Thermal Testing of Wax Layer Thickness in Crude Oil Pipeline

Fadi Alnaimat, Bobby Mathew, Mohammed Ziauddin

Department of Mechanical Engineering, College of Engineering, United Arab Emirates University, Al Ain, UAE
falnaimat@uaeu.ac.ae

Abstract. This article investigates thermal detection method for wax layer thickness inside pipeline. Crude oil temperature decreases as it flows through pipeline and this causes the wax to precipitate out of solution. Wax deposition increases the viscosity significantly near the wall as it solidifies. The proposed method of thermal wax testing of different operating conditions is investigated through this research. In order to determine the layer thickness using fluid and heat transfer analysis and obtain velocity and temperature distributions, mathematical modelling is achieved. The effect of different layer thicknesses on temperature and flow characteristic such as velocity and pressure distribution are examined in this study. The method is examined for different Reynold numbers and flow characteristic and wax thickness are examined. The proposed method is expected to be accurate, efficient and cost effective for online testing of wax layer thickness which find immediate utility in oil and gas operation.

Keywords: non-destructive testing, thermal sensing, wax thickness, wax apparent temperature, CFD

1. Introduction

Deposition of wax in the crude oil pipeline is considered as a critical issue in the oil and gas industry that need to be solved. Dissolved and suspended paraffin wax go through complex phase transformations. The increase in viscosity due to wax deposition inside pipelines is typically associated with more pumping requirements and more risk of complete clogging which is extremely costly. This issue is faced at different stages in the oil and gases industries such as during transportation, production, and storage of petroleum. In certain cases, wax deposition in pipeline can result in blockage of flow lines and sometimes can fully clog the flow causing significant damage to processing equipment as well as the storage tanks.

The crude oil thermal energy decreases gradually as oil flow through the pipeline due to the heat loss to the outside environment. Typically, wax precipitates on the inner surface of the pipe walls when the temperature of the oil goes below the Wax Apparent Temperature (WAT). If the pipeline experiences a very large amount of heat transfer, the rate of wax deposition is higher and very significant. Wax deposition is primarily based on the phenomenon related temperature variations. Wax deposition can be prevented effectively through application of thermal method.
For example, method of heating the pipe directly from outer surface is considered to be effective in alleviating or inhibiting wax deposition in pipeline as it helps in keeping temperature of the oil greater than temperature required for solidification. With direct heating, electric current should pass pipe wall so as to generate the heat inside. For the sub-sea pipelines of crude oil, this method of heating is considered as very reliable.

The electric heating happens through the material of pipe due to its electrical conductivity. The supply of electric current is by means of two cable connections, one at the near end and other at the far end of the pipe making a closed circuit for current flow. By means of direct heating, it can be assured that the temperature of the working fluid is raised higher than the WAT which is closely 20 °C inside and 6 °C outside that is ambient temperature.

Flow assurance is one of the methods to ensure continuous flow of hydrocarbons at the required point of need supplied successfully from the reservoir tank. Flow assurance is very critical process that is monitored in the oil and gas industry because it provides sufficient confirmation of supply of oil from one point to other. In oil production in very deep under water in sea or ocean, traditional approaches are sufficient because of the very low temperature, and long distances the pipeline of the petroleum fluid has to experience. Therefore, flow assurance is implemented widely for the sub-sea oil pipelines using different expert fields. Flow assurance typically includes the modeling pipeline network and also multiphase flow simulation. Furthermore, it includes carry of solidifying deposits just as paraffin wax, naphthenates as well as gas hydrates. The clogging of pipeline is typically due to interaction of these solid deposits. Disturbances or complete stop in the operation pipeline or at time of production are because of unsatisfactory flow assurance which can result in very large economic loss.

Flow assurance is not only restricted to wax deposition; it considers formation of hydrates in the pipeline which is crucial as well. The hydrates are formed in natural gas pipelines at higher temperature called hydrate formation temperature which is greater than freezing temperature, but also at lower temperature than the reservoir temperature. Prevention of hydrate formation is one of the significant concerns towards flow assurance and one of the common methods used to reduce this problem is to insulate the pipeline. This helps the crude oil as well as the natural gas to maintain the temperature more than that of the temperature at which the hydrates are formed. Another possible alternative to resolve this issue through utilizing MEG or also known as inhibitor Methanol. Naturally, crude oil reservoir pressure is high compared to the outlet of the well or at the receiving facility and this cause oil to flow to the surface through the pipeline. If the pipeline experience clogging or partial clogging, the pressure difference observed between the reservoir tank and point of receiving facility is felt very large and this will cause the reservoir to stop producing oil. With continuous increase in wax buildup in pipeline over time, drop in pressure felt increases and resulting in decrease of crude oil flowrate. With time, the oil reservoir may completely stop operation. Therefore, the process of transporting oil is considered to be a transient process. Because of continues change in the temperature, pressure and flow rates in different sections of the pipeline, it can affect the changes in the fluid phase as well as vary with production time.

The deposited wax is examined through different detection methods and these methods include prediction of deposited wax using measurement of electric resistance [1], applying pressure pulses [2], with heat transfer techniques [3], using ultrasound inducers and strain gauges [4], and radiography [5,6]. Although there have been some attempts in investigating the pressure pulse technique, there is high level of uncertainty noticed in the results with application of this technique to detect the deposited wax thickness. In addition, developing experimental apparatus, testing, and measuring using pressure sensing method is very costly and requires complex setup. On the other hand, methods implemented using thermal detection non-destructive testing can be effective in determining the wax thickness in the pipelines [7,8].
Other methods implemented using temperature oscillation have shown results on estimation of fouling of heat transfer surfaces studying heat exchanger [9-11]. Among the current methods, there is no method to online monitor and determine the wax thickness. However, the variations in the deposition rate with temperature influence is predicted using different deposition models [12-15]. The gap needed to be fulfilled is testing these models in order to predict the wax thickness accurately.

Investigation carried out in this study is examining a new approach in predicting thickness of deposited wax inside the pipe. It includes heat transfer analysis using a Computational Fluid Dynamics (CFD) software, ANSYS Fluent. Thermal sensing method for wax thickness predictions is anticipated to be effective in comparison to other wax prediction techniques. The main objective of this study is to examine method of monitoring pipelines and determining wax thickness accurately. This can assist the oil and gas industry supporting the pipeline operators for carrying out preventive maintenance and handling operations to avoid full clogging of pipelines due to wax deposition.

2. Theoretical Modelling

As the crude oil flows in the pipeline, it loses thermal energy to the pipeline which is subjected to external cooling by the low temperature seawater. This heat transfer can be quantified to estimate the wax thickness. The temperature of the fluid temperature varying in the axial direction is important in the heat transfer and wax thickness estimation. Since wax deposit inside the pipeline exhibits a certain thermal resistance for heat transfer from the working fluid or oil toward pipe surface, the increase in the oil temperature can exhibit increase in wax deposition. The proposed method is related to measurement of external pipeline surface temperature and oil temperature to predict the deposited thickness of wax. When the crude oil temperature reaches the wax solidification temperature, wax molecules start to precipitate. This is typically occurring on the pipe surface. The rate of crystallization of the wax particles onto the pipe surface increases and with time, it develops as a solid rigid wax layer on the inner wall of the pipeline.

The mathematical model consists of the continuity equation, Navier-Stokes equation, and energy equation. Crude oil is considered in this study to be the moving fluid. The boundary conditions of the model consist of the inlet temperature of the fluid, inlet velocity of the fluid, fluid velocity on the walls (no-slip condition), outlet pressure (set equal to zero), wall temperature, and the supplied heat via the electric heater. The heat and fluid flow in the pipeline can be carried out. Here, the boundary value problem to be solved is based on a cylindrical coordinate system (r, z). The Poiseuille solution provides the relation of the axial velocity in cylindrical coordinate for the flow in the pipeline:

\[ u(r) = -\frac{1}{4\mu} \frac{\partial p}{\partial z} (r_o^2 - r^2) \]  

Similarly, the energy equation is applied on the pipeline and it is given as:

\[ u \frac{\partial T}{\partial z} = k \rho c \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) \]  

Where, the term in the left-hand side represents the temperature variation in axial z-direction, and the term on the right hand represent the heat transfer in the radial direction for a differential fluid element volume.

The proposed method to estimate wax thickness is based on additional thermal resistance of wax. If wax exist inside the pipeline, there will be an additional thermal resistance that reduces the heat transfer from hot crude oil to the cold water touching on the external surface of the pipeline.
The following relations is used for calculating the total thermal resistance as well as the total heat loss:

\[ R_{\text{Total}} = R_{\text{conv,1}} + R_{\text{wax}} + R_{\text{wall}} + R_{\text{conv,2}} \]  

(3)

The following relations are given for the thermal resistance inside the pipeline, \( R_{\text{conv,1}} \), and thermal resistance on the external surface of the pipeline, \( R_{\text{conv,2}} \):

\[ R_{\text{conv,1}} = \frac{1}{(h_1) A_{\text{inner}}} \quad \text{and} \quad R_{\text{conv,2}} = \frac{1}{(h_2) A_{\text{outer}}} \]  

(4)

The thermal resistance of the pipeline wall that is based on the conductivity of the pipe wall can be determined using the following relation:

\[ R_{\text{wall}} = \frac{\ln \left( \frac{r_3}{r_2} \right)}{2\pi (k_{\text{wall}}) L} \]  

(5)

Similarly, the following relation is used to calculate the thermal resistance of the wax layer:

\[ R_{\text{wax}} = \frac{\ln \left( \frac{r_2}{r_1} \right)}{2\pi (k_{\text{wax}}) L} \]  

(6)

The heat transfer between the hot oil inside the pipe and the cold water outside the pipe can be estimated as below:

\[ Q = \frac{T_{\text{oil}} - T_{\text{outer water}}}{R_{\text{tot}}} \]  

(7)

In this study, the temperature condition at which the wax starts deposition is set to start when the temperature is below 301 K [16]. The density of the crude oil \( \rho_{\text{oil}} \) = 815 kg/m\(^3\), specific heat capacity of oil \( C_{\text{p,oil}} \) = 1950 J/kg.K, and thermal conductivity \( k_{\text{oil}} \) = 0.1344 W/m.K. Viscosity of the oil is determined using the following relation as function of temperature:

\[ \mu(T) = p_1 T^3 + p_2 T^2 + p_3 T + p_4 \]  

(8)

Where \( p_1, p_2, p_3, \) and \( p_4 \) are the constants taken from correlating properties data as reported in [16]. In simulating the heat transfer conditions in the pipeline, the wax thermal conductivity is set as \( k_{\text{wax}} \) = 0.15 W/m.K. Material selection of pipe in the simulation is selected as steel, and pipe dimensions were kept as length, \( L = 1 \) m, and inner diameter, \( D_{\text{in}} = 50 \) mm, and pipeline thickness as \( t = 10 \) mm. The effect of different operating conditions including Reynold number, inlet oil temperature, and pipe wall external temperature are studied.

3. Methodology

Computational Fluid Dynamics (CFD) software package, ANSYS Workbench/ Fluent, is employed for this study. A steady state flow condition is assumed in this study. All the calculation is carried out using the turbulent k-\( \varepsilon \) flow model. In this study, the influence of wax thermal resistance on the heat transfer in pipeline can be examined. This allows one to compare temperature evolution in a pipeline with wax deposit and compare it with case of pipe without wax.
For simulation, the pipeline is modeled using a 2D-axis-symmetric flow domain as shown in the Fig. 1-a. In the simulation study, heat transfer in both fluid and the pipeline solid are examined together. The study is consisting of a flow domain modeled along with an electric heater that is attached at the outer surface at axial location \( z = 0.75 \) m as shown in Fig. 1. The electric heater mounted on the pipeline outer surface supplies heat. This heat goes through the material, steel from outer surface to inner surface of the pipe, and then passes to the oil inside the pipeline. Thus, the pipeline is subjected to cooling at all outer surface except at the region of heater where it is located, and heat is applied.

Discretized mesh of the modeled flow domain is illustrated in the Fig. 1-b. Different boundary conditions are applied on the flow domain shown in Fig.1-a. The Reynold number varied between 2300, 3000, 4000, and 5000. The inlet oil temperature is kept constant \( T_{\text{wall,in}} = 320 \) K. Similarly, the wall external surface temperature is fixed at \( T_{\text{wall,out}} = 290 \) K. The electrical heater located at the outer wall is set to provide heat flux of 100 kW/m².

Figure 1. (a) Axis-symmetry flow domain, (b) Discretized mesh.

4. Results and Discussions

Figure 2 shows the velocity distribution along the axial direction for different Reynold number in the pipeline. These results are obtained with fixed inlet fluid, and surface temperatures of the outer wall. It can be clearly observed that the magnitude of velocity is low in the near wall regions. Also, the magnitude of the velocity in the axial direction near to the wall region decreases. Figure 3 shows temperature distribution in the pipeline for different Reynold number for fixed other operating conditions. A similar observation is seen as the temperature closer to the wall decreases along the axial direction. The explanation on this can be provided that as the fluid moves in the axial direction, moving it loses thermal energy. This impacts on temperature reduction moving temperature very close to solidification temperature of wax near the wall surface. Electric heater supplying the heat at the outer pipe surface increases the temperature of the oil fluid near the heater.

(a) \( \text{Re} = 2300 \)
Figure 2. Velocity distribution in pipeline with different Reynold number.

Figure 3. Temperature distribution in the pipeline with different Reynold number.
The temperature variations in the radial direction are illustrated in Figure 4 at the outlet as well as near the heater sections. It is shown that the fluid temperature decreases in both, outlet and near the heater, sections somewhat in the radial direction up to the inner wall. After that, the decrease in wall temperature causes a sudden decrease in the radial temperature noticed at the outlet region. Whereas, temperature near the heater region increases considerably. To determine the thermal resistance, this temperature difference observed in the radial direction can be used. Therefore, the calculated temperature difference in the radial direction can be leading to estimation of wax thickness.
Figure 4. Temperature profile in radial direction at outlet and near heater sections.

5. Conclusions

Thermal detection for wax thickness in crude oil pipeline is examined under different operating conditions. The simulation study included different operating parameters including Reynold number, inlet oil temperature, and applied heat flux. Thermal sensing method of wax thickness in pipeline is considered to be accurate and convenient technique especially that it can be achieved without being intrusive to the operation of pipeline.

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