CHEMICAL ENGINEERING TRANSACTIONS

VOL. 29, 2012

Guest Editors: Petar Sabev Varbanov, Hon Loong Lam, Jiří Jaromír Klemeš

ISBN 978-88-95608-20-4; **ISSN** 1974-9791

A publication of

AIDIC

The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet

DOI: 10.3303/CET1229244

Effect of Turbulence Enhancement on Crude Oil Fouling in a Batch Stirred Cell

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A simple batch stirred cell (Young et al., 2011) has been used to investigate crude oil fouling on bare mild steel test probes and on similar probes fitted with thin wires used to promote turbulence and increase surface shear stresses. The results show that, under otherwise identical operating conditions, the fouling rate on the surface of the probe fitted with wires was significantly lower than that on the surface of the bare probe. Moreover, the fouling resistance data using the wired probe were seen to be much more scattered over time, which suggests that the additional turbulence, and hence the associated additional shear stress, and perhaps even the associated uneven circumferential shear stress distribution, were all creating a greater random removal of the fouling deposit from the surface. CFD simulations of the fluid flow for both the bare and wired probes were conducted using the commercial multiphysics package Comsol 4.2. The simulation results show that, for otherwise identical conditions, the shear stress on the wired probe was significantly greater than that on original bare probe even at the point of lowest circumferential shear stress. The CFD results thereby allowed better interpretation of the experimental fouling data on the enhanced surface.

1. Introduction

Fouling concerns the formation of unwanted material on heat transfer surfaces. It reduces heat transfer efficiency, it undermines heat recovery, it increases energy consumption, it creates environmental problems, and it leads to financial penalties. Crude oil fouling on heat exchanger surfaces creates a chronic operational problem in the preheat exchanger trains of oil refineries. This worldwide problem is so big that it is estimated to cost the refining industry billions of dollars each year. The magnitude of this problem depends on two primary operational parameters, namely the surface temperature and the surface shear stress. In general, increasing the shear stress can reduce the fouling potential since fouling deposits can be supressed/removed from the heated surface by the action of shear force. A number of techniques, such as using inserts in shell and tube heat exchangers (Ritchie et al., 2009) and surface corrugation in plate heat exchangers (Anderson et al., 2009) have been developed to enhance the turbulence, and hence to increase the wall shear stress in order to mitigate the fouling. Experimental investigation of fouling when inserts are placed inside tubes is, nevertheless, not comprehensive. This could be due to the time consuming feature of fouling experiments. In previous research (Young et al., 2011) a batch stirred cell was constructed to a design that closely followed that of Eaton (1983). This cell can be operated under conditions close to those found in crude oil preheat trains, namely a maximum pressure of 30 bar and a surface temperature up to around 400 ^oC. The principal advantage of the cell design is that it offers extraordinary flexibility. Crude oils and the

Please cite this article as: Yang M., Wood Z., Rickard B., Crittenden B., Gough M. J., Droegemueller P. and Higley T., (2012), Effect of turbulence enhancement on crude oil fouling in a batch stirred cell, Chemical Engineering Transactions, 29, 1459-1464

operational conditions can be changed easily and relatively quickly, whilst the heat transfer surface can be easily inspected and changed. Furthermore, the test probe can be modified, for example such that the effect of wires, which may act in a manner similar to inserts in a tube, can be investigated.

2. Experiments and CFD simulation

2.1 Experiments

Details of the stirred cell system and the heated test probe are provided elsewhere by Young et al. (2011). The general arrangements are shown in Figure 1.

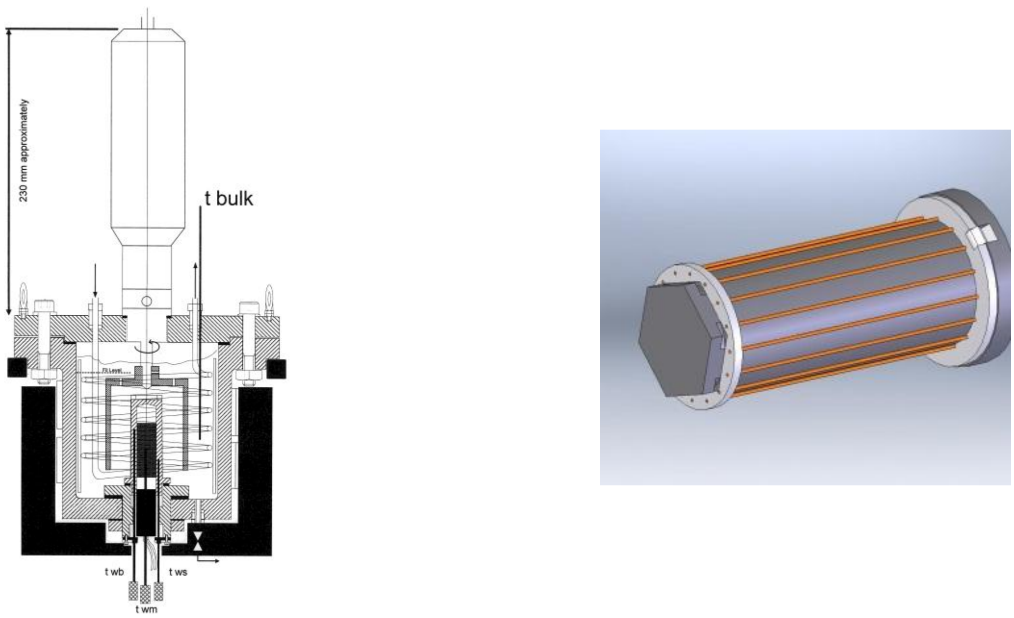

Figure 1 Left: The stirred cell system (Young et al., 2011); twb, twm, and tws are thermocouples Right: modified probe with wire nest on surface, the " wired probe" (for illustration only)

The plain surface probe described elsewhere (Young et al., 2011) has for the current study been modified by attaching a wire nest onto its surface. The wire nest consists of eight 0.72mm diameter wires distributed evenly over the probe surface. A batch of about 1.0 litres of crude oil is agitated by a downwards facing cylindrical stirrer mounted co-axially with the test probe and driven by an electric motor via a magnetic drive. External band heaters are incorporated to provide initial heating to the vessel and its contents. An internal cooling coil uses a non-fouling fluid (Paratherm) to remove heat at the rate that it is inputted via the cartridge heater during the fouling run. There is a single thermocouple to measure (and control) the crude oil bulk temperature. The mechanisms for control of the bulk temperature and the stirring speed are described elsewhere (Young et al., 2011). The surface temperature of the test probe can be changed by adjusting the input power to the embedded cartridge heater.

2.2 CFD simulation

CFD and heat transfer simulations are carried out using Comsol Version 4.2a. The model geometry is set up to be three dimensional. The boundary conditions are wall function for all solid-fluid boundaries, boundary layer heat sources for the cartridge heater and band heater, and variable temperature depending on the position from bottom to top for the cooling coil, respectively. The physical model is of non-isothermal flow in turbulent mode. A justification of the flow mode has been provided earlier (Yang et al., 2009).

3. Results and discussion

3.1 Fouling behaviour on the probe surface fitted with a wire nest

Figure 2 show typical fouling resistance curves on the surfaces of plain and wires probes. Compared with the fouling resistance data for the plain probe, the fouling resistance data on the wired probe shows much more scatter. This is likely due to the random removal of the deposit by the higher shear force on the wired probe; this will be discussed later.

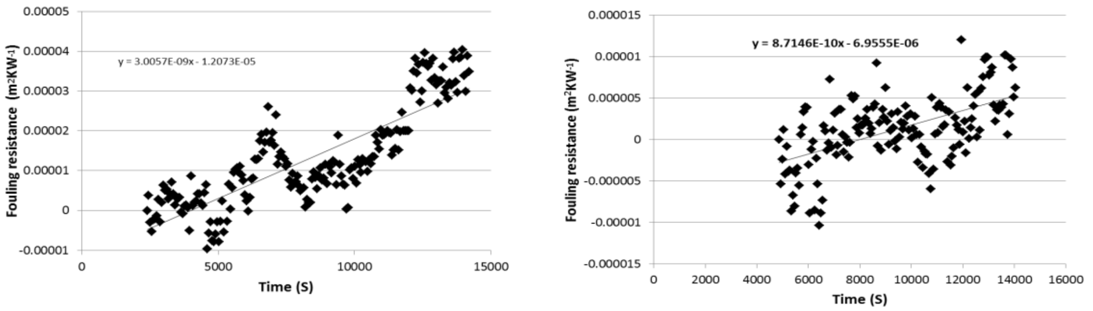

Figure 2 Fouling resistance curves
Left: plain probe, bulk temperature 258 °C; surface temperature 383 °C; stirring speed 160 rpm
Right: wired probe, bulk temperature 258 °C; surface temperature 399 °C; stirring speed 160 rpm

The fouling rate for the wired probe, 8.7E-10 m^2KW^{-1}, was noticably lower even at a higher surface temperature than that, 3.0E-9 m^2KW^{-1}, on the plain surface probe. This difference may also be attributed to the difference in shear stress over the plain and wired probes.

3.2 Shear stress

Figure 3 shows the velocity and temperature fields for the fluid flow in the stirred cell with the wired probe for a bulk temperature of 258 °C, a stirrer speed of 100 rpm, and a heat flux of 79 kW m^{-2}.

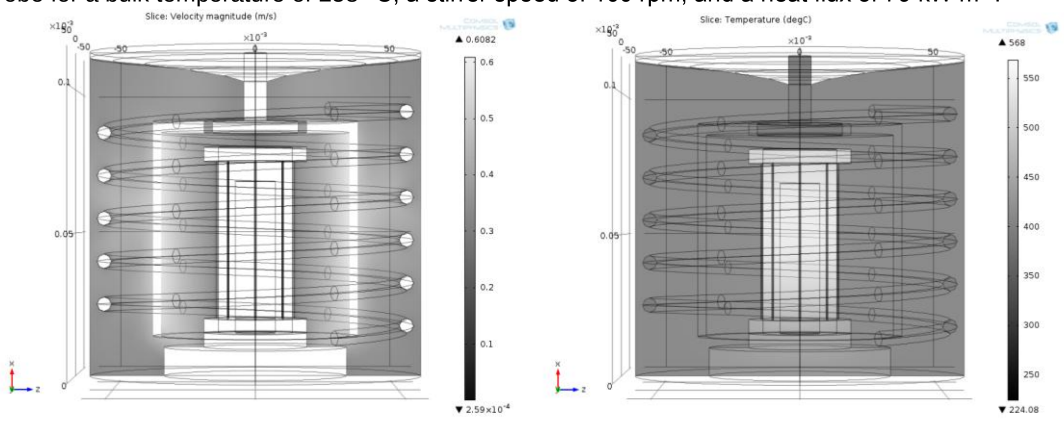

Figure 3 Velocity and temperature fields for the fluid flow in the stirred cell fitted with the wired probe
Left: velocity field; Right: temperature field

As shown in Figure 4, the shear stress around the plain probe is relatively even, whilst the shear stress around the wired probe is in a periodical manner, reaching a significant peak just ahead of the wire and dropping to a valley just behind the wire, in respect of the fluid flow swirling direction. Noticeable also is the significant difference in magnitude between the shear stress for the plain and wired probes. This demonstrates that the wires significantly enhance the turbulence, resulting in higher shear forces, auguring well for the mitigation of fouling.

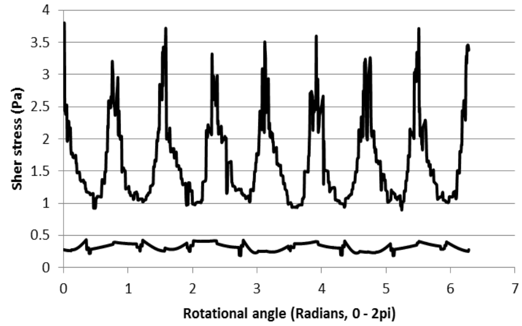

Figure 4 Shear stress distribution around the probe surface at the mid vertical position (0.04 m) in respect of the rotational angle from zero to 2 π
Bulk temperature 258 °C; stirring speed 200 rpm; heat flux 79 kW m^{-2}
Upper curve: wired probe; lower curve: plain probe

3.3 Equivalent Reynolds number

In previous work (Young et al., 2011) the concept of equivalent Reynolds number was proposed to enable the fouling data generated using the stirred cell to be translated for use in tubular heat exchangers. The equivalent Reynolds number is defined to be the Reynolds number in a plain round tube that gives the same shear stress as that in a more complex geometry such as the test surface in the batch stirred cell, whether or not this is fitted with wires. This concept was further developed for use in the case of tubes fitted with inserts (Yang and Crittenden, 2012). Shear stress data at a given linear velocity or given rotational speed are generated by CFD simulation, and hence a correlation is established to relate the operational parameters, such as the average linear velocity/rotational speed to an equivalent Reynolds number/velocity. For the fluid flow in the stirred cell, the average shear stress around plain and wired probes is shown in Figure 5; this data is used to generate the equivalent Reynolds numbers.

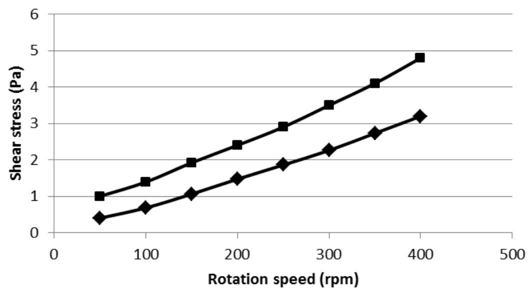

Figure 5 Average shear stress over the probe surface
Bulk temperature 250 °C; average heat flux 79 kW m^{-2}; Upper line: wired probe; lower line: plain probe

Figure 6 shows the equivalent numbers for the plain and wired probes in the batch stirred cell. It may be worth noting that at a given equivalent Reynolds number and surface temperature, the fouling behaviours should be similar regardless of the surface geometries, such that the fouling results generated using the stirred cell with a wired probe could be comparable with those generated using a tube fitted with inserts or the stirred cell fitted with just a plain probe. To demonstrate the application of the concept of equivalent Reynolds number, fouling rates were calculated using a fouling model (Ebert and Panchal, 1997) and compared with the experimental data generated using the stirred cell fitted with the wired probe of this study, and with a plain probe studied previously (Yang et al., 2011). The fouling rate model used is as follows:

$$\frac{dR_f}{dt} = \alpha\, Re^{\beta}\, e^{-\frac{E_A}{RT_f}} - \gamma\tau \quad (1)$$

The parameters used in this model were determined previously (Yang et al., 2011). For the crude oil tested in the experimental programme, the values were found to be 1190 $m^2K\ J^{-1}$, -0.88 (non-dimensional), 98.4kJ mol^{-1}, and 3.85 $m^2KJ^{-1}Pa^{-1}$ for α, β, E_A, and γ respectively. Figure 7 shows the comparison of the predicted fouling rate using the model with the equivalent Reynolds number and the experimental data.

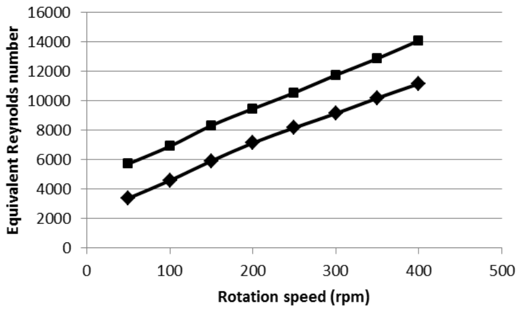

Figure 6. Equivalent Reynolds number for the crude fluid flow in the stirred cell
Upper line: wired probe; lower line: plain probe

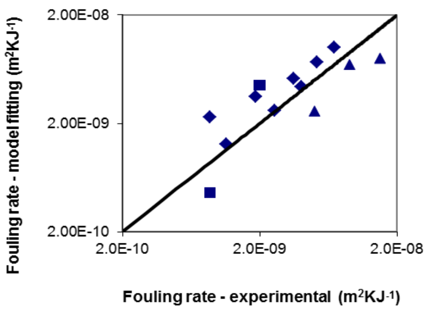

Figure 7. Comparison of the experimental data and the model predictions for the fouling rate ♦: fouling rate data - stirred cell with plain probe; ■: fouling rate data – stirred cell with wired probe ▲: fouling rate data - tube with hiTRAN® inserts. Note, the fluid tested was Maya crude, and hence the model parameters were different from those used for the above two cases, and therefore these data are shown in the figure for illustration only (Yang and Crittenden, 2012)

All these data indicate that with the help of the equivalent Reynolds number concept, fouling rate data become compatible regardless of the geometries of the test surfaces. Hence, fouling test results generated using a specific device, such as the stirred cell, can be made to be applicable in other types of heated surface.

4. Conclusion

A simple batch stirred cell has been used to investigate crude oil fouling on a plain test probe and on an otherwise similar probe but fitted with thin wires. The test results together with CFD simulations show that the wires on the probe surface promote turbulence and increase surface shear stresses, and hence under otherwise identical operating conditions, the fouling rate on the surface of the probe fitted with wires was found to be significantly lower than that on the surface of the plain probe. Moreover, the fouling resistance data using the wired probe were seen to be much more scattered over time which provides further evidence that the additional turbulence, and hence the associated additional shear stress, and perhaps even the associated uneven circumferential shear stress distribution, were creating a greater random removal of the fouling deposit from the surface.

With the help of the concept of equivalent Reynolds, fouling rate data become compatible regardless of the geometries of the test surfaces, such that fouling test results generated using a specific device, such as the stirred cell, can be applicable to other types of heated surface.

Acknowledgement

The authors are grateful to the European Commission for the award of research grant FP7-SME-2010-1-262205-INTHEAT to study intensified heat transfer technologies for enhanced heat recovery. The authors are also grateful to project partners at the University of Manchester, and to Cal Gavin Ltd for their support, advice and provision of the probe with wires attached.

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