# CRUDE HEAT EXCHANGER FOULING - FIELD OBSERVATIONS

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## ABSTRACT

This paper presents several aspects of crude heat exchanger fouling as observed in an operating refinery. These aspects include: typical fouling trends, fouling mechanisms, contents of fouling deposits, crude properties which affect fouling, monitoring techniques, and the use of fouling models for prediction.

The most prevalent fouling mechanism is that of deposition of inorganic and organic material at the tube surface and the thermal degradation of the organic material. There is roughly an even split of the quantity of the two types, which is borne out by deposit analysis. Heptane insoluble asphaltenes are believed to be the primary organic precursor, therefore the quantity of this precursor is a major property affecting the rate of fouling. Other petroleum fractions which affect the solubility of asphaltenes are also critical properties, as is the fluid viscosity which determines both the wall shear stress and the thickness of the boundary layer, where the fouling process is taking place.

Although the rate of thermal degradation of the organic precursors is dependent on temperature, the rate of increase of fouling resistance shows a much higher correlation with wall shear stress rather than with either the wall or the bulk temperature. Also, the tendency of the deposition materials to stick to the surface affects the rate of fouling, and at times can be independent of shear stress.

Predictive models need to account for all of the above and be easy to implement. Implementation is easy if the model is expressed in terms of measurable flow parameters or routinely measured crude properties. A good model should also include the correct fouling dynamics so correct mitigation techniques can be identified.

## PREHEAT CONFIGURATION AND THE FOULING PROBLEM

A typical crude preheat train (CPHT) consists of three sets of heat exchangers as shown in Fig. 1. The desalter removes inorganic material - salts and some other solids, the flash drum takes out light hydrocarbon components, and the furnace heats the remaining crude to the temperature required in the atmospheric distillation column which follows the furnace. The heat in the heat exchangers is provided by hot pumparounds and product streams from both the atmospheric and the vacuum distillation columns. The heat in the furnace is provided by fuels such as oil or natural gas.

The heat exchangers foul, mostly on the crude side, which is typically the tube side. Fouling of one or two of the hot streams is also common and these streams are usually on the shell side. As fouling progresses with time, the total CPHT heat duty (sum of the heat duties of all heat exchangers) and the furnace inlet temperature (FIT) decrease. A clean CPHT may operate at an FIT in the 250-260 °C range, while a highly fouled one will be near 200 °C.

One fouling related indicator of the performance of a CPHT is the Qa/Qc ratio. This is the ratio of the actual total operating heat duty to the heat duty that could be achieved if all heat exchangers were clean, at the same flow and supply temperatures as the actual operating conditions. At the high end Qa/Qc will be ~0.95 while on the low end it is < 0.80 and could be as low as 0.60.
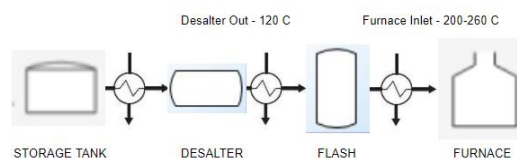


Fig. 1. Crude Preheat Train Configuration.

## IMPACT OF CRUDE FOULING

The impact of crude fouling on the CPHT is a combination of thermal (loss of heat recovery), hydraulic (potential cuts in processing rates), and safety concerns (increased maintenance, equipment integrity, and operator safety).

The Furnace Outlet Temperature (FOT) is critical to operating the distillation column as desired and is "fixed" in that sense. Any reduction of the CPHT heat duty needs to be compensated for in the furnace by firing more fuel. Although it is the heat exchangers which foul and resources might be spent in cleaning them, the largest impact in terms of both economics and operation is seen in the furnace.

The immediate consequence of fouling is an increase in fuel consumption and an associated increase in greenhouse gas emissions. Depending on the crude processing rate and when heat exchangers were last cleaned, a CPHT could be

operating with a deficit (Qc – Qa) of between 5-30 MW. The MW can be easily converted to the economic impact using the actual cost of the furnace fuel, and to the penalty in increased emissions using the quantity of fuel burnt.

In addition to the above, and just as critical, are other furnace parameters which get affected. One example is that of the tube metal temperatures (TMT) of the furnace tubes. The more the fuel fired in the furnace the hotter the tubes get and since there is a limit to the maximum fuel firing, there is a point beyond which it is not possible to provide more heat. The consequence of reaching a limit on either the TMT or fuel firing is that the crude rate must be cut back to maintain the FOT. Usually this is a far larger economic loss than the increased fuel firing.

## FOULING MECHANISMS

Fouling of crude in a CPHT occurs from two mechanisms, both represented by the schematic in Fig. 2. This figure is the author's conception of how crudes foul, based on experience with deposit analysis and observations of fouled tube surfaces under a microscope. The most prevalent mechanism, let's call it the Common Mechanism, is that of deposition of inorganic and organic material at the tube surface and the conversion of the organics to coke-like material over time. The deposited organic material is likely the crude itself, but the conversion is that of certain "precursor" components in the crude. Asphaltenes, usually defined as heptane insolubles, are the most prevalent precursor and they are present in a dissolved form in the raw crude. As the coke-like material forms the overall deposit becomes more and more solid and relatively harder. If this deposit is analyzed for its components, typically we see 40-60% by weight inorganic material and 40-50% organic material. Fouling build-up to a high or unacceptable level takes 6+ months, perhaps as long as 18 months.

The second mechanism is purely asphaltene based, occurring when the crude is incompatible (aka unstable) with respect to asphaltenes. Incompatibility means the asphaltenes are already precipitated and present as solids. Data and deposit analysis indicate that the asphaltenes tend to deposit much more rapidly than inorganic material and their conversion to coke-like material happens in a relatively short time with fouling build-up to a high or unacceptable level happening in weeks. Deposit analysis shows the organic portion of the foulant to be 70%+ by weight. This mechanism is rare in operation because systems are in place to avoid the processing of incompatible crude blends. It happens only if an incompatible blend is run by mistake.

Although Fig. 2 shows the surface roughness and the cavities created by the roughness can trap material as shown, deposits can stick even to relatively smooth surfaces depending on the surface energies of the material vs the precursors.
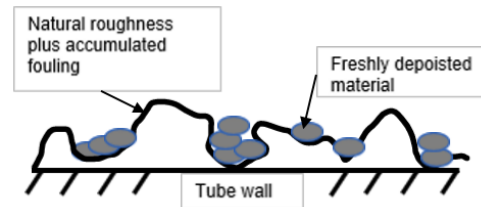


Fig. 2. Fouling Process Schematic.

## FOULING TRENDS

Typical fouling trends, with relatively high fouling rates, are shown in Fig. 3. Trends 1 and 2 represent the Common Mechanism while trend 3 is for an incompatible crude blend. The fouling resistance is what we would calculate using the heat duty based on measured flows and temperatures, and a simulation of the heat exchanger to determine the clean performance. Linear behavior is typical, especially for durations of 12 months or less.

Two aspects to be noted in Fig. 3 are the much higher (5X-10X) rate of fouling exhibited by the incompatible blend (trend 3) compared to the other two trends, and the dip in trend 2 shown at about 300 days. The latter was discussed in Ref. [1] as perhaps an artifact of process operations such as opening or closing bypasses. For trend 1 a cleaning is done at 360 days and another typical observation is shown – the new trend after cleaning duplicates the previous trend.
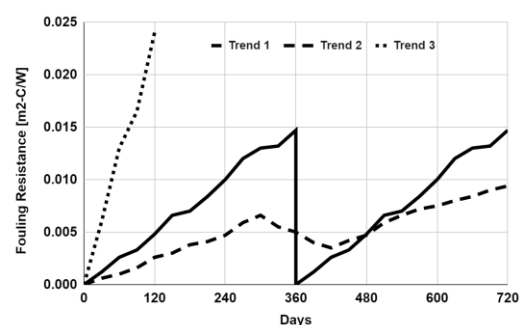


Fig. 3. Typical Fouling Trends.

## EFFECT OF SHEAR STRESS

For the Common Mechanism shear stress is the dominant parameter controlling the rate of fouling, whether on the tube side or the shell side. Fig. 4 (Ref. [2]) shows field data with a power law dependence of tube side fouling on shear stress. This data was presented in 2009, but several more CPHTs and data from a tubular test unit have reinforced this behavior. The scatter and the low $R^2$ are mostly because the different CPHTs process

different types of crudes. An equation of the form shown below can be used to predict the two Common Mechanism trends from Fig. 3 with good accuracy for both the tube and shell sides.

$$dRf/dt = A * (\tau)^{-b} \qquad (1)$$

In Eq. (1) the fouling coefficient 'A' is dependent on certain properties of the crude. Fig. 4 also shows the weak dependence of fouling on temperature. The temperatures shown are the hot side bulk temperatures, and although not exactly applicable, are used as a proxy for the crude side wall temperature. It is not uncommon for heat exchangers right after the desalter or the flash column to show higher fouling rates compared to the hottest heat exchangers. The notion that the hottest heat exchangers are the worst foulers is not always true, and when they are, there is a substantial amount of fouling on the hot side.
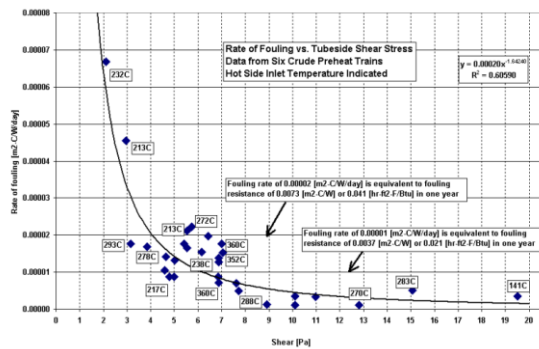


Fig. 4. Rate of Tube Side Fouling vs Shear Stress.

For the asphaltene based mechanism some other factors seem to have a large influence, not shear stress. Field data shows that high shear stress is unable to mitigate fouling. Using Fig. 4 as a reference, the rate of fouling with incompatible crudes will be in the 0.0003-0.0004 range, even at shear stresses > 8 Pa.

**A WORKING FOULING MODEL**

For the Common Mechanism, an empirical model of the form of Eq. (1) can be used to get good match with historical data and to predict future operation. Numerous network simulations have shown that such a model works well when modelling the total CPHT heat duty (Qa). For individual heat exchangers the model can match the trends in Fig. 3 well, including the changes in slope when the crude diet changes. A major limitation of the model is seen when it is applied to Trend 2. The downward slope, seen between the time of 2-½ and 3 months cannot be matched - the model as currently shown always increases fouling. It is unclear why fouling decreases, when operating data

usually doesn't indicate any major changes in operation. Ref. [1] discussed this issue with several possible causes for the phenomenon, but no clear reason has been identified.

In Eq. (1) the fouling coefficient 'A' can be correlated to various properties of the crude, so does not require any curve-fitting constants or assumptions regarding the conversion reaction. The major effort is in identifying which crude properties affect the common mechanism and then developing a method to calculate 'A' for each crude/blend. Broadly speaking, the important properties are related to the quantity of the known precursors (asphaltenes, polymers, others), the effect of the crude component fractions on the precursors (are the precursors soluble at all temperatures), and the behavior of the fluid at the surface (shear stress, adhesion of precursors). As stated before, field data shows a weak dependence on crude temperature, but the effect could be included by using the crude properties at variable operating temperatures, or by including a temperature correction in Eq. (1). One possible modification of Eq. (1), which includes a dependence on viscosity is shown in Eq. (2). This is mentioned here as a possible improvement to include temperature, but the author has done no analysis to quantify the possible improvement in model accuracy. Ref. [4] contains a discussion of a model of a similar form under conditions when deposition is mass transfer controlled.

$$dRf/dt = A * (\mu)^{c} * (\tau)^{-b} \qquad (2)$$

For actual crudes the coefficient 'A' varies by roughly two orders of magnitude. The crudes with the lowest fouling tendency have A = 1.0E-5 while the highest are about 5.0E-4. The shear stress exponent 'b' has a value between 0.9 and 1.4 for the tube side and between 0.3 and 0.5 for the shell side.

Most published crude fouling models attempt to model the organic conversion reaction to coke-like material using an activation energy and the tubewall temperature, with viscosity used to represent the crude. Such models only partially represent the actual mechanism (maybe half of what's happening) and ignore the dominance of shear stress. Also, the assumed activation energy typically represents a different, high temperature coking mechanism such as one that may occur in a furnace at temperatures in excess of 450 °C. CPHT temperatures are much lower and the organic material may not go through the same conversion process. Secondly, it is impossible to know or calculate the wall temperature in a heat exchanger so it limits how effectively such models can be applied to operating data.

No corresponding model is available for the asphaltene based mechanism. As stated above, the

fouling rates are much higher than the Common Mechanism and seem to have little dependence on shear stress. It may be possible to develop a model based on the asphaltene content, the degree of incompatibility, and how asphaltenes tend to deposit and stick to the tube surface. Fouling models that include the conversion reaction of asphaltenes to coke, dependent on temperature, could be more applicable to this mechanism rather than the common fouling mechanism.

## FOULING MITIGATION

A major concern for any operating unit is how to prevent (or slow down) fouling or how to mitigate the impact of fouling, given that the heat exchanger designs are fixed and the crude blend is driven by supply/demand and the associated economics. Several mitigation technologies are available and have been proven in operation. There are two broad classes of mitigation methods – those that affect the shear stress and those that affect the surface. In the former category the simplest method is to increase the velocity, but techniques such as tube inserts and vibration also work well. In the latter category are the use of different tube metallurgies, the application of coatings, and textured surfaces. With all of these techniques fouling reductions >50% can be obtained (Fig. 5) and the reduction could be independent of the base shear stress. There are a few methods which can reduce fouling to near zero, but a price has to be paid both in terms of the cost of the mitigation and pressure drop.

To make decisions about which of these mitigation techniques is best requires a somewhat complicated analysis of a combination of base velocities (or shear stress), expected benefit, available pressure drop, fixed and recurring costs of implementing the technology, the price of fuel and heat exchanger cleaning, tube material, and the need for other facilities, for example, electricity. The expected improvement and the implementation cost can be evaluated as a straight cost-benefit ratio over a fixed duration like one turnaround, or as life-cycle cost covering multiple turnarounds.
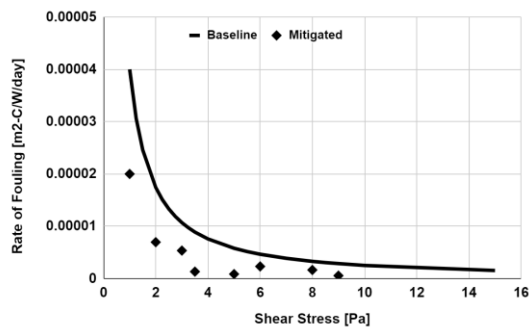


Fig. 5. Illustration of Fouling Mitigation.

Fig. 6 shows the effect of mitigation methods plotted against pressure drop. In general, the mitigation techniques falling to the right of the baseline curve will be unacceptable because the same fouling rate could be obtained at a lower pressure drop using some other technique. Conversely, the methods to the left of the baseline are advantageous as they can provide benefit at lower velocities.
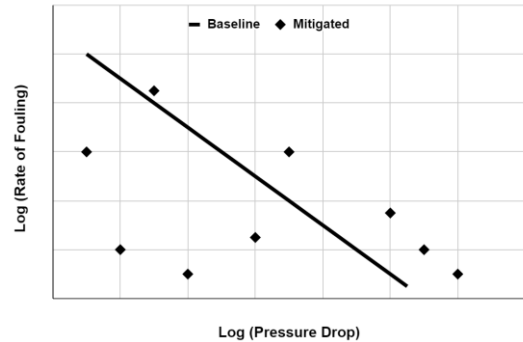


Fig. 6. Fouling Mitigation vs Pressure Drop.

Operating experience has also shown that some mitigation techniques have velocity constraints – they will not work well if the base velocity is below a certain value.

## DEPOSIT ANALYSIS

Many of the observations stated in this paper are based on a few dozen analyses of crude heat exchanger fouling deposits. Fig. 7 (Ref. [3]), shows typical results for the common mechanism (sample E) and for the asphaltene-based mechanism (sample F).

Sample E is about 50% organic material (carbon, hydrogen, and some of the nitrogen and sulfur), with 22% hardened coke – which is the material that is "combusted" in a Thermogravimetric Analysis (TGA) test. The interpretation is that although a conversion of organics to a coke-like material is taking place, it is not the dominant mechanism. The deposition of inorganic material (indicated by 46% ash) is also a major component of the fouling mechanism.

Sample F, which was from an incompatible crude incident is 85-90% organic with 46% hardened coke-like material and only 4% ash. This illustrates the difference between the two mechanisms and indicates why fouling models based on a coking reaction are difficult to use for the common mechanism but could possibly be applied when crude incompatibility is involved.

**Table 4.2** Elemental analysis and TGA summary for Sample E and Sample F.

| Element | Sample E wt% | Sample F wt% |
|---|---|---|
| C | 46.20 | 77.20 |
| H | 3.30 | 5.00 |
| N | 1.00 | 1.00 |
| S | 9.10 | 2.80 |
| Si | 3.10 | 3.50 |
| Cl | 6.90 | — |
| Fe | 4.50 | 4.50 |
| Ca | 2.80 | — |
| Na | 3.30 | — |
| Al | 1.50 | — |
| Mg | 0.60 | — |
| Ni | 0.20 | — |
| V | 0.40 | — |
| Total | 82.90 | 94.00 |
| O calculated | 13.06 | 4.00 |
| Overall | 95.96 | 98.00 |
| TGA | — | — |
| Volatilized | 32.0 | 50.0 |
| Combusted at 800 °C | 22.0 | 46.0 |
| Ash | 46.0 | 4.0 |

Fig. 7. Elemental Analysis of Crude Foulant Deposits.

## CONCLUSION

Fouling of heat exchangers can result in as much as a 40% loss in the heat duty in a crude preheat train, which not only leads to increased fuel consumption and GHG emissions but can also result in a throughput cutback.

Tube side crude fouling of heat exchangers is dominated by a mechanism of inorganic plus organic deposition and is a strong function of shear stress. Field and pilot-scale data show that all crudes exhibit a similar dependence on shear stress and an empirical model can be developed incorporating crude properties and a power law dependence on shear stress. Such a model has been used effectively to match operating data with a variety of crudes, without requiring any fitting constants. A major deficiency of this model is its inability to match downward fouling trends which are sometimes observed in the field.

Several technologies are available to reduce fouling rates by >50%. Decisions about which technology is optimum for a given situation involves many variables, but a systematic economic analysis in terms of immediate cost-benefit and a life-cycle costs is possible.

Crude incompatibility induced fouling happens at a much faster rate than the deposition phenomenon mentioned above and is not dependent on shear stress but occurs rarely in practice. No models are available to predict the rates of fouling for incompatible crudes.

## ABBREVIATIONS

CPHT  Crude Preheat Train
FIT  Furnace Inlet Temperature
FOT  Furnace Outlet Temperature
GHG  Greenhouse Gases
TGA  Thermogravimetric Analysis
TMT  Tube Metal Temperature

## NOMENCLATURE

$A$  Fouling Coefficient
$b$  Shear Stress exponent, dimensionless
$c$  Viscosity exponent, dimensionless
$\Delta P$  Pressure Drop, kPa
$Q_a$  Actual Heat Duty, MW
$Q_c$  Heat Duty with all Heat Exchangers Clean, MW
$R_f$  Fouling Resistance, °C
$\tau$  Shear Stress, Pa
$t$  Time, day

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