INTRODUCTION

Deposits in piping are known to cause operational problems, such as reduced flow rates and piping blockages. For example, deposits of waxes, asphaltenes, hydrates, and the like pose a major concern in oil and gas business areas. The intra-pipe deposit growth process is difficult to predict in advance due to various affecting factors, including the components, temperature, pressure, and flow velocity of the fluid in pipe. Moreover, deposits often occur in nonuniform shapes with greater thicknesses on the bottoms or sides of piping, for example. Therefore, it is important to monitor these deposits during pipeline operation.

Several technologies are known and available for estimating deposit shapes in piping. However, pipelines are often operated without measuring actual deposit thicknesses because of the technological limitations in estimating deposit thicknesses and shapes in real time at low cost.

Accordingly, we have developed a technology that measures piping surface temperatures to estimate deposit shapes and thicknesses. This technology requires temperature sensors to be installed only on the outer side of the piping and can noninvasively estimate deposit shapes and thicknesses in real time. This technology provides a constant deposit buildup monitoring method, allowing optimum pipeline operation, including deposit removal timing prediction or blockage prevention.

PRINCIPLE OF TEMPERATURE MEASUREMENT-BASED DEPOSIT ESTIMATION

This section describes the principle of the technology. Suppose a deposit builds up in a pipe when the temperature of the fluid in the pipe exceeds the ambient temperature of the pipe. In that case, a temperature difference occurs between the inner and outer sides of the deposit, disturbing the heat transfer from the liquid in the pipe to the pipe exterior, resulting in a lower piping surface temperature. The technology herein uses this phenomenon of deposit-induced piping surface temperature change and can noninvasively estimate deposit thicknesses in pipes from temperature measurements taken by temperature sensors installed on the pipe surfaces. Reliant on the difference in the internal and external temperatures of the pipe, this technology cannot be used if there is no difference between the temperature of the liquid in the pipe and the ambient temperature.
Deposits Uniform in Thickness

This subsection presents a typical method of estimating the deposit thickness in a pipe from the piping surface temperature when the deposit thickness can be deemed uniform. The rate of heat flow between any two points is expressed as the heat flow rate = temperature difference/thermal resistance from the temperature difference and thermal resistance between the two points\(^4\). From this relationship, the heat flow rate \(Q\) from the fluid in the pipe in the length \(L\) region in the pipe axial direction to the piping exterior is given as follows:

\[
Q = (T_i - T_o) / \left\{ \frac{1}{2\pi r_p L h_i} + \frac{\ln(r_p / (r_p - \delta))}{2\pi L k_p} + \frac{\ln(r_p / r_i)}{2\pi L k_d} \right\}
\]

\(T_i\): Temperature of fluid in pipe
\(T_o\): Piping ambient temperature
\(h_i\): Heat transfer coefficient inside piping
\(r_p\): Piping inside radius
\(h_o\): Heat transfer coefficient outside piping
\(r_o\): Piping outside radius
\(k_d\): Thermal conductivity of deposit
\(k_p\): Piping thermal conductivity
\(\delta\): Deposit thickness

Considering the heat flow from inside the piping to the piping surface, the heat flow rate \(Q\) can also be expressed as follows:

\[
Q = (T_i - T_o) / \left\{ \frac{1}{2\pi r_i L h_i} + \frac{\ln(r_p / (r_p - \delta))}{2\pi L k_p} + \frac{\ln(r_p / r_i)}{2\pi L k_d} \right\}
\]

\(T_i\): Piping surface temperature

From Eqs. (1) and (2), the deposit thickness, \(\delta\), can be derived from the piping surface temperature, \(T_o\), and the temperature of fluid in the pipe, \(T_i\), as follows:

\[
\delta = r_p - r_i \exp \left\{ -k_p \left( \frac{1}{r_p h_p} (T_i - T_o) - \frac{1}{r_i h_i} \ln(r_p / r_i) \right) \right\}
\]

The above example shows the case of uninsulated piping. For insulated piping, the deposit thickness can be estimated by solving a similar heat flow equation with temperature sensors installed on the inner side of the insulation.

Deposits Non-uniform in Thickness

Eq. (3) assumes a uniform deposit thickness and hence cannot be applied to deposits adhering nonuniformly. Therefore, we developed an algorithm\(^1\) that estimates the shape of such a deposit from the piping surface temperatures measured at multiple points, as shown in Figure 1, even when the deposit is nonuniform in thickness. We applied this algorithm to simulations of deposits with different shapes to verify that the algorithm can correctly estimate shapes and thicknesses.

DEMONSTRATION EXPERIMENTS

We conducted two demonstration experiments to show that our developed algorithm can estimate the deposit shape and changes over time in real piping.

Shape Estimation Experiment Using Simulated Deposit Layers

We conducted the following experiment to confirm that our developed algorithm can correctly estimate deposit shapes. Assuming that the vinyl chloride layer of a 100A vinyl chloride-lined pipe was a deposit, we cut two 100 mm sections from the pipe and processed the vinyl chloride layers into different shapes as shown in Figure 2. The pipe in Figure 2(a) had its vinyl chloride layer shaped thicker in the 180-degree clockwise direction (bottom side) with the top side at 0°. Similarly, the pipe in Figure 2(b) had its vinyl chloride layer shaped thicker in the 90-degree and 270-degree directions (right and left). Assuming insulated piping, we wrapped the piping in Figures 2(a) and 2(b) with insulation and installed temperature sensors around the circumferential surface of the piping underneath. With two water circulation pumps circulating 40°C warm water inside the piping and 0°C cold water outside the piping, the temperature sensors measured the circumferential surface temperature distribution of the piping. Eight temperature sensors were installed on Figure 2(a) piping, while 16 were installed on Figure 2(b) piping lined with a complex-shaped vinyl chloride layer. We applied our developed algorithm to the measured temperature distributions to estimate the shapes of the vinyl chloride layers.

\(^{1}\) For intra-pipe deposits nonuniform in thickness, the algorithm also generates a heat equation for the heat transfer from the fluid in pipe to the piping exterior and estimates the deposit shape by solving the equation. This paper refrains from going into the details of this algorithm.
Figure 3 shows the measured temperatures by the temperature sensors installed on the circumferential surfaces of the pipes. In Case (a), the temperature was lower in the 180° direction where the vinyl chloride layer was thicker. Similarly, in Case (b), the temperature was lower in the 90° and 270° directions where the vinyl chloride layer was thicker.

Figure 4 shows the deposit thickness distributions our developed algorithm estimated from these temperature distributions. The deposit shapes in both pipes were correctly estimated. The vinyl chloride layer lining the pipe in Figure 2(b) had a more complex shape than in Figure 2(a). However, its shape was successfully estimated by an increased number of measurement points, which indicates that our shape estimation algorithm works effectively even for complex shapes, providing a sufficient number of temperature measurement points.

The vinyl chloride layer in Figure 2(a) showed thickness estimation errors ranging from 0.3 mm to 0.6 mm at the measurement points on the piping, which means that the estimated thickness of the vinyl chloride layer was slightly larger than its actual thickness. These errors are probably due to the pipe used, which was cut 100 mm long, resulting in different heat flows from the top and bottom cut surfaces than from the actual piping. With the actual piping, we expect much smaller errors.

Wax Deposition Experiment
We conducted a demonstration experiment to confirm that our developed algorithm can estimate deposit thickness increases in pipes over time in real time\(^6\). It is known in oil and gas business areas that wax deposits in piping occur mainly because of the decreased oil temperatures in pipes. Hence, using an experimental device for causing wax deposits inside by cooling a built-in crude oil passage pipe from around it, we empirically estimated the change in wax thickness over time based on the pipe surface temperature.

Figures 5 and 6 show a photo of the experimental device and its schematic diagram, respectively. Both figures show a 10 mm diameter pipe filled with crude oil heated to approximately 45°C. The crude oil was cooled by a cooling jacket around the pipe, causing wax deposits inside the pipe as shown in Figure 7. The temperature of the refrigerant flowing through the cooling jacket was kept to 18°C. To estimate the deposited wax thickness, we placed thermocouples on the pipe surface, as shown in Figure 6, and fitted heat-shrink tubing over them for insulation. With a total of 10 thermocouples thus placed, we analyzed the longitudinal thickness distribution of the deposited wax. We filled the gap between the pipe and the heat-shrink tubing with heat-conductive grease to prevent the contact thermal resistance between them. In this experiment, the crude oil flowed at the rate of 1,100 ml/min for 17 hours, increasing the wax thickness in the pipe to about 0.8 mm by the end of the experiment.
Figure 8 shows the results of measuring the pipe surface temperature. At all measurement points, the pipe surface temperature decreased with the elapsed time. This temperature change suggests that the wax thickness gradually increased until about 10 hours after the start of this experiment.

From the measured temperatures, the average wax thickness of the entire pipe was estimated using the technology herein. The average value of the measured temperatures by the thermocouples was used as the piping surface temperature, the crude oil temperature measured at a position upstream from the cooling jacket was used as the temperature of the fluid in the pipe, and the measured value by a temperature sensor installed inside the cooling jacket was used as the piping ambient temperature. Figure 9 shows the estimation results. The gradual increase in wax thickness over time was successfully estimated based on the temperature measurements. To verify the correctness of the wax thickness estimated from the temperatures, we estimated the wax thickness from the differential pressure measured between the cooling jacket’s inlet and outlet during the experiment. Moreover, from the mass of the wax taken out after the experiment, we made another estimation of the wax thickness based on the wax density measured beforehand. The wax thickness estimated from the temperature agreed well with those estimated from the differential pressure and the wax mass, confirming that the change in wax thickness over time was successfully estimated with good accuracy from the temperatures.

CONCLUSIONS

For piping with a difference between the temperature of the liquid in the pipe and the piping ambient temperature, we developed an algorithm to measure the piping surface temperature distribution to estimate the deposit shape and thickness in a pipe. Conducting a demonstration experiment using simulated deposit layers processed into different shapes, we confirmed that the algorithm can correctly estimate the shapes of actual deposits. In another demonstration experiment, we caused wax deposits in a pipe, showing that the algorithm can monitor changes in deposit thickness over time in real time.

Based on the changes in pipe surface temperature due to deposit formation, the technology herein can estimate deposit shapes and thicknesses based on measurements by temperature sensors added to the pipe surface and various parameters. Therefore, this technology allows us to monitor deposits noninvasively and inexpensively and will be useful in pipeline operation. For example, retrofitting a pipeline with pressure gauges to determine deposit thicknesses from differential pressures would be more time-consuming and costly than applying the technology herein. Going forward, we will investigate the need for deposit thickness and shape estimation and pursue further development of this estimation technology.

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REFERENCES


(4) S. Mochizuki, M. Akira, Dennetsukogaku no kiso [basic heat transfer engineering], Nishin Shuppan, 1994 (in Japanese)


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Monitoring of Deposit Thickness and Distribution inside Pipes Based on Pipe Surface Temperature Measurements