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INCORPORATION OF A CONSIDERATION OF FOULING INTO THE DESIGN OF VERTICAL THERMO-SIPHON RE-BOILERS

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ABSTRACT

Two causes of under-performance within the tubes of vertical thermo-siphon re-boilers (VTR's) are considered: premature dry-out within the unit and chemical reaction fouling at the tube wall. In many cases dryout is itself a cause of fouling.

Both of these causes depend on re-boiler geometry. Some geometry performs satisfactorily. Other geometry performs poorly.

There are two basic forms of flow boiling: nucleate flow boiling and convective flow boiling. In nucleate flow boiling part of the vaporisation results from the formation of bubbles of vapour on the heated surface. Unfortunately, a thin liquid film (the micro-layer) formed beneath these bubbles can fully evaporate and dissolved solids can deposit on the heated surface.

Under convective flow boiling conditions the vapour shear generated by the two-phase flow results in the formation of a thin liquid film on the tube wall. This film moves at high velocity and provides very effective heat transfer. The result is a marked reduction in wall temperature and suppression of the nucleate boiling process. It is clearly desirable to move from a nucleate boiling mechanism to a convective boiling situation over as short a tube length as possible. The length of tube that is subject to nucleate boiling is again a function of re-boiler geometry.

Wall shear is important in suppression of chemical reaction type fouling. Shear is function of recirculation rate and vapour mass quality. Again these factors depend on reboiler geometry.

In this paper the authors describe how the better geometry can be identified.

Dry-out within VTR`s

The efficiency of a vaporisation process is affected by how well the liquid wets the hot surface. If only partial wetting occurs then two problems immediately arise. The first is a fall-off in the flow boiling coefficient; the second is increased wall temperature and possibly full evaporation of droplets of liquid that impinge upon the hot surface. The full evaporation of liquid then gives rise to deposition of otherwise dissolved salts or suspended solids on the heat transfer surface.

The dry-out process is extremely complex and has more than one fundamental cause. At low vapour mass qualities dry-out only occurs at very high mass fluxes and is due to either excessive vapour flow generated by vigorous nucleate boiling (similar to the form of dry-out that occurs in pool boiling) or to the formation of bubble swarms that flow close to the tube surface and prevent liquid from the bulk contacting the surface.

At high vapour mass qualities dry-out is mainly due to the vapour flow exerting a high shear on the liquid film and pulling it away from the tube surface.

A group of heat transfer experts (forming ESDU`s Heat Transfer Steering Group) oversaw the development of an comprehensive methodology for the determination of dry-out conditions in upward flow through circular tubes (1). This work was an extension of the comprehensive work conducted by Groeneveld (2) at AECL. The predictions of the methodology were tested against a large data base.

This methodology has been incorporated into a new computer program that is being developed for the design and simulation of vertical thermo-siphon re-boilers.

Chemical Reaction Fouling

Chemical reaction fouling has been the subject of much study in recent years. This has mainly been promoted by the problem of fouling in heat exchangers used in pre-heat trains processing crude oil.

The work conducted by ESDU (3) and by oil companies such as Total (4) has centred on the use of the Ebert-Panchal Model for prediction of chemical reaction fouling rates. This model assumes that competing mechanisms occur. The mechanism that promotes fouling is assumed to be chemical reaction close to the heated surface. The rate at which this occurs is assumed to be given by the product of a "reaction rate" (characterised by an Arrhenius equation) and "reaction volume" (which depends on the "thickness" of the thermal film). The mechanism that suppresses fouling is assumed to be related to the shear stresses developed at the surface of the deposit (and, so far, it has been assumed that the mechanism follows a linear relationship with respect to shear stress).

The model published by Ebert & Panchal is only applicable to single phase flow in tubes. However, studies of fouling in tubes with and without tube inserts (5) has indicated that the model can be extended beyond its original scope. This has lead to the development of a new equation (the derivation of which is to be published in separate work (6)) that can be used for both the prediction of fouling in tubes fitted with inserts and prediction of fouling rates under convective boiling conditions. The equation is:

$$\frac{\delta R_D}{\delta \theta} = \frac{A}{\alpha_{fc}} \exp\left(\frac{-E}{RT_f}\right) - \gamma \tau_w$$

is a function of convective heat transfer coefficient α_{fc}, film temperature T_f and wall shear stress τ_w. The fouling process is characterised by Activation Energy E and by a suppression constant γ.

This model has been incorporated into the new re-boiler program. It should be noted that is this type of equipment the convective heat transfer coefficient is a function of mass flux and vapour mass quality and varies from point to point in the tube. This coefficient does not necessarily provide a measure of the heat transfer resistance on the cold side of the reboiler. Both nucleate boiling effects and vapour phase mass transfer resistance (where mixtures are being vaporised) also influence wall (and hence film) temperature.

Regimes Occurring in VTR`s

The prediction of VTR recirculation rates, internal wall temperature and heat transfer distributions have been reported elsewhere (7).

On entering the reboiler the recirculating liquid is at higher pressure (due to the head of liquid above it) than the saturated liquid in the feed reservoir. So, relative to the local pressure it is sub-cooled. Consequently, at low temperature driving forces the heat transfer in the lower parts of the tube is single phase convective heat transfer.

At high temperature driving forces the wall temperature becomes high enough for nucleation to occur. The result is sub-cooled boiling. In this situation the heat transfer is enhanced. However, this is an undesirable heat transfer regime. For bubbles formed at the wall initially grow but then collapse once they come into contact with cooler liquid within the thermal boundary layer or in the bulk of the flow. The collapse of the bubbles is accompanied by rapid influx of cold liquid which strikes the wall of the tube. The result can be erosion of the tube. This regime is to be avoided.

The recirculating liquid increases in temperature as it flows up the tube. The local pressure reduces with tube length. The liquid eventually reaches its saturation temperature. However, this does not necessarily correspond to the formation of vapour. Nucleation is necessary. This nucleation usually occurs at the tube wall and requires a finite superheat. The single phase convective heat transfer regime can extend into the saturated flow region.

Once nucleation occurs the superheat present in the bulk of the liquid is immediately extracted by vapour formation. From this point onwards the convective heat transfer is significantly enhanced by the presence of a two phase flow. It can also be enhanced by nucleate boiling at the tube wall. The heat transfer in this saturated flow boiling region is given by:

$$\alpha = \alpha_{FC} + S.\alpha_{NB}$$

where the heat transfer coefficient α is given by the sum of a the convective heat transfer coefficient α_{FC}, and a nucleate boiling coefficient α_{NB} multiplied by a "suppression factor".

We term the produce $S\alpha_{NB}$ the "nucleate boiling component". It is a measure of the degree to which nucleate boiling enhances the overall heat transfer coefficient above the (often high) convective coefficient.. It is not to be confused with a pool boiling heat transfer coefficient.

The onset of nucleate boiling is affected by the magnitude of the convective heat transfer coefficient (for this determines the temperature field close to the tube wall). The greater the convective heat transfer coefficient the higher is the wall temperature necessary for nucleation to occur. The model of Davis & Anderson (8) can be used to predict the onset of nucleate boiling.

Parameter Plot for VTR Design

Parameter plotting, first developed by Tarun Poddar (9) has proved to be a very effective means of imparting exchanger design and performance information. It forms an important component of ESDU`s EXPRESS^{TM} computer program for shell-and-tube heat exchanger design. There the parameter plot consists of lines showing the length of exchanger tube required in order to achieve a specified heat duty, the length of tube that fully absorbs the allowable tube-side pressure drop, and that which fully absorbs the allowable pressure drop for the shell-side of the unit. Where chemical reaction fouling is known to be a danger, a line representing the tube count above which fouling is present can be displayed. The program user can adjust the detailed geometry of the unit (baffle type, baffle cut, number of tube passes etc.) in order to obtain a geometry in which fouling is minimised.

The concept of parameter plotting can be extended to VTR`s. Here the primary line shows the number of tubes of given length (and specified percentage submergence) required to provide the specified heat duty. A typical result is shown in Figure 1.

The horizontal axis shows the number of tubes of length specified on the vertical axis that are required in order to achieve the specified heat duty.

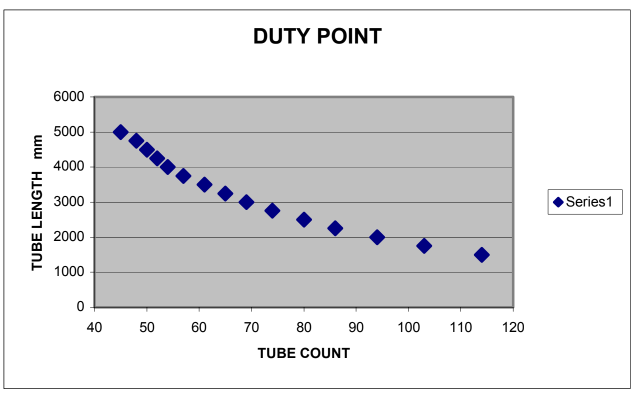

Figure 1. VTR Geometry, combinations of tube count and tube length providing Required Heat Duty

It can be seen that there is a wide range of geometry that provides satisfactory "clean" performance.

Each geometry performs in a different manner. For instance, the amount of vaporisation occurring within the re-boiler providing the specified heat duty (so tube length and count follow the relationship presented in Figure 1) increases as tube length increases and tube count reduces (Figure 2).

Since the design procedure generates information on mass flow-rates and vapour mass qualities at the exit to the re-boiler, it is possible to compare the heat flux employed within the unit to that associated with dry-out conditions (using the method mentioned above). The results for the current example are shown in Figure 3. Each of the available geometries is seen to operate a long way from the dry-out condition with operational heat fluxes around 2% of the critical value.

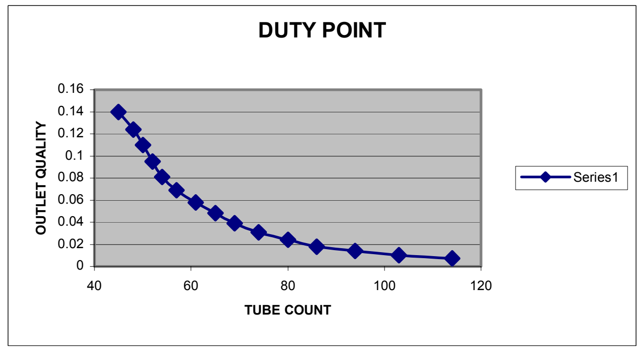

Figure 2. Effect of Geometry on Degree of Vaporisation outlet vapour mass quality for geometry providing required duty

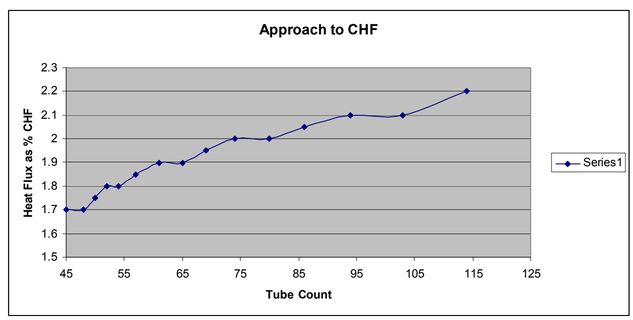

Figure 3. Approach to Critical Heat Flux

Since local wall temperatures and shear rates are known, the rate at which chemical reaction fouling occurs within the re-boiler can be determined. The fouling rate varies along the length of the tube. For initial design purposes the results of the fouling analysis can be presented in terms of mean and maximum fouling rates (as $m^2K/W.hr$, Figure 4). The Activation Energy (used to characterise the rate process defined by the Arrhenius Equation) assumed for the chemical reaction and the removal constant assumed for the suppression term are values that have been observed to be typical in pre-heat trains. At the moment it is unclear what values should be used in other services. However, it is hoped that industrial performance information will soon be provided for analysis (by oil companies sponsoring ESDU`s work on fouling mitigation).

These various plots provide the designer with clear guidance regarding the influence of geometry on fouling rate. However, the analysis does not end there because a more detailed analysis of a particular design can lead to the identification of means of mitigation.

More Detailed Analysis of Fouling Rates and Heat Transfer

As already mentioned the design procedures provide determinations of local fouling rates. The can be examined for a particular design.

Examination of Figure 1 indicates that a unit having a tube length of 2500 mm would need 80 tubes in order to provide the specified heat duty under clean conditions. Figure 5 shows how fouling (again as as $m^2K/W.hr$) would develop in such a unit.

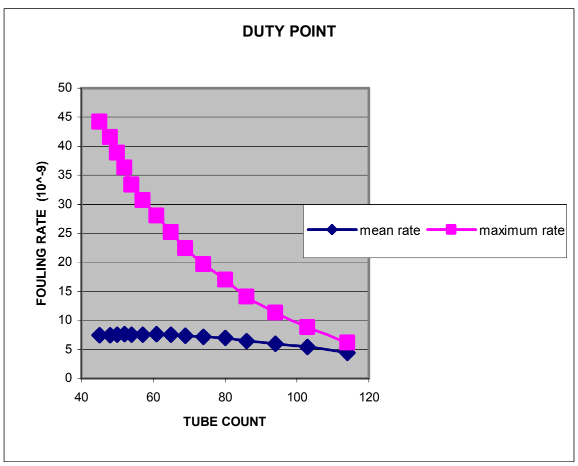

Figure 4. Fouling Rates as a function of design mean and maximum fouling rates as function of tube count for specified duty.

We observe that fouling occurs at a moderate rate over the bottom 600 mm of the tubes. However, above this point the fouling rate falls dramatically and after 1200 mm fouling is suppressed.

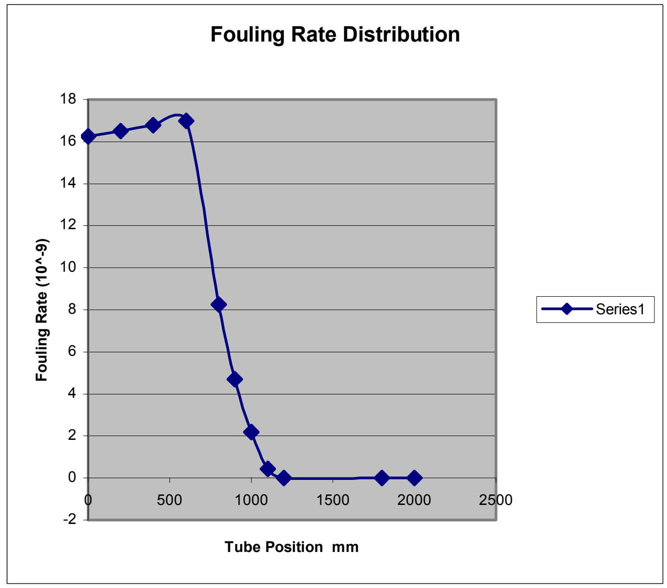

Figure 5. Development of fouling in unit having 80 tubes of 2500 mm length, fouling rate as function of position in tube

The causes of this behaviour become apparent once the local heat transfer rates are observed (Figure 6).

At the entry to the tube the heat transfer coefficient is low and is solely due to single phase forced convection. At 400 mm up the tube nucleation occurs and the heat transfer is supplemented by nucleate boiling. The flow is still sub-cooled and the convective coefficient is that associated with the liquid flow alone. Once saturated conditions have been achieved a two-phase flow is initiated and the convective heat transfer coefficient increases rapidly. After about 800 mm the two-phase flow provides a sufficiently high heat transfer coefficient that nucleation is suppressed. The heat transfer coefficient increases very rapidly as the vapour mass quality of the fluid increases. The combination of increased shear and reduced wall temperature is sufficient to suppress the chemical reaction fouling.

The enhancement due to the onset of nucleate boiling is observed to be low. This is because the enhancement is associated with the generation of bubbles at the tube wall. At the onset of boiling there are relatively few active cavities.

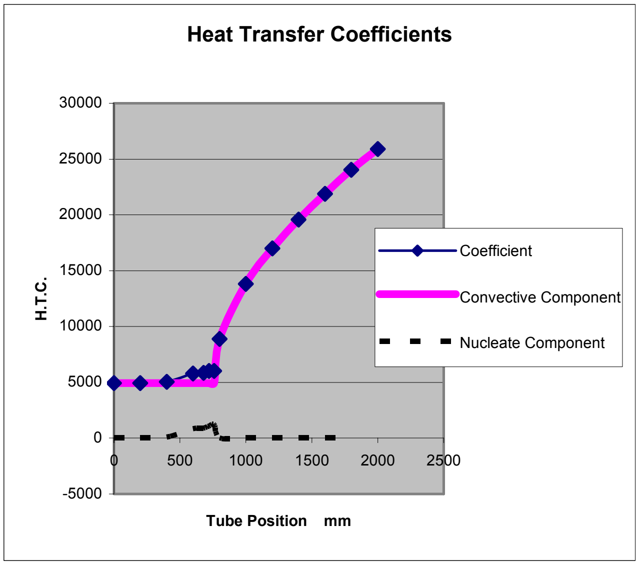

Figure 6. Local heat transfer coefficients in unit having 80 tubes of 2500 mm length

The heat transfer behaviour is analogous to what is observed prior to fully established pool boiling. In pool boiling the heat transfer is initially solely through convection. The generation of the first bubbles is accompanied by a small enhancement in heat transfer. Then as the wall superheat is increased the behaviour goes through an "isolated bubble region" as the number of active sites increases. The very high heat transfer rates associated with pool boiling occur after this region has been passed.

In the case studied here the nucleate boiling is quickly suppressed. This is not surprising for a case in which the onset of nucleate boiling occurs in the super-heated region. As already noted, in this region the onset of boiling will be accompanied by rapid extraction of super-heat from the bulk of the liquid through vapour formation. This, in turn, leads to significant increase in convective heat transfer accompanied by a reduction in wall super-heat and suppression of nucleation at the wall.

Importance of Sub-Cooled Region

In the case considered here it is clear that the fouling is primarily occurring in the single phase region. Where the fouling follows an Ebert-Panchal Model it will generally be the case that fouling will be highest in this region. Clearly, if heat transfer in this region can be improved, the fouling rate can be reduced.

Another problem identified in this analysis is that of the onset of sub-cooled nucleate boiling. Again this can be suppressed or delayed if the heat transfer in this region can be improved.

A simple way of improving heat transfer in this region is the use of a tube insert (7,10).

Inserts do not need to run the full length of the re-boiler. Short inserts can be installed in the entrance region. Since the liquid re-circulation rates in VTR`s are quite low, the inserts do not impose a major flow resistance.

The use of tube inserts to minimise the length of the single phase region can be investigated using the software described in this paper.

Significance for Integrated Reboilers

When reboilers are driven by steam many of the problems identified and discussed above can be alleviated by designing the reboiler for operation at a lower steam pressure.

A similar philosophy can be followed for integrated plants. Here the process engineer needs to give careful consideration to the temperature at which the hot fluid used to drive the reboiler enters the unit. If this temperature is too high then fouling or tube erosion will result. The design of a heat recovery network should not be conducted without adequate consideration of heat exchanger behaviour.

Conclusions

There are several potential causes for under-performance of Vertical Themo-siphon Reboilers. The major ones are dry-out of the liquid film, dry-out beneath vapour bubbles produced at nucleation sites on the heated surface, and chemical reaction fouling. Models for each of these phenomena can be incorporated into software for the design of this type of equipment.

Each of the above mechanisms is a function of the flow behaviour of the unit. This behaviour is a function of design geometry. Software that couples identification of re-boiler geometry that satisfies the required heat duty and evaluation of the fouling that can occur within such geometry has been developed.

The predictions of this software are to be compared with industrial performance data.

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