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STUDIES OF PARAFFIN WAX DEPOSITION ON COATED AND NON-COATED STEEL SURFACES

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ABSTRACT

A novel cold baffle wax deposition (CoBWaD) stirred reactor is developed for studying deposition from wax rich hydrocarbon liquids. The reactor consists of a heated jacket to maintain the bulk temperature of the test fluid, and four PVC baffles positioned perpendicular to the cylindrical vessel wall. The baffles have a section with an exchangeable cooled surface. Fouling may thus be studied at different solid surfaces, under variable heat transfer regimes. In addition, due to the wide range of impeller rotational velocities, flow regimes ranging from laminar to highly turbulent are accessible. The apparatus is designed to enable easy and low-cost assessment of the effect of surface coatings, on paraffin wax fouling of cold surfaces.

Fouling results and observations are reported for a binary test-fluid consisting of n-decane (nC10) and n-tetracosane (nC24), on non-coated and coated steel surfaces, for different flow conditions and exposure times.

Parameters affecting wax deposition in the CoBWaD apparatus were coating thickness (wall temperature/heat transfer), flow velocity, and surface properties. Effects of temperature, pressure or test-fluid composition were not investigated.

Evidence is presented that the deposition rate-flow velocity relationship is non-monotonous, and indications are given that the wall heat flux is an important factor in wax deposition. It was also seen that one coating gave an efficient fouling protection while another promoted wax deposition. A third coating, tested at different thicknesses, demonstrated that the insulation effect of the coating layer may be more important than the surface properties.

INTRODUCTION

Petroleum wax crystals and precipitates in crude oil predominantly consist of n-paraffinic components. Wax crystallizes when changes in pressure and/or temperature result in super saturation. Decreased pressure will cause loss of light-end components, which act as natural solvents for the waxes, and decreased temperature gives a decreased solubility of wax molecules in the oil. Paraffin wax fouling of oil production pipelines is a costly and common problem in the petroleum industry. The wax crystallization poses three main problems in the oil industry, higher viscosity, higher yield stress for restarts after shut-in periods, and fouling of solid surfaces such as tubing, pipelines, tanks, process equipment and sucker rods.

In this paper, the focus is on wax fouling of cold surfaces due to decreased liquid temperatures close to the wall. Subsea gas and oil production pipelines may typically be exposed to water temperatures below the wax appearance temperature (WAT), giving crystal and agglomerate formation of wax particles in the bulk and potentially a wax deposition problem. The WAT is defined as the temperature at which wax precipitation takes place and the oil becomes cloudy. Several methods for establishing the WAT exist, (Lira-Galeana and Hammami, 2000), e.g. the standardized ASTM D2500 for petroleum oils and ASTM D3117 for distillate fuels, the cold finger method, viscometry, calorimetry, microscopy, and others. The pour point (PP) is defined as the temperature at which the oil ceases to flow.

In Figure 1 a schematic of the temperature profile of a waxy oil-cold wall system is shown; the temperature steadily increases from the cold side of the wall to the bulk liquid; a solid, but porous, wax layer forms at the cold wall, and the solid wax layer surface is at the pour-point temperature; between the PP and the wax appearance temperature there is a mushy zone of gel-like properties;

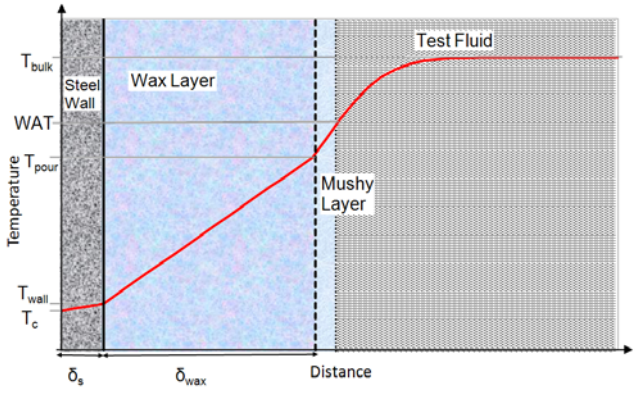


Figure 1. The temperature profile, from the coolant, through the steel wall, through a wax deposit layer, and through the thermal boundary layer of the test fluid. Close to the solid wax layer there is a mushy zone where the temperature is higher than the pour point, but lower than the wax appearance temperature.

beyond the mushy zone, the wax is dissolved in the oil.

Fouling may occur either by wax crystal growth directly on the cold surface (crystallization fouling) or by solid wax particles, precipitating from a supersaturated fluid, being transported to the wall (particulate fouling). To mitigate wax precipitation/deposition related issues, several remediation techniques exist; removal of deposits by mechanical means (pigging) or fouling prevention by heating or chemical treatment (inhibitors) are common techniques, and surface treatment of the pipeline, e.g. by painting/coating, is a method that can provide improved insulation of the pipeline, reduced wall friction and reduced adhesive forces between the wall and the foulant. Finding economically feasible as well as environmentally acceptable solutions have become a key element to development of deep-water petroleum reserves. The literature includes a vast number of published papers on surface treatment, chemical treatment, paraffin thermodynamics, precipitation, transport processes and fouling. Recent reviews on paraffin wax topics include (Azevedo and Teixeira, 2003; Elsharkawy et al., 2000; Lira-Galeana and Hammami, 2000; Merino-Garcia and Correra, 2008; Misra et al., 1995; Paso et al., 2009).

In this work an experimental apparatus is described. The apparatus is designed for testing coatings on solid surfaces, with respect to wax deposition, and experimental results are given from deposition experiments on different types of surfaces under various flowing and heat transfer conditions. The apparatus is an example of a batch experimental apparatus. Several authors (Hamouda, 1993; Hunt, 1962; Jorda, 1966; Newberry, 1984; Patton and Casad, 1970; Wu et al., 2002) have published their results from experiments in similar devices. Zougari et al. (2006) give a short review of the main conclusions of wax (and asphaltenes) deposition studies in batch set-ups (as well as flow-through set-ups).

Wu et al. (2002) performed wax deposition experiments in a Cold Disk Deposition Apparatus using a binary test fluid consisting of n-tetracosane (nC24) and n-decane (nC10). The Wu et al. wax deposition apparatus consists of a cylindrical tank with an impeller in the middle. A cold disk, onto which wax is deposited, is embedded in the cylindrical tank wall. Wu et al. report that the wax deposition results from their apparatus are comparable to those from pipe loop experiments, and that the deposition results using a binary decane-tetracosane mixture are comparable to North Sea crude oil experimental results.

The motivation for designing and building the CoBWaD reactor tank was mainly to have an apparatus where the effects of different surface treatments, with respect to wax deposition, can be assessed. In addition it was desired to study the heat flux and flow velocity/wall shear stress dependency of wax deposition. Key adjustable parameters of the wax deposition experiments are the flow velocity of the test fluid, the test-surface and test-fluid temperatures, in addition to the surface treatment of the test-sections and the duration of the experiment. This study focused on varying the impeller velocity and experiment duration, as well as the surface coating.

THE EXPERIMENTAL APPARATUS

The reactor tank consists of a water heated stainless steel jacket and four PVC baffles positioned perpendicular to the cylindrical vessel wall, as shown in Figure 2. An impeller mounted in the middle of the tank, enables a wide range of flowing velocities and turbulence intensities. The baffles have a section with an exchangeable cooled surface, as is shown in Figure 3. In the current wax deposition experiments coated and non-coated steel test-sections were employed. The test-sections are exposed to coolant flowing through a zigzag patterned cavity in the baffle, making it possible to adjust the test-section wall temperature. Fouling may thus be studied at different solid surfaces, under variable heat transfer regimes, and due to the symmetry of the apparatus and the positioning of the baffles it is possible to perform multiple screening tests in the same experimental run. The coolant temperatures are measured at the in- and outlets of all baffles, giving a measure of the heat transport through the test surface.

The inner tank diameter is 500 mm, and the height is 600 mm. The baffles are 20 mm thick, 170 mm wide and 500 mm tall, and are mounted perpendicular to and 10 mm apart from the vessel wall, to avoid direct contact with the

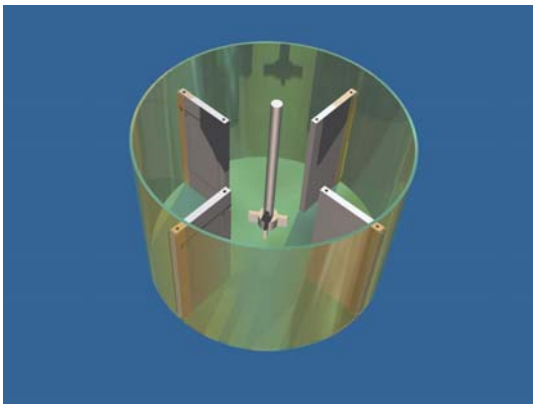


Figure 2. The CoBWaD apparatus, a cylindrical reactor tank with a water heated jacket, four water cooled baffles and a centrally positioned impeller.

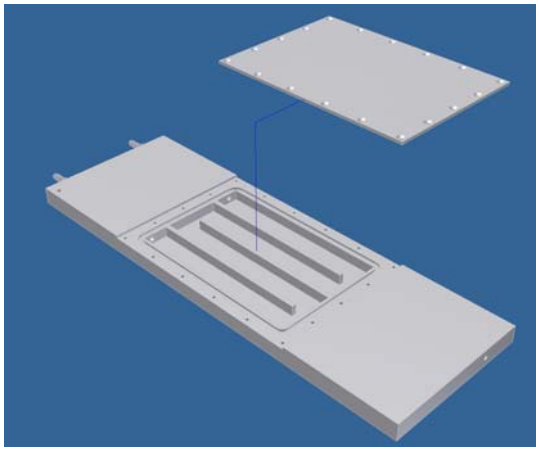


Figure 3. Schematic of a baffle with a water cooled, exchangeable test surface.

heating jacket. The exchangeable steel test-sections are 3 mm thick, 170 mm wide and 240 mm tall, and they are attached in the middle of the baffles using 18 screws along the edge. A rubber o-ring prevents the coolant from contaminating the test-fluid. The test-section area directly exposed to the coolant measures 130 by 200 mm^2.

The impeller consists of four flat blades mounted vertically, in an x configuration, onto the circular axle. The Rotor blades are 20 mm thick and 200 mm tall, and the rotor diameter, including the blades and the axle, is 100 mm. The rotor- baffle spacing thus becomes 20 mm. The rotor is mounted 15 cm from the bottom of the vessel, such that it is level with the water cooled test sections. The impeller rotates so that the test-fluid is pushed towards the cooled test-section giving a high wall shear stress at the test surface.

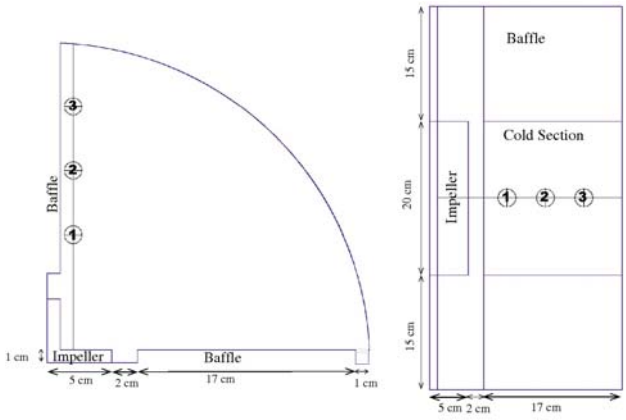
Resting on top of the baffles, there is a lid to avoid splashing and to minimize evaporation of the test fluid. The apparatus is, however, not pressurized at the current stage. The baffles and the impeller are mounted in a submersible framework, thus it is easy to lift them in and out of the test fluid. Deposited material is easily and quickly removed from the test-sections by lifting the baffles out of the test fluid. Hence, additional accumulation of wax on the test-sections after the test is finished is minimized.

CFD SIMULATION OF THE COBWAD APPARATUS

Simulations of the internal flow of the CoBWaD geometry were performed in the commercially available CFD code Ansys Fluent 6.3 to evaluate the heat transfer and flow velocities in the apparatus, as the impeller rotational velocity was varied. A Multiple Reference Frame approach was employed to capture the impeller-test-fluid interaction. A cell zone surrounding the impeller only was separated from the rest of the tank interior, to hold the rotating reference frame. Due to the symmetry of the problem, only one quarter of the apparatus was modeled. A range of different impeller velocities were employed to study the effect on liquid velocity homogeneity and magnitude close to the test section, the wall heat flux and the homogeneity of temperature in the test-fluid. The standard k-ε turbulence model was employed.

Impeller velocities of 200, 400, 600, 800 and 1000 rpm were studied. Liquid velocities were recorded in a plane placed 1cm away from the baffle, as indicated in Figure 4. The locations are 25 cm from the bottom, at 1) 10 cm, 2) 15 cm and 3) 20 cm distance from the centre axis. In Figure 5 it is seen how the test fluid velocity increases linearly for increasing impeller velocities in the three specific locations indicated by circles in Figure 4.

The simulations reveal that the flowing pattern does not change significantly by varying the impeller rotational velocity, although the velocity magnitude changes. In Figure 6, velocity vectors colored by velocity magnitude are shown for impeller rotational velocities of (a) 200 rpm and (b) 1000 rpm, and in Figure 7 velocity contours and vectors are drawn on the vertical plane 1 cm outside the test section. The flow pattern is essentially the same for the 200 and 1000 rpm models. It can be seen that although the flow direction along the test sections is fairly homogeneous, the velocity magnitude is much higher in the middle of the test section than along the edges. In the actual experiments, however, only occasional topographical variations in the



(a) Top view. (b) Side view.

Figure 4. One quarter of the experimental apparatus. Simulation velocity measurement plane and locations.

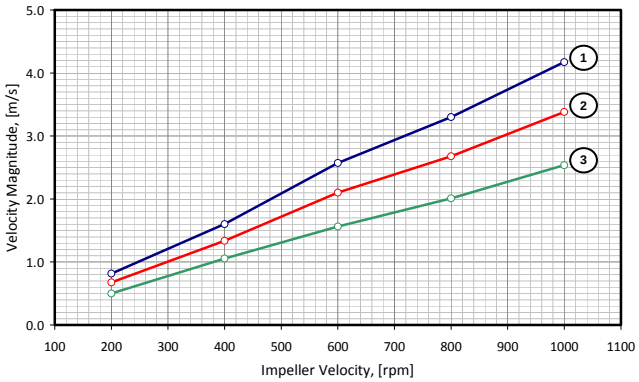
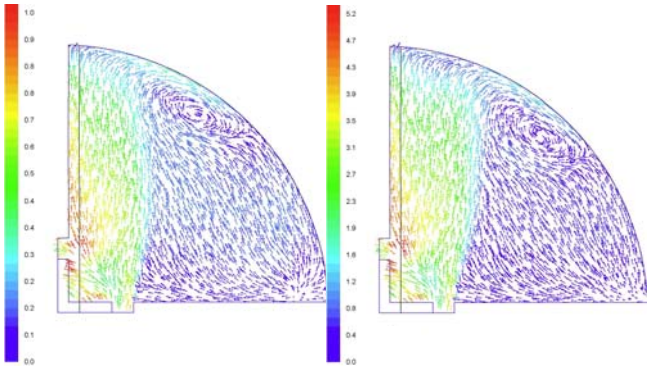
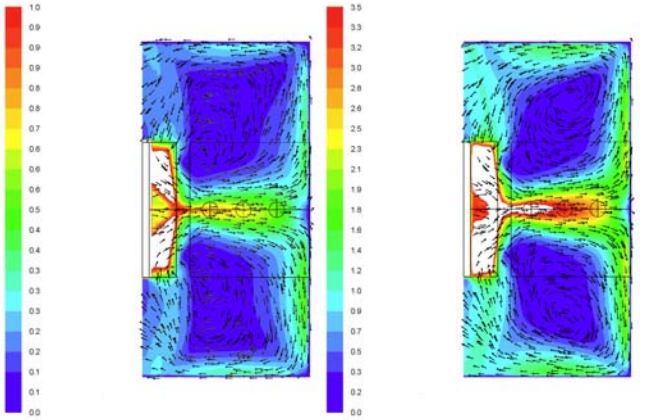


Figure 5. Test fluid velocity as a function of position and impeller velocity. The velocities are taken 1 cm outside the cooled test section, as indicated in Figure 4.



(a) 200 rpm. (b) 1000 rpm.

Figure 6. Simulation velocity vectors, in the horizontal symmetry plane, colored by velocity magnitude (m/s), for 200 and 1000 rpm impeller rotational velocities.



(a) 200 rpm. (b) 1000 rpm.

Figure 7. Simulation velocity contours (m/s) and directional vectors 1cm outside the test section, for 200 and 1000 rpm impeller rotational velocities.

deposit layers were observed, and no further investigation of the deposit layer thickness distribution was performed.

TEST-FLUID

Following Wu et al. (2002), the deposition experiments were performed with a binary test-fluid consisting of a paraffinic solvent, Sigma-Aldrich n-decane ($CH_3(CH_2)_8CH_3$) of Reagent Plus (99+ %) purity, and a paraffin wax solute, Aldrich n-tetracosane ($CH_3(CH_2)_{22}CH_3$) of 99 + % purity. The n-tetracosane content in the test-fluid was ca. 6 wt.-%, and the WAT was at ca. $15^{\circ}C$. In the following, we will refer to the tetracosane as wax and the decane as oil.

COATINGS

In addition to bare steel surfaces, three different coatings were tested. These are referred to as coatings *1*, *2* and *3*. Coating *1* was an industrial prototype; Coating *2* was a commercially available flow-coating; Coating *3* was developed as part of this study. The coating thicknesses are reported in Table 1. The coatings were applied to st52 steel.

Coating 1 was a slightly hydrophilic (80° water droplet contact angle) coating that was tested in two different thicknesses. In addition, the coating was modified by adding 3 wt.-% commercially available nano-particles, to make it slightly hydrophobic (100° contact angle), and tested at an intermediate thickness. We will refer to these coatings as *1.thick*, *1.thin* and *1.mod*, respectively. The *1*-coatings were applied to the steel sections by paintbrush, resulting in an unpredictable thickness with a high macro roughness. The thickness was measured by an *Elcometer 256FN T2 Coating Thickness Gauge.*

Coating 2 was applied to the steel test-sections by spray by the manufacturer, giving a very smooth and uniform coating layer.

Coating 3 was an inorganic-organic hybrid coating based on (Aldrich) aminopropylsilane (Männle et al., 2005), with a water-silane ratio of 1.6 and a solvent-silane ratio of 6. The coating was applied to the test-sections by dipping into a bath of the aminopropylsilane based sol. The coating was thermally cured in air, at 160°C for three hours, and the coating thickness was measured by a *Veeco Dektak 150 profilometer*.

Table 1. Coating thicknesses for the coatings applied in the wax deposition experiments.

	Coating Thickness [µm]				
Coating	*Baffle 1*	*Baffle 2*	*Baffle 3*	*Baffle 4*	*Avg*
Bare Steel	0	0	0	0	0
1.thin	66± 8	60± 20	68± 7		65
1.mod	281± 63	194± 23	169±16		215
1.thick	563±148	526±105	426±96		505
2	75± 5	75± 5	75± 5		75
3	0.4±0.01	0.4±0.01	0.4±0.01		0.4

EXPERIMENTAL METHOD

During the deposition experiments, the test fluid was kept at a constant temperature above the WAT, by the heating jacket. The test-sections were kept at a low temperature by the cooling circuit. We have no knowledge of the actual wall temperature, but the coolant temperature was measured at both the in- and outlets of each baffle. The increase in temperature from the in- to the outlet is a measure of the amount of heat going from the test fluid through the test section wall. In all the coating tests, the Baffle 1-3 coatings were identical, while Baffle 4 was kept uncoated.

The different phases of the experiments are;

1. *Heating phase:* The test-fluid is heated to a temperature well above the WAT ($\sim 20^{\circ}C$) under a high impeller velocity (750 rpm).
2. *Cooling phase*: Cooling of the baffles is commenced, at $8^{\circ}C$ inlet temperature. The test-fluid temperature is reduced to the desired set point of $15.5-16^{\circ}C$ while maintaining the high impeller velocity, to avoid deposition.
3. *Deposition phase:* When stabilized at the desired test-fluid temperature, the impeller velocity is reduced to the desired value, to allow for deposition.
4. *Recovery phase:* After the specified deposition experiment duration, the baffles are lifted out of the test-fluid, and after a five minute period of evaporation/drainage, the deposits are collected from each baffle.

The deposits were harvested after three different deposition phase durations (exposure times), 60, 30 and 15 minutes.

Experiments were performed with three different impeller velocities (150, 250 and 350 rpm), but the fouling of the coated surfaces, for the 350 rpm velocity, was miniscule and is reported only for bare steel.

In Figure 8, the temperature log from an experimental run is shown; the bulk test-fluid temperature is shown along with each baffle in- and outlet temperatures for all the experimental phases, for a specific impeller velocity. The

different experimental phases can be recognized in the temperature plot.

EVALUATION OF THE DEPOSIT LAYER

To evaluate the amount of wax deposited, several methods have been suggested. Chen et al. (1997) give a review of existing methods; these include indirect measurements by pressure drop or temperature (heat transfer) measurements, their own method, the Liquid Displacement-Level Detection Method, as well as direct measurements by weighing. In addition a method using ultra-sound has been proposed by Andersen et al. (1997). Most of these are developed for pipe-flow experiments but could be adapted to the current experiments.

Indirect deposit layer thickness measurement by monitoring the baffle coolant outlet temperature, initially seemed like an attractive method, but the outlet temperature decreased too rapidly and fluctuates too much to reveal the transient behavior due to deposit layer growth. In Figure 9 the outlet-inlet temperature difference of the four baffles are shown at the end of the cooling period (2), as the deposition phase (3) begins. Baffles 1-3 were coated while Baffle 4 was non-coated. It can be seen that this results in a higher outlet temperature for Baffle 4 than the others, due to the thermal insulation of the coating, during the cooling phase, where no deposits are forming. As the impeller velocity is reduced, and the deposit layer is allowed to form, the Baffle 4 temperature difference immediately drops and becomes close to the Baffle 1-3 outlet temperature differences. In agreement with the hypothesis of Figure 1, this indicates that a wax deposit layer immediately forms, so that the surface temperature is at the pour-point temperature, and that the combined thermal insulation effect of the deposit layer and the coating is identical for all baffles. It is therefore proposed that the transient behavior of the deposit layer consists of near-instantaneous deposit layer formation/re-entrainment, giving the temperature fluctuations seen in Figure 9, in addition to a hardening effect due to the increasing deposit layer wax-to-oil ratio.

The deposits were removed from the test-sections by mechanical scraping, as shown in Figure 10. The harvested deposits were weighed and analyzed by gas chromatography (GC) to establish the amount of wax deposited.

EXPERIMENTAL RESULTS

The experimental results are reported as either amount of wax, in grams, accumulated on the test-sections or as an *average deposition rate* (amount of wax harvested divided by exposure time), in grams per minute. The amount of wax was calculated based on the mass-fraction obtained by GC and the mass of deposits removed from each baffle.

Due to the high number of experiments performed and the high number of curves produced, only a few representative curves are presented here.

By visual inspection, the deposit layer forming on *Coating 2* had quite different characteristics from the deposit layers forming on the other surfaces. Whereas the deposit layer forming on bare steel or Coatings *1* and *3* was

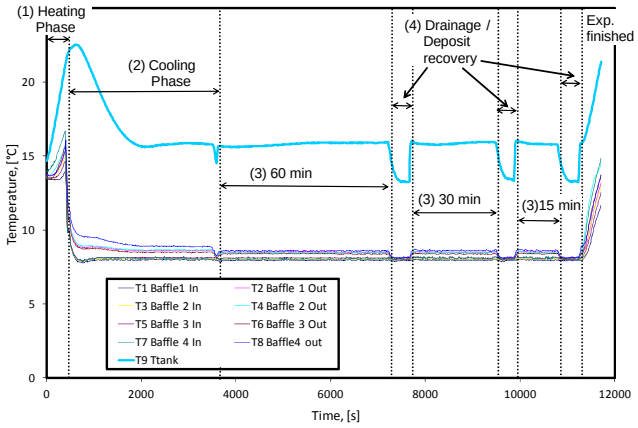


Figure 8. Temperature log from a wax deposition experiment. The different phases of the experiment are influencing the temperatures and are evident in the temperature plot. The different phases are (1) an initial *heating phase* to dissolve any residual wax deposits in the apparatus; (2) a *cooling phase* to reach the target bulk temperature; (3) wax *deposition phases* (60min, 30min, 15min) separated by (4) *drainage/recovery phases*.

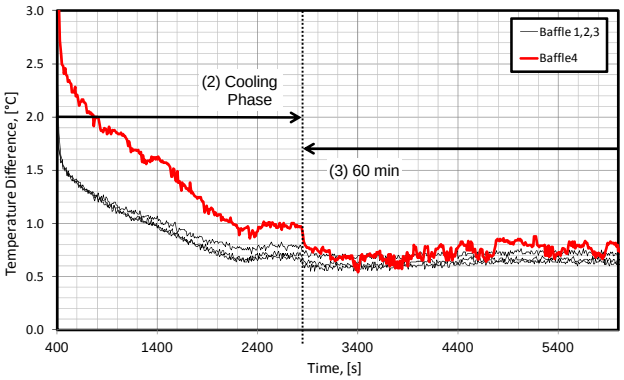


Figure 9. Outlet-inlet temperature difference versus time, during the *cooling phase* and 60 min *deposition phase* for baffles 1-3 (black) coated with *Coating 1.mod*, and non-coated bare steel Baffle 4 (red).

Figure 10. Mechanical removal of wax deposit layer from a cold bare steel test-section.

moist and porous, the deposit layer forming on *Coating 2* seemed drier, denser and brittle. The GC analyzes revealed that the wax content in the *Coating 2* deposits were more than twice the amount in the other deposits.

Velocity Dependency

For the bare steel and *1*-coatings, the amount of deposits increased for decreasing impeller velocities, independent of the exposure time. *Coating 3* followed the same trend as the bare steel and Coating 1, but it was less affected by the exposure time, so that the longer the exposure time the better it performed, with respect to fouling prevention, compared to the others. For *Coating 2*, however, it was observed that the amount of wax deposits was increasing with the impeller velocity, as seen in Figure 11.

Exposure Time Dependency

For the bare steel and *1*-coatings it was evident that the amount of deposits increased for increasing exposure times, but *Coating 3* had a very weak exposure time dependency. *Coating 2* gave an increased amount of deposits, with time, for 250 rpm, but a decreased amount for 150 rpm.

Deposit Layer Aging

In the literature it is reported that the wax deposit layer is subject to an aging effect; e.g. Wu et al. (2002) demonstrate that the tetracosane content in the deposit layer increases with time. Singh et al. (2000) explain how the porous wax deposit structure, saturated with solvent, gradually hardens as wax molecules diffuse into the porous structure and oil counter diffuses out of the deposit layer, resulting in a time-dependent composition of the deposit.

In the current experiments it was seen that the influence of the flow velocity decreased with increasing exposure times, as the deposit amount seemed to approach a steady state. Furthermore it was seen that the GC-reported deposit wax content was increasing for increasing exposure times. Since we do not have control of the *drainage phase* evaporation and drainage of oil, however, the deposit layer wax content is uncertain.

Coating Thickness Dependency

Since Coating 1 was tested in three different thicknesses, we had the opportunity to study the effect of the coating thickness on the deposition of wax. In general, one would expect that a thicker coating will give a higher wall temperature, resulting in a thinner deposit layer; ultimately, a thick coating may raise the wall temperature above the pour-point. In Figure 12, evidence of the coating thickness dependency is shown. In fact, it seems that the coating thickness is more important, for *Coating 1* than the modification of the wetting properties.

Wall Heat Flux Dependency

The baffle inlet-outlet temperature increase is a measure of the heat-flux from the test-fluid to the coolant. An explanation for the apparent coating thickness dependency of the deposition rate might be that the wall heat flux is impeded by the coating layer, suggesting that the deposition rate is a function of the wall heat flux. In Figure 13 the average deposition rate is shown as a function of average wall heat-flux for the bare steel and *Coating 1*

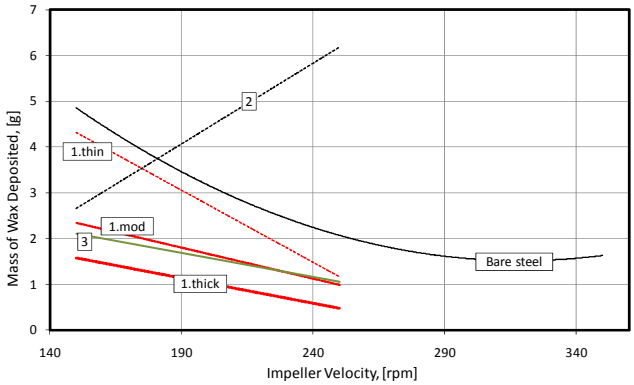


Figure 11. 2nd order polynomial trend-lines for measured amounts of wax deposit recovered after 30 minutes exposure time, as functions of impeller velocity (rpm), for bare steel (solid black), *1*-coatings (red), *Coating 2* (dashed black), and *Coating 3* (green).

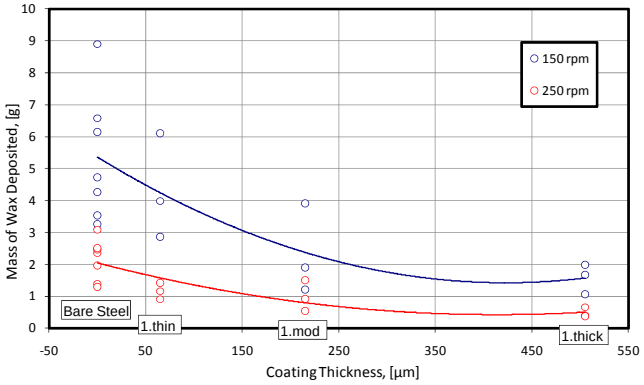


Figure 12. Measured amounts of wax deposit recovered, on bare steel and the *1*-coatings, with 2nd order polynomial trend-lines, after 30 minutes exposure time as functions of average coating thickness (µm), for different impeller velocities (rpm).

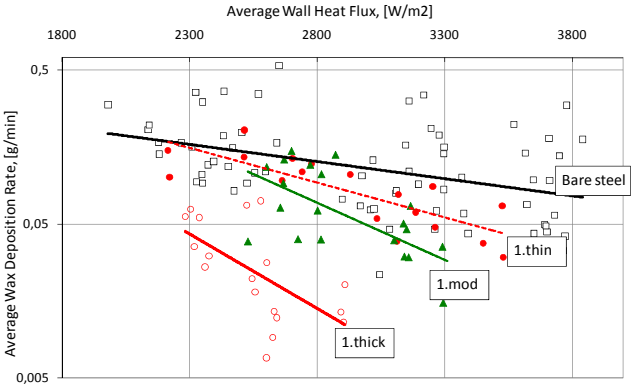


Figure 13. Measured average wax deposition rates, with exponential trend-lines, as functions of the average wall heat flux, for bare steel and the *1*-coatings.

surfaces. The average deposition rate is the total amount of wax collected, for each baffle, divided by the exposure time. The average heat flux is based on the time average of the baffle in-/outlet temperature difference, the coolant flow rate, the coolant mass density and heat capacity, and the test section area.

The wall heat flux depends on the bulk and wall temperatures, the over-all wall heat conductivity, and the flow velocity. Thus, the heat flux dependency of the deposition rate may be masked by these factors.

DISCUSSION

The CoBWaD reactor tank is a novel apparatus for studying wax fouling on cold surfaces. The apparatus is designed to study the relation between wax deposition rates, surface properties, wall shear stress and heat flux. In this way we can learn about these fundamental relations that are expected to be largely independent of the flow geometry as long as the flow is fully turbulent. Although the apparatus is not directly comparable to field-scale pipe flow, the apparatus has some advantages over traditional flow-loop experiments; small liquid volumes are required; the test-surfaces are easily accessible and exchangeable; a wide range of turbulence regimes are easily accessible at no additional cost; there is no need for extensive compressor power; good temperature control of the bulk test-fluid and walls is achieved; an experimental series is typically performed in a matter of hours; low building and maintenance costs. In the present design, the main disadvantages are that neither the flow velocity nor the heat transfer rate is homogeneous across the test-surfaces; we cannot measure the flow velocities; we cannot measure the wall temperature; and there is no possibility of performing pressurized experiments.

Ideally, to ensure experiment repeatability, each baffle should give the same amount of deposit, under the same conditions, and also give the same amount of deposit if the experiment is repeated. Currently, no repeatability studies has been done for baffles 1-3, but for all experimental runs, Baffle 4 was kept non-coated, for reference. Thus, the Baffle 4 data give insight into the repeatability. The scatter is significant, even between identical surfaces (bare steel), in the same experiment. Due to the turbulent nature of the experiment, reproducibility is not expected on individual experiment basis, but it is expected that a stable ensemble average will be established after a large number of experiments is performed. Although not enough experiments have been run, it can be seen that the cumulative moving average amount of deposited wax is fairly stable. As is seen in Figure 9, the outlet-inlet temperature difference, which is a direct measure of the heat transfer through the test-sections, is oscillating in a stepwise, erratic manner. It is believed that this is due to the variations in the over-all heat transfer coefficient, of the test-section, because of sudden re-entrainment of chunks of deposits. It is thus evident that the resulting "amount of wax deposited" is strongly dependent on the timing of the harvest relative to the oscillatory amount of wax deposited.

By visual assessment of the wax layer, it seemed that there was a difference in the way the wax layer was growing on the bare steel and the coated surfaces. Whereas the bare steel wax layer seemed quite homogeneous and smooth, patches of wax were growing on the coated surfaces. If the wax-wall adhesive forces are weak, wax molecules will not easily attach to the wall, to build the first layer of wax molecules. When some wax molecules have attached, however, more wax will readily grow on the existing wax deposit. Thus, patches of wax deposit may grow from separated nucleation sites. Eventually, the patches may cover the entire surface.

Net deposition rate will generally increase with increasing flow velocity until a point where the wall shear stress becomes so great that the re-entrainment rate becomes similar, in magnitude, to the gross deposition rate. After this point, the net deposition rate will decrease for increasing velocity, such that there is a critical velocity/shear stress for which a maximum net deposition rate exists. This point will, in general, depend on the surface properties (adhesive forces between deposit and wall), deposit material yield strength and thickness, and the temperature gradient. Thus, the critical velocity will depend on the surface treatment/coating employed, since this will affect both the deposit-wall adhesion force and the wall heat flux/temperature gradient. If *Coating 2* has a significantly higher critical velocity than the other test surfaces, such a non-monotonous behavior versus flow velocity may explain why the *Coating 2* deposit amount increases with impeller velocity, while the deposit amount decreases with velocity on the other test surfaces.

For *Coating 1* it seemed that the effect of coating thickness and thermal insulation was more important than the wetting property modification, but it is evident that surface properties also play a role. For the extremely thin *Coating 3*, for which the wall temperature is expected to be equal to that of bare steel, a significant improvement in the fouling prevention was observed, implying a strong effect of the surface properties, on the deposit growth.

The coating thickness affects the wall heat flux, and it was shown in Figure 13 that there is a relationship between the deposition rate and the wall heat flux. It is evident, however, that also the wall temperature is of importance, else the *1.thick* and *1.thin* curves in Figure 13, would have coincided. Future studies should consider the coating thickness and roughness as experimental parameters, and better control of thickness/roughness/wall temperature and heat flux should be enforced to yield conclusive results on the significance of surface properties.

The current studies have shown that factors directly affecting the deposit growth are flow velocity, coating thickness, and surface properties. It was seen that at high enough flow velocities, deposition was avoided, and indications were given that the deposition rate-flow velocity relationship is non-monotonous. The coating thickness will affect the wall temperature and the wall heat-flux. It was seen that there is a relationship between the deposition rate and the wall heat flux. Although the effect of bulk and wall temperatures have not been studied, it is reasonable to

assume that these are also important contributors to the deposition mechanism. Finally, it was seen that the surface properties may alter the deposition regime significantly, by both increasing and decreasing deposition. It was seen, however, that an initial improved fouling prevention is forfeit as soon as the deposit layer starts to grow, as *Coating 1.thin* had a delayed deposition problem, but caught up to the bare steel surface with time.

There are still many things we do not understand about the wax deposition mechanism and how the use of coatings may inhibit, or even promote, wax deposition. To what extent are thermal insulation, surface roughness, and surface activation energy responsible for wax deposit reduction? Open questions are if the focus should be on hydrophilicity or hydrophobicity, or if other surface properties such as lipophobicity or oleophobicity are more relevant. Further questions concern the structure/ morphology of the wax deposits as parameters like flow velocity, wall heat flux or surface properties are changed, and how these affect the adhesion of the wax.

CONCLUSIONS

1. A novel apparatus has been designed to study wax deposition from wax-rich hydrocarbon oils onto cold surfaces when subject to a constant bulk temperature above the wax appearance temperature, and flow velocity. The test-surfaces are easily exchanged, so that deposition onto different types of surfaces may be studied.
2. Due to the stochastic nature of deposition under turbulent conditions, experimental repeatability is not to be expected on individual scale; a large number of experiments should be performed to establish ensemble averages.
3. Although measured data are subject to severe scatter, clear trends have been observed.
4. The current studies have shown that the factors directly affecting the deposit growth are flow velocity, coating thickness, and surface properties.
5. While a decreasing deposition rate for increasing flow velocity was observed for the majority of the surfaces tested, one of the coatings had the opposite behavior. Furthermore, at high flow rates no deposition occurred on any of the surfaces. Thus, the deposition rate-flow velocity relationship is non-monotonous.
6. An aging effect has been observed in the sense that the accumulated amount of deposit increases with time. Preliminary results indicate that the amount of deposit approaches a steady state, and that the wax content in the deposit layer is increasing with time.

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