.00031 | 4.9671 | 48.892| 4.898 | 44.279| 3.1098 | 16.471 |
| 17.50008 | 4.9646 | 48.811| 4.89  | 45.879| 3.2003 | 17.385 |
| 18.00144 | 4.9621 | 48.727| 4.8817| 47.472| 3.291  | 18.302 |
| 18.50081 | 4.9595 | 48.641| 4.8732| 49.049| 3.3813 | 19.215 |
| 19.00019 | 4.9568 | 48.552| 4.8644| 50.613| 3.4714 | 20.128 |
| 20.00128 | 4.9513 | 48.367| 4.846 | 53.712| 3.6521 | 21.955 |
| 21.00233 | 4.9503 | 48.369| 4.8463| 54.269| 3.4916 | 20.314 |
| 21.50111 | 4.9522 | 48.437| 4.8531| 53.252| 3.4039 | 19.425 |
| 22.00164 | 4.9547 | 48.52 | 4.8613| 51.89 | 3.3142 | 18.518 |
| 23.00344 | 4.9601 | 48.7  | 4.8792| 48.701| 3.1324 | 16.681 |
| 23.50281 | 4.9629 | 48.79 | 4.888 | 47.004| 3.0412 | 15.761 |
| 23.59136 | 4.9634 | 48.806| 4.8896| 46.698| 3.0251 | 15.598 |
| 24        | 4.9656 | 48.877| 4.8967| 45.275| 2.9502 | 14.843 |

**Note:** in this case, data has been shortened because it is too large. All data of results could be provided if it is needed.
- **Case 4**: short single pipeline.
  - Pressure history at the inlet and outlet of the pipeline.

| Time (s) | $P_{in}$ (MPa) | $P_{out}$ (MPa) |
|---------|----------------|-----------------|
| 0       | 4.1368         | 4.136           |
| 0.0053  | 4.1396         | 4.136           |
| 0.0105  | 4.1467         | 4.136           |
| 0.0157  | 4.1539         | 4.136           |
| 0.021   | 4.161          | 4.136           |
| 0.0262  | 4.1682         | 4.136           |
| 0.0314  | 4.1753         | 4.136           |
| 0.0366  | 4.1825         | 4.136           |
| 0.0418  | 4.1896         | 4.136           |
| 0.0522  | 4.2039         | 4.136           |
| 0.0573  | 4.2111         | 4.136           |
| 0.0599  | 4.2147         | 4.136           |
| 0.0651  | 4.2219         | 4.136           |
| 0.0702  | 4.2291         | 4.136           |
| 0.0754  | 4.2363         | 4.136           |
| 0.0805  | 4.2435         | 4.136           |
| 0.0856  | 4.2507         | 4.136           |
| 0.0907  | 4.2579         | 4.136           |
| 0.0959  | 4.2651         | 4.136           |
| 0.101   | 4.2724         | 4.136           |
| 0.106   | 4.2796         | 4.136           |
| 0.1111  | 4.2869         | 4.136           |
| 0.1162  | 4.2941         | 4.136           |
| 0.1238  | 4.3051         | 4.136           |
| 0.1263  | 4.3087         | 4.136           |
| 0.1289  | 4.3124         | 4.136           |
| 0.1314  | 4.316          | 4.136           |
| 0.1339  | 4.3197         | 4.136           |
| 0.1364  | 4.3234         | 4.136           |
| 0.1389  | 4.327          | 4.136           |
| 0.1415  | 4.3307         | 4.136           |
| 0.144   | 4.3344         | 4.136           |
| 0.1465  | 4.3381         | 4.136           |
| 0.149   | 4.3376         | 4.136           |
| 0.1514  | 4.3341         | 4.136           |
| 0.1538  | 4.3308         | 4.136           |
| 0.1562  | 4.3275         | 4.136           |
| 0.1585  | 4.3242         | 4.136           |
| 0.1609  | 4.3209         | 4.136           |
| 0.1657  | 4.3142         | 4.136           |
| 0.1705  | 4.3076         | 4.136           |
| 0.1753  | 4.301          | 4.136           |
| 0.1801  | 4.2943         | 4.136           |
| 0.1849  | 4.2876         | 4.136           |
| Value | 1st Column | 2nd Column | 3rd Column |
|-------|------------|------------|------------|
| 0.1922 | 4.2776 | 4.136 |
| 0.1946 | 4.2743 | 4.136 |
| 0.2019 | 4.2642 | 4.136 |
| 0.2043 | 4.2609 | 4.136 |
| 0.2116 | 4.2508 | 4.136 |
| 0.2164 | 4.2441 | 4.136 |
| 0.2213 | 4.2373 | 4.136 |
| 0.2262 | 4.2306 | 4.136 |
| 0.2311 | 4.2239 | 4.136 |
| 0.2335 | 4.2205 | 4.136 |
| 0.236  | 4.2171 | 4.136 |
| 0.2384 | 4.2137 | 4.136 |
| 0.2409 | 4.2104 | 4.136 |
| 0.2458 | 4.2036 | 4.136 |
| 0.2507 | 4.1968 | 4.136 |
| 0.2556 | 4.1901 | 4.1361 |
| 0.2605 | 4.1833 | 4.1375 |
| 0.2655 | 4.1765 | 4.1427 |
| 0.2704 | 4.1697 | 4.1528 |
| 0.2754 | 4.163  | 4.166  |
| 0.2803 | 4.1562 | 4.1803 |
| 0.2853 | 4.1494 | 4.195  |
| 0.2903 | 4.1426 | 4.2097 |
| 0.2953 | 4.1396 | 4.2244 |
| 0.3003 | 4.1396 | 4.2391 |
| 0.3152 | 4.1396 | 4.2831 |
| 0.3202 | 4.1396 | 4.2978 |
| 0.3252 | 4.1396 | 4.3125 |
| 0.3302 | 4.1396 | 4.3271 |
| 0.3352 | 4.1396 | 4.3418 |
| 0.3402 | 4.1396 | 4.3565 |
| 0.3452 | 4.1396 | 4.3712 |
| 0.3502 | 4.1395 | 4.3859 |
| 0.3552 | 4.1395 | 4.4006 |
| 0.3602 | 4.1395 | 4.4153 |
| 0.3652 | 4.1395 | 4.43  |
| 0.3702 | 4.1395 | 4.4448 |
| 0.3777 | 4.1395 | 4.4669 |
| 0.3801 | 4.1395 | 4.4743 |
| 0.3901 | 4.1395 | 4.5039 |
| 0.4001 | 4.1395 | 4.5247 |
| 0.4101 | 4.1395 | 4.5092 |
| 0.4151 | 4.1395 | 4.4973 |
| 0.4201 | 4.1395 | 4.4851 |
| 0.4251 | 4.1395 | 4.4729 |
| 0.4301 | 4.1395 | 4.4607 |
| 0.4351 | 4.1395 | 4.4484 |
| 0.4401 | 4.1395 | 4.4361 |
|   |       |       |       |
|---|-------|-------|-------|
|   | 0.4451 | 4.1395 | 4.4238 |
|   | 0.45   | 4.1395 | 4.4114 |
|   | 0.455  | 4.1395 | 4.3991 |
|   | 0.46   | 4.1395 | 4.3867 |
|   | 0.465  | 4.1395 | 4.3743 |
|   | 0.47   | 4.1395 | 4.3619 |
|   | 0.475  | 4.1395 | 4.3495 |
|   | 0.48   | 4.1395 | 4.3371 |
|   | 0.485  | 4.1395 | 4.3247 |
|   | 0.49   | 4.1395 | 4.3122 |
|   | 0.495  | 4.1395 | 4.2998 |
|   | 0.5    | 4.1395 | 4.2874 |
|   | 0.505  | 4.1395 | 4.275  |
|   | 0.51   | 4.1395 | 4.2626 |
|   | 0.5149 | 4.1396 | 4.2503 |
|   | 0.5199 | 4.1402 | 4.2379 |
|   | 0.5249 | 4.1424 | 4.2255 |
|   | 0.5299 | 4.1475 | 4.2132 |
|   | 0.5349 | 4.1562 | 4.2009 |
|   | 0.5399 | 4.1682 | 4.1887 |
|   | 0.5449 | 4.1824 | 4.1764 |
|   | 0.5499 | 4.1976 | 4.1647 |
|   | 0.5548 | 4.2131 | 4.1547 |
|   | 0.5598 | 4.2288 | 4.148  |
|   | 0.5648 | 4.2444 | 4.1447 |
|   | 0.5698 | 4.26    | 4.1434 |
|   | 0.5748 | 4.2756 | 4.143  |
|   | 0.5798 | 4.2911 | 4.1429 |
|   | 0.5847 | 4.3066 | 4.1429 |
|   | 0.5872 | 4.3144 | 4.1429 |
|   | 0.5897 | 4.3221 | 4.1429 |
|   | 0.5922 | 4.3298 | 4.1429 |
|   | 0.5947 | 4.3375 | 4.1429 |
|   | 0.5997 | 4.3529 | 4.1429 |
|   | 0.6047 | 4.3683 | 4.1429 |
|   | 0.6097 | 4.3837 | 4.1429 |
|   | 0.6146 | 4.399  | 4.1428 |
|   | 0.6196 | 4.4142 | 4.1428 |
|   | 0.6246 | 4.4295 | 4.1428 |
|   | 0.6296 | 4.4447 | 4.1428 |
|   | 0.6346 | 4.4599 | 4.1428 |
|   | 0.6396 | 4.4751 | 4.1428 |
|   | 0.6445 | 4.4901 | 4.1428 |
|   | 0.6495 | 4.5034 | 4.1428 |
|   | 0.6545 | 4.5097 | 4.1428 |
|   | 0.6595 | 4.5074 | 4.1428 |
|   | 0.6645 | 4.4997 | 4.1428 |
|   | 0.667  | 4.4949 | 4.1428 |
| 0.6695 | 4.4898 | 4.1428 |
| 0.672  | 4.4846 | 4.1428 |
| 0.6745 | 4.4793 | 4.1428 |
| 0.677  | 4.4739 | 4.1428 |
| 0.6795 | 4.4685 | 4.1428 |
| 0.6819 | 4.4631 | 4.1428 |
| 0.6844 | 4.4577 | 4.1428 |
| 0.6869 | 4.4523 | 4.1428 |
| 0.6894 | 4.4469 | 4.1428 |
| 0.6919 | 4.4414 | 4.1428 |
| 0.6944 | 4.436  | 4.1428 |
| 0.6994 | 4.425  | 4.1428 |
| 0.7044 | 4.414  | 4.1428 |
| 0.7094 | 4.403  | 4.1428 |
| 0.7144 | 4.392  | 4.1428 |
| 0.7218 | 4.3754 | 4.1427 |
| 0.7243 | 4.3698 | 4.1427 |
| 0.7318 | 4.3531 | 4.1427 |
| 0.7343 | 4.3476 | 4.1427 |
| 0.7368 | 4.342  | 4.1427 |
| 0.7393 | 4.3364 | 4.1427 |
| 0.7418 | 4.3308 | 4.1427 |
| 0.7443 | 4.3253 | 4.1427 |
| 0.7468 | 4.3197 | 4.1427 |
| 0.7493 | 4.3141 | 4.1427 |
| 0.7517 | 4.3085 | 4.1427 |
| 0.7542 | 4.3029 | 4.1427 |
| 0.7567 | 4.2973 | 4.1427 |
| 0.7592 | 4.2917 | 4.1427 |
| 0.7617 | 4.2861 | 4.1427 |
| 0.7642 | 4.2805 | 4.1427 |
| 0.7667 | 4.2749 | 4.1427 |
| 0.7692 | 4.2693 | 4.1427 |
| 0.7717 | 4.2638 | 4.1427 |
| 0.7742 | 4.2582 | 4.1428 |
| 0.7767 | 4.2526 | 4.1429 |
| 0.7792 | 4.247  | 4.1431 |
| 0.7842 | 4.2358 | 4.1441 |
| 0.7866 | 4.2302 | 4.145  |
| 0.7891 | 4.2247 | 4.1465 |
| 0.7966 | 4.208  | 4.1549 |
| 0.7991 | 4.2024 | 4.1593 |
| 0.8   | 4.1969 | 4.1644 |

**Note:** in this case, data has been shortened because it is too large. All data of results could be provided if it is needed.
Case 5: Influence of the natural gas wall friction.
  o Temperature change along transmission gas pipeline.

| L (km) | T (K)   |
|--------|---------|
| 0      | 315.65  |
| 1.22   | 314.7094|
| 2.44   | 313.7984|
| 3.66   | 312.9159|
| 4.88   | 312.0613|
| 6.1    | 311.2335|
| 7.32   | 310.4317|
| 8.54   | 309.6552|
| 9.76   | 308.9032|
| 10.98  | 308.1749|
| 12.2   | 307.4696|
| 13.42  | 306.7866|
| 14.64  | 306.1251|
| 15.86  | 305.4845|
| 17.08  | 304.8642|
| 18.3   | 304.2635|
| 19.52  | 303.6818|
| 20.74  | 303.1185|
| 21.96  | 302.5731|
| 23.18  | 302.0449|
| 24.4   | 301.5335|
| 25.62  | 301.0383|
| 26.84  | 300.5588|
| 28.06  | 300.0946|
| 29.28  | 299.645 |
| 30.5   | 299.2098|
| 31.72  | 298.7883|
| 32.94  | 298.3803|
| 34.16  | 297.9852|
| 35.38  | 297.6027|
| 36.6   | 297.2324|
| 37.82  | 296.8739|
| 39.04  | 296.5267|
| 40.26  | 296.1906|
| 41.48  | 295.8653|
| 42.7   | 295.5502|
| 43.92  | 295.2453|
| 45.14  | 294.95  |
| 46.36  | 294.6642|
| 47.58  | 294.3875|
| 48.8   | 294.1196|
| 50.02  | 293.8602|
| 51.24  | 293.6092|
| 52.46  | 293.3661|
|   |   |
|---|---|
| 53.68 | 293.1309 |
| 54.9 | 292.9031 |
| 56.12 | 292.6826 |
| 57.34 | 292.4692 |
| 58.56 | 292.2626 |
| 59.78 | 292.0626 |
| 61 | 291.869 |
| 62.22 | 291.6817 |
| 63.44 | 291.5003 |
| 64.66 | 291.3247 |
| 65.88 | 291.1547 |
| 67.1 | 290.9902 |
| 68.32 | 290.831 |
| 69.54 | 290.6769 |
| 70.76 | 290.5277 |
| 71.98 | 290.3833 |
| 73.2 | 290.2435 |
| 74.42 | 290.1083 |
| 75.64 | 289.9774 |
| 76.86 | 289.8506 |
| 78.08 | 289.728 |
| 79.3 | 289.6093 |
| 80.52 | 289.4944 |
| 81.74 | 289.3833 |
| 82.96 | 289.2757 |
| 84.18 | 289.1715 |
| 85.4 | 289.0708 |
| 86.62 | 288.9733 |
| 87.84 | 288.8789 |
| 89.06 | 288.7875 |
| 90.28 | 288.6992 |
| 91.5 | 288.6136 |
| 92.72 | 288.5309 |
| 93.94 | 288.4508 |
| 95.16 | 288.3733 |
| 96.38 | 288.2983 |
| 97.6 | 288.2258 |
| 98.82 | 288.1556 |
| 100.04 | 288.0876 |
| 101.26 | 288.0219 |
| 102.48 | 287.9583 |
| 103.7 | 287.8968 |
| 104.92 | 287.8373 |
| 106.14 | 287.7797 |
| 107.36 | 287.724 |
| 108.58 | 287.6701 |
| 109.8 | 287.618 |
| 111.02 | 287.5675 |
| 112.24 | 287.5188 |
|--------|----------|
| 113.46 | 287.4716 |
| 114.68 | 287.4259 |
| 115.9  | 287.3818 |
| 117.12 | 287.3391 |
| 118.34 | 287.2978 |
| 119.56 | 287.2578 |
| 120.78 | 287.2192 |
| 122    | 287.1818 |
- **Case 5-Scenario 1**: thermal effect of the heat generation by wall friction.
  - Temperature flow with and without gas wall friction (Fig. 5.16)

| L (km) | \( k=0.8 \text{ W/m}^2\text{K} \) | \( k=1.6 \text{ W/m}^2\text{K} \) | \( k=5.8 \text{ W/m}^2\text{K} \) |
|-------|------------------|------------------|------------------|
|       | Temp. (K) with   | Temp. (K) with   | Temp. (K) with   |
|       |                  |                  |                  |
|       |                  |                  |                  |
|       |                  |                  |                  |
| 0     | 315.65           | 315.65           | 315.65           |
| 1.5   | 315.522508       | 315.4805         | 315.354641       |
| 3     | 315.394956       | 315.311944       | 315.3191446      |
| 4.5   | 315.2674093      | 315.14432        | 314.771454       |
| 6     | 315.139908       | 314.97762        | 314.483678       |
| 7.5   | 315.0125034      | 314.81184        | 314.198476       |
| 9     | 314.88524        | 314.64698        | 313.915866       |
| 10.5  | 314.7581593      | 314.48303        | 313.635862       |
| 12    | 314.6313002      | 314.31999        | 313.358476       |
| 13.5  | 314.5046987      | 314.15784        | 313.083716       |
| 15    | 314.3783886      | 313.9966         | 312.811589       |
| 16.5  | 314.2524014      | 313.83625        | 312.542098       |
| 18    | 314.1267663      | 313.67678        | 312.275247       |
| 19.5  | 314.0015106      | 313.5182         | 312.011034       |
| 21    | 313.8766597      | 313.36049        | 311.749457       |
| 22.5  | 313.752237       | 313.20365        | 311.490514       |
| 24    | 313.6282645      | 313.04769        | 311.234199       |
| 25.5  | 313.5047623      | 312.89258        | 310.980505       |
| 27    | 313.3817494      | 312.73833        | 310.729423       |
| 28.5  | 313.2592431      | 312.58494        | 310.480946       |
| 30    | 313.1372594      | 312.43239        | 310.235062       |
| 31.5  | 313.0158132      | 312.28069        | 309.99176        |
| 33    | 312.8949182      | 312.12983        | 309.751027       |
| 34.5  | 312.7745869      | 311.9798         | 309.512851       |
| 36    | 312.6548309      | 311.8306         | 309.272716       |
| 37.5  | 312.5356608      | 311.68222        | 309.044107       |
| 39    | 312.4170862      | 311.53467        | 308.81351        |
| 40.5  | 312.299116       | 311.38793        | 308.585408       |
| 42    | 312.1817581      | 311.242          | 308.359783       |
| 43.5  | 312.06502        | 311.09688        | 308.13662        |
| 45    | 311.948908       | 310.95256        | 307.915899       |
| 46.5  | 311.8334282      | 310.80904        | 307.697602       |
| 48    | 311.7185858      | 310.66632        | 307.481711       |
| 49.5  | 311.6043855      | 310.52438        | 307.268207       |
| 51    | 311.4908314      | 310.38323        | 307.057071       |
| 52.5  | 311.3779272      | 310.24286        | 306.848282       |
| 54    | 311.2656761      | 310.10327        | 306.641822       |
| 55.5  | 311.1540807      | 309.96444        | 306.43767        |

\( k = 0.8 \text{ W/m}^2\text{K} \)

\( k = 1.6 \text{ W/m}^2\text{K} \)

\( k = 5.8 \text{ W/m}^2\text{K} \)

\( \Delta T = 0.8 \text{ W/m}^2\text{K} \)

\( \Delta T = 1.6 \text{ W/m}^2\text{K} \)

\( \Delta T = 5.8 \text{ W/m}^2\text{K} \)

**Note:** The table represents temperature variations with and without wall friction for different wall conductivities.
| Time  | Temperature (°C) | Expected Temperature (°C) | Error (°C) |
|-------|-----------------|----------------------------|------------|
| 192   | 303.5546939     | 300.07172                  | -9.48217   |
| 193.5 | 303.4954557     | 299.9838                   | -3.4719    |
| 195   | 303.4366617     | 299.90549                  | -3.8559    |
| 196.5 | 303.3783096     | 299.82306                  | -4.1304    |
| 198   | 303.320397      | 299.74109                  | -3.6301    |
| 199.5 | 303.2629217     | 299.65957                  | -3.5642    |
| 201   | 303.2058815     | 299.5785                   | -3.6061    |
| 202.5 | 303.149274      | 299.49788                  | -3.5702    |
| 204   | 303.0930971     | 299.41771                  | -3.5820    |
| 205.5 | 303.0373485     | 299.33798                  | -3.5967    |
| 207   | 302.9820261     | 299.25869                  | -3.6032    |
| 208.5 | 302.9271277     | 299.17984                  | -3.6143    |
| 210   | 302.8726512     | 299.10142                  | -3.6104    |
| 211.5 | 302.8185943     | 299.02344                  | -3.5961    |
| 213   | 302.7694551     | 298.94589                  | -3.5992    |
| 214.5 | 302.7117314     | 298.86877                  | -3.6045    |
| 216   | 302.658921      | 298.79207                  | -3.6074    |
| 217.5 | 302.606522      | 298.7158                   | -3.5994    |
| 219   | 302.554324      | 298.63995                  | -3.5906    |
| 220.5 | 302.5029499     | 298.56452                  | -3.5893    |
| 222   | 302.4517728     | 298.48951                  | -3.5882    |
| 223.5 | 302.4009988     | 298.41491                  | -3.5883    |
| 225   | 302.3506262     | 298.34073                  | -3.5889    |
| 226.5 | 302.3006528     | 298.26695                  | -3.5884    |
| 228   | 302.2510768     | 298.19358                  | -3.5889    |
| 229.5 | 302.2018961     | 298.12062                  | -3.5883    |
| 231   | 302.1513109     | 298.04806                  | -3.5883    |
| 232.5 | 302.1047135     | 297.97591                  | -3.5883    |
| 234   | 302.0567076     | 297.90415                  | -3.5883    |
| 235.5 | 302.0090896     | 297.83279                  | -3.5883    |
| 237   | 301.961857      | 297.76182                  | -3.5883    |
| 238.5 | 301.9150096     | 297.69125                  | -3.5883    |
| 240   | 301.8685439     | 297.62107                  | -3.5883    |
| 241.5 | 301.8224587     | 297.55127                  | -3.5883    |
| 243   | 301.7767522     | 297.48186                  | -3.5883    |
| 244.5 | 301.7314226     | 297.41284                  | -3.5883    |
| 246   | 301.6864681     | 297.34419                  | -3.5883    |
| 247.5 | 301.641887      | 297.27593                  | -3.5883    |
| 249   | 301.5976775     | 297.20804                  | -3.5883    |
| 250.5 | 301.5538379     | 297.14053                  | -3.5883    |
| 252   | 301.5103665     | 297.07339                  | -3.5883    |
| 253.5 | 301.4672616     | 297.00663                  | -3.5883    |
| 255   | 301.4245214     | 296.94023                  | -3.5883    |
| 256.5 | 301.3821445     | 296.8742                   | -3.5883    |
| 258   | 301.3401289     | 296.80853                  | -3.5883    |
| 259.5 | 301.2984732 | 296.74323 | 292.713369 | 289.4992984 | 286.186292 | 285.030978 |
|-------|-------------|-----------|------------|-------------|------------|------------|
| 261   | 301.2571757 | 296.67829 | 292.675368 | 289.4496732 | 286.186922 | 285.029767 |
| 262.5 | 301.2162348 | 296.61371 | 292.637889 | 289.4005953 | 286.187604 | 285.028604 |
| 264   | 301.1756489 | 296.54948 | 292.600926 | 289.3520588 | 286.188337 | 285.027486 |
| 265.5 | 301.1354163 | 296.48562 | 292.564473 | 289.3040576 | 286.189119 | 285.026412 |
| 267   | 301.0955355 | 296.4221 | 292.528524 | 289.2565858 | 286.189948 | 285.02538 |
| 268.5 | 301.056005  | 296.35893 | 292.493076 | 289.2096376 | 286.190823 | 285.024388 |
| 270   | 301.0168232 | 296.29612 | 292.458121 | 289.1632073 | 286.191741 | 285.023435 |
| 271.5 | 300.9779885 | 296.23656 | 292.423656 | 289.117289  | 286.192702 | 285.022519 |
| 273   | 300.9394994 | 296.17153 | 292.389674 | 289.0718772 | 286.193705 | 285.021639 |
| 274.5 | 300.9013545 | 296.1075 | 292.356172 | 289.0269663 | 286.194747 | 285.020793 |
| 276   | 300.8635521 | 296.04831 | 292.323144 | 288.9825507 | 286.195828 | 285.019998 |
| 277.5 | 300.8260908 | 295.98721 | 292.290584 | 288.938625  | 286.196946 | 285.019199 |
| 279   | 300.7889692 | 295.92645 | 292.258489 | 288.8951838 | 286.198101 | 285.018449 |
| 280.5 | 300.7521858 | 295.86603 | 292.226853 | 288.8522217 | 286.19929  | 285.017728 |
| 282   | 300.7157391 | 295.80594 | 292.195672 | 288.8097334 | 286.200514 | 285.017035 |
| 283.5 | 300.6796276 | 295.74618 | 292.164944 | 288.7677138 | 286.20177  | 285.016369 |
| 285   | 300.64385  | 295.68676 | 292.134654 | 288.7261577 | 286.203059 | 285.01573 |
| 286.5 | 300.6084049 | 295.62766 | 292.104808 | 288.6850599 | 286.204379 | 285.015115 |
| 288   | 300.5732908 | 295.56889 | 292.075399 | 288.6444154 | 286.205728 | 285.014524 |
| 289.5 | 300.5385063 | 295.51044 | 292.046421 | 288.6042191 | 286.207107 | 285.013957 |
| 291   | 300.50405  | 295.45232 | 292.01787 | 288.5644663 | 286.208514 | 285.013411 |
| 292.5 | 300.4699207 | 295.39451 | 291.989742 | 288.5251518 | 286.209949 | 285.012887 |
| 294   | 300.4361169 | 295.33703 | 291.962032 | 288.486271  | 286.21141  | 285.012383 |
| 295.5 | 300.4026372 | 295.27987 | 291.934736 | 288.4478191 | 286.212898 | 285.0119 |
| 297   | 300.3694804 | 295.22302 | 291.907851 | 288.4097912 | 286.214411 | 285.011434 |
| 298.5 | 300.3366452 | 295.16648 | 291.881371 | 288.3721828 | 286.215948 | 285.010988 |
| 300   | 300.3041301 | 295.11026 | 291.855292 | 288.3349892 | 286.21751  | 285.010558 |

**Note:** because of the huge number of data, the other results of this calculation of Case 5-scenario 2 are in the CD.
### Scenario 1: Trip of the gas supply

Flow rate behaviour in the gas pipeline of the Western Libya Gas Project (Fig. 6.5)

| Time (hr) | $m_{\text{lin}}$ (kg/s) | $m_{\text{lin}}$ (kg/s) | $m_{\text{lin}}$ (kg/s) | $m_{\text{lin}}$ (kg/s) | $m_{\text{lin}}$ (kg/s) | $m_{\text{lin}}$ (kg/s) |
|----------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| 0        | 80.365                  | 80.251                  | 38.565                  | 39.151                  | 47.486                  | 51.191                  |
| 0.251306 | 80.37                   | 80.256                  | 38.57                   | 39.151                  | 47.485                  | 51.191                  |
| 0.502111 | 80.375                  | 80.258                  | 38.574                  | 39.151                  | 47.484                  | 51.191                  |
| 0.75075  | 80.384                  | 80.262                  | 38.578                  | 39.151                  | 47.483                  | 51.191                  |
| 1.001556 | 80.388                  | 80.264                  | 38.584                  | 39.151                  | 47.482                  | 51.191                  |
| 1.300361 | 80.395                  | 80.267                  | 38.586                  | 39.151                  | 47.482                  | 51.191                  |
| 1.601333 | 80.401                  | 80.271                  | 38.59                   | 39.151                  | 47.482                  | 51.191                  |
| 1.901111 | 80.41                   | 80.274                  | 38.596                  | 39.151                  | 47.479                  | 51.191                  |
| 2.201083 | 0                      | 80.278                  | 38.6                    | 39.151                  | 47.478                  | 51.191                  |
| 2.502083 | 0                      | 80.28                   | 38.604                  | 39.151                  | 47.477                  | 51.191                  |
| 2.800861 | 0                      | 80.27                   | 38.594                  | 39.151                  | 47.475                  | 51.191                  |
| 3.101833 | 0                      | 80.122                  | 38.453                  | 39.151                  | 47.468                  | 51.191                  |
| 3.400639 | 0                      | 79.673                  | 38.025                  | 39.151                  | 47.448                  | 51.191                  |
| 3.701611 | 0                      | 78.862                  | 37.243                  | 39.151                  | 47.418                  | 51.191                  |
| 4.000417 | 0                      | 77.739                  | 36.162                  | 39.151                  | 47.378                  | 51.191                  |
| 4.301389 | 0                      | 76.373                  | 34.844                  | 39.151                  | 47.329                  | 51.191                  |
| 4.600194 | 0                      | 74.867                  | 33.395                  | 39.151                  | 47.272                  | 51.191                  |
| 4.901167 | 0                      | 73.281                  | 31.872                  | 39.151                  | 47.209                  | 51.191                  |
| 5.202139 | 0                      | 71.677                  | 30.339                  | 39.151                  | 47.139                  | 51.191                  |
| 5.500944 | 0                      | 70.115                  | 28.853                  | 39.151                  | 47.062                  | 51.191                  |
| 5.801917 | 0                      | 68.598                  | 27.418                  | 39.151                  | 46.979                  | 51.191                  |
| 6.100389 | 0                      | 67.168                  | 26.078                  | 39.151                  | 46.891                  | 51.191                  |
| 6.401    | 0                      | 65.815                  | 24.82                   | 39.151                  | 46.794                  | 51.191                  |
| 6.701611 | 0                      | 64.553                  | 23.661                  | 39.151                  | 46.692                  | 51.191                  |
| 7.000028 | 0                      | 63.391                 | 22.609                  | 39.151                  | 46.583                  | 51.191                  |
| 7.400833 | 0                      | 61.97                  | 21.344                  | 39.151                  | 46.426                  | 51.191                  |
| 7.801639 | 0                      | 60.699                 | 20.243                  | 39.151                  | 46.257                  | 51.191                  |
| 8.204611 | 0                      | 59.559                 | 19.286                  | 39.151                  | 46.073                  | 51.191                  |
| 8.600583 | 0                      | 58.557                 | 18.479                  | 39.151                  | 45.878                  | 51.191                  |
| 9.000889 | 0                      | 57.652                 | 17.785                  | 39.151                  | 45.667                  | 51.191                  |
| 9.401194 | 0                      | 56.84                  | 17.199                  | 39.151                  | 45.441                  | 51.191                  |
| 9.8015   | 0                      | 56.109                 | 16.711                  | 39.151                  | 45.199                  | 51.191                  |
| 10.2105  | 0                      | 55.432                 | 16.298                  | 39.151                  | 44.935                  | 51.191                  |
| 10.61081 | 0                      | 54.829                 | 15.97                   | 39.151                  | 44.659                  | 51.191                  |
| 11.06103 | 0                      | 54.205                 | 15.677                  | 39.151                  | 44.328                  | 51.191                  |
| 11.40175 | 0                      | 53.765                 | 15.504                  | 39.151                  | 44.061                  | 51.191                  |
| 11.80756 | 0                      | 53.269                 | 15.345                  | 39.151                  | 43.724                  | 51.191                  |
| 12.20469 | 0                      | 52.809                 | 15.234                  | 39.151                  | 43.375                  | 51.191                  |
| 12.61486 | 0                      | 52.354                 | 15.159                  | 39.151                  | 42.994                  | 51.191                  |
| 13.00114 | 0                      | 51.937                 | 15.122                  | 39.151                  | 42.615                  | 51.191                  |
|      |      |       |      |      |      |      |      |      |      |      |      |      | 13.40044 |      |      |      |      |      |      |      |
|------|------|-------|------|------|------|------|------|------|------|------|------|------|---------|------|------|------|------|------|------|------|------|
| 13.80408 | 0     | 51.516 | 15.113 | 39.15 | 42.203 | 51.19 |
| 14.20122 | 0     | 50.686 | 15.173 | 39.15 | 41.764 | 51.19 |
| 14.60053 | 0     | 50.273 | 15.236 | 39.15 | 40.836 | 51.19 |
| 15.01286 | 0     | 49.844 | 15.321 | 39.15 | 40.523 | 51.19 |
| 15.40256 | 0     | 49.435 | 15.418 | 39.15 | 39.817 | 51.19 |
| 15.81603 | 0     | 48.995 | 15.534 | 39.15 | 39.26  | 51.19 |
| 16.2035  | 0     | 48.576 | 15.657 | 39.15 | 38.72  | 51.19 |
| 16.60181 | 0     | 48.141 | 15.792 | 39.15 | 38.148 | 51.19 |
| 17.00011 | 0     | 47.697 | 15.938 | 39.15 | 37.559 | 51.19 |
| 17.40275 | 0     | 47.241 | 16.092 | 39.15 | 36.949 | 51.19 |
| 17.82056 | 0     | 46.761 | 16.259 | 39.15 | 36.302 | 51.19 |
| 18.20153 | 0     | 46.315 | 16.415 | 39.15 | 35.699 | 51.19 |
| 18.55525 | 0     | 45.897 | 16.564 | 39.15 | 35.133 | 51.19 |
| 19.00231 | 0     | 45.36  | 16.754 | 39.15 | 34.407 | 51.19 |
| 19.19753 | 0     | 45.123 | 16.837 | 39.15 | 34.087 | 51.19 |
| 19.502   | 0     | 44.75  | 16.967 | 39.15 | 33.582 | 51.19 |
| 19.80214 | 0     | 44.377 | 17.097 | 39.15 | 33.081 | 51.19 |
| 20.11092 | 0     | 43.99  | 17.229 | 39.15 | 32.562 | 51.19 |
| 20.43481 | 0     | 43.582 | 17.368 | 39.15 | 32.014 | 51.19 |
| 20.71767 | 0     | 43.223 | 17.489 | 39.15 | 31.534 | 51.19 |
| 21.04372 | 0     | 42.805 | 17.626 | 39.15 | 30.979 | 51.19 |
| 21.28772 | 0     | 42.49  | 17.728 | 39.15 | 30.562 | 51.19 |
| 21.62456 | 0     | 42.053 | 17.867 | 39.149| 29.986 | 51.19 |
| 22.002   | 0     | 41.562 | 18.02  | 39.149| 29.342 | 51.19 |
| 22.30364 | 0     | 41.167 | 18.141 | 39.149| 28.826 | 51.19 |
| 22.64003 | 0     | 40.724 | 18.273 | 39.149| 28.251 | 51.19 |
| 23.51419 | 0     | 40.219 | 17.653 | 39.149| 28.366 | 51.189|
| 23.69369 | 0     | 39.991 | 17.723 | 39.149| 28.068 | 51.19 |
| 24      | 0     | 39.604 | 17.839 | 39.149| 27.565 | 51.19 |
Pressure history in the gas pipeline of the Western Libya Gas Project during the gas supply trip (Fig. 6.6)

| Time (hr) | $P_{in}$ (bar) | $P_{out}$ (bar) | $P_{in}$ (bar) | $P_{out}$ (bar) | $P_{in}$ (bar) | $P_{out}$ (bar) |
|-----------|----------------|----------------|----------------|----------------|----------------|----------------|
| 0         | 63.9           | 42.993         | 42.993         | 40.509         | 42.993         | 37.695         |
| 0.251306  | 63.9           | 42.989         | 42.989         | 40.504         | 42.989         | 37.69         |
| 0.502111  | 63.9           | 42.985         | 42.985         | 40.5           | 42.985         | 37.686         |
| 0.75075   | 63.9           | 42.981         | 42.981         | 40.496         | 42.981         | 37.682         |
| 1.001556  | 63.9           | 42.978         | 42.978         | 40.491         | 42.978         | 37.678         |
| 1.300361  | 63.9           | 42.973         | 42.973         | 40.486         | 42.973         | 37.673         |
| 1.601333  | 63.9           | 42.969         | 42.969         | 40.481         | 42.969         | 37.668         |
| 1.900111  | 63.9           | 42.965         | 42.965         | 40.477         | 42.965         | 37.663         |
| 2.201083  | 50.68          | 42.96         | 42.96         | 40.472         | 42.96         | 37.659         |
| 2.502083  | 58.529         | 42.956         | 42.956         | 40.467         | 42.956         | 37.654         |
| 2.808061  | 57.013         | 42.952         | 42.952         | 40.463         | 42.952         | 37.65          |
| 3.101833  | 55.754         | 42.943         | 42.943         | 40.458         | 42.943         | 37.64          |
| 3.400639  | 54.662         | 42.919         | 42.919         | 40.452         | 42.919         | 37.615         |
| 3.701611  | 53.672         | 42.87         | 42.87         | 40.442         | 42.87         | 37.564         |
| 4.000417  | 52.768         | 42.792         | 42.792         | 40.421         | 42.792         | 37.479         |
| 4.301389  | 51.922         | 42.681         | 42.681         | 40.403         | 42.681         | 37.358         |
| 4.600194  | 51.131         | 42.539         | 42.539         | 40.325         | 42.539         | 37.204         |
| 4.901167  | 50.377         | 42.367         | 42.367         | 40.239         | 42.367         | 37.015         |
| 5.202139  | 49.66          | 42.167         | 42.167         | 40.126         | 42.167         | 36.796         |
| 5.509944  | 48.978         | 41.944         | 41.944         | 39.984         | 41.944         | 36.55          |
| 5.801917  | 48.319         | 41.697         | 41.697         | 39.812         | 41.697         | 36.277         |
| 6.100389  | 47.689         | 41.43         | 41.43         | 39.613         | 41.43         | 35.982         |
| 6.401     | 47.077         | 41.142         | 41.142         | 39.385         | 41.142         | 35.664         |
| 6.701611  | 46.485         | 40.837         | 40.837         | 39.132         | 40.837         | 35.326         |
| 7.000028  | 45.915         | 40.518         | 40.518         | 38.858         | 40.518         | 34.972         |
| 7.400833  | 45.175         | 40.068         | 40.068         | 38.458         | 40.068         | 34.473         |
| 7.801639  | 44.461         | 39.596         | 39.596         | 38.023         | 39.596         | 33.948         |
| 8.204611  | 43.767         | 39.101         | 39.101         | 37.557         | 39.101         | 33.398         |
| 8.600583  | 43.104         | 38.598         | 38.598         | 37.074         | 38.598         | 32.839         |
| 9.000889  | 42.451         | 38.076         | 38.076         | 36.564         | 38.076         | 32.257         |
| 9.401194  | 41.814         | 37.543         | 37.543         | 36.036         | 37.543         | 31.663         |
| 9.8015    | 41.192         | 36.999         | 36.999         | 35.492         | 36.999         | 31.059         |
| 10.2105   | 40.568         | 36.436         | 36.436         | 34.923         | 36.436         | 30.432         |
| 10.61081  | 39.969         | 35.879         | 35.879         | 34.356         | 35.879         | 29.813         |
| 11.06103  | 39.306         | 35.247         | 35.247         | 33.706         | 35.247         | 29.112         |
| 11.40175  | 38.811         | 34.765         | 34.765         | 33.208         | 34.765         | 28.578         |
| 11.80756  | 38.229         | 34.189         | 34.189         | 32.61          | 34.189         | 27.942         |
| 12.20469  | 37.666         | 33.624         | 33.624         | 32.019         | 33.624         | 27.32          |
| 12.61486  | 37.092         | 33.04          | 33.04          | 31.406         | 33.04          | 26.681         |
| 13.00114  | 36.557         | 32.491         | 32.491         | 30.827         | 32.491         | 26.082         |
| 13.40044  | 36.009         | 31.924         | 31.924         | 30.227         | 31.924         | 25.469         |
| 13.80408  | 35.461         | 31.354         | 31.354         | 29.619         | 31.354         | 24.855         |
| 14.20122  | 34.927         | 30.796         | 30.796         | 29.022         | 30.796         | 24.26          |
| 14.60053 | 34.395 | 30.237 | 30.237 | 28.422 | 30.237 | 23.67 |
| 15.01286 | 33.85  | 29.665 | 29.665 | 27.803 | 29.665 | 23.071|
| 15.40256 | 33.339 | 29.126 | 29.126 | 27.218 | 29.126 | 22.515|
| 15.81603 | 32.801 | 28.559 | 28.559 | 26.6   | 28.559 | 21.937|
| 16.2035  | 32.301 | 28.033 | 28.033 | 26.023 | 28.033 | 21.408|
| 16.60181 | 31.792 | 27.497 | 27.497 | 25.433 | 27.497 | 20.878|
| 17.00011 | 31.287 | 26.966 | 26.966 | 24.845 | 26.966 | 20.362|
| 17.40275 | 30.781 | 26.435 | 26.435 | 24.254 | 26.435 | 19.854|
| 17.82056 | 30.261 | 25.89  | 25.89  | 23.644 | 25.89  | 19.344|
| 18.20153 | 29.79  | 25.399 | 25.399 | 23.091 | 25.399 | 18.893|
| 18.55525 | 29.359 | 24.949 | 24.949 | 22.582 | 24.949 | 18.487|
| 19.00231 | 28.818 | 24.387 | 24.387 | 21.943 | 24.387 | 17.991|
| 19.19753 | 28.584 | 24.145 | 24.145 | 21.665 | 24.145 | 17.78 |
| 19.502   | 28.218 | 23.767 | 23.767 | 21.231 | 23.767 | 17.456|
| 19.80214 | 27.861 | 23.398 | 23.398 | 20.805 | 23.398 | 17.145|
| 20.11092 | 27.496 | 23.023 | 23.023 | 20.37  | 23.023 | 16.833|
| 20.43481 | 27.117 | 22.633 | 22.633 | 19.915 | 22.633 | 16.515|
| 20.71767 | 26.787 | 22.296 | 22.296 | 19.52  | 22.296 | 16.244|
| 21.04372 | 26.411 | 21.912 | 21.912 | 19.066 | 21.912 | 15.94 |
| 21.28772 | 26.132 | 21.627 | 21.627 | 18.728 | 21.627 | 15.717|
| 21.62456 | 25.749 | 21.238 | 21.238 | 18.264 | 21.238 | 15.418|
| 22.002   | 25.325 | 20.81  | 20.81  | 17.749 | 20.81  | 15.094|
| 22.30364 | 24.991 | 20.472 | 20.472 | 17.339 | 20.472 | 14.842|
| 22.64003 | 24.62  | 20.099 | 20.099 | 16.885 | 20.099 | 14.568|
| 23.51419 | 23.672 | 19.074 | 19.074 | 15.699 | 19.074 | 13.045|
| 23.69369 | 23.48  | 18.867 | 18.867 | 15.45  | 18.867 | 12.882|
| 24       | 23.154 | 18.522 | 18.522 | 15.024 | 18.522 | 12.612|
**Scenario 2:** gas delivery stops at the Mellitah Complex after one hour.

- Flow rate behavior in the gas pipeline of the Western Libya Gas Project Fig. (6.7).

| Time (hr) | $m_{1\text{in}}$ (kg/s) | $m_{1\text{out}}$ (kg/s) | $m_{2\text{in}}$ (kg/s) | $m_{2\text{out}}$ (kg/s) | $m_{3\text{in}}$ (kg/s) | $m_{3\text{out}}$ (kg/s) |
|-----------|-------------------------|--------------------------|-------------------------|-------------------------|-------------------------|--------------------------|
| 0         | 78.122                  | 78.128                   | 38.644                  | 39.151                  | 45.494                  | 51.191                   |
| 0.049472  | 78.123                  | 78.13                    | 38.646                  | 39.151                  | 45.494                  | 51.191                   |
| 0.102833  | 78.124                  | 78.13                    | 38.646                  | 39.151                  | 45.493                  | 51.191                   |
| 0.149083  | 78.125                  | 78.13                    | 38.647                  | 39.151                  | 45.493                  | 51.191                   |
| 0.202472  | 78.127                  | 78.13                    | 38.648                  | 39.151                  | 45.493                  | 51.191                   |
| 0.252278  | 78.127                  | 78.132                   | 38.649                  | 39.151                  | 45.493                  | 51.191                   |
| 0.298556  | 78.128                  | 78.131                   | 38.649                  | 39.151                  | 45.492                  | 51.191                   |
| 0.351917  | 78.129                  | 78.132                   | 38.649                  | 39.151                  | 45.492                  | 51.191                   |
| ...       | ...                     | ...                      | ...                     | ...                     | ...                     | ...                      |
| 1.003111  | 78.14                   | 78.136                   | 38.656                  | 39.151                  | 45.49                  | 51.191                   |
| 1.102722  | 78.142                  | 78.137                   | 38.657                  | 39.151                  | 45.489                  | 51.191                   |
| 1.203261  | 78.144                  | 77.428                   | 37.854                  | 39.151                  | 45.584                  | 51.191                   |
| 1.302     | 78.145                  | 75.749                   | 36.013                  | 39.151                  | 45.747                  | 51.192                   |
| 1.401639  | 78.147                  | 73.927                   | 34.056                  | 39.151                  | 45.882                  | 51.192                   |
| 1.501278  | 78.149                  | 72.269                   | 32.294                  | 39.151                  | 45.985                  | 51.192                   |
| 1.600917  | 78.15                   | 70.83                    | 30.773                  | 39.151                  | 46.067                  | 51.192                   |
| 1.700528  | 78.152                  | 69.594                   | 29.466                  | 39.151                  | 46.138                  | 51.192                   |
| 1.800167  | 78.153                  | 68.524                   | 28.334                  | 39.151                  | 46.201                  | 51.192                   |
| 1.900828  | 78.155                  | 67.494                   | 27.239                  | 39.151                  | 46.266                  | 51.192                   |
| 2.003     | 78.154                  | 66.734                   | 26.427                  | 39.151                  | 46.317                  | 51.192                   |
| 2.202278  | 78.156                  | 65.329                   | 24.919                  | 39.151                  | 46.419                  | 51.192                   |
| 2.4015    | 78.152                  | 64.166                   | 23.662                  | 39.151                  | 46.516                  | 51.192                   |
| 2.60075   | 78.137                  | 63.182                   | 22.586                  | 39.151                  | 46.605                  | 51.192                   |
| 2.803528  | 78.109                  | 62.314                   | 21.633                  | 39.151                  | 46.692                  | 51.192                   |
| 3.00275   | 78.062                  | 61.568                   | 20.806                  | 39.151                  | 46.772                  | 51.192                   |
| 3.202     | 77.996                  | 60.904                   | 20.065                  | 39.151                  | 46.848                  | 51.192                   |
| 3.301667  | 77.954                  | 60.599                   | 19.724                  | 39.151                  | 46.885                  | 51.192                   |
| 3.401306  | 77.907                  | 60.309                   | 19.398                  | 39.151                  | 46.921                  | 51.192                   |
| 3.600611  | 77.798                  | 59.77                    | 18.79                   | 39.151                  | 46.991                  | 51.192                   |
| 3.803472  | 77.662                  | 59.275                   | 18.227                  | 39.151                  | 47.058                  | 51.192                   |
| 3.999222  | 77.513                  | 58.834                   | 17.723                  | 39.151                  | 47.12                   | 51.192                   |
| 4.202083  | 77.34                   | 58.415                   | 17.243                  | 39.151                  | 47.181                  | 51.192                   |
| 4.401389  | 77.148                  | 58.034                   | 16.804                  | 39.151                  | 47.24                   | 51.192                   |
| 4.600694  | 76.943                  | 57.679                   | 16.394                  | 39.151                  | 47.296                  | 51.192                   |
| 4.8       | 76.72                   | 57.349                   | 16.011                  | 39.151                  | 47.35                   | 51.192                   |
| Time  | Energy       | Temperature | Pressure | Mass  | Density | Porosity | Beacons | Area   |
|-------|--------------|-------------|----------|-------|---------|----------|---------|--------|
| 5.00261 | 76.482 | 57.035 | 15.645 | 0 | 47.402 | 51.192 |
| 5.20167 | 76.234 | 56.744 | 15.302 | 0 | 47.452 | 51.192 |
| 5.401472 | 75.975 | 56.471 | 14.981 | 0 | 47.5 | 51.192 |
| 5.600778 | 75.707 | 56.212 | 14.676 | 0 | 47.546 | 51.192 |
| 5.800083 | 75.431 | 55.965 | 14.384 | 0 | 47.591 | 51.192 |
| 5.999389 | 75.149 | 55.73 | 14.106 | 0 | 47.634 | 51.192 |
| 6.20225 | 74.854 | 55.503 | 13.836 | 0 | 47.676 | 51.192 |
| 6.401556 | 74.56 | 55.287 | 13.581 | 0 | 47.717 | 51.192 |
| 6.600861 | 74.26 | 55.081 | 13.335 | 0 | 47.756 | 51.192 |
| 6.800167 | 73.958 | 54.882 | 13.099 | 0 | 47.794 | 51.192 |
| 7.003056 | 73.645 | 54.686 | 12.865 | 0 | 47.831 | 51.192 |
| 7.202361 | 73.338 | 54.5 | 12.645 | 0 | 47.866 | 51.192 |
| 7.401667 | 73.028 | 54.318 | 12.427 | 0 | 47.901 | 51.192 |
| 7.600972 | 72.717 | 54.143 | 12.219 | 0 | 47.934 | 51.192 |
| 7.800278 | 72.403 | 53.972 | 12.016 | 0 | 47.966 | 51.192 |
| 8.003139 | 72.086 | 53.801 | 11.812 | 0 | 47.998 | 51.192 |
| 8.305889 | 71.612 | 53.555 | 11.521 | 0 | 48.044 | 51.192 |
| 8.601528 | 71.15 | 53.321 | 11.244 | 0 | 48.087 | 51.192 |
| 8.9185 | 70.656 | 53.077 | 10.957 | 0 | 48.131 | 51.192 |
| 9.199806 | 70.219 | 52.869 | 10.711 | 0 | 48.167 | 51.192 |
| 9.498778 | 69.758 | 52.648 | 10.452 | 0 | 48.206 | 51.191 |
| 9.779944 | 69.329 | 52.449 | 10.219 | 0 | 48.24 | 51.191 |
| 10.10025 | 68.842 | 52.222 | 9.955 | 0 | 48.278 | 51.191 |
| 10.39564 | 68.399 | 52.021 | 9.722 | 0 | 48.311 | 51.191 |
| 10.69842 | 67.95 | 51.817 | 9.484 | 0 | 48.343 | 51.191 |
| 11.00139 | 67.507 | 51.616 | 9.253 | 0 | 48.374 | 51.191 |
| 11.27231 | 67.114 | 51.442 | 9.052 | 0 | 48.401 | 51.191 |
| 11.54319 | 66.726 | 51.27 | 8.854 | 0 | 48.426 | 51.191 |
| 11.84975 | 66.294 | 51.077 | 8.632 | 0 | 48.455 | 51.191 |
| 12 | 66.083 | 50.984 | 8.526 | 0 | 48.468 | 51.191 |
Pressure history behaviour in the gas pipeline of the Western Libya Gas Project during the trip of gas delivery to the Mellitah Complex (Fig. 6.8)

| Time (hr) | $P_{in}$ (bar) | $P_{out}$ (bar) | $P_{in}$ (bar) | $P_{out}$ (bar) | $P_{in}$ (bar) | $P_{out}$ (bar) |
|----------|----------------|----------------|----------------|----------------|----------------|----------------|
| 0        | 63.9           | 44.478         | 44.478         | 42.089         | 44.478         | 39.732         |
| 0.049472 | 63.9           | 44.477         | 44.477         | 42.088         | 44.477         | 39.731         |
| 0.102833 | 63.9           | 44.477         | 44.477         | 42.088         | 44.477         | 39.73         |
| 0.149083 | 63.9           | 44.476         | 44.476         | 42.087         | 44.476         | 39.73         |
| 0.202472 | 63.9           | 44.476         | 44.476         | 42.086         | 44.476         | 39.729         |
| 0.252278 | 63.9           | 44.475         | 44.475         | 42.086         | 44.475         | 39.729         |
| 0.298556 | 63.9           | 44.475         | 44.475         | 42.085         | 44.475         | 39.728         |
| 0.351917 | 63.9           | 44.474         | 44.474         | 42.085         | 44.474         | 39.728         |
| 0.40175  | 63.9           | 44.474         | 44.474         | 42.084         | 44.474         | 39.727         |
| 0.451556 | 63.9           | 44.473         | 44.473         | 42.084         | 44.473         | 39.727         |
| 0.501361 | 63.9           | 44.473         | 44.473         | 42.083         | 44.473         | 39.726         |
| 0.551194 | 63.9           | 44.472         | 44.472         | 42.083         | 44.472         | 39.726         |
| 0.601    | 63.9           | 44.472         | 44.472         | 42.082         | 44.472         | 39.725         |
| 0.700639 | 63.9           | 44.471         | 44.471         | 42.081         | 44.471         | 39.724         |
| 0.800278 | 63.9           | 44.47         | 44.47         | 42.08         | 44.47         | 39.723         |
| 0.903472 | 63.9           | 44.469         | 44.469         | 42.079         | 44.469         | 39.722         |
| 1.005111 | 63.9           | 44.468         | 44.468         | 42.375         | 44.468         | 39.721         |
| 1.102722 | 63.9           | 44.467         | 44.467         | 43.118         | 44.467         | 39.72         |
| 1.202361 | 63.9           | 44.483         | 44.483         | 43.524         | 44.483         | 39.728         |
| 1.302    | 63.9           | 44.551         | 44.551         | 43.837         | 44.551         | 39.784         |
| 1.401639 | 63.9           | 44.656         | 44.656         | 44.102         | 44.656         | 39.886         |
| 1.501278 | 63.9           | 44.784         | 44.784         | 44.336         | 44.784         | 40.016         |
| 1.600917 | 63.9           | 44.922         | 44.922         | 44.551         | 44.922         | 40.159         |
| 1.700528 | 63.9           | 45.065         | 45.065         | 44.751         | 45.065         | 40.31         |
| 1.800167 | 63.9           | 45.21         | 45.21         | 44.941         | 45.21         | 40.462         |
| 1.910472 | 63.9           | 45.369         | 45.369         | 45.14         | 45.369         | 40.631         |
| 2.003    | 63.9           | 45.501         | 45.501         | 45.301         | 45.501         | 40.772         |
| 2.202278 | 63.9           | 45.78         | 45.78         | 45.629         | 45.78         | 41.069         |
| 2.4015   | 63.9           | 46.051         | 46.051         | 45.938         | 46.051         | 41.358         |
| 2.60075  | 63.9           | 46.313         | 46.313         | 46.23         | 46.313         | 41.638         |
| 2.803528 | 63.9           | 46.571         | 46.571         | 46.514         | 46.571         | 41.913         |
| 3.00275  | 63.9           | 46.817         | 46.817         | 46.781         | 46.817         | 42.176         |
| 3.202    | 63.9           | 47.055         | 47.055         | 47.038         | 47.055         | 42.431         |
| 3.301667 | 63.9           | 47.172         | 47.172         | 47.163         | 47.172         | 42.555         |
| 3.401366 | 63.9           | 47.287         | 47.287         | 47.286         | 47.287         | 42.678         |
| 3.600611 | 63.9           | 47.512         | 47.512         | 47.525         | 47.512         | 42.919         |
| 3.803472 | 63.9           | 47.735         | 47.735         | 47.761         | 47.735         | 43.158         |
| 3.999222 | 63.9           | 47.946         | 47.946         | 47.983         | 47.946         | 43.382         |
| 4.202083 | 63.9           | 48.158         | 48.158         | 48.205         | 48.158         | 43.61         |
| 4.401389 | 63.9           | 48.362         | 48.362         | 48.418         | 48.362         | 43.827         |
| 4.600694 | 63.9           | 48.561         | 48.561         | 48.626         | 48.561         | 44.04         |
| 4.8     | 63.9           | 48.756         | 48.756         | 48.828         | 48.756         | 44.249         |
| 5.002861 | 63.9           | 48.95         | 48.95         | 49.03         | 48.95         | 44.456         |
| 5.202167 | 63.9           | 49.137         | 49.137         | 49.223         | 49.137         | 44.656         |
| 5.401472 | 63.9           | 49.32         | 49.32         | 49.412         | 49.32         | 44.852         |
|      |      |      |      |      |      |      |
|------|------|------|------|------|------|------|
| 5.600778 | 63.9 | 49.5 | 49.5 | 49.598 | 49.5 | 45.044 |
| 5.800083 | 63.9 | 49.676 | 49.676 | 49.779 | 49.676 | 45.232 |
| 5.999389 | 63.9 | 49.849 | 49.849 | 49.957 | 49.849 | 45.417 |
| 6.20225   | 63.9 | 50.022 | 50.022 | 50.135 | 50.022 | 45.602 |
| 6.401556 | 63.9 | 50.189 | 50.189 | 50.306 | 50.189 | 45.78  |
| 6.600861 | 63.9 | 50.352 | 50.352 | 50.474 | 50.352 | 45.956 |
| 6.800167 | 63.9 | 50.514 | 50.514 | 50.639 | 50.514 | 46.128 |
| 7.003056 | 63.9 | 50.675 | 50.675 | 50.804 | 50.675 | 46.3  |
| 7.202361 | 63.9 | 50.83  | 50.83  | 50.963 | 50.83  | 46.467 |
| 7.401667 | 63.9 | 50.984 | 50.984 | 51.12  | 50.984 | 46.63  |
| 7.600972 | 63.9 | 51.134 | 51.134 | 51.274 | 51.134 | 46.791 |
| 7.800278 | 63.9 | 51.282 | 51.282 | 51.425 | 51.282 | 46.95  |
| 8.003139 | 63.9 | 51.431 | 51.431 | 51.577 | 51.431 | 47.108 |
| 8.305889 | 63.9 | 51.648 | 51.648 | 51.798 | 51.648 | 47.34  |
| 8.601528 | 63.9 | 51.854 | 51.854 | 52.009 | 51.854 | 47.561 |
| 8.9185  | 63.9 | 52.071 | 52.071 | 52.229 | 52.071 | 47.792 |
| 9.199806 | 63.9 | 52.258 | 52.258 | 52.42  | 52.258 | 47.992 |
| 9.498778 | 63.9 | 52.453 | 52.453 | 52.619 | 52.453 | 48.2  |
| 9.779944 | 63.9 | 52.632 | 52.632 | 52.801 | 52.632 | 48.391 |
| 10.10025 | 63.9 | 52.831 | 52.831 | 53.003 | 52.831 | 48.604 |
| 10.39564 | 63.9 | 53.01  | 53.01  | 53.186 | 53.01  | 48.795 |
| 10.69842 | 63.9 | 53.19  | 53.19  | 53.368 | 53.19  | 48.986 |
| 11.00139 | 63.9 | 53.365 | 53.365 | 53.546 | 53.365 | 49.173 |
| 11.27231 | 63.9 | 53.518 | 53.518 | 53.701 | 53.518 | 49.336 |
| 11.54319 | 63.9 | 53.667 | 53.667 | 53.853 | 53.667 | 49.496 |
| 11.84975 | 63.9 | 53.833 | 53.833 | 54.021 | 53.833 | 49.672 |
| 12      | 63.9 | 53.912 | 53.912 | 54.102 | 53.912 | 49.757 |
**Scenario 3:** trip of gas delivery both in the Mellitah Complex and in the TPP.

- Flow rate behaviour in the gas pipeline of the Western Libya Gas Project

| Time (hr) | $m_{1\text{in}}$ (kg/s) | $m_{1\text{out}}$ (kg/s) | $m_{2\text{in}}$ (kg/s) | $m_{2\text{out}}$ (kg/s) | $m_{3\text{in}}$ (kg/s) | $m_{3\text{out}}$ (kg/s) |
|-----------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| 0         | 78.122                  | 78.118                  | 38.644                  | 39.151                  | 45.494                  | 45.191                  |
| 0.20247   | 78.127                  | 78.12                   | 38.648                  | 39.151                  | 45.493                  | 45.191                  |
| 0.40175   | 78.131                  | 78.122                  | 38.65                   | 39.151                  | 45.492                  | 45.191                  |
| 0.601     | 78.135                  | 78.123                  | 38.652                  | 39.151                  | 45.491                  | 45.191                  |
| 0.80028   | 78.138                  | 78.125                  | 38.656                  | 39.151                  | 45.491                  | 45.191                  |
| 1.00667   | 78.141                  | 74.814                  | 42.156                  | 0                       | 38.679                  | 0                       |
| 1.21661   | 78.144                  | 63.586                  | 63.154                  | 0                       | 0.432                   | 0                       |
| 1.41231   | 78.147                  | 61.035                  | 60.648                  | 0                       | 0.387                   | 0                       |
| 1.60092   | 78.149                  | 58.505                  | 58.135                  | 0                       | 0.37                    | 0                       |
| 1.80372   | 78.15                   | 55.957                  | 55.597                  | 0                       | 0.359                   | 0                       |
| 2.003     | 78.136                  | 53.632                  | 53.279                  | 0                       | 0.353                   | 0                       |
| 2.20583   | 78.094                  | 51.445                  | 51.099                  | 0                       | 0.345                   | 0                       |
| 2.4015    | 78.017                  | 49.497                  | 49.157                  | 0                       | 0.339                   | 0                       |
| 2.59725   | 77.895                  | 47.699                  | 47.366                  | 0                       | 0.333                   | 0                       |
| 2.80367   | 77.713                  | 45.95                   | 45.624                  | 0                       | 0.326                   | 0                       |
| 3.00653   | 77.476                  | 44.368                  | 44.048                  | 0                       | 0.319                   | 0                       |
| 3.20583   | 77.187                  | 42.93                   | 42.617                  | 0                       | 0.312                   | 0                       |
| 3.40514   | 76.842                  | 41.597                  | 41.291                  | 0                       | 0.305                   | 0                       |
| 3.60444   | 76.442                  | 40.357                  | 40.058                  | 0                       | 0.299                   | 0                       |
| 3.80019   | 75.994                  | 39.222                  | 38.929                  | 0                       | 0.293                   | 0                       |
| 4.00661   | 75.469                  | 38.104                  | 37.819                  | 0                       | 0.287                   | 0                       |
| 4.20592   | 74.91                   | 37.096                  | 36.814                  | 0                       | 0.282                   | 0                       |
| 4.40167   | 74.314                  | 36.162                  | 35.886                  | 0                       | 0.275                   | 0                       |
| 4.601     | 73.661                  | 35.264                  | 34.996                  | 0                       | 0.27                    | 0                       |
| 4.82167   | 72.891                  | 34.33                   | 34.066                  | 0                       | 0.264                   | 0                       |
| 5.00319   | 72.218                  | 33.599                  | 33.342                  | 0                       | 0.259                   | 0                       |
| 5.20975   | 71.416                  | 32.808                  | 32.554                  | 0                       | 0.254                   | 0                       |
| 5.427     | 70.532                  | 32.013                  | 31.764                  | 0                       | 0.249                   | 0                       |
| 5.60508   | 69.778                  | 31.388                  | 31.145                  | 0                       | 0.244                   | 0                       |
| 5.81167   | 68.871                  | 30.69                   | 30.452                  | 0                       | 0.239                   | 0                       |
| 6.00044   | 68.017                  | 30.073                  | 29.838                  | 0                       | 0.235                   | 0                       |
| 6.20347   | 67.07                   | 29.432                  | 29.201                  | 0                       | 0.231                   | 0                       |
| 6.4065    | 66.1                    | 28.808                  | 28.581                  | 0                       | 0.226                   | 0                       |
| 6.61664   | 65.069                  | 28.178                  | 27.957                  | 0                       | 0.222                   | 0                       |
| 6.80542   | 64.125                  | 27.628                  | 27.411                  | 0                       | 0.218                   | 0                       |
| 7.00147   | 63.125                  | 27.063                  | 26.849                  | 0                       | 0.213                   | 0                       |
| 7.21178   | 62.036                  | 26.474                  | 26.264                  | 0                       | 0.209                   | 0                       |
| 7.40425   | 61.021                  | 25.938                  | 25.733                  | 0                       | 0.205                   | 0                       |
| 7.611     | 59.915                  | 25.373                  | 25.173                  | 0                       | 0.201                   | 0                       |
| 7.80703   | 58.853                  | 24.841                  | 24.645                  | 0                       | 0.196                   | 0                       |
|     | 57.6 | 24.231 | 24.039 | 0   | 0.191 | 0   |
|-----|------|--------|--------|-----|-------|-----|
| 8.03517 | 56.69 | 23.795 | 23.604 | 0  | 0.189 | 0   |
| 8.406 | 55.53 | 23.249 | 23.064 | 0  | 0.184 | 0   |
| 8.60575 | 54.4  | 22.724 | 22.543 | 0  | 0.18  | 0   |
| 8.80194 | 53.278| 22.211 | 22.034 | 0  | 0.177 | 0   |
| 9.00528 | 52.107| 21.681 | 21.51  | 0  | 0.172 | 0   |
| 9.20156 | 50.969| 21.173 | 21.003 | 0  | 0.168 | 0   |
| 9.40144 | 49.8  | 20.653 | 20.489 | 0  | 0.164 | 0   |
| 9.60136 | 48.624| 20.135 | 19.975 | 0  | 0.161 | 0   |
| 9.80486 | 47.416| 19.61  | 19.453 | 0  | 0.156 | 0   |
| 10.0226 | 46.116| 19.045 | 18.894 | 0  | 0.152 | 0   |
| 10.2154 | 44.96 | 18.548 | 18.401 | 0  | 0.148 | 0   |
| 10.401 | 43.837 | 18.067 | 17.923 | 0  | 0.143 | 0   |
| 10.6009 | 42.623| 17.551 | 17.41  | 0  | 0.14  | 0   |
| 10.808 | 41.36 | 17.013 | 16.878 | 0  | 0.137 | 0   |
| 11.0043 | 40.156| 16.503 | 16.37  | 0  | 0.132 | 0   |
| 11.2078 | 38.902| 15.976 | 15.85  | 0  | 0.128 | 0   |
| 11.4006 | 37.708| 15.476 | 15.353 | 0  | 0.124 | 0   |
| 11.6042 | 36.442| 14.946 | 14.826 | 0  | 0.12  | 0   |
| 11.8008 | 35.216| 14.433 | 14.317 | 0  | 0.115 | 0   |
| 12   | 33.982| 13.922 | 13.811 | 0  | 0.111 | 0   |
Pressure behaviour in the gas pipeline of the Western Libya Gas Project during the trip of total gas delivery

| Time (hr) | $P_{1\text{in}}$ (bar) | $P_{1\text{out}}$ (bar) | $P_{2\text{in}}$ (bar) | $P_{2\text{out}}$ (bar) | $P_{3\text{in}}$ (bar) | $P_{3\text{out}}$ (bar) |
|-----------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| 0         | 63.9                   | 43.478                 | 43.478                 | 41.089                 | 43.478                 | 38.732                 |
| 0.20247   | 63.9                   | 43.476                 | 43.476                 | 41.086                 | 43.476                 | 38.729                 |
| 0.40175   | 63.9                   | 43.474                 | 43.474                 | 41.084                 | 43.474                 | 38.727                 |
| 0.601     | 63.9                   | 43.472                 | 43.472                 | 41.082                 | 43.472                 | 38.725                 |
| 0.80028   | 63.9                   | 43.47                  | 43.47                  | 41.08                  | 43.47                  | 38.723                 |
| 1.00667   | 63.9                   | 43.493                 | 43.493                 | 41.422                 | 43.493                 | 42.535                 |
| 1.21661   | 63.9                   | 44.704                 | 44.704                 | 42.609                 | 44.704                 | 44.704                 |
| 1.41231   | 63.9                   | 45.296                 | 45.296                 | 43.39                  | 45.296                 | 45.296                 |
| 1.60992   | 63.9                   | 45.83                  | 45.83                  | 44.117                 | 45.83                  | 45.83                  |
| 1.80372   | 63.9                   | 46.385                 | 46.385                 | 44.867                 | 46.385                 | 46.385                 |
| 2.003     | 63.9                   | 46.918                 | 46.918                 | 45.57                  | 46.918                 | 46.918                 |
| 2.20583   | 63.9                   | 47.449                 | 47.449                 | 46.254                 | 47.449                 | 47.449                 |
| 2.4015    | 63.9                   | 47.952                 | 47.952                 | 46.885                 | 47.952                 | 47.952                 |
| 2.59725   | 63.9                   | 48.446                 | 48.446                 | 47.49                  | 48.446                 | 48.446                 |
| 2.80367   | 63.9                   | 48.956                 | 48.956                 | 48.102                 | 48.956                 | 48.956                 |
| 3.00653   | 63.9                   | 49.447                 | 49.447                 | 48.681                 | 49.447                 | 49.447                 |
| 3.20583   | 63.9                   | 49.919                 | 49.919                 | 49.229                 | 49.919                 | 49.919                 |
| 3.40514   | 63.9                   | 50.381                 | 50.381                 | 49.758                 | 50.381                 | 50.381                 |
| 3.60444   | 63.9                   | 50.833                 | 50.833                 | 50.271                 | 50.833                 | 50.833                 |
| 3.80019   | 63.9                   | 51.268                 | 51.268                 | 50.759                 | 51.268                 | 51.268                 |
| 4.00661   | 63.9                   | 51.717                 | 51.717                 | 51.258                 | 51.717                 | 51.717                 |
| 4.20592   | 63.9                   | 52.142                 | 52.142                 | 51.726                 | 52.142                 | 52.142                 |
| 4.40167   | 63.9                   | 52.551                 | 52.551                 | 52.174                 | 52.551                 | 52.551                 |
| 4.601     | 63.9                   | 52.959                 | 52.959                 | 52.618                 | 52.959                 | 52.959                 |
| 4.82167   | 63.9                   | 53.401                 | 53.401                 | 53.097                 | 53.401                 | 53.401                 |
| 5.00319   | 63.9                   | 53.757                 | 53.757                 | 53.481                 | 53.757                 | 53.757                 |
| 5.20975   | 63.9                   | 54.155                 | 54.155                 | 53.908                 | 54.155                 | 54.155                 |
| 5.427     | 63.9                   | 54.565                 | 54.565                 | 54.346                 | 54.565                 | 54.565                 |
| 5.60508   | 63.9                   | 54.895                 | 54.895                 | 54.697                 | 54.895                 | 54.895                 |
| 5.81167   | 63.9                   | 55.27                  | 55.27                  | 55.095                 | 55.27                  | 55.27                  |
| 6.00044   | 63.9                   | 55.606                 | 55.606                 | 55.452                 | 55.606                 | 55.606                 |
| 6.20347   | 63.9                   | 55.961                 | 55.961                 | 55.828                 | 55.961                 | 55.961                 |
| 6.4065    | 63.9                   | 56.31                  | 56.31                  | 56.195                 | 56.31                  | 56.31                  |
| 6.61664   | 63.9                   | 56.663                 | 56.663                 | 56.567                 | 56.663                 | 56.663                 |
| 6.80542   | 63.9                   | 56.975                 | 56.975                 | 56.895                 | 56.975                 | 56.974                 |
| 7.00147   | 63.9                   | 57.292                 | 57.292                 | 57.228                 | 57.292                 | 57.292                 |
| 7.21178   | 63.9                   | 57.625                 | 57.625                 | 57.578                 | 57.625                 | 57.625                 |
| 7.40425   | 63.9                   | 57.924                 | 57.924                 | 57.891                 | 57.924                 | 57.924                 |
| 7.611     | 63.9                   | 58.24                  | 58.24                  | 58.221                 | 58.24                  | 58.239                 |
| 7.80703   | 63.9                   | 58.532                 | 58.532                 | 58.527                 | 58.532                 | 58.532                 |
| 8.03517   | 63.9                   | 58.865                 | 58.865                 | 58.875                 | 58.865                 | 58.865                 |
| 8.19914 | 63.9 | 59.1 | 59.1 | 59.12 | 59.1 | 59.1 |
| 8.406   | 63.9 | 59.39 | 59.39 | 59.423 | 59.39 | 59.39 |
| 8.60575 | 63.9 | 59.664 | 59.664 | 59.709 | 59.664 | 59.664 |
| 8.80194 | 63.9 | 59.927 | 59.927 | 59.983 | 59.927 | 59.927 |
| 9.00528 | 63.9 | 60.193 | 60.193 | 60.261 | 60.193 | 60.193 |
| 9.20156 | 63.9 | 60.445 | 60.445 | 60.522 | 60.445 | 60.445 |
| 9.40144 | 63.9 | 60.694 | 60.694 | 60.782 | 60.694 | 60.694 |
| 9.60136 | 63.9 | 60.938 | 60.938 | 61.036 | 60.938 | 60.938 |
| 9.80486 | 63.9 | 61.18 | 61.18 | 61.288 | 61.18 | 61.18 |
| 10.0226 | 63.9 | 61.432 | 61.432 | 61.55 | 61.432 | 61.432 |
| 10.2154 | 63.9 | 61.649 | 61.649 | 61.776 | 61.649 | 61.649 |
| 10.401  | 63.9 | 61.853 | 61.853 | 61.988 | 61.853 | 61.853 |
| 10.609  | 63.9 | 62.067 | 62.067 | 62.21 | 62.067 | 62.067 |
| 10.808  | 63.9 | 62.282 | 62.282 | 62.433 | 62.282 | 62.282 |
| 11.0043 | 63.9 | 62.479 | 62.479 | 62.638 | 62.479 | 62.479 |
| 11.2078 | 63.9 | 62.678 | 62.678 | 62.844 | 62.678 | 62.678 |
| 11.4006 | 63.9 | 62.86 | 62.86 | 63.034 | 62.86 | 62.86 |
| 11.6042 | 63.9 | 63.046 | 63.046 | 63.227 | 63.046 | 63.046 |
| 11.8008 | 63.9 | 63.22 | 63.22 | 63.407 | 63.22 | 63.22 |
| 12      | 63.9 | 63.387 | 63.387 | 63.581 | 63.387 | 63.387 |
AUTHOR BIOGRAPHY

Abdo-almonaim S. M. Alghlam was born on April 12, 1973 in Tripoli, Libya. He attended primary, secondary, and high school in Libya between 1980 and 1992. At the Faculty of Engineering of 7th of April University he enrolled in the academic year 1992/1993. Years at the same University he graduated in July 1997 from the department of Mechanical Engineering where he got his Bachelor of sciences (BSc). In 2000 he started to work as a teaching assistant at the same faculty as a part time job, also from 2000 to 2006 Mr Alghlam worked at the General Electricity Company of Libya (GECOL) as an Operation Engineer of Gas Turbine Power Plant (Tripoli South Power Plant). As an engineer of the Gecol he sent to India for training in 2004 where he got certificate in Gas Turbine Power Plant operation and control (BHEL and SIEMENS) companies.

Mr Alghlam enrolled for postgraduate studying at the School of Engineering - Liverpool John Moores University, UK in 2006 and got the master of sciences (MSc) in Mechanical Engineering in 2007. The title of project was “Study, Evaluation, and Improvement of Tripoli South Power Plant Performance”. In 2008, he started to study at the University of Technology Malaysia UTM for a master of engineering ME at the Faculty of Mechanical Engineering in Thermo-fluid Engineering Department where he graduated in 2012. The research topic was “Numerical Scheme for modeling Natural Gas Flow in Cross-Border Pipelines.

From 2012 to 2014, Mr Alghlam worked as a lecture at the Faculty of Engineering of 7th of April University, and he was the organizer of the education quality brunch at the mechanical engineering department.
Прилог 1.

Изјава о ауторству

Потписан Abdoalmonaim S.M. Alghlam
број индекса Д27-2014

Изјављујем

да је докторска дисертација под насловом

Нумеричка симулација прелазних процеса у гасоводима

(„Numerical simulation of natural gas pipeline transients“)

- резултат сопственог истраживачког рада,
- да предложена дисертација у целини ни у деловима није била предложена за добијање било које дипломе према студијским програмима других високошколских установа,
- да су резултати коректно наведени и
- да нисам кршио/ла ауторска права и користио интелектуалну својину других лица.

Потпис докторанда

У Београду, 15.01.2020.
Изјава о истоветности штампане и електронске верзије докторског рада

Име и презиме аутора  Abdoalmonaim S.M. Alghlam

Број индекса Д27-2014

Студијски програм  Докторске студије

Наслов рада  Нумеричка симулација прелазних процеса у гасоводима

(„Numerical simulation of natural gas pipeline transients“)

Ментор  проф. др Владимир Д. Стевановић

Потписани Abdoalmonaim S.M. Alghlam

Изјављујем да је штампана верзија могу докторског рада истоветна електронској верзији коју сам предао/ла за објављивање на порталу Дигиталног репозиторијума Универзитета у Београду.

Дозвољавам да се објаве моји лични подаци везани за добијање академског звања доктор наука, као што су име и презиме, година и место рођења и датум одбране рада.

Ови лични подаци могу се објавити на мрежним страницама дигиталне библиотеке, у електронском каталогу и у публикацијама Универзитета у Београду.

Потпис докторанда

У Београду, 06.02.2020.

_________________________
Изјава о коришћењу

Овлашћујем Универзитетску библиотеку „Светозар Марковић“ да у Дигитални репозиторијум Универзитета у Београду унесе моју докторску дисертацију под насловом:

Нумеричка симулација прелазних процеса у гасоводима

(„Numerical simulation of natural gas pipeline transients“)

која је моје ауторско дело.

Дисертацију са свим прилозима предао/ла сам у електронском формату погодном за трајно архивирање.

Моју докторску дисертацију похрањену у Дигитални репозиторијум Универзитета у Београду могу да користе сви који поштују одредбе садржане у одабраном типу лиценце Креативне заједнице (Creative Commons) за коју сам се одлучио/ла.

1. Ауторство
2. Ауторство - некомерцијално
3. Ауторство – некомерцијално – без прераде
4. Ауторство – некомерцијално – делити под истим условима
5. Ауторство – без прераде
6. Ауторство – делити под истим условима

(Молимо да заокружите само једну од шест понуђених лиценци, кратак опис лиценци дат је на полеђини листа).

Потпис докторанда

У Београду, 15.01.2020.

____________________
1. Ауторство - Дозвољавате умножавање, дистрибуцију и јавно саопштавање дела, и прераде, ако се наведе име аутора на начин одређен од стране аутора или даваоца лиценце, чак и у комерцијалне сврхе. Ово је најслободнија од свих лиценци.

2. Ауторство – некомерцијално. Дозвољавате умножавање, дистрибуцију и јавно саопштавање дела, и прераде, ако се наведе име аутора на начин одређен од стране аутора или даваоца лиценце. Ова лиценца не дозвољава комерцијалну употребу дела.

3. Ауторство - некомерцијално – без прераде. Дозвољавате умножавање, дистрибуцију и јавно саопштавање дела, без промена, преобликовања или употребе дела у свом делу, ако се наведе име аутора на начин одређен од стране аутора или даваоца лиценце. Ова лиценца не дозвољава комерцијалну употребу дела. У односу на све остале лиценце, овом лиценцом се ограничава највећи обим права коришћења дела.

4. Ауторство - некомерцијално – делити под истим условима. Дозвољавате умножавање, дистрибуцију и јавно саопштавање дела, и прераде, ако се наведе име аутора на начин одређен од стране аутора или даваоца лиценце и ако се прерада дистрибуира под истом или сличном лиценцом. Ова лиценца не дозвољава комерцијалну употребу дела и прерада.

5. Ауторство – без прераде. Дозвољавате умножавање, дистрибуцију и јавно саопштавање дела, без промена, преобликовања или употребе дела у свом делу, ако се наведе име аутора на начин одређен од стране аутора или даваоца лиценце. Ова лиценца дозвољава комерцијалну употребу дела.

6. Ауторство - делити под истим условима. Дозвољавате умножавање, дистрибуцију и јавно саопштавање дела, и прераде, ако се наведе име аутора на начин одређен од стране аутора или даваоца лиценце и ако се прерада дистрибуира под истом или сличном лиценцом. Ова лиценца дозвољава комерцијалну употребу дела и прерада. Слична је софтверским лиценцама, односно лиценцама отвореног кода.