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Mitigation of crude oil fouling by turbulence enhancement in a batch stirred cell

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HIGHLIGHTS

► Investigation of crude oil fouling using a compact stirred cell.
► Mitigation of crude oil fouling using surface enhancement.
► Use of CFD to correlate fouling behaviour.
► Concept of equivalent Reynolds number for enhanced heat transfer.

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ABSTRACT

A compact batch stirred cell has been used to investigate crude oil fouling on bare mild steel test probes and on similar probes fitted with thin wires 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 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 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 CFD simulation results show that the surface shear stress indeed varies in a periodic manner around the wired probe surface, being greater immediately in front of a wire, and lower immediately behind a wire in respect of the flow direction. The CFD 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 allow better interpretation of the experimental fouling data on the enhanced surface.

1. Introduction

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. For a given crude oil, the extent of fouling depends primarily on two operational parameters, namely, the surface temperature and the surface shear stress. In general, increasing shear stress can reduce the fouling potential since foulants can be suppressed/removed from the heated surface by the shear force. A number of techniques, such as use of an insert in shell and tube type heat exchangers [1] and surface corrugation in plate heat exchangers [2] have been developed to enhance turbulence, and hence to increase the wall shear stress in order to mitigate fouling. Some experimental investigations of fouling on enhanced surfaces have been reported. For example, Zhang et al. [3] reported fouling of a cyclic olefin on plain and enhanced surfaces, and Watkinson [4] has reviewed the literature on fouling of augmented heat transfer tubes. Experimental investigation on fouling in the case of inserts in tubes is nevertheless not comprehensive. This could be due to the complexity and time consuming nature of fouling experiments.

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Use of a batch stirred cell to investigate crude oil fouling has been reported previously [5]. This compact device was constructed to a design that closely followed that of Eaton [6] and can be operated under conditions close to those found in crude oil preheat trains, namely a maximum pressure of 30 bar and a maximum surface temperature of around 400 °C. The principal advantage of the cell design is that it offers extraordinary flexibility, and requires only small volumes of crude oil samples. The oils and the 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 by attaching wires, for example, so that the effect of this kind of heat transfer enhancement which may virtually act in the same manner as an insert within a tube, on the fluid flow can be investigated. With this test system it is possible to obtain a large number of fouling experimental results within a relatively short experimental period [5].

2. Experiments and CFD simulation

2.1. Experiments

Details of the stirred cell system and the heated test probe are provided by Young et al. [5] and the general arrangements are shown in Fig. 1. The cell comprises a pressure vessel made in-house from a block of 304 stainless steel together with a top flange. The base of the vessel houses an upwards pointing test probe heated internally by a cartridge heater, the heat flux from which is controlled electrically. The mild steel plain test probe as described elsewhere [5], is modified by attaching a wire cage onto its surface. The wire cage consists of eight strands of 0.72 mm mild steel wire, which are held by two steel flanges. The wire cage is attached to the probe by the two flanges, as shown schematically in Fig. 1.

A batch of about 1.0 L 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 from Paratherm Corporation, West Conshohocken, PA 19428, USA) to remove heat at the rate that it is inputted via the cartridge heater during the fouling run. The vessel is fitted with a pressure relief valve and there is a single thermocouple to measure the crude oil bulk temperature. Bulk temperature and stirring speed control is described elsewhere [5]. The surface temperature of the test probe can be altered by adjusting the power input to the embedded cartridge heater. The surface temperature was determined from the embedded thermocouple temperature by taking into account the temperature decrease over the distance from the thermocouple to surface. This temperature decrease was determined by heat transfer simulation.

Each fouling test is carried out in a periodic manner, that is, a single fouling test run lasts typically for less than 10 h during one day but continues the next day and so on. The stirred cell rig was operated under constant heat flux conditions. No changes in fouling rate were found by operation in this manner provided that the same stirrer speed and cartridge heater power were used, as demonstrated in previous work [5]. At the end of the experiment, the probe could be removed for inspection of the fouling deposit. In most cases, the fouling deposits were gum like. The operational conditions are listed in Table 1 and the properties of the crude oil are listed in Table 2.

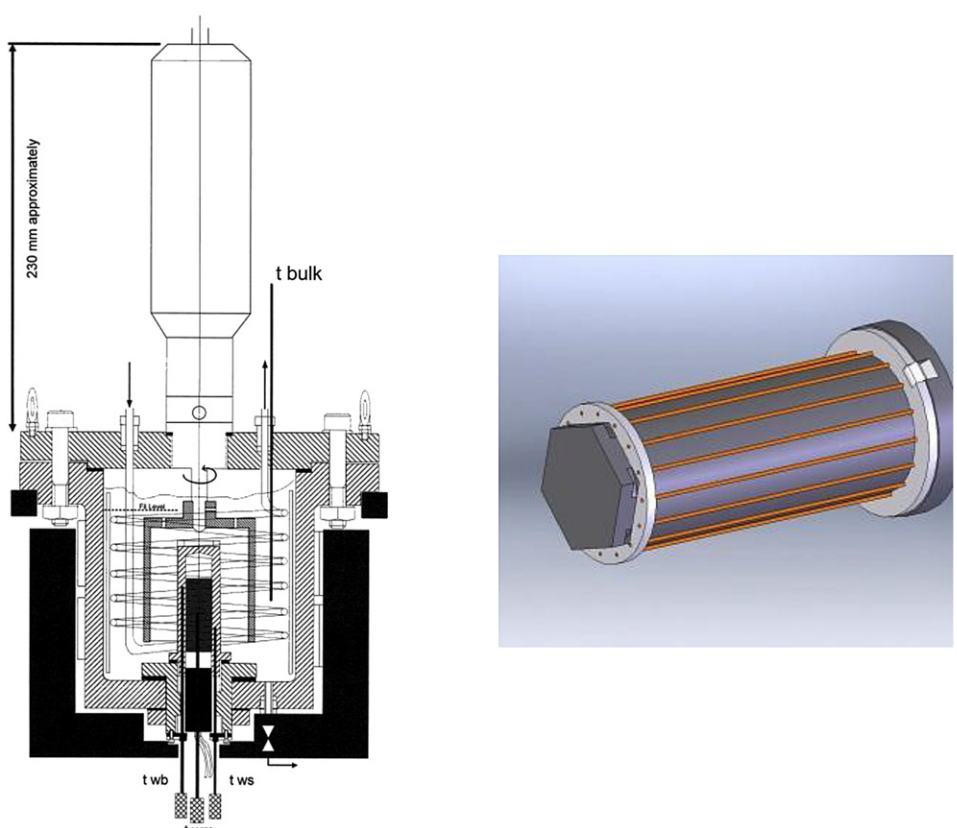

Fig. 1. Left: The stirred cell system [1] twb, twm, and tws are thermocouples. Right: Modified probe with wire nest on surface (for illustration only).