Wax Thickness and Distribution Monitoring Inside Petroleum Pipes Based on External Temperature Measurements

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ABSTRACT: A method to estimate wax thickness inside petroleum pipes from the external pipe temperature measurements is proposed. When wax is deposited inside the pipe, the external pipe surface temperature decreases because the heat resistance of the wax reduces the heat flow from the fluid inside the pipe to the fluid outside the pipe. The decrease in the external pipe temperature can be calculated by solving a heat equation about the heat transfer from the pipe inner fluid to external ambient fluid, and thus the wax thickness can be estimated by measuring the pipe surface temperature. An experiment to validate the method was performed. Crude oil was passed through a pipe with an inner diameter of about 8 mm. Ten thermocouples were installed on the pipe. The pipe was covered by a heat-shrink tube as a substitute for an insulation material. The pipe was cooled by a coolant jacket, and wax about 0.8 mm thick was deposited in the pipe. The wax thickness estimated from the temperature measurements agreed well with the thickness estimated from the pressure rise because of the wax layer and from the final gross weight of the wax. The difference between wax thickness estimated from the temperature measurements and from the final gross weight was less than 0.2 mm.

INTRODUCTION

The build-up of solid waxy deposits on the inside of pipelines is one of a number of significant problems faced by the upstream oil industry. Because the thickness of these deposits increases over time, they can restrict throughput substantially and may lead to total blockages if left unchecked. Early detection and remedial intervention are required either by removal, such as pigging, or via chemical or thermal treatments. However, these operations carry large costs and risks to production and thus should only be performed when necessary.

The process of deposition is influenced by conditions around the pipeline such as crude oil components, pressure, temperature, flow rate, and flow pattern. Several research papers have been published about the physical deposition mechanism by flow loop experiences and have proposed models to predict the deposition rate based on the conditions. Several methods of estimating the real time volumes of wax deposition by measuring something have also been proposed, including electric resistance, applying pressure pulse, heat transfer techniques, using ultrasound and a strain gauge, radiography, acoustic chemometrics, and external heating. However, there is currently little in situ monitoring, which could be used to optimize interventions and minimize costs, and current methods cannot estimate the distribution of the deposition thickness along the length and around the circumference of the pipe. Wax thickness can be estimated from the oil temperature difference between two points along the pipe length. This is likely to be impractical for full scale...

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sub-sea lines as it would require the measurement of oil temperatures at regular intervals along the inside of the pipe, which potentially impedes cleaning/pigging operations and carries significant cost implications. In addition, methods to estimate the wax thickness from the external pipe temperature have been proposed,\textsuperscript{7,8} although these methods require a heating device.

In this study, we developed a method for estimating the real-time wax deposition thickness inside the pipe from the external surface temperature of the pipe. A flow loop experiment was performed to validate the method.

### WAX THICKNESS ESTIMATION METHODS AND EXPERIMENT

In the upstream oil industry, the fluid temperature in the pipe is higher than the external ambient temperature. When wax is deposited inside the pipe, the pipe surface temperature decreases because the wax reduces the heat flow from the fluid inside the pipe to the pipe exterior. In our method, the wax thickness is estimated from the pipe surface temperature decrease by solving a heat equation about the heat flux from the hot fluid in the pipe to external ambient fluid. Heat resistance of each step of heat transfer from the fluid in the pipe to external ambient fluid excluding the wax layer can be calculated based on diameters, thermal conductivity, and heat transfer coefficient in advance. The heat equation can be obtained based on the heat resistance of each step. Heat resistance of the wax layer is estimated by solving the heat equation.

We performed an experiment to validate our method. A schematic of the experimental device is shown in Figure 1. The crude oil (waxy black oil) was heated to about 70 °C in the oil reservoir and exchanger, it was cooled to about 45 °C in the oil inlet heat exchanger, and then flowed to the test section. The dynamic viscosity, density, thermal conductivity, and specific heat capacity of the crude oil were 0.0075 Pa·s, 843 kg/m³, 0.118 W/m·K, and 2.0 kJ/kg·K at 40 °C, respectively. Wax deposits were produced by passing warm crude oil through the independently cooled test section. A schematic and a photograph of the test section are shown in Figures 2 and 3. Ten thermocouples (TCs) (type T) and a heat flux meter (Hioki E.E. Corp., Z2015) were installed on the top and bottom surface of the stainless-steel 316 pipe with an inner diameter of about 8 mm. The pipe was covered with a heat shrink tube (polyethylene) as a substitute for the insulation material. To avoid heat resistance because of the gap between the pipe and the heat shrink tube, the gap was filled with thermal grease. Wires for TCs and the heat flux sensor run along the pipe inside the heat shrink tube, and connections are done at both ends of the pipe. The oil flow rate was 1100 mL/min and the flow velocity in the test section was 0.39 m/s. The Reynolds number of the flow in the test section was calculated as approximately 340 from the flow velocity, the oil parameters, and the pipe inner diameter. Accordingly, the flow was laminar in the test section. The coolant flowed in the coolant jacket to cool the test section. A mixture of 50% water and glycol was used as a coolant. The coolant temperature and flow rate were 18 °C and 10,000 mL/min, respectively. A schematic of the sensor arrangement is shown in Figure 4. The whole setup is installed inside an enclosure to ensure stable boundary conditions during the experiment, and ambient temperature was monitored as well. A heat flux meter was located between TC 8 and 10. To measure the actual wax thickness at each position, we cut test sections after the experiment and measured the gross weight of wax in each section. The cut positions are shown in Figure 5.

![Figure 1. Schematic of the experimental device. ID, inner diameter.](image)

![Figure 2. Schematic of the test section.](image)

![Figure 3. Photograph of the test section.](image)

![Figure 4. Schematic of placement of TCs and the heat flux meter. TC, thermocouple.](image)

![Figure 5. Cut positions in the test section.](image)
close proximity to the tube. A summed average of the three sensors provided an environmental calibration deviation of not more than 0.1 °C. The pipe surface temperature were measured by ten TCs. Ten TCs were calibrated based on the measured coolant temperature.

Deposited wax chokes the flow inside the pipe, which results in pressure rise. Deposition thickness can be, therefore, calculated assuming laminar Newtonian flow and uniform wax thickness. Time-series data from a differential pressure meter are compared in this study, which is independent from the proposed temperature-based method.

The estimated wax thickness from the proposed method was affected by the heat resistance of temperature measurement devices, such as the TCs, adhesives, and wires. However, the effect of the heat resistance was small because we used small TCs with a diameter of 0.8 mm. The estimated wax thicknesses from the differential pressure and gross weight were not affected by the thermal resistance.

■ EXPERIMENTAL RESULTS

In the experiment, the average wax thickness in the test section increased to about 0.8 mm over 17 h. Figure 6 shows a photograph of the generated wax. The temperatures of the pipe surface measured at each position are shown in Figure 7. We performed similar but not the same tests in a few times and got similar results. The temperature of TC4 could not be measured because of a sensor fault. The temperature at each position decreased with time, and the decrease depended on the increase in wax thickness. The temperatures measured by TC7–TC10 increased from 0 to 1 h because the oil temperature at the inlet of the test section was not stable and the temperature of the pipe, heat shrink tube, sensors, and sensor wires had not reached a steady state just after the experiment began.

Heat transfers are taken place in five steps; from oil to wax (convection), wax layer (conduction), pipe layer (conduction), insulation (conduction), and from the outer surface to fluid (convection). Consequently, the amount of heat transferred from the hot fluid in the pipe to the external ambient fluid, $Q$, in the range of the length along the axial direction of the pipe, $L_r$, is calculated as

$$Q = (T_f - T_o) \left( \frac{1}{2\pi r_{oi} L_{ki}} + \frac{\ln(r_{oi}/r_{pi})}{2\pi L_{ki}} + \frac{\ln(r_{wo}/r_{wp})}{2\pi L_{wp}} + \frac{\ln(r_{io}/r_{po})}{2\pi L_{po}} + \frac{1}{2\pi r_{io} L_{bo}} \right)$$

(1)

where $T_f$ is the temperature of the fluid inside the pipe, $T_o$ is the external ambient fluid temperature, $r_{oi}$ is the pipe inner radius, $r_{wo}$ is the pipe outer radius, $\delta$ is the wax thickness, $r_{io}$ is the insulation outer radius, $h_i$ is the heat transfer coefficient at the wax inner surface, $h_o$ is the heat transfer coefficient at the insulation outer surface, $k_w$ is the thermal conductivity of the wax, $k_p$ is the thermal conductivity of the pipe, and $k_b$ is the thermal conductivity of the insulation. Each term of the denominator represents thermal resistance in five steps, respectively. As the wax thickness increases, the wax inner diameter and the flow rate of the fluid inside the pipe change. Accordingly, wax inner radius $r_{pi} - \delta$ and inner heat transfer coefficient $h_i$ change because of the increase in wax thickness, although we ignore these parameter changes because the changes are small. During the experiment, bubbles adhered to the heat shrink tube surface and disturbed the heat transfer to the coolant. The effect of the bubbles is considered by the thermal resistance of the unit area because of bubbles, $R_b$. The amount of heat, $Q$, is calculated as

$$Q = (T_f - T_o) \left( \frac{1}{2\pi r_{pi} L_{hi}} + \frac{\ln(r_{oi}/r_{pi})}{2\pi L_{wi}} + \frac{\ln(r_{wo}/r_{wp})}{2\pi L_{wp}} + \frac{\ln(r_{io}/r_{po})}{2\pi L_{po}} + \frac{1}{2\pi r_{io} L_{bo}} + R_b \right)$$

(2)

Using the pipe surface temperature, $T_{po}$, $Q$ is also calculated as

$$Q = (T_f - T_o) \left( \frac{1}{2\pi r_{po} L_{hi}} + \frac{\ln(r_{oi}/r_{pi})}{2\pi L_{wi}} + \frac{\ln(r_{wo}/r_{wp})}{2\pi L_{wp}} + \frac{\ln(r_{io}/r_{po})}{2\pi L_{po}} + \frac{1}{2\pi r_{io} L_{bo}} \right)$$

(3)

Each term of the denominator represents thermal resistance of convection from oil to wax, conduction in the wax layer, and conduction in the pipe layer, respectively. From eqs 2 and 3, wax thickness $\delta$ is calculated as

![Figure 6. Photograph of the generated wax.](image)

![Figure 7. Measured pipe surface temperature.](image)
\[ \delta = r_{pi} - r_{pi} \exp \left( -k_w \frac{T_i - T_o}{T_p - T_o} \ln\left( \frac{r_{wi}}{r_{po}} \right) \right) + \frac{1}{r_{po}h_o} + \frac{R_k}{r_{so}} - \frac{1}{r_{pi}h_i} - \frac{\ln\left( r_{po}/r_{pi} \right)}{k_p} \] (4)

In this experiment, wax thickness is estimated using eq 4. The temperature difference between \( T_o \) and \( T_i \) is needed to estimate the wax thickness. It is also needed to measure or predict both \( T_o \) and \( T_i \). If we can know each heat resistance of each step of the heat transfer from the fluid in the pipe to the external ambient fluid, a deposit thickness can be estimated based on the same procedure in other test sections or pipelines.

In this experiment, the heat transfer coefficient at the insulation outer surface, \( h_o \), is not uniform. \( h_o \) near the inlet of the test section is different from \( h_o \) near the outlet because the coolant flows into the coolant jacket from three inlets (Figure 3). \( h_o \) is also different on the top and bottom of the heat shrink tube because of natural convection. Thus, we perform thermal fluid analysis to obtain \( h_o \) at each sensor position using ANSYS 19.2. The analysis model is shown in Figure 8. In the analysis, there are regions of the coolant flowing in the jacket, the heat shrink tube, and the pipe. The pipe inner boundary conditions are set to the convection with a heat transfer coefficient of 100 W/m² K and free stream temperature of 45 °C to represent the convection with oil. The coolant jacket outer boundary conditions are set to the convection with a heat transfer coefficient of 5 W/m² K and free stream temperature of 20 °C to represent the convection with air. Adhered bubbles are not considered in the analysis. The effect of bubbles is considered in the next step written in the next paragraph. The heat transfer coefficient distribution obtained from the analysis is shown in Figure 9. The heat transfer coefficient near the inlet of the coolant jacket is high because the coolant flow is disturbed near the three small coolant inlets. The heat transfer coefficient at the top of the heat shrink tube is lower than the bottom because of the natural convection. The distance between TC1 and the inlet is 0.19 m. The distribution of the heat transfer coefficient between TC1 and the outlet of the test section is almost uniform, and thus the heat transfer distribution along the pipe axis is neglected in the determination of \( h_i \). The circumferential distribution of the heat transfer coefficient obtained from the analysis, where the distance from the inlet is 0.5 m, is shown in Figure 10. The heat transfer coefficient around the top of the heat shrink tube is lower than around the bottom because of the natural convection. The heat transfer coefficient varies substantially around the top surface of the heat shrink tube. Therefore, the average of the heat transfer coefficient between 45 and 135° is used to calculate the wax thickness. The heat transfer coefficient, \( h_o \), is determined at each temperature sensor position based on the analysis (Table 1).

The heat transfer coefficient on the inner surface, \( h_i \), is not uniform because the temperature distribution of oil in the test section is not fully developed. \( h_i \) near the inlet of the test section is higher than that near the outlet. Based on the heat equation, \( h_i \) at the heat flux meter position is calculated using the measured heat flux and temperature just after the start of the experiment when wax thickness \( \delta \) is approximately 0. Heat flux measured by the heat flux meter on the pipe surface, \( q_{id} \) is represented as

\[ q_{id} = \frac{Q}{2\pi r_{po} L} \left( T_i - T_{id} \right) / r_{po} \left( \frac{1}{r_{pi}h_i} + \frac{\ln(r_{wi}/r_{po})}{k_p} + \frac{R_{hf}}{2r_{po}} \right) \] (5)

where \( R_{hf} \) is the thermal resistance of unit area of the heat flux meter and \( T_{id} \) is the temperature measured by the heat flux meter. From eq 5, \( h_i \) is calculated as

\[ h_i = 1/r_{pi} \left( \frac{T_i - T_{id}}{r_{po} q_{id}} - \frac{\ln(r_{wi}/r_{po})}{k_p} - \frac{R_{hf}}{2r_{po}} \right) \] (6)
Table 1. Heat Transfer Coefficient \( h_i \) on the Heat Shrink Tube Surface at Each Temperature Sensor Position

| sensor number | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| \( h_i \) (W/m² K) | 260 | 350 | 260 | 350 | 260 | 350 | 260 | 350 | 260 | 350 |

Table 2. Heat Transfer Coefficient \( h_o \) on the Inner Surface at Each Temperature Sensor Position

| sensor number | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| \( h_o \) (W/m² K) | 110 | 110 | 90  | 90  | 90  | 90  | 90  | 90  | 90  | 90  |

\( h_i \) at the heat flux meter position is calculated with eq 6 as approximately \( 90 \) W/m² K. Thermal fluid analysis of the oil in the pipe is performed considering the distribution of \( h_i \) along the pipe axis. We set the heat transfer coefficient \( h_i \) at each temperature sensor position using eq 6 and the analysis results (Table 2).

Thermal resistance because of bubbles \( R_b \) is also obtained using the measured heat flux just after the start of the experiment. Heat flux \( q_{bf} \) is written as

\[
q_{bf} = \frac{Q}{2\pi r_o L} = \left( T_{id} - T_o \right) / \left( r_o \right) \left\{ \frac{R_{id}}{2r_o} + \frac{\ln\left( r_o / r_{po} \right)}{k_i} + \frac{1}{r_o h_o} + \frac{R_b}{r_o} \right\}
\]

(7)

From eq 7, \( R_b \) is obtained as

\[
R_b = r_o \left\{ \frac{T_{id} - T_o}{r_o h_{id}} - \frac{R_{id}}{2r_o} - \frac{\ln\left( r_o / r_{po} \right)}{k_i} - \frac{1}{r_o h_o} \right\}
\]

(8)

\( R_b \) is calculated as approximately \( 6.0 \times 10^{-4} \) m² K/W with eq 8.

Figure 11 shows the wax thickness estimated from a measured average temperature of 10 temperature sensors, from the pressure rise because of the wax layer, and from the final gross weight of wax. These wax thicknesses, as shown in Figure 11, are the average thicknesses in the test section. The steps to estimate the wax thickness are shown in Figure 12. Thermal conductivities of the wax \( (k_w) \), pipe \( (k_p) \), and heat shrink tube \( (k_h) \) are assumed to be 0.17, 16.7, and 0.33 W/m K, respectively. \( k_w \) is calculated from the individual thermal conductivity of the crude oil and pure paraffin wax. \( k_p \) and \( k_h \) are based on the thermal conductivity of the SS316 stainless steel and polyethylene, respectively. The wax thickness is calculated with eq 4. The averages of \( h_i \) and \( h_o \) at each sensor position (Tables 1 and 2) are used in this calculation. The estimated wax thickness agrees well with the calculated thickness derived from the pressure rise and from the final gross weight. The wax thicknesses at each sensor position estimated from the temperature measured at each temperature sensor are shown in Figure 13. The wax thickness is also calculated with eq 4 using \( h_i \) and \( h_o \) at each sensor position.

**DISCUSSION**

We assumed the errors of the parameters used in the wax thickness estimation based on eq 4. Table 3 shows the assumed errors. Errors of temperatures are based on temperature measurement accuracy. The error of the thermal conductivity is assumed based on the individual variation of each material. Errors of the heat transfer coefficients are set assuming the 10% error because it is difficult to accurately predict the heat transfer coefficient by numerical simulations. We calculated the sensitivity of estimated wax thickness because of errors of the parameters based on the error propagation. Figure 14 shows the predicted errors of the estimated wax thickness. Errors of thermal conductivity of the wax \( k_w \) and insulation material \( k_i \) and heat transfer coefficients \( h_i \) and \( h_o \) have a large influence on the wax thickness estimation error. Errors of measured temperatures are not significant in this experience.

The wax thickness and its change over time at each position were calculated using our method based on eq 4. The final wax thickness estimated from the measured temperature and gross weight are shown in Figures 15 and 16. The wax thickness estimated from the temperature measured near the inlet is small and it agrees with the thickness estimated from the gross weight. However, the wax thickness from the measured temperature near the middle of the test section is large, whereas the wax thickness from the gross weight near the outlet is large. There are two main reasons for this difference. First, the epoxy adhesive and wires for the temperature sensors are between the pipe and the heat shrink tube. The heat resistance of the adhesive and wires depends on the position, and the effect of this heat resistance is not considered in estimating the wax thickness. In particular, the thick wire for the heat flux meter around TC7–TC10 has a large effect. Second, it is difficult to obtain the inner and outer heat transfer coefficients accurately at each position from the numerical simulation. The difference between the true and simulated heat transfer coefficients causes the wax thickness estimation error.

In subsea oil and gas pipeline, hot crude oil flows in the pipeline and the surrounding sea water temperature is low. Accordingly, we can use this technique for the subsea pipeline. Temperature sensors should be installed inside the wet insulation of the subsea pipeline. As the wax thickness inside the pipe increases, the measured temperature of the pipe surface decreases. Wax thickness can be estimated from the temperature of the pipe surface based on a heat equation. In this study, we performed the experiment with a small diameter pipe. It is different from the subsea pipeline. However, the
temperature distribution from the pipe inner oil to pipe external ambient fluid is not largely different from the subsea pipeline because the effect of the pipe diameter on the temperature distribution is not large, whereas the effect of thickness of wax, pipe, insulation and heat transfer coefficient are large. We will perform the experiment with a large diameter flow loop to validate our method as a future work.

![Flow chart](image12.png)

**Figure 12.** Flow chart to show steps of wax thickness estimation.

![Wax thickness as a function of time](image13.png)

**Figure 13.** Wax thickness as a function of time at each position estimated from the measured temperature.

| parameter | units | Errors | $k_w$ W/m K | $k_p$ W/m K | $k_i$ W/m K | $T_i$ °C | $T_o$ °C | $T_p$ °C | $h_i$ W/m K | $h_o$ W/m K |
|-----------|-------|--------|-------------|-------------|-------------|----------|----------|----------|-------------|-------------|
| $k_w$, $k_p$, and $k_i$, thermal conductivity. $T_i$, $T_o$, and $T_p$, temperature. $h_i$ and $h_o$, heat transfer coefficient. |

| parameter | units | Errors | $k_w$ W/m K | $k_p$ W/m K | $k_i$ W/m K | $T_i$ °C | $T_o$ °C | $T_p$ °C | $h_i$ W/m K | $h_o$ W/m K |
|-----------|-------|--------|-------------|-------------|-------------|----------|----------|----------|-------------|-------------|
| $k_w$, $k_p$, and $k_i$, thermal conductivity. $T_i$, $T_o$, and $T_p$, temperature. $h_i$ and $h_o$, heat transfer coefficient. |

![Predicted errors of the estimated wax thickness](image14.png)

**Figure 14.** Predicted errors of the estimated wax thickness because of errors of parameters. $k_w$, $k_p$, and $k_i$, thermal conductivity. $T_i$, $T_o$, and $T_p$, temperature. $h_i$ and $h_o$, heat transfer coefficient.

![Wax thickness estimated from the measured temperature](image15.png)

**Figure 15.** Wax thickness estimated from the measured temperature at each position.
In subsea pipelines, the effects of wires and adhesive would be small because the pipe diameter is large. The effect of the difference between the actual and predicted outer heat transfer coefficients is small because the heat transfer coefficient of sea water is high compared with the mixture of water and glycol. For example, the heat transfer coefficient for forced convection at the subsea pipeline with a diameter of 300 mm is approximately 450 W/m² K, when sea water flow velocity is 0.1 m/s. The distribution of the inner heat transfer coefficient of the subsea pipeline along the pipe axis is uniform because the temperature distribution and velocity distribution of the fluid in the pipe are fully developed. Consequently, our method may be suitable for use in subsea pipelines. The pressure in the subsea pipelines is higher than the experiment. To use our method, the inner heat transfer coefficient $h_i$ difference due to the pressure difference should be consider in subsea pipelines. In the experiment, the temperature sensors were only installed on the top and bottom of the pipe. If sensors were installed on multiple points on the circumference, the circumferential wax distribution could be estimated by our method.

Our proposed noninvasive method estimates the real-time thickness of the deposition in the pipe by measuring the pipe surface temperature. It is useful for the pipeline operation. For instance, the optimization of the pigging period for the subsea petroleum pipeline is possible. Our method can be also used in other industries to avoid the blockage because of deposits.

**CONCLUSIONS**

A method to estimate wax thickness from the measured pipe surface temperature was developed. The wax thickness was estimated from the measured pipe surface temperature and pipe parameters, such as radius, thermal conductivity, and heat transfer coefficient. To validate the method, a flow loop experiment was performed. The wax deposited inside the test section of the pipe with an internal diameter of 8 mm during the experiment. The average wax thickness increased up to 0.8 mm. The pipe surface temperatures were measured by the 10 TCS installed on the top and bottom of the pipe. The heat transfer coefficients of the pipe inside and outside were estimated from the thermal fluid analysis for our method. Both the average wax thickness and wax thickness at each TC position were estimated by our method. The variation of the average wax thickness with time estimated from the measured pipe surface temperature agreed well with the variation of thickness estimated from the differential pressure. The difference between the final average wax thickness estimated from the measured temperature and from the final gross weight was less than 0.2 mm.

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**Notes**

The authors declare no competing financial interest.

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