

CRUDE OIL FOULING FIELD DATA AND A MODEL FOR PILOT-PLANT SCALE DATA

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ABSTRACT

In a paper at the 2009 conference we presented fouling rates for heat exchangers in six crude preheat trains, Joshi et. al. (2009). That plot showed a stronger dependence on shear stress than temperature, where the representative temperature was the hot side inlet temperature. In the 2011 conference comments were presented on the paper with explanations for the fouling behavior, Epstein (2011).

This paper reviews the comments, shows additional data from two other crude preheat trains, presents background on how refinery data behaves, and shows pilot-plant scale fouling rates for a single tube heat exchanger, with an attempt to model that data.

The attempted model presumes no precursors or a chemical reaction in the bulk fluid, but simply a process of deposition and ageing. As will be seen, the data can be fit fairly well to the model but as of now there is very limited variation in the flows and temperatures.

ADDITIONAL CRUDE PREHEAT DATA

Fig. 1 shows data for rates of fouling [m²-C/W/day] in eight different crude preheat trains. This data is for many crude blends of varying densities, viscosities, and other properties. Additionally, it covers a wide range of velocities, from 0.9 to 2.7 m/s, with a majority being concentrated in the typical design range of 1.5-1.8 m/s, corresponding to 5-8 Pa shear stress. One major uncertainty in this data is the amount of shellside fouling, although based on visual observations we have assumed that it is minimal and that all fouling can be attributed to the tubeside.

The six points in red squares show data added since the original in 2009, and we see that the additional points perhaps create more scatter. Figs. 2 and 3 show the dangers of collecting data from the field – uncertain measurements, unsteady flow and temperature conditions, and varying fluid compositions. Fig. 2 shows no observable trends for any significant time frame and it is not possible to calculate a rate of fouling. In Fig. 3 we see trends of fouling and the effect of cleaning. The fouling cycles in this figure can be used to calculate a rate. Fig. 4 shows one of the cycles from Fig. 3 where a reasonable slope or rate could be estimated. These plots are based on a fully reconciled (heat and mass balanced) network, and the fouling resistances are calculated using a rigorous heat exchanger simulation at each data

point. From that standpoint, this is about as good field data as one can expect to get from currently operating refineries.

COMMENTS, EPSTEIN (2011)

Here are this author's responses to the points raised in the 2011 presentation:

1. "... the hot-side inlet temperature is a rather crude representation of the tube-side surface temperature ...". This is correct, however it is difficult if not impossible to estimate a representative surface temperature under long term operating conditions (see the variations in Fig. 2). An incremental simulation to determine local surface temperatures could be carried out, at every data point, and a representative value developed for each day's data, but in all likelihood it will not give us any better insight into the observed trends.
2. "... The model, which in the case of chemical reaction fouling, assumes the initial fouling rate, R_{fo} , is governed by mass transfer of a precursor from the bulk ...". It is also stated that this model has been "variously validated". However, there is no evidence in actual operating crude trains that this is the mechanism. Crudes with different thermophysical properties, different chemical compositions, from different sources, different blends, all exhibit (within a reasonable range) similar requirements for cleaning and loss of heat transfer. We have seen only two exceptions to this, where a precursor is present and affects fouling: when a crude is incompatible, so it has precipitated asphaltenes; and when a contaminant has been knowingly added (e.g., corrosion inhibitor, flow enhancer). Evidence that these precursors are responsible for high fouling rates is usually seen in deposit analysis.
"When the mass transfer resistance becomes negligible relative to that of attachment, which occurs eventually as the velocity is increased ...". In most crude fouling cases, we believe that no precursor is needed but it is only the attachment of the crude to the surface and its subsequent ageing that controls fouling. Particulates present in the crude (salts, corrosion products) may aid the attachment process and in that sense their mass transfer to the surface might become relevant, but it is not clear how that can be modeled. Based on deposit analysis of many (~50) samples from crude fouling, we believe that the mechanism for most crudes is essentially the same as mentioned above, and

that the major effect of temperature is in the ageing process.

3. "... the shear stress τ_w becomes less effective in resisting fouling when the fluid residence time near the wall increases due to increased viscosity". This is an important consideration and consistent with the

qualitative field observation that more viscous fluids exhibit faster fouling; for example vacuum residue. For some of these viscous fluids, corrosion (due to sulfur) and particulate matter (corrosion products and coke) also play an important role.

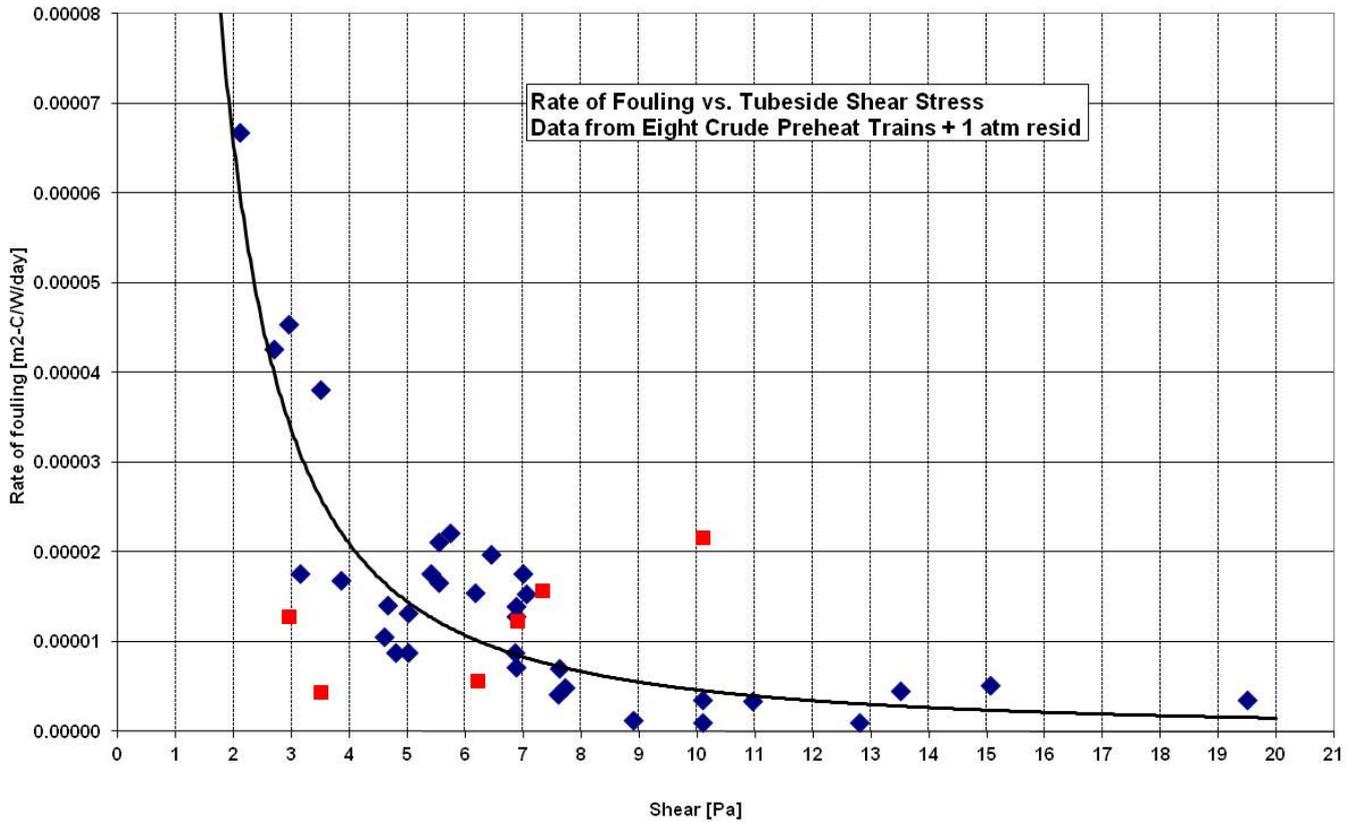


Fig. 1 Rate of Tubeside Fouling vs. Shear Stress

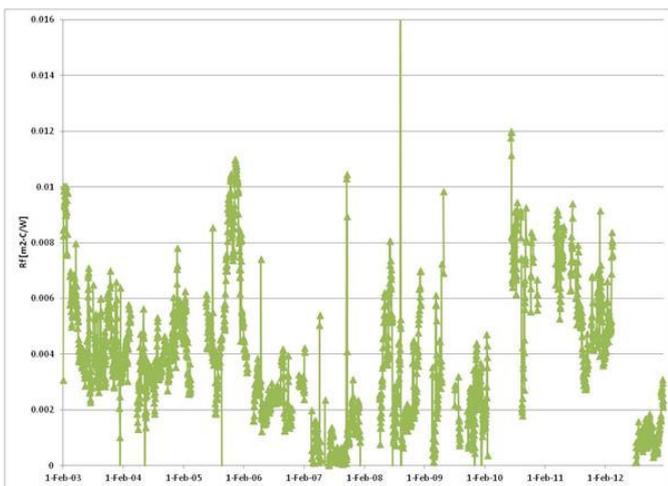


Fig. 2 Fouling Resistance vs Time for an Operating Heat Exchanger – No observable trend

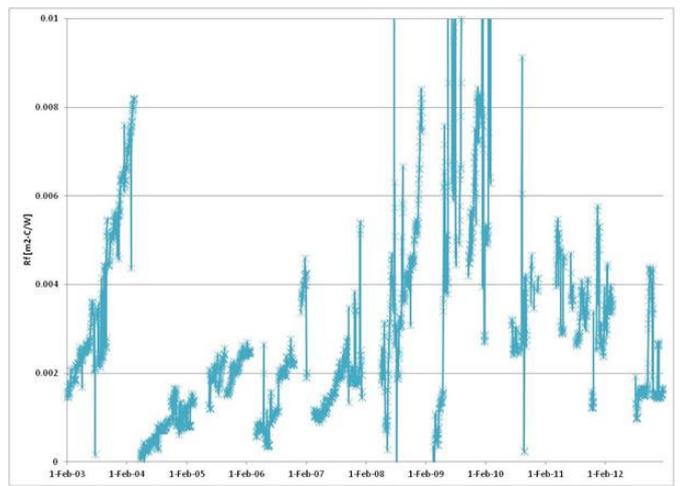


Fig. 3 Fouling Resistance vs Time for an Operating Heat Exchanger – Observable Trends



Fig. 4 Fouling Resistance vs Time for an Operating Heat Exchanger – Example of Measurable Fouling Rate

PILOT-PLANT SCALE DATA

Fouling rates measured in a single tube double-pipe heat exchanger of 3m length are shown in Fig. 5. The tube is 25 mm OD carbon steel, and the shell side has a hot oil with a temperature of 330-350 °C, surface temperature was not measured.

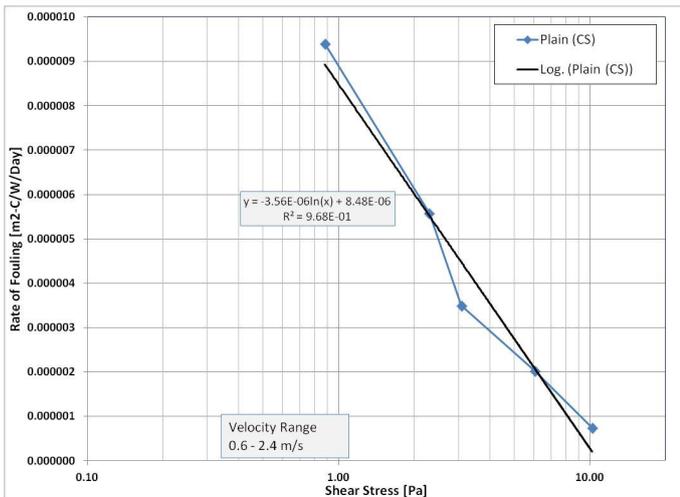


Fig. 5 Fouling Rates for One Crude in a Single Tube Heat Exchanger

Within the limitations of the data, there is a good fit of fouling rate with shear stress. If fit with a power law (not shown), the curve has an exponent of (-1.0) on the shear stress. The limitations to note are: From an experimental perspective – it is a single crude, there is only about a 20 °C variation in the average surface temperature, crude density and viscosity don't vary much over the bulk temperature range; and from a field perspective – flows, temperatures, and compositions are very steady, this is a single tube compared to 100's in a full scale unit, crude is recirculating and not once-through.

Although not shown in a plot, the rates in Fig. 5 are substantially lower than those in Fig.1, especially towards the low shear stress range.

MODEL OF PILOT-PLANT DATA

We attempted to model the fouling rate with the assumption that it depends on three parameters: shear stress (controls deposition), ageing (heat transfer resistance), and surface roughness (also controls deposition). There are no precursors except the crude itself and the only reaction type model is for ageing of the deposit, whereby it changes thermal conductivity.

The form of the model is:

$$R_f = (A1 * t * \tau^{-A2} * P[t]) / (k * \rho) \quad (1)$$

$$k = (k_a - A4 * e^{-A3 * T_w} * (k_a - k_c)) \quad (2)$$

Where R_f is the fouling resistance, t the time, τ the shear stress at the wall, P a roughness parameter which is a function of time, k the thermal conductivity of the deposit, ρ the density of the crude, k_a the aged (final) thermal conductivity of the deposit, T_s the surface temperature, and k_c the thermal conductivity of the crude. $A1$, $A2$, and $A3$ are fit constants.

It is assumed that P varies such that it reaches an asymptotic maximum.

Given that we have only five data points and with the limitations mentioned earlier, our initial approach was to fix some of the parameters in Eq. (1) and fit the others. Accordingly we assumed the following:

$A2 = 1.0$ (exponent on shear stress)

$A3 = 1 * 10^{-5}$ (ageing rate parameter)

$k_c = 0.07$ W/m-K (Crude thermal conductivity)

$k_a = 1.0$ W/m-K (Aged thermal conductivity of fouling deposit)

$P_0 = 1.0$ (Starting value for P at $t=0$)

The result is the following fit constants:

$A1 = 3.62 * 10^{-8}$

$A4 = 0.93$

$P_\infty = 2.644$ (final value of P)

Fig. 6 shows for each of the five data sets a plot of the measured fouling resistance over time compared to the predictions of the model. Fig. 7 shows the variation in P that is used by the model.

There are several ideas to improve the model and make it more widely applicable to this type of data.

- Make use of a procedure similar to that used by Ishiyama et. al. (2010), which will more accurately account for time variations in ageing, roughness, and deposition .
- Relate some of the fit constants to traditionally used activation energies.
- Incorporate viscosity in the model as suggested by Epstein (2011).

- Obtain data for different surfaces and investigate the behavior of the roughness parameter, P.
- Obtain data at wider temperature ranges to fully incorporate the effects of ageing and viscosity changes.
- Adjust values of P_0 , k_a , and k_c based on more physical data.

Note that there is still a large gap between any laboratory or pilot-scale data and data from operating plants, especially in terms of variable conditions and usable trends. The models eventually have to fit field data in some form so they can be used to predict fouling rates and cleaning needs.

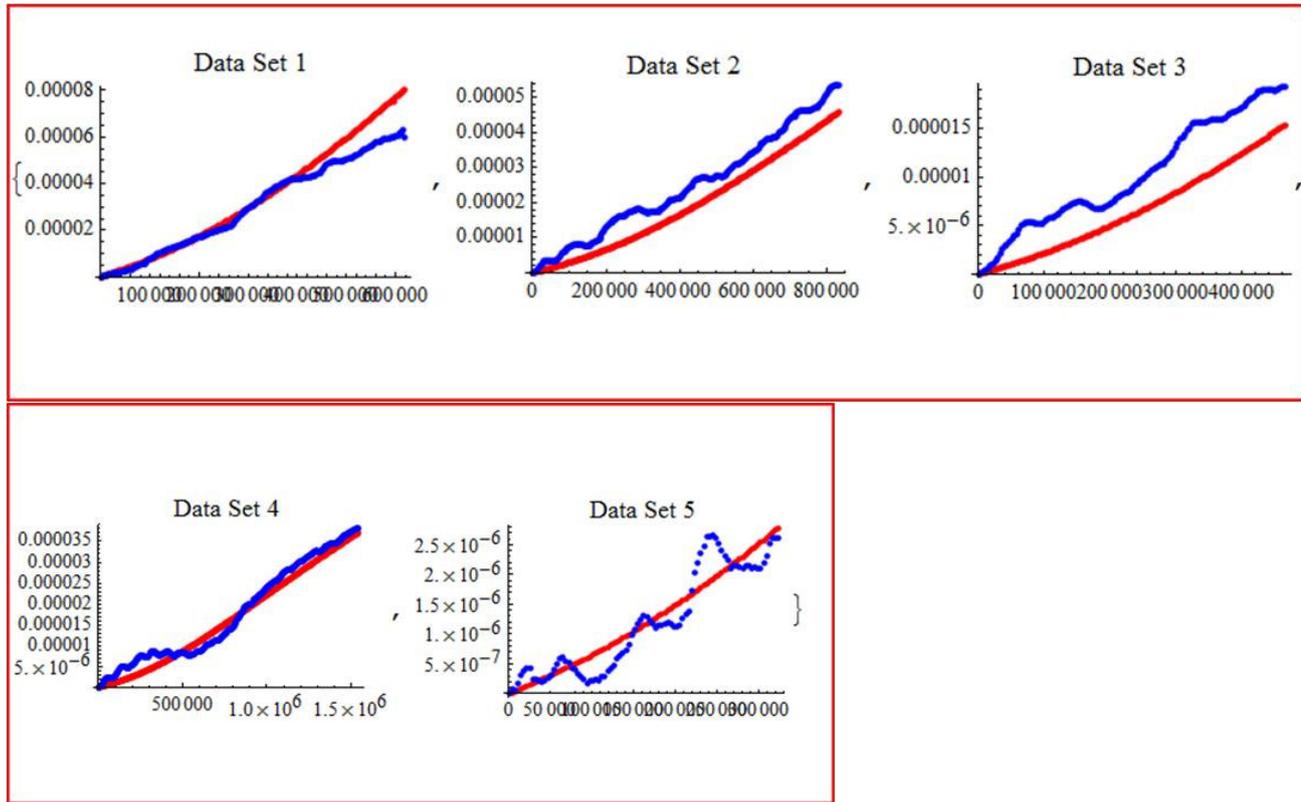


Fig. 6 Model Fit to Data of Fig. 5

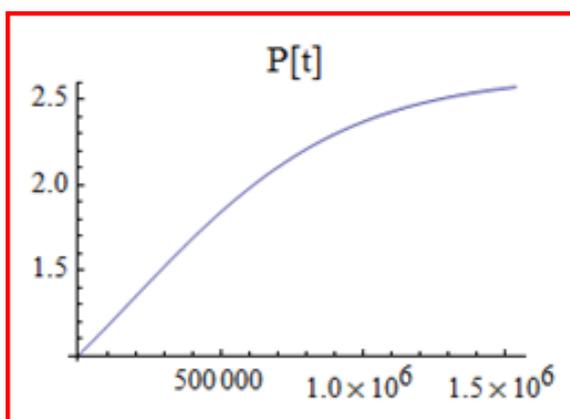


Fig. 7 Variation of Roughness Factor with time

CONCLUSIONS

With regard to modeling crude oil fouling, the goal of an operating company is to be able to use the models for prediction of fouling rates and to make cleaning decisions.

Another advantage of models is to be able to predict fouling behavior before a crude (or blend) is even processed. However, the data available in the field is from relatively unsteady operations and not necessarily amenable to models which might depend on accurate (and local) measurements of properties, temperatures, and flows. Laboratory or pilot plant measurements on the other hand take data under ideal conditions and it is difficult to apply models developed from this data.

This paper shows that even the best available field data could be difficult to model because of the lack of an obvious trend.

There are various proposed models to predict crude oil fouling, and many of them assume a reaction of a precursor. We have proposed a preliminary model which depends on shear stress and roughness to correlate deposition, and an ageing term to predict deposit thermal conductivity. There is an inbuilt assumption that the crude itself is the precursor to fouling, and not other species like polymers or asphaltenes. Model constants were developed for five data points obtained in a pilot-plant scale double pipe heat exchanger. We see a reasonable fit with data, but

plenty of improvement to the model is needed by taking data on a wider range of crudes, temperatures, and surfaces.

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NOMENCLATURE

A1	Fit Constant in Eq. (1)
A2	Fit Constant in Eq. (1)
A3	Fit Constant in Eq. (2)
A4	Fit Constant in Eq. (2)
k	Thermal conductivity, W/m-K
ka	Aged thermal conductivity of fouling deposit, W/m-K
kc	Crude thermal conductivity, W/m-K
P	Roughness parameter
T	Time, s
ρ	Density, kg/m ³
τ	Shear stress, Pa

Subscript

0	Time = 0
w	wall
∞	Final value

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