DESIGNING TWO-PHASE FLOW HEAT EXCHANGERS FOR MITIGATING FOULING

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Abstract

Significant progress has been made in understanding the underlying mechanisms of hydrocarbon fouling and characterizing the effects of physical and chemical parameters in single-phase flows. However, the interactive effects of two-phase flows and fouling mechanisms are poorly understood. Many of the industrial heat exchangers in refining and petrochemical processing operate under multi-phase flow conditions with varying flow regimes. Fouling and localized corrosion are generally experienced due to maldistribution of vapor and liquid phases in such heat exchangers. This is because design methods are inadequate to determine localized process conditions that could induce severe fouling locally, which could also lead to localized corrosion by concentrating corrosion species in the deposits. This paper discusses design approaches to evaluate two-phase flow conditions and design exchangers to minimize fouling. Such design approaches may not be optimum for heat transfer and pressure drop considerations; however, it will minimize fouling and localized corrosion. The paper focuses on improved design of feed/effluent exchangers with tube side flows and reboilers for minimizing shell-side fouling and a case study is presented. The result is lower lifecycle ownership cost of the exchanger.

Introduction

Heat exchangers with two-phase flows in petroleum processing that encounter fouling and coking are:

- Reboilers: localized fouling is generally caused by maldistribution of two-phase flow on the shell side creating localized environment for chemical reaction fouling and particulate deposition of corrosion products which might be generated in the overhead condenser/separation drums, transfer pipelines, and/or in the distillation column.

- Feed/Effluent (F/E) exchangers: fouling on tube side of F/E exchangers in hydrotreating and reforming processes is mostly caused by maldistribution of vapor and liquid phases among tubes and intermittent dry out caused by the mist flow at higher vapor qualities.

- Condensers/coolers: condensers/coolers (including air-cooled condensers) are used downstream of hydrocracking and hydrotreating reactors and they are prone to fouling caused by solid phase formation on cooling. Hydrocarbon process streams in overhead condensers of fractionation columns generally do not produce fouling, but fouling is mostly observed on cooling-water side.

- Heat recovery boilers: they are commonly used to recover heat from reactor effluent to generate high-pressure steam. Other than the transfer-line exchanger (TLE) in the ethylene process, fouling is not a major problem for heat recovery boilers.

- Fired process heater: the process side has normally two-phase flows with all possible flow regimes. Fouling/coking is generally localized; normally downstream of U-bends.

This study focuses on fouling mechanisms, methodology to determine root cause(s) of fouling in reboilers and F/E exchangers, and guidelines for designing exchangers with two-phase flow applications. A case study of mitigating fouling of a reboiler is presented to demonstrate how a proper design approach can mitigate fouling.

Reboiler Design Practice

The term 'reboiler' is generally used in the Process Industry to describe equipment whose function is to add a specified duty to a distillation or other separation process. They are broadly classified as once-through, thermosyphon, or forced flow. In practice, however, only three types of reboilers are common:

- Kettle;
- Vertical thermosyphon or forced circulation; and
- Horizontal thermosyphon or forced circulation.

The need for careful design of reboilers is well known. In fact, if operational problems are to be avoided the design process of this type of equipment calls for very careful thought.

Some basic guidelines are:

- Use a proven thermal design tool(s).
- Check the performance at every possible operating condition, especially at maximum turndown and at start-up (no fouling).
- Do not specify an excessive fouling resistance; this can lead to film boiling when the exchanger is clean and worse performance than if it were fouled.
- Always check the flow regimes, particularly at maximum turndown. Separated and mist flow regimes should be avoided.
- Consider designing reboilers with low residence time, which can be achieved with low liquid hold up and minimizing recirculation zones.

Nobody pretends design of reboilers is straightforward, but there is one thing we ought to be able to rely on: it's that the engineers working on a design should be doing more than playing hunches. We use certain methods because they work, right? We use certain procedures, embedded in commercial software suites because they work well, don't we? However, more often than not engineers realize

that no matter how rigorous design methods are, there's simply little evidence that their predictions are reliable. Obviously, before releasing design methods to end-users correlations are generally tested with available test data to show that they are effective and reliable. However, the two-phase flow with or without heat transfer in industrial heat exchangers, specifically on the shell side, cannot be reproduced with bench-scale test units. Often, engineers are left to propose a design based at least in part on engineering judgments and previous experiences, or even an educated guess. The primary objective of the design is to meet the performance in terms of duty for non-fouled conditions. The end users are generally responsible for taking corrective measures to minimize the effects of the two-phase pattern and localized thermal conditions on fouling. This current stop-gap practice is generally responsible for fouling of reboilers and costly corrective measures the end users have to implement in after-the-fact scenario.

Increasingly, designers seeking to provide end users with the best possible solution are relying on what is known as evidence-based engineering, a hard, cold, empirical look at what works what doesn't work, and how to distinguish between the two. This approach has been used with varying degree of success, but it should be effective in dismissing the most cherished beliefs in the industry, like the idea that higher fouling factors would result in longer cleaning cycles.

But is this possible or even desirable? Heat transfer engineering, after all is a service built around uniqueness of each particular design and engineers' ability to design equipment accordingly. Furthermore, how do we create the evidence the end-users demand, unless we test the untested? Whatever the merits of "evidence based engineering," further progress will require an increased reliance on "expert" opinion supported by knowledge-based prediction methods.

Feed/Effluent (F/E) Exchangers

F/E exchangers are used to recover process heat from reactor (hydrotreater and reformer) products and preheat the feed stream, which consists of petroleum feed and recycled hydrogen. In practice the following types of F/E exchangers are used.

- Horizontal shell and tube with U-tube bundles;
- Vertical combined feed exchanger (VCFE) also known as vertical Texas Tower F/E; and
- Vertical welded plate exchangers.

The two-phase flow feed is normally on tube side and the product stream is on the shell side. Non-uniform distribution of the petroleum feed and recycled hydrogen among tubes of horizontal as well as vertical F/E exchangers induces high localized wall temperatures. If these localized wall temperature are above threshold fouling conditions at prevailing liquid-phase wall shear stress, then formation of precursors (e.g. decomposition of organo-metallic complexes) would occur. Tubes with high vapor flows could produce undesired flow regimes (such as mist flows) with intermittent dryout or thin film, which could produce high fouling/coking. Tubes with low vapor flows would produce slug or separated flows with high residence time and low wall shear stress would increase the precursor formation in the liquid phase. Amelse et al [2004] analyzed the distribution of vapor and liquid phase in F/E exchanger of p-xylene plant using radioactive tracers. They correlated high rates of fouling with the hydrogen and hydrocarbon distribution. It was shown that the fouling rate was significantly high in tubes with high liquid to hydrogen flow ratios. Such conditions produce low wall shear in the liquid phase, separated flows, and higher wall temperatures particularly in regions of intermittent vapor-liquid interfaces on the wall. All these parameters are responsible for accelerated fouling rates. However, correlations are not available to determine threshold limits of these parameters for two phase flows in tubes and we are not sure how threshold conditions determined with the single phase flow can be applied to two phase flows. In order to avoid poor vapor and liquid phase distribution, vertical welded plate heat exchangers are being considered. They show low fouling propensity; however, the long-term performance of such exchangers under varying process conditions needs to be validated.

The current design practices focus on achieving the thermal performance for a given pressure drop limit. There are no adequate design guidelines to evaluate fouling propensity for two-phase flow conditions under varying process parameters. As a result, no corrective measures are built into designing F/E exchangers. Therefore, there is a need to examine the current practice of designing F/E exchangers, develop validated predictive methods for localized fouling/coking conditions, and evaluate new design configurations including alternate heat exchangers.

Major Fouling Mechanisms, Root Cause Analysis and Mitigation

The three major fouling mechanisms associated with reboilers and F/E heat exchangers are:

1. Reaction fouling – polymerization;
2. Deposition of corrosion products; and
3. Coking under dryout and/or under critical heat-flux conditions.

Polymerization fouling, generally induced by iron-sulfide formation in refining, is commonly observed on feed side, generally tube side, of F/E exchangers of hydrotreating and reforming process units [Limke, 1999]. Polymerization of diolefins [Brons et al. 1999] is a common problem in reboilers and reactor overhead condensers of hydrotreaters, hydrocrackers, and FCC fractionators. The root cause analysis should focus on: 1) two-phase flow patterns at the inlet, particularly on how vapor and liquid are fed to the exchanger, 2) flow regimes in return passes, 3) chemical analysis of deposits collected from different parts of the exchanger to determine the main precursor(s) and hence identify the most probable chemical mechanism, 4) thermal profiles, 5) distribution of fouling deposits within the exchangers, and 6) change in

pressure drop between cleaning. Maldistribution of liquid and vapor phases at the feed point and also in return passes of multi-pass exchangers can produce conditions with high propensity of localized fouling, which can then propagate to the rest of exchangers. Understanding the governing fouling mechanisms and designing the exchanger to operate below threshold wall conditions (temperature and wall shear stress) provides necessary design information for an alternate tube bundle to minimize fouling. The primary choices for alternate tube bundles are different tube size, twisted tubes, and spiral baffles to alter thermal profiles and two-phase flow patterns. If alternate tube bundle cannot meet necessary conditions to minimize conditions then consider altogether different heat exchanger. Exchangers that provide good distributions of liquid and vapor phases and minimize the overall resident time would minimize fouling by reducing the rate of precursor formation in the exchanger. Welded plate heat exchangers with narrow flow passages have been shown to reduce fouling; however, it is important to evaluate individual applications for suitability of such exchangers. F/E exchangers with two-phase flow on shell side provide low residence time and should have relatively uniform distributions to minimize fouling.

The deposition of corrosion products is more common in reboilers, where corrosion products may be generated in the distillation column or overhead condensers/separation drums. These corrosion products tend to deposit in recirculation zones. The root cause analysis should focus on deposit analysis and tracking the source of corrosion. The localized deposition can alter the flow patterns and thermal conditions locally, producing conditions of higher fouling propensity for organic fouling (polymerization) in other regions. Combined corrosion and polymerization fouling can be difficult to manage. However, controlling corrosion fouling could minimize organic fouling. The reboiler in general should have provision purge corrosion products collected at the feed point. Alternate heat exchanger designs which provide good flow patterns on shell side

(twisted tubes or spiral baffles) should be considered.

Polymerization fouling may lead to further coking reaction within the deposits as wall temperatures increase after significant fouling occurs. More commonly coking in reboilers and F/E exchangers is caused by dryout and critical heat flux with high wall temperatures. Intermittent wetting and dryout produce droplets and thin film and the transient heat transfer induces coke-like deposits separating out as solid or semi-solid phase. The top region of reboilers is prone to coking, if mist flow occurs and high-temperature heating media (e.g. high-pressure steam) is used. The root-cause analysis should focus on analysis of deposits to determine coking mechanisms (solubility tests) and identifying regions with high coking within the exchanger. Improved or alternate heat exchanger design to minimize mist flow, avoiding super heated steam, and evaluating threshold coking conditions during turn-down operation (e.g. use of recirculation pump) are possible mitigation steps based on design.

Application of Single-Phase Fouling Data to Two-Phase Flows

Fouling data are generally obtained with single-phase flow fouling units. Such fouling data or an empirical correlation based on these data cannot be directly applied to exchangers with two-phase flows. If the flow regimes are known and reliable correlations are available to predict the local wall shear stress and heat transfer rates, then Kuru and Panchal [1997] showed how the fouling data obtained with single-phase fouling unit could be applied to tube side annular two-phase flow regimes.

Panchal et al [1997] developed a threshold fouling model applicable to preheat train. The rate of fouling is expressed in terms of generation of precursor in the boundary layer and its removal before firm adhesion of deposits on the wall occurs.

$$dR_f/dt = \alpha \, Re^{-\beta} \, Pr^{-0.33} \, exp^{(-E/RT_f)} - \lambda \, \tau_s \qquad (1)$$

Where Reynolds number, Re and Prandtl number, Pr are calculated for properties at the bulk and film temperature T_f (average of bulk and metal wall temperatures), respectively. The Reynolds number in this equation was based on the two-phase flow viscosity. The wall shear stress, τ_s is calculated for the liquid flow at the wall surface. Constants α, β, λ and the activation energy E are determined from laboratory and/or field data. When the equation is equated to zero, it provides threshold fouling/coking conditions between in-side tube metal temperature and the wall shear stress.

The model was developed for single-phase flows; however, it can be applicable to two phase flows provided local fluid dynamics can be calculated. Panchal et al. [2006] applied the fouling correlation in Eqn. 1 developed for crude preheat train to the process side of a crude fired heater. This case study is presented here to demonstrate applicability of the fouling model to an industrial fired heater to evaluate the localized fouling propensity. Figure 1 shows circumferentially averaged tube-metal temperature (TMT) for selected pipes of a crude heater predicted by the process model and API 530 (American Petroleum Institute design standard 530), which is commonly used by the petroleum industry to estimate TMTs.
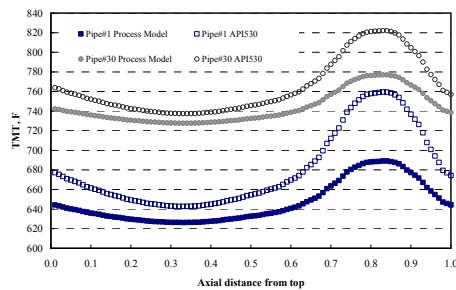

Fig. 1 TMTs predicted by the process model and API-530

The localized coking rate predicted using Eqn. 1 is shown in Figure 2. The predicted results show gradual increase in the coking rates as the TMT temperature rises, although the wall shear stress also increases with increase of the vapor quality. When the circumferential variations of

the heat fluxes and hence TMTs are incorporated, the localized coking rates increases significantly. The distribution of vapor and liquid phases in the U-bend regions further increases propensity of localized coking. Figure 3 shows the CFD-based prediction of distribution of vapor and liquid phase downstream of U-bend. Similar flow distribution is expected for horizontal F/E exchanges with U-bend tube bundles.
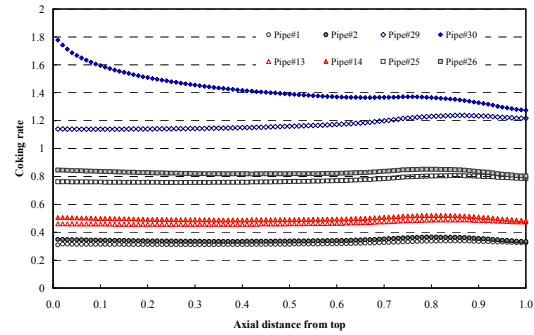

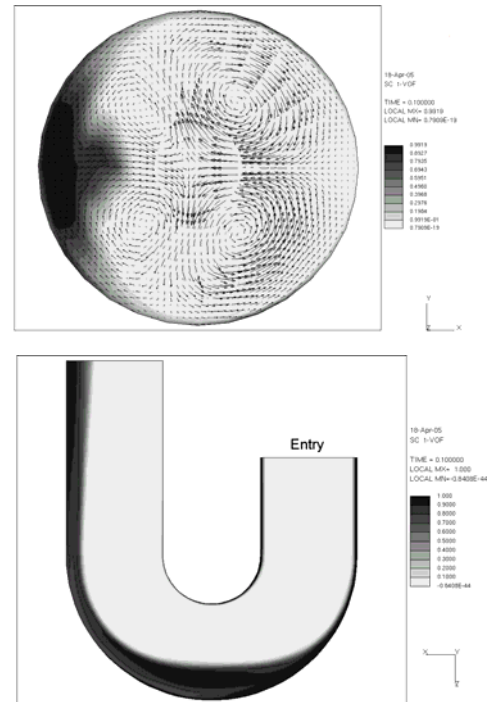Fig.2 Coking rate (hr ft^2 F/Btu (10^{-4}) per day) distribution.

Fig. 3 Cross section at up flow exit of a down flow U-bend

Figure 3 shows secondary flow patterns and accumulation of liquid (dark region) on the outer

wall of the bend and liquid distribution at mid-plane of a down flow U-bend.

This case study shows potential application of a fouling model developed and validated with single-phase flow data applied to two-phase flows. However, very little work has been done to develop such predictive methods for fouling in two-phase flows. Therefore, the future research and development should focus on developing and validating the fouling prediction correlation for different flow regimes. This will significantly improve design capabilities of exchangers with two-phase flows and minimize fouling.

Swirl Flow - Twisted Tube Technology

Swirl flow velocity and temperature field generated by twisted tubes, Figure 4, offer unique advantages in F/E exchanger applications. There are several reasons for this. First, all surface-induced reactions as well as heat-induced reactions take place within the boundary layers of velocity, temperature, and concentration; all develop at the heating surfaces. Within the boundary layers of twisted tube flows, temperatures, velocities, concentrations, reaction rates are quite different from those encountered in conventional rounded tubes. Studies show that boiling inside and outside twisted tubes is effective in increasing critical heat fluxes, the condition at which vapor blanketing is initiated causing accelerated fouling. In fact, nucleate boiling characteristics of twisted tubes are similar to those of conventional, rounded tubes. However, for the same pressure drop, the critical flux of twisted tubes (inside and outside) is approximately twice that of straight, rounded tubes. In addition, the swirl flow (with its secondary flows in the boundary layer) is expected to enhance the fouling removal rate from the surface, as a result of momentum and heat and mass transport phenomena occurring within the boundary layer.

Using the process data to make direct comparisons about fouling in different geometries is difficult in most cases. In comparing twisted-tube bundle to conventional baffled heat exchangers, it should be noted that
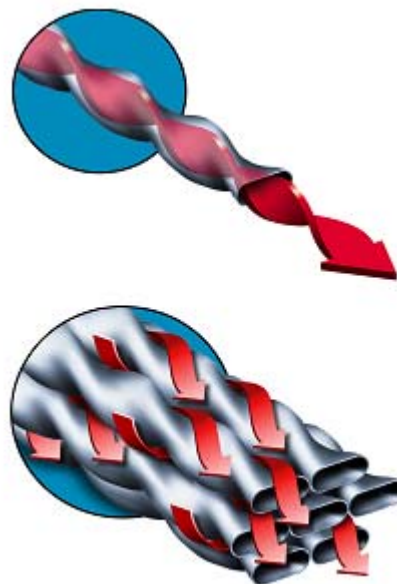

Fig.4 Tube-side/shell-side swirl flow enhancement in TT bundles

twisted tube bundles have a more uniform flow and temperature field with almost no shell-side dead areas providing better conversion of available pressure drop to heat transfer. Thus, twisted tube exchangers, compared to plain tube units, tend by its very nature to have lower tendency to fouling

Swirling flows in twisted and spirally fluted tubes alter the flow pattern and extend the annular flow regime. The resulting effects of minimizing the intermittent (slug and plug) and mist flows maintains good distribution of liquid phase on the wall surface, which maintain high heat transfer coefficient, lower wall temperatures and thereby minimize the fouling propensity. Figure 5 shows that twisted tube dramatically shifts the mist flow regime, shown as dotted line. Panchal et al. [1988] showed that the heat transfer coefficient of flow boiling in vertical spirally fluted tubes remains relatively high for vapor qualities 90% to 95%, as compared to vertical circular tube where the performance drops significantly for vapor qualities greater than 80%.
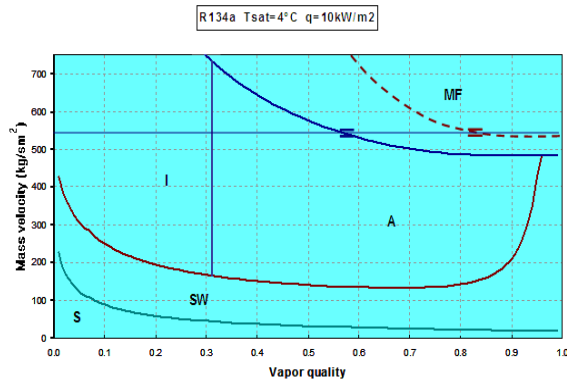
Fig. 5 Comparison of two-phase flow regimes in rounded and twisted tubes

In horizontal tubes, the performance would drop for lower vapor qualities. The horizontal twisted tubes maintain relatively high heat transfer coefficient for vapor qualities upto about 80% as shown in Figure 6.
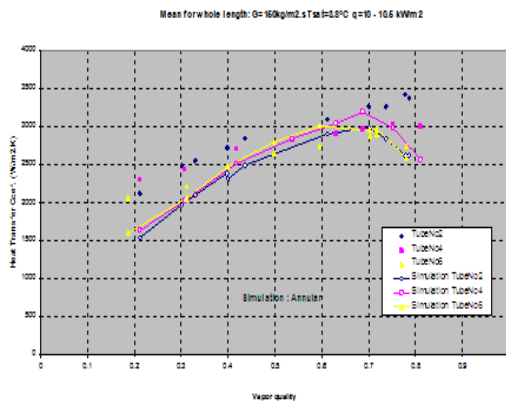

Fig. 6 Convective boiling in twisted tubes

The thermal performance results clearly indicate that tubes with swirling flows should be considered for F/E exchangers with high vapor qualities to minimize fouling by maintaining extended annular flows and minimizing the high localized wall temperatures.

Case Study

The future improvements in both increased energy efficiency and extended runtimes will likely come from the use of closer temperature approaches. As the temperature difference

required to instigate nucleate boiling could be high, conventional exchangers will in most cases pose a severe limitation. One option is the use of special boiling surfaces. However, these are expensive and investments hard to installations, including kettles. Revamping with Twisted Tube heat exchangers is often the cheapest and most cost effective way to debottleneck the plant.

Here, data from installation of a Twisted Tube bundle in a reboiler service is discussed. The objective of the installation was to extend the mean runtime between reboiler cleaning and debottleneck depropaniser column capacity. An analysis of initial startup conditions quickly revealed that Twisted Tube bundle was operating at considerably lower steam pressure, indicating potential longer runtime. Data available in the open literature indicate that the most probable cause of performance degradation in conventional kettle reboilers is due to insufficient liquid recirculation through the
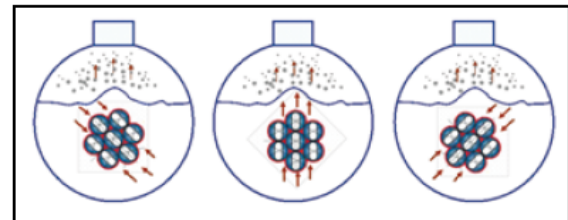
bundle.

Fig. 7 Twisted Tube geometry

This limit is not related to the boiling crises observed in pool boiling experiments. Kettles are not pool boiling devices and their operation is limited by the flow boiling critical flux. With fresh liquid entering the bundle from five directions, Twisted Tube bundle geometry (Figure 7) provides better recirculation rate compared with only three in the conventional configuration.

As we did not have all operating data required to calculate heat transfer coefficients on a daily basis, reboiler performance and fouling was assessed or 'trended' using indirect process

parameters such as opening of the flow control valve (FCV) steam or the pressure of the reboiler steam condensate drum. In the short term, operating variable such as column feed rates, feed composition and light key bottom specification can affect the results; however, over an extended period, FCV opening and condensate pressure provided reliable fouling rate trends. In addition, the fact that plant is operating three parallel fractionation trains further helped in the analysis of reboiler fouling. Other parameters such as steam rate to each reboiler were also evaluated; however, pressure readings and valve openings are significantly more accurate with fewer variations and therefore easier to analyze. In this analysis, both the opening of the steam FCV and the pressure of the steam condensate drum had a definite upper limits; 100% for the FCV and 155 - 160 psig for the steam condensate drum. Fouling in kettle reboilers is common and unfortunately not well understood. Understanding of many fouling mechanisms is incomplete, and the ability to predict fouling rates is limited. However, this application proved that fouling rate within Twisted Tube bundles has been significantly reduced. Although it remains unclear how to cast the observed improvements into quantitative correlations, it is encouraging to see that the same mechanisms that enhance thermal performance also reduce fouling propensity.

Figure 8 provides a comparison of the fouling rates for five reboilers; two that were acid cleaned, two decontamination cleaned, and the Twisted Tube reboiler. The trend line of steam pressure is a linear correlation of the operating data depicting the fouling rate. The figure shows that the Twisted Tube has the lowest rate of fouling (slope of steam pressure vs time).

It is important to notice that the start of run pressure is significantly lower in some reboilers, indicating more available surface area and higher cleaning efficiency.

Since there is an upper limit on condensate pressure (steam pressure is approximately 160 psig), low condensate pressure at startup should translate into longer runtimes.
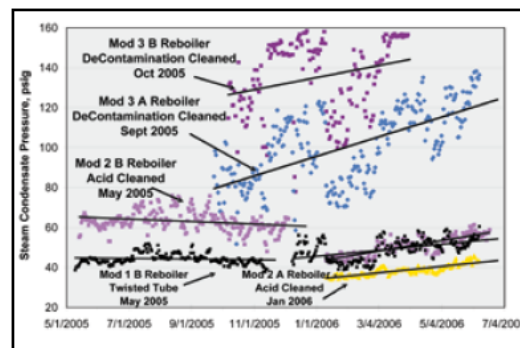

Fig.8 Comparison of DeC3 reboilers

Conclusions

An overview of technical issues of designing heat exchangers with two-phase flows is presented and how significant fouling/coking can occur due to poorly designed reboilers and F/E exchangers. The major technical issues of designing two-phase flow exchangers and minimize fouling the propensity are as follows:

- ➢ Although, design methods have progressed significantly, the interactive effects of two-phase flows and fouling mechanisms cannot be predicted.

- ➢ Potentials of making design mistakes for reboilers and F/E exchangers are greater than that for designing single-phase exchanger under comparable fouling propensity.

- ➢ In order to take corrective steps at the design level, the governing fouling mechanisms should be identified and the effects of process parameters on fouling should be evaluated when designing or revamping existing reboilers and F/E exchangers.

- ➢ Alternate designs are available to reduce two-phase flow maldistribution and thereby minimizing conditions for high fouling and coking.

- ➢ Two-phase fouling beyond the critical conditions, (mist flow, film boiling), can be improved by use of Twisted Tube technology.

➢ The uncertainty of the appropriate value for the critical flux and onset of fouling for horizontal F/E exchangers grows as the size of the unit becomes larger. There is limited amount of data on critical flux with geometries and conditions relevant large industrial designs.

➢ As energy and efficiency of thermal systems become more important factors in the overall economics of process industry, the broader acceptance of enhancement technologies in industrial practice will take place.

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