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PERFORMANCE OF FLEXIBLE CERAMIC COATED SURFACES SUBJECTED TO CRUDE OIL FOULING

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ABSTRACT

An oil repellent organic inorganic hybrid coating was applied on titanium plate heat exchanger plates and field tested in a crude oil rig. The trial consisted in two coated plate heat exchangers (PHE). The PHEs work as interchangers to heat up a crude oil water mixture using de-watered crude oil. The duty is highly fouling with wax solidifying on the plate wall together with crystalline substances. Waxing will affect the performance of the heat exchanger leading to an increase of the outlet temperature of the stabilized crude oil (de-watered crude oil). When this temperature reaches too high values the flow rate of the cold side (crude oil water mixture) will be reduced in order to increase the temperature on the crude oil side and therefore partly dissolving the solidified wax at the surface of the plate. The latter process, called hot runs, is performed on one train every 3rd day with a duration of 2 days in the normal operation with the uncoated trains. The process was monitored with an overall flow and temperature meter for all four trains. The following parameters were assessed: Heat load and total flow rate. At the end of the test period a higher heat load and flow rate was measured on the coated PHEs compared to the reference PHEs indicating that the coated PHEs are cleaner. The trial will be continued for longer periods of time to be able to detect the onset of loss of performance on both the coated and uncoated PHEs.

INTRODUCTION

Fouling of heat exchangers in the oil industry results in a loss of performance which leads to production stops for cleaning and therefore increased operation costs (Deshannavar, et al., 2010). During crude oil processing, heating and cooling are common procedures which will lead to fouling on the heat exchanger wall. When crude oil is cooled to temperatures lower than the wax appearance temperature (WAT) it will cause paraffin wax to crystallize at the plate wall of the heat exchanger. The WAT depends on the crude oil composition and also on the determination method. Elsharkawy et al. (2000) used differential scanning calorimetry to determine the WAT for different crude oils and reported values ranging from 32 to 38°C. The composition of the wax deposit is time dependent starting with a porous structure which gradually becomes denser as more wax molecules diffuses into the porous structure and oil diffuses out (Singh et al., 2000). The denser the deposit layer the higher the impairment on the heat transfer due to the insulating effect of the wax layer (thermal conductivity of 0.073 W / m K, Torresola, 1998) at the surface and the more challenging the cleaning becomes. Several approaches to mitigate oil fouling are reported in the literature including heating, chemical treatment (inhibitors), paraffin hydrodynamics and surface treatment (Merino-Garcia and Correra, 2008; Paso et al., 2009). In this work we follow the later approach i.e. alteration of the surface properties of the metal substrate.

The literature is abundant with the use of coatings in heat exchangers for fouling reduction in food applications, mainly dairy (Rosmaninho et al., 2006; Balasubramanian and Puri, 2009; Patel et al., 2013; Barish and Goddard, 2013; Boxler et al., 2013), and mineral scaling (Dowling et al., 2010; Boxler et al., 2013). For crude oil cooling applications the use of coated plate heat exchangers installed on a North Sea oil platform was previously investigated by the authors (Santos et al., 2013). It was proven that the coating led to a significantly prolonged service interval (by a factor of 3) making it very economically attractive. Other coatings have also been tested in crude oil. Fernandez and Rothan (2009) compared the performance of coated and uncoated shell and tube reboilers. The coating, a phenolic epoxy polymer, was applied on the tube side where the crude oil flows and was heated with steam on the shell side. No fouling reduction was achieved on the coated reboilers and the coating diminished the heat transfer due to its low thermal conductivity. The effect of different coatings on paraffin wax fouling of cold steel surfaces have also been investigated (Johnsen et al., 2011). Three coatings (no details were reported on two of the coatings while the third consisted of an organic inorganic hybrid coating based on aminopropylsilane) were tested in a batch baffle stirred reactor with a binary test fluid consisting of a paraffinic solvent (n-decane) and paraffin wax solute (n-tetracosane) at different flow velocities. Two of the coatings reduced the amount of wax deposit independent of the flow velocity. While some improvements in fouling and cleaning were observed for some of the coatings, there is only, to the author's knowledge, a commercially available coated plate heat exchanger for a specific application (dry crude oil cooling launched by Alfa Laval in 2014). This is due to the complexity of both the fouling mechanism and the coating properties. Besides being able to reduce foulant adhesion a coating, to be suitable to use in a heat exchanger, needs to have a decent thermal conductivity, good wear and abrasion resistance, good temperature and chemical resistance and a good adhesion to the metal substrate.

A second full-scale industrial case study in a crude oil rig in the North Sea was performed with the same organic inorganic hybrid coating as used in the previous field test (Santos, et al., 2013). The coating was applied on heat exchanger plates and the coated plates assembled on a MX25-B unit. The duty was heating a crude oil water mixture from around 39 to 84 °C using dewatered crude oil as a heating media. The duty is highly fouling with wax solidifying on the plate wall together with crystalline substances. During the operating time the heat exchanger is cleaned at regular intervals by the so-called hot runs (the flow rate of the cold side, crude oil water mixture, is turned off and the hot side, dewatered crude oil has a reduced/ low flow resulting in wax being partially dissolved).

EXPERIMENTAL

Coated Surfaces

The oil repellent organic inorganic hybrid coating (ORC) used in the field test was manufactured and applied by the Danish Technological Institute (DTI). The surface properties of the coating in comparison to the titanium substrate were reported in a previously contribution (Santos et al., 2013) and are presented in Table 1. The surface energy was calculated according to the van Oss approach.

Table 1. Surface properties of the reference and coated substrates.

Surface	Water contact angle (°)	α-Bromonaphthalene	Surface energy (mN/m)	Surface roughness (µm)
Titanium	80-40[a]	36 ± 2	39-47	1,03 ± 0,04
ORC	105 ± 1	66 ± 2	21	0,52 ± 0,14

[a]Dynamic contact angle. Decrease during the first 3 min.

Full-Scale Industrial Field Test

Process description. The plate heat exchangers (PHE) in the oil rig are installed in series of four trains with two PHEs in each train (Fig. 1). Two of these PHE are installed with plates coated on one side (hot side, dewatered crude oil) of the plate. Each coated PHE consists of 651 MX25-B plates in Titanium grade 1 and thickness of 0.75 mm. The plate heat exchangers work as interchangers to heat up a crude oil water mixture (unstabilized crude) using de-watered crude oil (stabilized crude). The oil rig pumps in unstabilized crude oil in pipelines from an oilfield in the North Sea. It is then heated from 39 to 84 °C by the stabilized crude oil. The unstabilized crude oil is heated further in a gas heater to around 100 °C to improve the separation of processed water and gases in the scrubber. The resulting stabilized crude oil (water cut below 0.5 %) is cooled down to 45 °C in the interchangers and then further to 27 °C in other PHEs before being stored.

Process operation. The interchangers were operated according to the following:

- Two trains in operation (coated and uncoated) and two trains on hot run (1st and 2nd tests);
- One train in continuous operation for two weeks and the other three are run in the following manner: one train in operation for two days while the other two are in hot run, the train that is in operation is changed every 3rd day (3rd test);
- Operation time started with two days (1st and 2nd tests) and was later prolonged to two weeks (3rd test);
- Total process flow 350 – 450 m^3/ h (hot - cold side);
- Hot run is performed by closing the flow of the unstabilized crude oil and by reducing the flow on the stabilized crude side resulting in an increase of the stabilized crude oil to around 80 – 85 °C.

Process monitoring. The process is monitored with an overall flow (Flexus ADM 8027 digital) and temperature meter for all four trains. The flow meter was installed at the outlet of the stabilized crude (see Fig. 1). Data are logged in a daily basis. Every train has pressure / temperature gauge on the train outlet that can be manually inspected. The data was monitored both manually and automatically in the central control room. The readings were performed once a day.

Manual readings on each PHE:

- Outlet temperature unstabilized crude;
- Outlet temperature stabilized crude;
- Outlet flow stabilized crude.

Automatic readings on the PHEs:

- Inlet temperature unstabilized crude (process total);
- Inlet temperature stabilized crude (process total);
- Outlet total temperature stabilized crude (process total including hot run flow);
- Outlet total flow stabilized crude (process total);
- Inlet total flow unstabilized crude (process total).

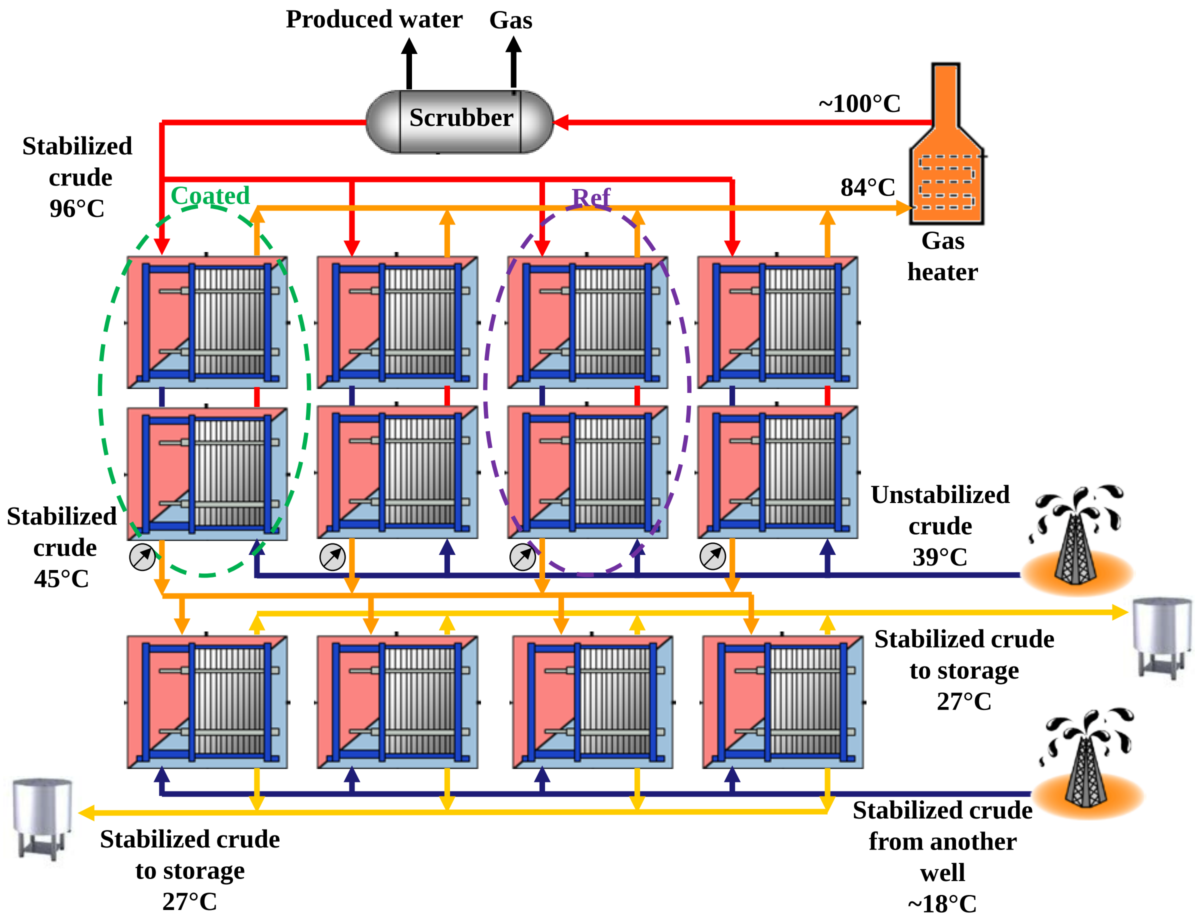

Fig. 1 – Process diagram showing the positions of the coated and reference PHEs.

RESULTS

The flow rate of the stabilized crude and the heat load on both coated and reference trains were the parameters selected for performance comparison. The results will be presented for the 1st and 2nd tests and then separately for the 3rd test since the operation time differed between these. In the oil rig a train is normally operated only for two days and then set to hot run for one day. In the beginning of the field test (1st and 2nd tests) the same schedule was followed were two trains (coated and reference) were in operation and two in hot run. Since no indication of fouling was detected the operation time was prolonged to two weeks in the 3rd test.

1st and 2nd Field Test – Total Operation Time 6 days

The heat load was calculated for both the coated and reference train by the use of the following simplified equation:

$$\text{Heat load (kW)} = (T_{\text{Stab In}} - T_{\text{Stab Out}}) \times \text{Flow rate} / 1000$$

where $T_{\text{Stab In}}$ is the inlet temperature and $T_{\text{Stab Out}}$ the outlet temperature of the stabilized crude oil. Fig. 2 compares the heat load for both coated and reference train. It is seen that the heat load on the coated train was 5 - 8% higher compared to the reference train over the first test period. The difference dropped to ~2% higher heat load at the end of second test period. The ratio between the heat load on the coated and reference train is shown in Fig. 3. The heat load on the coated train was constant and 1.05 - 1.08 higher over the test period compared to the reference train.

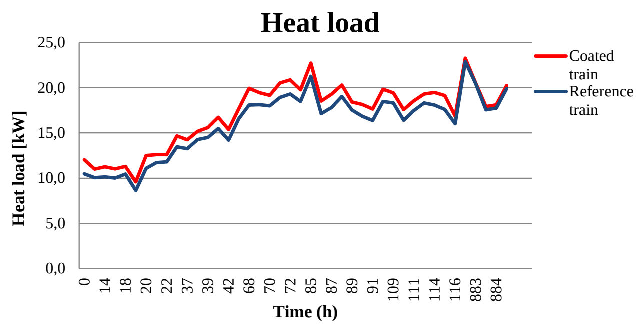

Fig. 2 – Calculated heat load for both the coated and reference train during the 1st and 2nd field trial.

The flow rate of the stabilized crude oil through the coated and reference train is presented in Fig. 4. On the coated train a larger amount of crude oil passed through the PHEs compared to the reference train. An increase of ~3% to 5 % (6 to13 m^3 h^{-1}) in the flow through the coated train during the 1st test period and ~1-2 % increase in the flow through the coated train at the end of 2nd test period.

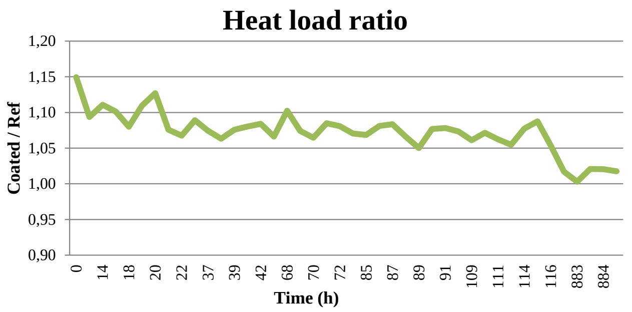

Fig. 3 – Heat load ratio between the coated and reference train during the 1st and 2nd field trial.

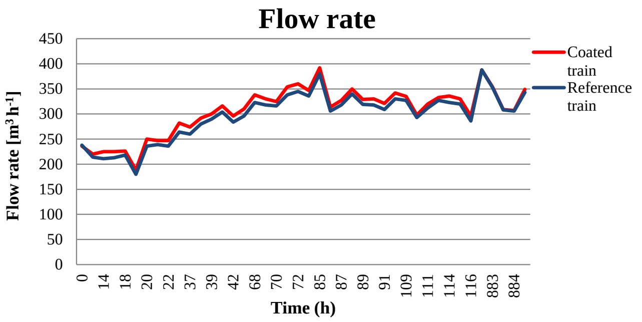

Fig. 4 – Monitored flow rate of the stabilized crude oil for both the coated and reference train during the 1st and 2nd field trial.

3rd Field Test – Total Operation Time 27 days

During the 3rd trial period the coated / reference train was in operation for 2 weeks followed by 2 weeks in hot run and then 2 more weeks in operation. The calculated heat load and measured flow rate during the operation time is presented in Figs. 5 and 6. An average of ~ 4% higher heat load was achieved on the coated train compared to the reference train (Fig. 5). The average flow rate on both coated and reference trains did not differ greatly, an increase of only 0.3 % on the coated train flow rate compared to the reference train was measured (Fig. 6).

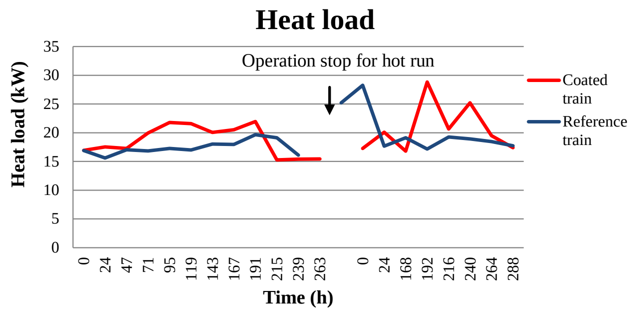

Fig. 5 – Calculated heat load for both the coated and reference train during the 3rd field trial. Note that the coated and reference trains were run at the same time.

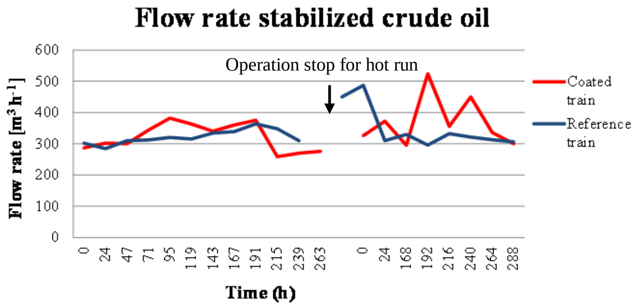

Fig. 6 - Monitored flow rate of the stabilized crude oil for both the coated and reference train during the 3rd field trial. Note that the coated and reference trains were run at the same time.

Figs. 7 and 8 shows the variation on the temperature values of the stabilized crude (inlet and outlet) and outlet unstabilized crude for both the coated and reference train, respectively during the 3rd test period. The temperatures were very stable showing no indication of waxing fouling on neither the coated or reference train.

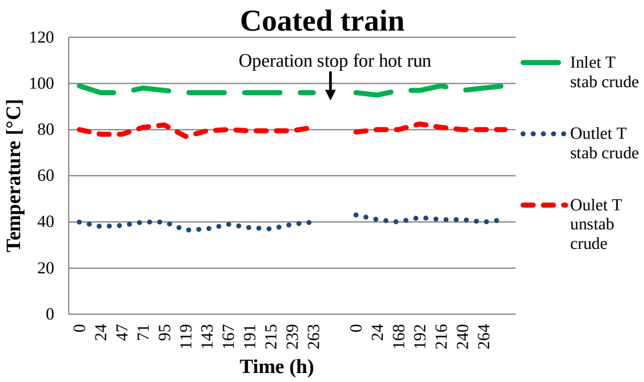

Fig. 7 – Temperatures of the inlet and outlet stabilized crude and outlet unstabilized crude for the coated train during the 3rd trial period.

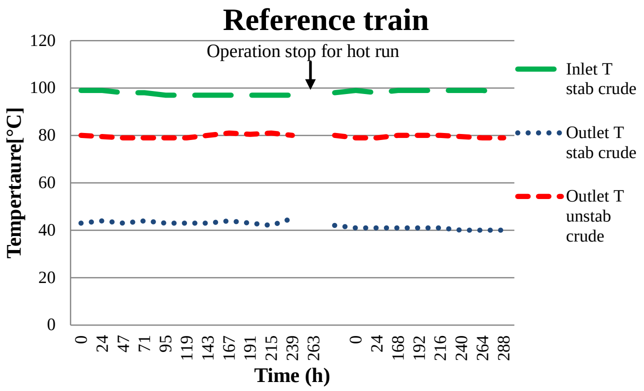

Fig. 8 - Temperatures of the inlet and outlet stabilized crude and outlet unstabilized crude for the reference train during the 3rd trial period.

DISCUSSION

Adhesion of a substance to a substrate depends on many different parameters such as operating conditions, physicochemical properties, substrate chemical composition, roughness and surface free energy. It is observed, in general, that low surface free energies lead to minimal adsorption forces between the surfaces and deposit (Britten et al., 1988; Zhao et al., 2005). An increase in the roughness of steel surfaces was found to result in a larger wax deposition probably due to an increase of heterogeneous nucleation sites (Jorda, 1966). Therefore, a coating with both lower surface energy and lower roughness compared to the metal surface should reduce the amount of wax deposition. This was in fact observed in our previous work (Santos et al., 2013). In the present work, the limited waxing on the plates due to the short operation times, led only to small increases in both the heat load and flow rate of the stabilized crude oil (Figs. 2 to 6). The fluctuations in the heat load for both coated and reference trains (Figs. 2 and 6) is caused by fluctuations in the flow rate of the stabilized crude. This in turn is due to the flow rate being regulated by the volume in the scrubber and the vent that regulates the flow being placed after the coated / reference trains (before the 4 PHEs at the bottom in Fig. 1).

The influence the coating will have on the thermal performance of the PHE has been discussed in a previous contribution by the authors (Santos et al., 2013). It was concluded that the low thickness and reasonable thermal conductivity (~ 2 W / m K) of the present coating will lead to a reduction in heat transfer of around 4%. Since a slightly higher heat load and flow rate were observed on the coated compared to the reference train it further supports the fact that the reference train had more wax solidified at the plate wall as compared to the coated plates. This is explained by the much lower heat conductivity of a compact wax deposit (by a factor of around 30) as compared to the coating with only a few wax molecules.

The field test will be continued with longer operation times between hot runs in order to detect the onset of large amounts of waxing on the trains.

CONCLUSIONS

The conclusions of this study are as follows.

1. The short operation times prevented the build-up of a large amount of wax at the surface of the plate heat exchangers.
2. The coated train showed a slightly better performance compared to the reference train in terms of a higher heat load and a larger flow rate.
3. The ORC showed promising initial results in reducing fouling in crude oil interchangers.

NOMENCLATURE

ORC	Oil repellent coating
PHE	Plate heat exchanger
WAT	Wax appearance temperature
DTI	Danish technological institute

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