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## DESIGN OF SHELL-AND-TUBE HEAT EXCHANGERS TO ACHIEVE A SPECIFIED OPERATING PERIOD IN REFINERY PRE-HEAT TRAINS

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#### ABSTRACT

Fouling dominates the design of heat exchangers for use in crude pre-heat trains. It also dominates the life time cost of pre-heat trains. The most important cost factor is lost profit through reduced production. So, the design objective should be the identification of geometry that provides acceptable performance throughout a desired operating period.

# CURRENT STATUS OF DESIGN FOR FOULING SERVICE

Heat exchangers for use in pre-heat trains currently appear to be designed on the basis of pre-specified fouling factors. However, the validity of fouling factors (such as those specified by such organisations as TEMA) has been questioned and discussed since the early 1990's (see for example Crittenden *et al*, 1992)

Given that the fouling resistances that can be expected in heat exchangers situated in the hot end of a pre-heat train present a thermal resistance that is much larger than any of the other resistances present in the heat exchanger, this approach appears to be highly arbitrary.

In recent years it has been suggested (Nesta & Bennett, 2004) that provided the crude being processed is at a temperature below 300 C, the shear stress generated by using a tube-side velocity of 2 m/s will be sufficient to suppress fouling – thereby producing a "no fouling design". Experience does not support this claim. For instance, recent measurements (both thermal and hydraulic) of fouling in compact exchangers found that fouling was not fully suppressed under shear stress conditions that were ten greater than this recommended value (Andersson *et al*, 2009).

Analysis of refinery monitoring data (e.g. Polley *et* al, 2007) shows that crude fouling at the hot end of a preheat train is a function of both wall temperature and shear stress. Cases have been identified where even at higher flow velocities (above 2 m/s) high fouling rates occur because of high wall temperatures. These observations highlight the importance of considering fouling rates in both individual

exchanger design and pre-heat trains structure (Yeap *et al*, 2003). Following the conventional pinch rules drives leads to a maximization of wall temperatures and fouling rates.

The designer needs to give careful consideration to the velocities within individual exchangers for the use of high flow velocities throughput a preheat train leads to excessive pumping power requirements. Again this has been considered by Yeap *et al* (2003).

Some years ago refiners would shut down pre-heat trains for cleaning and maintenance after one or two years of operation. In recent years operators have sought to extend run times to as much ad five years. This paper address the designer challenge posed by such ambitions.

### COST CONSIDERATIONS

The life-time cost of a crude distillation unit is dominated by throughput considerations. In the early months of 2009 the cost of lost production varied from just above 2\$/barrel in some USA refineries to over 5\$/barrel in some Asian refineries and one refinery in India reports a value in excess of 10 \$/barrel (Rediff,2009).

It therefore appears sensible that heat exchangers that are to be used in the pre-heat trains feeding the distillation columns should be designed such that they provide satisfactory operation throughout the period between scheduled shutdowns. Since fouling is the main cause of unscheduled maintenance that gives rise to a reduction in throughput, this objective requires consideration of fouling to be an integral part of exchanger design.

#### SELECTING TUBE PASS ARRANGEMENT

Shell-and-tube heat exchangers generally employ more than a single tube pass. With a multi-pass exchanger the designer can choose to have the first pass co-current with the shell-side flow or counter-current to the shell-side flow. The choice does not effect the "effective mean temperature difference" used for the design. So, for heat exchangers used for "clean" duties this choice has no effect on heat exchanger performance. However, with exchangers that are to be used on duties where fouling occurs the choice is important. The designer needs to understand the relationship between wall temperature and fouling rate. For instance, if the fouling rate increases significantly with increasing wall temperature then a pass arrangement that minimizes the wall temperature should be chosen. Wall temperature is maximized when the incoming hot fluid is matched against the outgoing cold fluid. In a unit in which the hot fluid is on the shell-side this situation is avoided if the hot fluid enters the exchanger at the opposite end of the shell to the inlet/outlet header. The better arrangement is therefore for the first pass in counter-flow to shell-side fluid (Polley *et al*, 2002).

# LINKING EXCHANGER GEOMETRY AND ACCEPTABLE FOULING RATE

Given the observations made above, it is suggested that exchangers should be designed such that the fouling rate encountered within the unit does not exceed a level that would require the unit to be taken off-stream for cleaning. So, the first step in developing a procedure that incorporates this philosophy is to provide a linkage between exchanger geometry and fouling rate.

The starting point is to determine the size of exchanger necessary to perform the required duty in a clean condition. The heat exchanger analysis program EXPRESSplus from IHS ESDU has been used for this illustration and for other calculation described in this paper. In Fig. 1 we show the relationship between exchanger tube count (or, velocity) and tube length required for an exchanger that is matching crude oil having an inlet temperature of 200 C with a pump around stream having an inlet temperature of 280 C. The crude oil outlet temperature is 225 C. (The example is taken from a pre-heat train previously studied by Polley *et al*, 2007). The crude being processed has not been reported.

Whilst the clean duty could be accommodated in a single shell, the proposed unit has two shells-in-series in order to handle the deterioration that occurs through fouling.

The chosen design will have a tube of standard length (see below) rather than the length required under clean conditions. The difference in these lengths provides the over-surface installed to accommodate the fouling that accrues over the operating period.

Under start-up conditions the unit would overperform. Consequently, a fraction of the hot stream needs to bypass the exchanger. This fraction steadily reduces until the bypass is fully closed at the end of the specified operating period.

The bypass has to be positioned on the hot stream because a reduction in crude velocity would lead to increased fouling rate. A reduction in the hot side flow-rate leads to reduced coefficient on the shell-side and reduced hot stream outlet temperature. Both of these factors lead to reduced fouling rates – so the strategy is conservative.

The standard tube length adopted for heat exchanger s used in oil refineries is typically 6.1 m (i.e. 20 feet). So, the next step is to determine how much fouling can be accommodated in a unit having the standard length (rather

than the length  $L_Q$  given on the plot). The fouling resistance that can be accommodated after time  $\theta$  is given by:

$$R_d(\theta) = \frac{1}{U_c} \left(\frac{6.1}{L_Q} - 1\right)$$

(1)



Figure 1. Range of Geometry Providing Required Clean Performance

This value can be adjusted for the allowance for shellside fouling. The acceptable fouling rate for the tube-side (based on outside area) can then be determined by dividing the result by the required operating period (Table 1.).

The task is now to compare these acceptable rates with those occurring within the exchanger. This can be accomplished using of a "fouling map" (Figure 2). This map (ESDU, 2009) consists of a family of curves relating velocity and temperature conditions that lead to a specific rate of fouling. The lowest curve is for a rate of 0.5e-8. The other curves are for rates of 1e-7, 2e-7, 4e-7, 6e-7, 8e-7, 1e-6, 2e-6, 4e-6 and finally 6e-6.

We observe that the design having a velocity of 2 m/s has a fouling rate just below the permitted value of 4.5e-7. This design is accepted.

However, the designer may wish to explore the options available and introduce a consideration of risk.

Tube Count	540	400	360
Tube velocity	2.0	2.7	3.0
m/s			
Clean	1048	1270	1372
OHTC.			
$W/m^2.K$			
Duty length	1.15	1.24	1.3
m			
Duty OHTC	197.6	258.2	292.4
$W/m^2.K$			
<i>R</i> <sub>d</sub> at 8000 h	0.0041	0.0031	0.0027
Fouling Rate	4.51e-7	3.23e-7	2.74e-7
m <sup>2</sup> .K/W.hr			

Table 1. Acceptable Fouling Rates (shell-side  $R_d = 0.0005$ )



Figure 2. Predicted Fouling Rate (m<sup>2</sup>.K/W.hr \* 1e-6)

#### RISK ANALYSIS

Calculation of the length of clean tube required for a specified duty requires determination of the hot and cold film heat transfer coefficients. Given this information the calculation of the wall temperatures at the inlet and outlet of the exchanger is straightforward. Since, we also know velocities and shear stresses at these points we have enough information to predict fouling rates that can be expected in an exchanger of given tube count using a suitable fouling model (Polley & Garcia Gonzales, 2009).

Allowable and predicted fouling rates can both be plotted as a function of tube count (Figure 3).

Where the line showing allowable rates lies above that for predicted rates the design should provide the required performance throughout the required operating period. The greater the vertical separation between the two lines the more likely is it that the design will operate for the required operating period without needing to be cleaned.

In the example considered here the lines diverge with increasing tube count. Thus, the risk of needing

unscheduled cleaning decreases with increasing exchanger



Figure 3. Fouling Rates for Example 1



Figure 4. Fouling Rates for Example 2.

# IDENTIFYING WHEN TUBE INSERTS SHOULD BE USED

Our next example involves an exchanger positioned at a hotter position in the train. The hot stream is to enter the exchanger at a temperature of 370 C and leave at 280 C. The crude is to enter at 225 C and leave at 265 C. Again a unit using two shells-in-series was designed. When this unit is analysed the results presented in Table 2 are obtained.

Tube Count	580	400
Tube velocity m/s	2.0	2.9
Clean OHTC. W/m <sup>2</sup> .K	495	618
Duty length m	3.48	3.98
Duty OHTC W/m <sup>2</sup> .K	282	403
<i>R</i> <sub>d</sub> at 8000 h	0.00152	0.00086
Permitted Fouling Rate	1.28e-7	4.52e-8
m <sup>2</sup> .K/W.hr		

Table 2. Results for Hotter Exchanger

A comparison between allowable and predicted fouling rates for this example is made in Figure 4.

For all acceptable tube velocities the predicted rate is greater than the allowable rate. To obtain a suitable design would require the installation of further exchangers in series. However, given that predicted rate exceeds the allowable rate by an order of magnitude this will clearly be economically unacceptable.

Under these circumstances the designer needs to instigate a cleaning schedule that allows individual exchangers to be cleaned without reducing the plant throughput (a analysis for such scheduling has been introduced by Polley *et al*, 2009) or use tube inserts (Turbotal<sup>TM</sup> or Spirelf<sup>TM</sup>) that first reduce the fouling rate and then control the level of fouling occurring within the unit (Petitjean *et al*, 2007).

# SPECIAL CASE FOR APPLICATION OF TUBE INSERTS

Our discussion has related to the design of heat exchangers that are to be installed at the hot end of the preheat train. There is one typical duty conducted at the cold end of the train where tube inserts can be used to provide a major benefit.

It is common to find that the unit positioned immediately prior to the de-salter recovers heat from column residues. These residues are usually viscous and contain suspended solids. Since it is difficult to obtain good heat transfer on the tube-side when processing viscous liquids, the residues are usually assigned to the shell-side.

Unfortunately, the velocities in the shell are low and sedimentation occurs. The solution to the problem is to assign the residues to the tube-sided of the exchanger and install wire matrix inserts (Cal Gavin, 1996 and Petitjean *et al*, 2007). These inserts promote relatively high shear forces at the surface of the tubes. These shear forces not only enhance the heat transfer but keep small particles in suspension (Ritchie *et al*, 2007).

# ANALYSING MONITORING DATA FOR USE IN DESIGN

The philosophy suggested above can only be effectively applied if the fouling process is reasonably well modelled. The problem here is that the fouling process is strongly dependant upon the composition of the crude oil. This composition is not only difficult to fully quantify but each source of oil has a different make-up and this can vary over time.

The picture is further complicated by the fact that plant operating conditions (such as the conditions under which the de-salter operates) also affect fouling rates. However, it should be recognised that a refinery that processes a similar crude slate to the one specified for the new plant is the best available source for design information.

In recent years a significant amount of work has been undertaken on modelling fouling in pre-heat trains. As discussed by Yeap et al (2004) a number of models are available.

The philosophy developed above does not relate to any particular fouling model. It can be applied using with future models as well as with existing models.

The model that has currently found the most widespread application is that proposed by Ebert & Panchal (1997). A more generalised form of this equation is now under investigation (Polley & Morales Fuentes, 2009). This equation has the form:

$$\frac{dR_d}{d\theta} = \frac{A}{\alpha} \exp\left(\frac{-E}{RT_f}\right) - \gamma \tau_w \tag{2}$$

This model has three parameters: a deposition constant A, an Activation Energy E and a suppression constant  $\gamma$ . The rate is dependant upon film heat transfer coefficient,  $(\alpha)$ , film temperature  $(T_f)$  and shear at the surface of the deposit  $(\tau_w)$ .

Where an exchanger is being designed for an exiting plant these parameters can be determined from plant monitoring data using a procedure pioneered by Petitjean (Polley et al, 2007).

Where an exchanger is being designed for a new plant, the parameters can be determined from analysis of an existing plant processing a similar crude slate. Where such a plant does not exist the designer can undertake a "sensitivity analysis" relating to the chosen parameters.

#### PRESSURE DROP

The traditional approach to heat exchanger design is for the user to specify the thermal duty and allowable pressure drops for the hot and cold streams being handled. The designer will then develop a design that provides the required thermal performance whilst observing the pressure drop constraints.

It can be argued that this approach cannot be adopted for exchangers used on fouling duties because the operational pressure drop is strongly affected by fouling. However, in the two examples considered above the end of run fouling resistances are quite low. This means that the effect of fouling on pressure drop will not be excessive. The

traditional approach can be used provided the designer checks on the fouled pressure drop obtained for the final design.

For the change in pressure drop across the required operating period of the exchanger developed for our first example is shown in Fig. 5.



#### Figure 5. Pressure Drop Changes Over Operating Period

In cases in which the pressure drop is found to be unacceptably high the designer should move to a larger tube diameter.

### **OTHER UNCERTAINTIES**

So far we have assumed that the calculation of film heat transfer coefficients have been accurate. This is often not the case. The correlations used for the prediction of heat transfer coefficient are inaccurate. The use of these correlations requires the specification of physical properties (which again are often not known accurately).

Consequently, once a design geometry has been the sensitivity of the fouling rate to errors in wall temperature calculation needs to be determined. This can be achieved using various response plots (Polley, 2002).

It should also be recognised that whilst exchangers are designed on the basis of operation at a specified crude throughput, this flow will actually vary quite widely throughout the plant operating period.

The effect that both of these factors have upon the behaviour of the exchanger can be examined using "response plots".

The plots required for fouling analysis have not yet been fully defined. However, two plots can be envisaged. The first will show the effect of errors in the calculation of overall heat transfer coefficient (referred to as "design margin") on wall temperature (Figure 6). The upper line shows the wall temperature at the crude outlet. The lower line shows the wall temperature at the crude inlet.



Figure 6. Effect of Error in OHTC Calculation on Wall Temperatures

The other plot can be expected to take a form similar to the plot shown in Figure 7.



Figure 7. Exchanger Response Plot

The top line shows the effect of throughput on the temperature of the wall at the crude oil outlet. The lower line shows the wall temperature at the crude inlet.

The dotted lines cutting across these lines show the wall temperatures for specified fouling rates. A family of lines can be produced. The intersection of the rate and wall temperature lines will then provide guidance on fouling rates change with changing throughput. Situations in which the allowable rate is exceeded would be readily identified.

### NEXT STEP

Heat exchanger fouling is more sensitive to changes in film temperature than it is to changes in velocity. The film temperature is largely controlled by the hot stream inlet and cold stream outlet temperatures. The engineer can rarely adjust the hot stream inlet temperature. However, the crude oil temperatures are set by the structure of the pre-heat train.

Film temperature can be reduced by moving the heat recovery match to a lower poison in the train such that the crude oil temperatures are reduced.

The next stage of this work is to develop a procedure in which the fouling map is used to guide pre-heat train structure.

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