Experimental study and empirical prediction of fuel flow parameters under air evolution conditions

E E Kitanina¹, E L Kitanin¹, D A Bondarenko², P A Kravtsov³, M M Peganova⁴, S G Stepanov⁴ and V L Zherebzov⁴

¹Peter the Great St.Petersburg Polytechnic University, Polytechnicheskaya 29, Saint-Petersburg, 195251 Russia
²Moscow Aviation Institute, 4 Volokolamskoe shosse, Moscow, 125993 Russia
³National Research Center “Kurchatov Institute” Petersburg Nuclear Physics Institute, Gatchina, 188300 Russia
⁴RSC “Applied Chemistry”, Krylenko street 26A, Saint-Petersburg, 193232 Russia

E-mail: kkitanina@mail.ru

Abstract. Air evolution in kerosene under the effect of gravity flow with various hydraulic resistances in the pipeline was studied experimentally. The study was conducted at pressure ranging from 0.2 to 1.0 bar and temperature varying between -20ºС and +20ºС. Through these experiments, the oversaturation limit beyond which dissolved air starts evolving intensively from the fuel was established and the correlations for the calculation of pressure losses and air evolution on local loss elements were obtained. A method of calculating two-phase flow behaviour in a titled pipeline segment with very low mass flow quality and fairly high volume flow quality was developed. The complete set of empirical correlations obtained by experimental analysis was implemented in the engineering code. The software simulation results were repeatedly verified against our experimental findings and Airbus test data to show that the two-phase flow simulation agrees quite well with the experimental results obtained in the complex branched pipelines.

1. Introduction
Air evolution in kerosene flow may cause issues in aircraft fuel systems. The fuel supplied to the aircraft during fueling is usually saturated with air under atmospheric pressure and ground temperature conditions. In cruise flight the ambient pressure drops, leading to the fuel oversaturation with air. Moreover, the oversaturation of the fuel with air is large due to the temperature decrease down to -30ºС. In the case of pump deselection, pressure in the pipeline with pure gravity flow is contingent on the ambient pressure and fuel level in the tank only. Air can evolve from fuel, resulting in a flow rate decrease. The air flow rate decline can be due to both the flow conditions (pressure, temperature) and the pipeline design. Substantial air evolution may occur as oversaturated fuel passes through the flow limiter (diaphragm) or other local resistance.

The gas phase effect on pressure losses related to friction and the pressure leveling component can be quite reliably handled within the Chisholm model based on the Lockhart and Martinelli approach [1]. The much less studied issues are the calculation of the pressure losses at the local resistances
under air release conditions and establishing the gas fraction in the flow downstream of the local resistances [2]. Moreover the transition from stratified to foamy flow can occur in a tilted pipeline segment. However the standard calculation methods mentioned above are devised for the foamy flow mode and do not allow the transition point coordinate determination. Numerical simulation of two-phase flow in such systems still remains an intractable task. As an alternative to this approach, we developed a flow simulation tool that can take into account the experimental data on air evolution in pipeline elements and pressure losses in individual segments.

2. Results and discussion

2.1. Experimental technique and pipeline designs

More than 200 experiments were performed to study the dissolved air evolution process and pressure losses in individual pipeline elements. The experiments were conducted using TS-1 jet fuel (substitute for Jet A1 fuel) in several test pipelines. The study was performed at pressure ranging from 0.2 to 1.0 bar and temperature varying between -20°C and +20°C. All test rigs included two fuel tanks and a working section of pipeline, isolated by a valve. In all cases the test rig was prepared for the test following the same steps. First, fuel was saturated by dry air at atmospheric pressure and temperature level in the supply tank. Then air was evacuated from the entire system. As a result the fuel in the supply tank became oversaturated with air. Finally, the valve was opened to let the fuel flow into the experimental pipeline. Fuel temperature and pressure along the pipeline working section and fuel flow rates and pressures at the pipeline inlet were measured for every experiment. A special technique based on the measurement of the dissolved air concentration was applied for air evolution calculation. The mass flow quality of evolved air was equated with the difference between dissolved air concentration values at the pipeline inlet and at the section under consideration. The dissolved air concentration was measured by chromatographs within the range of $5 \cdot 10^{-5} \div 2.5 \cdot 10^{-4}$ kg/kg. A fuel sample was supplied to chromatographs by a specifically designed sampling system. In addition to instrumental measurements, the two-phase flow modes were observed through clear pipeline segments.

Initially, the fuel flow was studied in an unbranched pipeline [3]. The experimental pipeline included vertical and horizontal segments connected by a smooth bend (see figure 1). A diaphragm was installed in the upper part of the working pipeline section. Two diaphragms with holes of different diameters were used. Temperature, pressure and dissolved air concentration were measured at several sections located after the diaphragm.

![Figure 1. Test pipeline with various local loss segments (view from above)](image1)

![Figure 2. Branched pipeline simulating the refuelling system (view from above)](image2)
The second test rig [4] was built specifically for the study of air release at local resistances and assessment of their resistance value, therefore measurement of the flow mass quality downstream of each resistance appeared as a big challenge in the testing. A diaphragm installed downstream of the inlet diffuser was followed by a clear section of the same inner diameter, a set of local resistances, including a ball valve, a pipe expansion, a contraction, 90° bends and a ball valve. Specific tests were performed to study the effect of the tilted segment on the two-phase flow rate. The pipelines had clear sections for viewing and recording the two-phase flow behaviour downstream of the local resistances.

In further experiments, we built a branched pipeline to simulate a real refueling system [5]. A schematic view of the pipeline is shown in figure 2. The working pipe section contains two diaphragms, expansions, contractions and bends. The pipeline has branchings at the upper tank outlet and the lower tank inlet. Pressure, temperature and mass flow quality were measured at the sections a-f. In addition, differential pressure sensors were placed along the pipeline. A pipeline segment located between sections c and d was tilted by 10 and 20 degrees to verify the equations obtained by previous experiments.

2.2. Key experimental outcomes

Our measurements indicate that air evolution in oversaturated fuel starts as pressure drops abruptly to a certain boundary value. Figure 3 illustrates a fuel velocity dependence on environment pressure under gravity flow conditions. As can be seen from the figure, the fuel velocity decreases slightly due to pressure change from 100 kPa to 40 kPa. When the pressure value reaches the level of 20 kPa a dramatic velocity drop takes place. The flow drop is accompanied by an intensive air evolution process. The driving force is decreased due to effective flow density reduction. It turned out that the flow kinetic energy and the fuel temperature have an additive influence on this value. The method elaborated for boundary pressure evaluation is discussed in detail in [3].

![Figure 3](image_url)

**Figure 3.** Fuel velocity depending on environment pressure value by gravity flow in a pipeline with a diaphragm

![Figure 4](image_url)

**Figure 4.** Flow after a diaphragm (pressure in the supply tank equal to 60kPa (above) and 20kPa (below))

We notice that almost no air evolves downstream of the segments generating a minor pressure drop, e.g. bends, contractions, expansions and branching, whereas the diaphragm provokes intensive air evolution in fuel flow (see figure 4). A large set of experimental data was analyzed to produce empirical correlations for the pressure drop and air evolution after the diaphragm. It was discovered
that the diaphragm pressure loss coefficient depends on the volume flow quality downstream of the diaphragm. This correlation provides adequate results in a wide range of diaphragm to pipeline diameters ratios [4].

As a result of experimental data analyze a special method of calculating the two-phase flow pressure in a titled pipeline segment was developed [5]. Conventional methods prove to be inefficient under the conditions at hand (very low mass flow quality and fairly high volume flow quality) due to co-existence of two flow modes in different parts of the titled segment. In many experiments we observed stratified flow in the upper part and foamy (bubble) flow in the lower part (figure 5). Though it is easy enough to calculate the pressure in each individual part, the flow mode transition point was a priori unknown. We built a complete calculation chain including pressure drop equations for both flow modes, an equation taking into account the change in kinetic energy during transition and an empirical equation for calculating the pressure drop in the tilted pipeline segment. This helped to estimate the stratified to foamy flow transition point coordinate.

![Figure 5. Flow modes in the tilted segment](image)

3. Comparison of calculations and experimental data
The complete set of empirical correlations obtained by experimental analysis was implemented in the engineering code specifically developed for two-phase gravity flow calculations [6]. The computational algorithm is based on the balance (Bernoulli) equations written for every pipeline segment and for the whole pipeline system. Hence the velocity at the supply tank exit is proportional to the difference in fuel levels in the tanks and inversely proportional to the total pressure loss including two-phase flow acceleration loss, local loss and friction loss that are initially evaluated for each pipeline segment. We notice that the flow parameters (e.g. density, velocity and pressure loss coefficients) strongly depend on the evolved air content in the fuel. Air evolution in its turn depends on pressure, temperature and fuel velocity. Consequently an iterative process was realized for fuel velocity calculations. A postponed recursion technique provided computations of the flow in a pipeline with branching and junctions.

3.1. Flow parameters after a diaphragm
Our experiments on different test rigs demonstrated that in most cases a pressure drop after the diaphragm provokes intensive air evolution. The two-phase flow modes downstream of the diaphragm can lead to considerable changes in fuel flow rate in a pipeline.

Figures 6 and 7 show the distributions of pressure and evolved air mass flow quality along the pipeline (second test rig). The calculation results are compared with the experimental data. The charts reveal tendencies typical for the entire experimental series. A dramatic pressure drop is clearly seen after the diaphragm (figure 6). This corresponds to an increase in the amount of the evolved air (figure 7). As can be seen from the figure, the other local loss segments located downstream of the diaphragm have much weaker influence on the flow parameters as compared to the diaphragm.

Generally, we observe strong consistency between the calculated and experimental results for the pressure value downstream of the diaphragm (difference less than 8%) and fuel velocity (relative error
not exceeding 10\%). The flow quality is calculated with higher errors of 10-35\%. This can stem from both the calculation model constraints and experimental errors.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{Distribution of pressure along the pipeline}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure7.png}
\caption{Distribution of mass flow quality along the pipeline}
\end{figure}

3.2. Flow in pipelines simulating refuelling system

This paragraph features the flow simulation results obtained for the pipelines that were specially designed to simulate refueling systems. All the tests addressed the gravity flow in the pipelines comprising two restrictors (diaphragms), expansions, contractions, bends, tilted parts and branches near inlet and outlet tanks.

Figures 8 and 9 illustrate the pressure and mass flow quality distribution along the main branch of the tilted pipeline corresponding to the third test rig used in our experiments. An abrupt pressure drop is observed downstream of the diaphragms. The two-phase flow regime changes between the first and second diaphragms, with the pressure remaining constant in the laminated flow segment and growing higher in the rest of the tilted segment where the foamy flow develops.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8.png}
\caption{Distribution of pressure along the main branch of the horizontal pipeline along the main branch of the tilted pipeline}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure9.png}
\caption{Distribution of mass flow quality along the main branch along the main branch of the tilted pipeline}
\end{figure}

The comparison of the calculated and experimental data for the tilted pipeline reveals a 4 to 23\% error in the mean fuel flow velocity calculation. The error is largely due to the inaccuracy in calculating the flow transition coordinate, which proved to be quite a challenge for the test pipeline in question. It is evident that the uncertainties in the simulation of the two-phase flow mode transition in a tilted pipeline can result in inaccurate fuel flow rate values both for the entire pipeline and in its
individual branches. On the other hand, these experiments revealed high flow pulsations that affected the measurement accuracy of the flow meters.

Our empirical equations and calculation results were further verified against the independent experimental results provided by Airbus. The test rig represents the left wing and centre tank refuel sub-system. Besides the full scale size, the main difference of the Airbus pipeline from our test rigs is connected with two inclined segments, the first tilted by 5 degrees and bounded by two diaphragms and the second tilted by 39 degrees and immediately following the first and ending with a horizontal segment before the branching. A change from stratified flow to foamy flow in both segments was clearly observed though transparent pipes. Besides, the experiments revealed high flow pulsations. In Airbus’s tests, the fuel flow rate was found from the data on time steps and fuel levels in the tank. This method could lead to a rather substantial errors. A comparison of the experimental data and our calculations is shown in figure 10. The flow rate results differ by about 25% at the beginning and about 20% at the end of the process. The uncertainty may result both from simplifications of our empirical models and experimental errors. However the simulation results show that the developed method can be applied to complicated pipelines similar to real refueling systems.

Figure 10. Fuel flow rate versus time. Simulation and Airbus test results

4. Conclusions
Several experimental rigs were built to study the effects of different local loss segments on the gravity fuel flow under air evolution conditions. Through these experiments, we established the oversaturation limit beyond which dissolved air starts evolving intensively from the fuel. We also obtained correlations for pressure losses and air evolution on pipeline segments. To predict two-phase flow parameters a special software tool based upon the empirical formulas was developed. The simulation results were compared to the experimental studies of steady and unsteady flow in different pipelines of complex geometry. The verifications proved the reliability of the empirical methods developed for gravity flow calculations in fuel systems under air evolution conditions.

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