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IN COOLED HEAT EXCHANGER TUBES

T. R. BOTT AND J. S. GUDMUNDSSON
BIRMINGHAM UNIVERSITY
Birmingham, U.K.

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CSME: Suite 700, 2050 Mansfield Street, Montreal, Quebec
H3A 1Y9

DEPOSITION OF PARAFFIN WAX FROM KEROSENE IN COOLED HEAT EXCHANGER TUBES

by

T.R. Bott and J.S. Gudmundsson
Chemical Engineering Department, Birmingham University,
Birmingham B15 2TT

ABSTRACT

Studies of the deposition of wax from wax/kerosene mixtures onto cooled simulated heat transfer tubes has demonstrated that, following an initial deposition taking a relatively short period of time, the heat transfer resistance fluctuates with time.

Theoretical estimates of temperature distribution in the experimental flowing wax/kerosene system suggest that the cloud point temperature of the mixture falls within the laminar boundary layer. Since the cloud point is considered the temperature at which particles of wax appear, the conditions within the boundary layer will influence deposition. Increased flowrate and temperature decrease the number of particles able to deposit while the number is increased by greater wax concentration in the bulk solution.

INTRODUCTION

In petroleum oil processing the deposition of paraffin wax, or similar substances, from hydrocarbon liquids is an important consideration. Not only does this give rise to problems in pipe lines but in other equipment such as heat exchangers, where hot solutions are being cooled, resulting in efficiency and resistance to heat transfer.

It is of interest therefore to examine the effects of deposition on the rates of heat transfer under specified conditions. A knowledge of the extent of this fouling and the mechanism by which the foulant arrives at the heat transfer surface will be important in design considerations.

EXPERIMENTAL WORK

In order to investigate the phenomenon of wax deposition from cooled solutions and to measure changes in heat transfer resistance a special apparatus was designed and operated.

Briefly the equipment consisted of ten simulated heat exchanger tubes of copper 13.1 mm I.D. and 15.00 mm O.D. having an entry length of

762 mm with a further water jacketed section 914 mm long. The water jacket was made from 0.75 in I.D. pipe. The tubes were mounted vertically between horizontal inlet (bottom) and outlet (top) manifolds. Wax/kerosene mixtures were pumped from a steam heated storage tank of 2660 litres capacity up through the tubes and back to the storage tank. The tank was thermally insulated and temperature controlled. Clean cooling water was passed at high flow rate from the main through the jacket to drain.

Inlet and outlet temperatures of the experimental solution and cooling water were measured with mercury in glass thermometers calibrated in 0.1°C divisions. Flow rates were measured by previously calibrated orifice meters. In all tests the experimental conditions were such that the bulk temperature of the solution was always above the cloud point of the test solution. After adjustment of conditions, temperatures and flow rates were recorded every three hours during the day although no readings were taken during an eight hour period of the night. The apparatus ran for up to 240 hours. At least five tubes had to be operated at a time in order to remove the heat generated by the pump.

Tests showed that the amount of paraffin wax dissolved in the kerosene had negligible effect on specific gravity. The viscosity of the solutions were measured in a capillary viscometer. Because kerosene and paraffin wax are similar in chemical nature, the specific heat and thermal conductivity of kerosene can be used with reasonable accuracy for the solutions examined in the present studies. The physical property data used in the subsequent calculations were based on those obtained by Walker¹ and the equations summarized in Table 1.

The solubility of the paraffin wax in kerosene was assessed by the standard cloud point method² and the pour point was also determined from a standard method³. For a given concentration the pour point was found to be 3-4°C below the cloud point.

The commercial grade kerosene used in the experiments was quoted as having a specific gravity of 0.780 at 15.5°C and a flash point of 55°C. The wax used in the studies was 51/54°C fully refined wax.

Table 1. Equations used for physical property data

Property	Equation
Viscosity	$\log \log (\nu + 0.953) = \alpha \log T + \beta$ ν is kinematic viscosity. cS T is temperature °K Constants α and β depend upon concentration.
Thermal conductivity	$k = (8.69 - 0.0045T)/100$ k is thermal conductivity B.T.U./in.ft.°F T = temperature °C
Specific gravity	$S = 0.7962 - 0.000729T$ S is specific gravity T is temperature °C
Specific heat	$C_p = 0.4038 + 0.00162T$ C_p is specific heat B.T.U./lb°F T is temperature °C

Note: The specific gravity and specific heat corresponds to an oil with an A.P.I. gravity of 50.4°C.

THE RESULTS

As an indication of the change of fouling resistance with time, the overall heat transfer resistance was determined experimentally at different stages throughout a run of constant conditions. The overall resistance was used as criterion since the resistances to heat flow the water side and through the metal wall, are low in all runs. For a given set of experimental conditions the heat transfer resistance to the flowing kerosene/wax solution is constant and the resistance through the wax layer will be larger and likely to be changing. Changes in the overall resistance therefore reflect changes in the fouling resistance.

A typical plot of the variation of overall heat transfer coefficient with time is shown in Figure 1. It would seem that the foulant wax layer rapidly builds up in less than two hours (see later discussion) to give a fluctuating resistance, about some mean value. The corresponding average clean resistance is shown on Figure 1; the effects of the foulant layer are apparent. It is at the high values of wax concentration (26 per cent) that the fluctuations in overall resistance are pronounced.

These observations are in agreement with previous work^{4,5}. Measurements with this particular apparatus were not capable of demonstrating the shape of the curve of change in heat transfer resistance with time for the initial period of under two hours.

The overall heat transfer resistance is, in itself, of little value to designers and operators of heat exchange equipment; of much more significance is the actual value of the fouling resistance. It is therefore necessary to estimate the values of the other resistances (water side, copper wall, and kerosene side) for the experimental conditions and subtract these from the overall resistance. There was no evidence of fouling on the water side; the cooling water was pure soft town's water on a "once through" basis. It is known that equations of the Dittus Boelter type including the E.S.D.U. correlation⁶ predict heat transfer coefficients which are about 10% lower than those determined experimentally for commercial tube⁷. A correction of this magnitude has been included in calculating the water and kerosene side "film coefficients" in order to give a realistic value. The tubes in the apparatus are "as purchased" commercial tube, therefore, this assumption is satisfactory for the water side. Clearly there could be argument about the validity of the correction for the kerosene side i.e. in relation to the surface of the wax deposit, but in the absence of accurate data on actual wax surface roughness the heat transfer resistance on the kerosene side has been reduced by 10% to provide a better estimate of the true conditions. The assumption is not without some supporting qualitative evidence; from a preliminary examination of the wax layer⁸ and in the light of the effects of other deposits⁹. The mean value of the "equilibrium" fouling resistance i.e. after the initial development of the wax layer, has been calculated by this method.

The data are summarized in Table 2 and some of these data are plotted on Figure 2. The results demonstrate the intuitive observation that fouling increases with wax concentration and decreases with increasing velocity (Reynolds Number).

In order to study the initial fouling period a small apparatus was constructed basically similar to the large equipment except that, in a plastic test section a removable copper plate (2 x 10 cm) separated the kerosene and water flows. The rate of wax deposition was measured by weighing the plate and associated wax deposit at different intervals of time. In general the results show a steady increase in deposit over a relatively short time. Figure 3 is a typical example and confirms that within two hours the wax deposit reached its "equilibrium value".

DISCUSSION

Although the experiments have shown that, in the deposition of wax from kerosene onto cooled surfaces, there is a rapid build-up to an "equilibrium" heat transfer resistance of some magnitude, it would be of interest to have some conception of the mechanism of deposition. Since

the solubility of the wax in kerosene is temperature dependent and a cooling operation is being examined the temperature distribution within the kerosene/wax mixture as it flows across the cooled surface will be important.

Knudsen and Katz¹⁰ report the Deissler¹¹ predictions for temperature distribution in a channel as follows:-

Defining y^+ the dimensionless distance as

$$\frac{u^*y}{\nu_w}$$

u^* is the shearing stress velocity

y is the distance

ν_w is the kinematic velocity at the wall

Away from the wall where $y^+ > 26$

$$T^+ = \frac{1}{K} \ln \frac{y^+}{y_1^+} + T_1^+$$

T^+ is dimensionless temperature

T_1^+ is dimensionless temperature at y_1^+

y_1^+ is dimensionless distance

K is a constant

Near the wall where $y^+ < 26$

$$T^+ = \int_0^{y^+} \frac{c_p y^+}{Pr \frac{1+n^2 u^+ y^+}{\mu} \left\{ 1 - \exp\left(-n^2 \frac{\mu_w}{\mu} u^+ y^+\right) \right\}} dy^+$$

Pr is the Prandtl number

n is a constant

μ is the viscosity

μ_w is the viscosity at the wall

Properties evaluated at the tube wall temperature.

Using an iterative procedure a computer programme based on these equations was written⁸ to make the calculations and subsequent analysis. In the analysis it was assumed that the equations apply to the wax/kerosene mixture, under the same conditions of the experiments i.e. to Reynolds numbers as low as 4500. A further limitation on the calculations was imposed by the use of average values in the computer program; this was necessary because of the fluctuating nature of the deposition.

In the data required by the computer program where one temperature was unknown, the "wall temperature" T_w . Reynolds number and inlet and outlet temperatures were determined experimentally in the preliminary studies as already described. In the present analysis the wall temperature T_w was considered as being the temperature of a surface that represented the effective boundary of a flow in a channel. For a given experimental run the average solution bulk temperature was determined. By

adjusting the wall temperature in the calculations a temperature profile could be produced corresponding to the real distribution and compared to the average bulk temperature.

From the total runs obtained in the work some six runs were selected, covering two bulk temperatures and a range of Reynolds numbers. The particulars are given in Table 3. A typical graph of the data (for one particular run) is shown on Figure 4. The results show that, if the selected wall temperature is equal or close to the solution cloud point, the calculated temperature profile corresponds well with the experimental bulk temperature. The cloud point was therefore the temperature of that surface representing the effective boundary to the flow in the tube passage. The pour point of 51/54°C paraffin wax in kerosene being 3-4°C below the cloud point meant that a thin boundary layer suspension or slurry existed. The above would only be true where the difference between the cooling water temperature and the cloud point was great enough to allow the latter to be reached in the boundary layer on the solution side.

A qualitative physical model of the paraffin wax deposition process could be based on the results; it is shown in Figure 5 as an ideal temperature profile across the wall of a cooling studies heat exchanger tube. In this Cloud Point Model wax crystals or particles, will be formed within the laminar layer, at the cloud point temperature interface and they then either move across the shear field into the bulk of the solution to be redissolved, or move to the cold wall and deposit. Under the conditions the wax particles will follow the well known behaviour for particulate deposition within the boundary layer.

When a wax deposit has increased its thickness to some critical value, a cohesive failure within it is possible at some plane of weakness in the matrix structure, when part of the layer is shed and is carried away by the liquid flow. Build-up and removal of foulant in this way is the most likely reason for the fluctuating nature of the heat transfer resistance. The amount removed at any one time is considered to be only part of the total deposit. The failure mechanism is further complicated by the presence of the liquid kerosene which, particularly in the outer layers of deposit where the temperature approaches the cloud point, will produce a weak "mushy" deposit.

It has been shown how deposition at asymptotic conditions decreases with increased flowrate (see Table 2). Since both heat and mass transfer rates increase with flowrate, in contrast to deposition, they are not likely to control the paraffin wax deposition. Momentum transfer or shear stresses also increase with flowrate and decrease the number of particles able to deposit. The transport of material to the surface is therefore not the limiting factor, but the cohesive properties of the particles depositing. Increased shear stresses will decrease the number of particles capable of depositing because of their different sizes, shapes and packing properties.

While heat transfer is not the limiting factor asymptotic conditions it was shown earlier how t flux decreased during the rapid asymptotic build-up. It is anticipated that heat transfer may be an equally important part as momentum transfer, immediately after breakdown and removal of the layer from the surface.

Cohesive properties of wax particles are also affected by temperature. If experimental conditions are such that the temperature is increased, other variables remaining constant, the wax layer thickness will decrease and the temperature increase in the boundary layer will decrease the cohesive properties of the paraffin wax particles.

An increase in wax concentration, at unchanged temperature and flow conditions, will move the mud point temperature interface away from the wall. More particles will be formed in the extended boundary layer suspension and the greater number of particles increases the probability of deposition.

Increased flowrate and temperature therefore will decrease the number of particles having cohesive properties for deposition while increased concentration increases the total number of particles present and thereby the deposition.

CONCLUSIONS

The conclusions to be drawn from the limited data reported are relatively simple:-

1. The main factors influencing the asymptotic behaviour of paraffin wax deposition and fouling are the heat flux and shear stresses which decrease and increase respectively, as the mud point time deposition process takes place. The main factors causing breakdown of paraffin wax deposits are most likely the creation of planes of weakness inside the deposits and the effects of shear stresses as deposits grow in thickness.

2. The amount of wax that deposits or is removed, giving rise to the random fluctuations in the overall heat transfer resistances in the fouling studies, represents only a small percentage of the total wax deposited at any one time.

3. The mechanism of paraffin wax deposition and fouling will be controlled by the cohesive properties of the wax particles formed in the boundary layer and the behaviour of the fluid in the boundary layer. Flowrate and temperature decrease the number of particles able to deposit while the number is increased by greater concentration in the bulk solution.

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Nomenclature

C_p	:	Heat capacity
k	:	Thermal conductivity
K	:	Constant
n	:	Constant or exponent
Pr	:	Prandtl number
R^o	:	Clean overall resistance
\bar{R}_f^*	:	Average fouling resistance
Re	:	Reynolds number
\bar{Re}	:	Average Reynolds number
s	:	Specific gravity
T	:	Temperature
T_w	:	Temperature at the wall
\bar{T}	:	Average temperature
T^+	:	Dimensionless temperature

- : Dimensionless temperature at y_1^+
- : Average cooling water temperature
- : Average bulk temperature
- : Cloud point
- : Dimensionless velocity
- : Shearing stress velocity
- : Radial distance
- : Dimensionless distance
- : Dimensionless distance at u_1^+

greek Letters

- : Constant
- : Constant
- : Viscosity
- : Viscosity at the wall
- : Kinematic viscosity
- : Kinematic viscosity at the wall

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Table 2. Wax Fouling Resistances Under Different Conditions

Run No.	Run Duration Hours	Average Reynolds No. \overline{Re}	Average Bulk Temperature $^{\circ}C$ \overline{T}_b	Concentration of wax % by weight C	Cloud Point of Solution $^{\circ}C$ T_c	Average Fouling Resistance $(kW/m^2 \text{ } ^{\circ}C)^{-1}$ \overline{R}_f	Average overall "clean" resistance $(kW/m^2 \text{ } ^{\circ}C)^{-1}$ R'
6	24	13922	30.2	14.6	28	1.4295	0.7764
0	70	20868	28.6	9.6	20	0.4480	0.5257
1	70	8699	28.4	9.6	20	1.0142	1.0268
2	70	11741	28.5	9.6	20	0.7370	0.8147
2	55	20819	47.0	4.2	10	0.0232	0.5845
1	75	25451	45.9	6.0	14	0.0088	0.4961
6	50	27123	46.2	7.9	17	0.0878	0.4691
5	100	7635	42.5	26	32	2.1864	1.2050
3	100	13311	42.8	26	32	1.5359	0.7844
10-13	100	6716	42.4	26	32	3.0117	1.3318
14	240	8890	38.2	26	32	2.2584	1.0533
16	240	6888	38.2	26	32	3.2116	1.2849
20	240	4635	38.1	26	32	5.6461	1.7519

Notes: The results are averaged over the whole run (after initial deposition) Physical properties are taken at the mean bulk temperature \overline{T}_b . The bulk temperature \overline{T}_b is the average between inlet and outlet temperature.

Table 3. Estimation of the "wall" temperature T_w for six experimental runs

Run No.	Solution Cloud Point $^{\circ}C$ T_c	Reynolds No. \overline{Re}	Bulk Cooling Water Temperature $^{\circ}C$ \overline{T}_a	Average Bulk Temperature $^{\circ}C$ \overline{T}_b	Estimated Wall Temperature $^{\circ}C$ T_w
8 1-5	32	7635	7.1	42.5	32
3 6-9	32	13311	7.1	42.5	32
310-13	32	6716	6.8	42.4	33
3 1-14	32	8890	6.9	38.2	31
3 5-16	32	6888	6.8	38.2	31
3 8-20	32	4635	6.7	38.1	32

Note: \overline{T}_b is the average bulk temperature when the foulant wax has reached its asymptotic value.

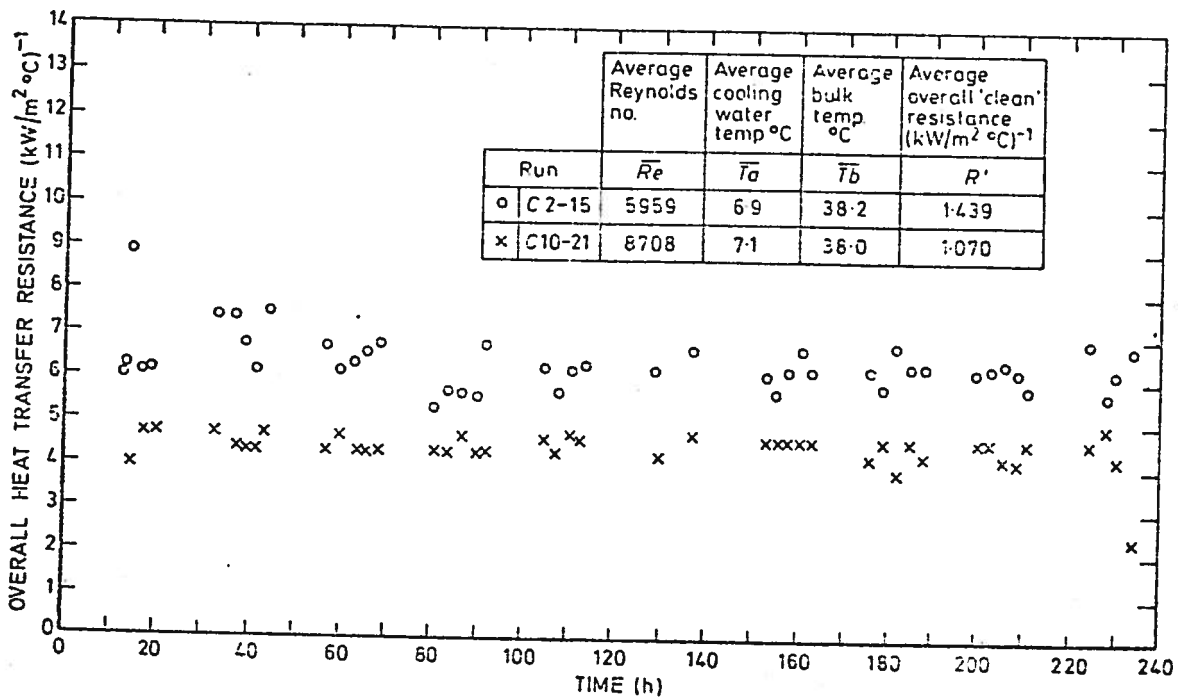


Fig. 1. Heat transfer resistance v time where $T_c=32^\circ\text{C}$ and $C=26$ percent

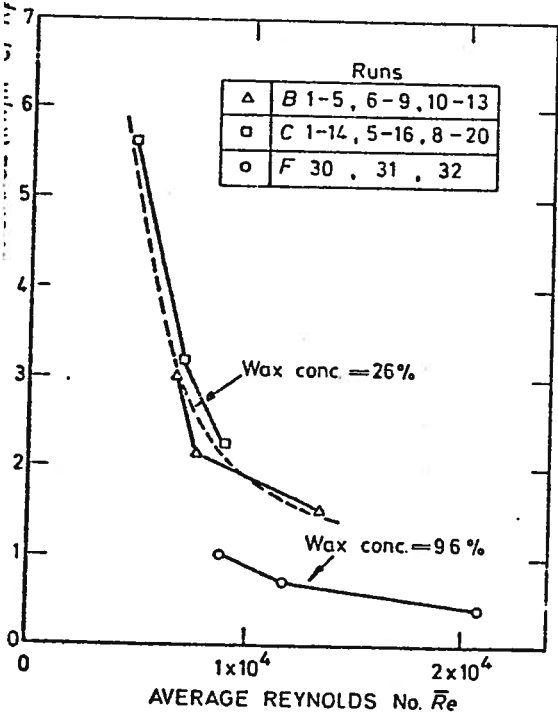


Fig. 2. Average equilibrium fouling resistance at different average Reynolds no.

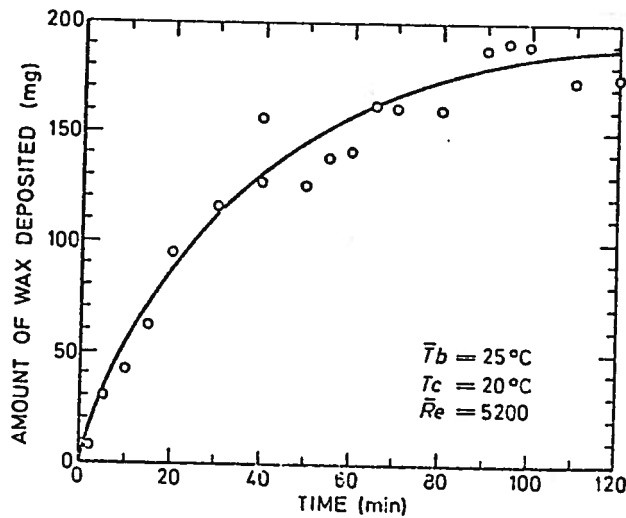


Fig. 3. Amount of wax deposited v. time

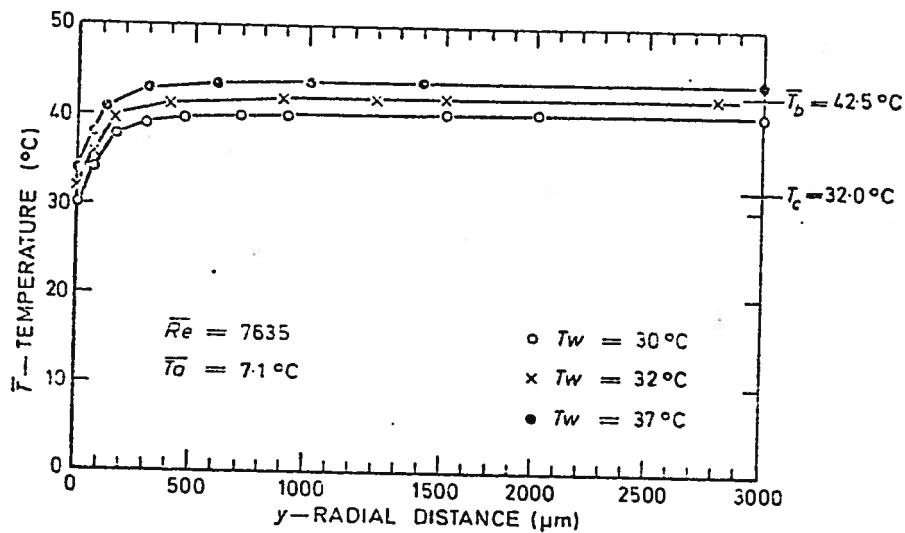


Fig. 4. Temperature v radial distance at different wall temperatures in run B1-5 where C = 26 per cent

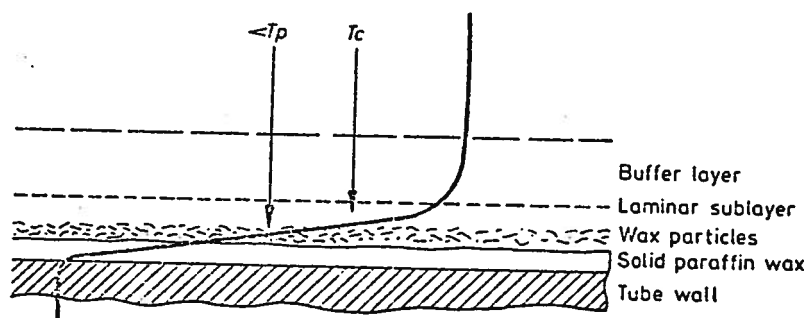


Fig. 5. An ideal temperature profile across the wall of a fouling studies heat exchanger tube.