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Dynamic Microscopic Visualization of Thermal Wax Removal in Turbulent Flow

Gabriel Santos, Elijah Bell, Nagu Daraboina*, and Cem Sarica
Tulsa University Paraffin Deposition Projects, The University of Tulsa, USA, *nagu-daraboina@utulsa.edu

Abstract
Active heating is increasingly explored as a cost-effective strategy for managing wax deposition in offshore flowlines. While these methods have an established presence throughout the industry, few studies have been conducted focusing on understanding the mechanism of wax removal. A dynamic microscopic visualization technique is employed to explore the removal mechanism during active heating. Tests are conducted confirm the theory that detachment is the primary removal mechanism during active heating. Evidence for a counter-diffusion mechanism that precedes this detachment is shown. The deposit becomes less dense with wax crystals over time, reducing the deposit stability and allowing the shear forces of the bulk fluid to carry large chunks of the deposited wax.

Keywords
Wax deposition; Thermal removal; Active Heating

Introduction
Wax deposition in subsea crude oil pipelines is a major operational and safety issue in oil production and transportation. The low ambient temperatures in deep subsea environments cause heat loss from the pipeline; eventually, temperatures drop below the wax appearance temperature (WAT). These wax particles deposit on the pipe walls and reduce the area available for flow, affecting the production or abandoning entirely in extreme cases [1-3]. Active heating technology is one of many techniques to prevent and remediate this issue. Active heating describes the use of either electrical means or the circulation of a hot fluid to heat the pipe wall, maintaining or raising the temperature of the production fluid to above the WAT [4]. Previous research has explored necessary temperatures for the thermal removal of wax deposits in conventional flow loops [5]; it was proposed that removal by active heating is characterized by a sudden catastrophic reduction of the wax deposit. The authors speculated a removal mechanism by detaching large chunks from the wall or within the deposit based on these observations. There are no validated models to simulate the wax removal process during active heating. Understanding the mechanisms at play during removal will be necessary to develop an accurate model.

Microscopic visualization techniques have been used to elucidate the wax deposition process. These techniques involve visually observing the deposition process to grant confirmation of a process usually hidden behind the pipe wall. Some researchers have used microscopes to study deposition phenomena under static conditions; however, wax precipitation and deposition phenomena behave differently in flowing conditions. Dynamic microscopic facilities have been developed recently and used to study deposition phenomena during flow [6-8] to address these issues. In this study, an active microscopic facility is employed to observe the thermal removal of wax deposits. This investigation will aid in providing visual confirmation of removal phenomena under flowing conditions and develop accurate models.

Methodology
A microscopic *in-situ* visualization system is used on a bench-scale single-phase facility for wax deposition and removal experiments. The observations are performed in a rectangular test section composed of two channels that can flow oil (upper) and coolant (lower) separately. These two channels directly contact a copper plate that allows heat transfer between them. The visualization system is positioned perpendicular to the channel to observe deposition and removal through a window.

The experiments are divided into two steps: forming a wax deposit, followed by the removal process by active heating. The single-phase flow loop is equipped with two circulator chillers responsible for circulating coolant through the bottom test section channel at low temperatures (cold chiller – wax formation stage) and high temperatures (hot chiller – wax removal stage). The recorded videos and the images are analyzed qualitatively and quantitatively to understand the mechanisms.

Experimental Procedure

A synthetic model oil composed of a mixture of CSP-165 food grade wax and mineral oil at a mass rate of 5/95 is used as the testing fluid. The physical properties of the model oil are presented in Table 1. The operational conditions are maintained constant for all experiments during the formation and removal steps. However, during the removal step, the coolant temperature is changed.

The oil system contains an airtight tank with a capacity of 0.189 m^3. A centrifugal pump propels the fluid with a maximum capacity of $2.2*10^{-3}$ m^3/s into a precision electrical heater responsible for maintaining the oil temperature. A constant oil temperature of 37.8±1.1°C was maintained during the entire experiment.

After the heater, the oil flows through an embedded Coriolis flowmeter (Micro Motion Model F100S), which provides real-time information on the flow rate and density of the oil. As the oil leaves the flowmeter, it is directed to the test section, which allows the flow to enter through valve V1 and exit through valve V2, and reach the tank. The test section specifications are presented in Table 2.

The water coolant and heating systems are decoupled from the oil system. Two refrigerators/heater circulators are used to control the coolant temperature. At the formation stage, the cold circulator (Figure 1)) allows water to flow in a closed loop, entering the test section through valve V3 and leaving through valve V4. The cold circulator operates at a flow rate of $5.5*10^{-5}$ m^3/s and has a maximum capacity of 0.013 m^3.

The wax removal process starts after 95 minutes of wax deposition by redirecting the flow on the bottom channel of the test section from the cold to the hot circulator. Valves V3 and V4 are three-way valves that allow an instant introduction of the hot water into the system to start the wax removal process. The Dynamic Microscopic Facility (DMF) layout is depicted in Figure 1.

The formation and removal were observed under different wall heating temperatures using an optical magnification of 1.5x and recorded at 60 frames per second. The resolution of the recording was 1920x1440. The wall temperature was measured by the use of four Thermal probes (T1-T4) located around the visualization window [7]. The experimental test matrix for this investigation is shown in Table 3.

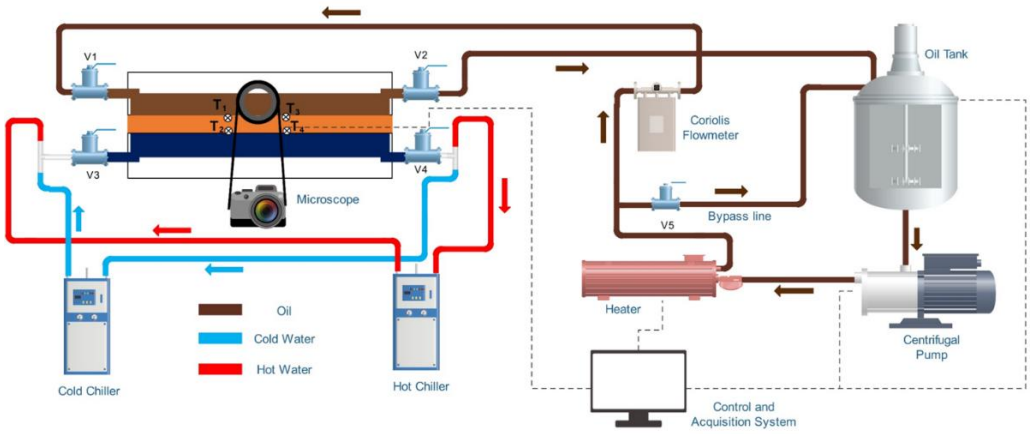

Figure 1: Schematic of the microscopic flow loop facility

Table 1. MO-20 Fluid Properties

Parameter	Value	Method
Viscosity at 37.8°C (cP)	1.23	Rheometer
Viscosity range from 15-60°C (cP)	0.9-7.9	Rheometer
WAT (°C)	32.9±0.1	Differential Scanning Calorimeter (DSC)
Wax content (%)	5	Weighing scale
Density at 37.8°C (g/cm^3)	0.78	Coriolis flowmeter

Table 2. Specification of the test section.

Parameter	**Value**	**Parameter**	**Value**
Oil duct width [cm]	1.27	Length [cm]	56.50
Oil duct height [cm]	3.96	Observation window diameter [cm]	4.00
Water duct width [cm]	1.27	Copper layer thickness [cm]	3.96
Water duct height [cm]	3.96		

Table 3. Experimental Test Matrix

Test #	Test Stage	T_{bulk} (°C)	$T_{coolant}$ (°C)	Re	Time (min)
1	Deposition	37.8	19.4	3975	0-95
	Removal		50.6		95-end
2	Deposition	37.8	19.4	3975	0-95
	Removal		43.3		95-end
3	Deposition	37.8	19.4	3975	0-95
	Removal		37.0		95-end
4	Deposition	37.8	19.4	3975	0-95
	Removal		30.6		95-end

Data Analysis

The dynamic visualization of wax is quantitatively analyzed by direct measurements of representative pictures extracted at different times along the deposition and removal. The details were given in previous dynamic studies of wax deposition [7]. The relationship between the pixel quantity and the actual size of an object was calibrated using known size micrometric graduated glass beads.The average thickness of wax deposits during deposition or removal is calculated by the average of equally spaced deposit measurements, as presented in Figure *2*. Equation 1 summarizes the averaging process.

$$\delta_{avg} = \frac{\sum \delta_{deposit}}{N} \quad (1)$$

Where N is the number of equally spaced measurements taken and $\delta_{deposit}$ is the thickness of measurements. In addition to the thickness, the growth rate over time can be calculated using Eq. (2).

$$growth\ rate = \frac{\delta_{x1} - \delta_{x2}}{t_{x1} - t_{x2}} \quad (2)$$

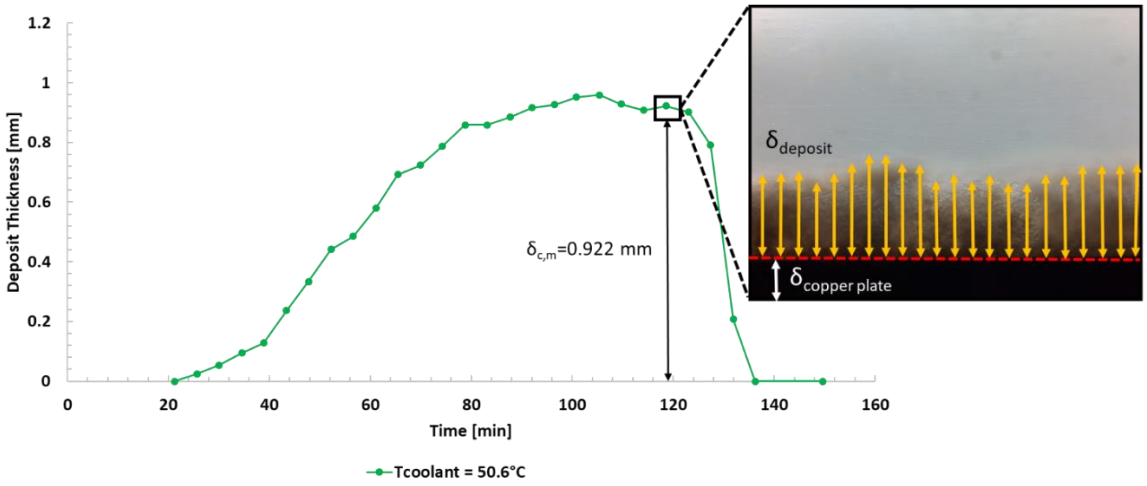

Figure 2: The average deposit thickness measurement at 118.5 minutes after the beginning of the experiment for Toil =37.8°C, Twall= 39.4°C, and Reynolds number equal to 3975.

Results and Discussion

Tests were conducted to investigate the influence of wall temperatures on the wax removal process. Each test consists of a deposition and a removal stage.

The deposition stage for each test had a runtime of 95 minutes. An oil flow rate of $1.9*10^{-4}$ m^3/s was used during the deposition and removal stages, resulting in a Re of 3975. Table 3 shows the removal temperatures used in each test. Figure *3* shows the thickness over time for all experiments, resulting in complete, partial, and no deposit removal depending on removal temperature.

In traditional flow loop experiments, it has been seen that the removal of wax deposits is characterized by a sudden decrease in thickness [5]. It is evident from Figure *2* andFigure *3* that a similar removal process was observed in this set of experiments (Tests 1 and 2). However, the visualization aspect of these experiments reveals the physical understanding of the process.

For the removal stage, starting at the 95-minute mark, the average removal wall temperature was measured for each experiment being equal to 39.4°C, 37.7°C, 35.2°C, and 33.6°C for experiments 1 to 4, respectively. A significant reduction in thickness was observed at the 105-minute in Test 1 and at the 180-minute in Test 2. For Test 3 a different behavior is observed, with the removal taking place gradually after 309-minutes and not reaching complete removal.

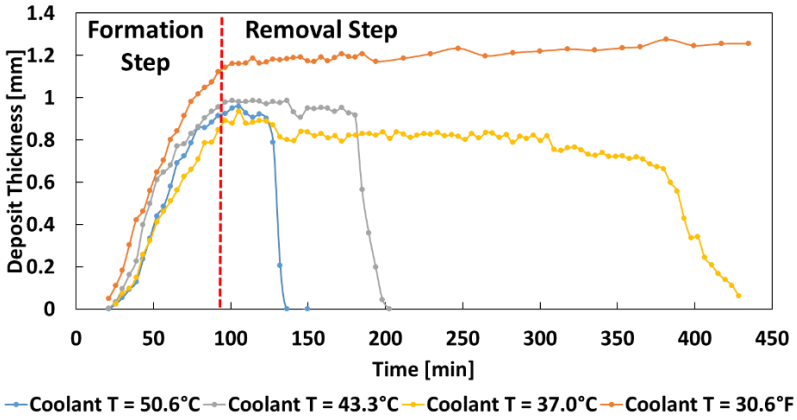

Figure 3: Change in thickness and wall temperature across the test section over time for all four experiments.

In contrast to the three first experiments, Test 4 did not present a significant reduction in the deposit, conserving similar thickness in comparison to the end of the deposition stage even after being exposed to the heated coolant fluid for more than 340 minutes. During the removal period, when the deposit is exposed to heat but removal has not yet occurred, the deposit can be seen to become visually less densely packed with crystals. Such behavior is depicted by the larger intensity of light allowed to pass through the deposits along with time. Even though there is little to no change observed in the thickness of the wax, the reduction in the deposit's opacity is probably attributed to wax crystals within the deposit beginning to melt and diffuse back into the bulk fluid. This can be hypothesized as a counter-diffusion: wax crystals diffuse from the deposit into the bulk fluid, while oil diffuses into the deposit.

This counter-diffusion step eventually leads to the deposit becoming less stable and, therefore, unable to resist the flowing oil's shear forces. This causes the large-scale detachment that occurs. This detachment can be characterized by several chunks of deposit rapidly being removed. These chunks continue to flow through the system until they are eventually dissolved into the bulk fluid. The time required for the detachment step depends on the removal temperature. Higher removal temperatures require less time for the deposit to diffuse.

Conclusions

A bench-scale visualization facility was used to study wax removal. The effect of different removal temperatures in the turbulent flow regime is examined. A two-step removal process is proposed based on observations. The first step is a counter-diffusion process caused by the radial temperature difference between the heated wall and the fluid. Wax crystals melt and diffuse out of the deposit. This leads to the second step of removal, with the deposit becoming less stable and succumbing to the shear forces of the flowing oil due to the deposit being weakened during the first step.

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Responsibility Notice

The authors are the only ones responsible for the paper content.

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