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CALCULATION OF CONDITIONS AT WHICH DRYOUT OCCURS IN THE SERPENTINE CHANNELS OF FIRED REBOILERS

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To provide back up to the current rather simple design rule deployed to avoid dryout, and thence coking, in fired reboilers, an extension of a phenomenological model has been developed. This has integrated elements for annular flow up to dryout and for dispersed flow for the post burnout region. The complication caused by the bends in the traditional serpentine geometry is dealt with by focusing on the effect identified as the most important: deposition of drops. A dryout map, plots of allowable combinations of mass fluxes/heat fluxes, and a wall temperature profile, have been produced. The model developed in the current work serves as a starting point for future refinement.

Keywords: fired reboilers; annular flow; dryout; coking; modelling.

INTRODUCTION

The simultaneous flow of gas and liquid occurs in many types of process equipment such as boilers, reboilers and heat exchangers. Although there is an increasing interest in falling film evaporators, the majority of equipment involves boiling in vertical tubes. In most of these components, the prediction of burnout or dryout is an important design consideration.

It is now generally accepted that the term 'dryout' is used for the physical mechanism of the drying out of the liquid phase in the process side of the equipment due to evaporation and entrainment that occurs in the annular flow pattern. Beyond dryout, the flow is termed post-dryout dispersed flow and is characterized by a vapour-laden droplet flow. The loss of liquid on the wall leads to serious consequences because the heat transfer surface will overheat and possibly melt, the intermittent wetting and drying encourages corrosion, and the temporal heat transfer variations that occur within the enclosure will reduce the required thermal duty. Predictions of the occurrences of dryout and wall temperatures beyond the inception of dryout are hence vital for the design optimisation, in terms of safety, cost and efficiency of industrial equipment.

The potentially serious consequences of dryout have led to a large amount of research aimed at providing reliable prediction methods. Models on the processes in the annular flow leading to the dryout and post-dryout regions have been developed with relative success for the past 30 years. However, much emphasis, theoretically and experimentally, has been paid to flows in straight channels. In a realistic industrial environment, equipment consists of many fittings such as bends, enlargements, valves and contractions. Therefore, there is a need to model flows in these conditions.

The aim of this study is therefore to provide a basic model for flows in specific type of industrial equipment—the fired reboiler. The approach taken here is to apply the existing techniques of modelling flows in straight channels to the flow geometry found in a typical fired reboiler. It is hoped that the model developed here will serve as a starting point for model refinement. Because of the complexity of the geometry found in fired reboilers, various assumptions had to be made and these are discussed in the following sections. The findings from the current study show that the results are in line with plant observation.

FIRED REBOILER

Fired heaters are used in diverse areas such as power generation, glass making and metallurgy, and there is considerable experiences of such unit in the oil refining industry including applications as reboilers. This last application is most common when the processes temperatures are above those of the available heating medium—usually steam.

Design methods on the flame side use standard furnace models. On the process side, the main thrust of the design is involved with the selection of tube dimensions using

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sensible and standard sizes so as to fit the required area around the flames into a reasonable volume. Additional constraints are the need for even number of tubes so as to have entrance and exit at the same end of the unit. Moreover, if parallel paths are chosen, these should also be an even number to make it easier to balance the flows. It is recognized that one problem to be avoided is coking which can occur if there are unsaturated hydrocarbon components in the feed stream and if the wall temperatures rise above critical values. Such temperature rises are linked to the dryout of the liquid film on the inside of the tube walls. Current design practice uses a simple rule of thumb that the mass flux (mass flow rate per tube cross sectional area) should not be less than $1000\,\mathrm{kg/m^2s}$. However, this is a value drawn from many years experience and not one for which technical antecedents can be traced.

Fired reboilers are, therefore, complex units to design as they combine the difficulties of furnace calculation on the flame side with the multicomponent boiling on the process side. The problems are best seen through an example; the reboiler for an aromatics prefractionation splitter column. In this unit, built in the 1970s, the process fluid is a mixture of heavy hydrocarbons (C9 and above) containing some unsaturated material. The bottoms flow from the splitter column first passes through a horizontal convective section before reaching the evaporator in a subcooled state. The evaporator is the component studied in this research and it operates under a pressure of 6 bar absolute. The saturation temperature of the mixture is 258.3°C at this pressure. The evaporator consists of an ensemble of vertical serpentine arrangements, with each pass consisting of six tubes, each 13.5 m long and 0.15 m in diameter joined by 180° bends (Figure 1). The pitch is 0.305 m with an in-line layout. There are eight sets of these arrangements placed around an oil-fired unit employing six burners producing approximately 20 MW heat input. The maximum heat flux occurs towards the bottom parts of the tubes where heat intensity is highest as shown in Figure 1. The design mass flux of the fluid entering each tube of the evaporator was approximately $870\,\mathrm{kg/m^2s}$. The reasons why this value, below the rule of thumb minimum, was used are lost in the mists of time. Since its initial operation, the feedstock has changed though it is similar to that handled initially and still contains unsaturated components.

Early in its operation, coking was observed to occur in the tubes. This was identified through higher than usual measurements of tube wall temperatures. It occurred towards the bottom of the last and penultimate tube, i.e., areas near bend 5 in Figure 1, specifically over the last 2 m of the tube, where heat intensity is highest. Wall temperatures of 320–340°C were noted. The problem was overcome by lagging the appropriate lengths of pipe. Maldistribution of the flow between the parallel flow paths has been suggested as a possible cause of the dryout. The original arrangement for ensuring equal flow in each of the eight parallel paths was fairly rudimentary. The control system consisted of manually operated gate valves which appear to have been installed as an aid to start up. Subsequently, these have been replaced by globe valves and flow meters have been installed in all eight lines.

As in most industrial plant, data is very sparse and difficult to come by. The above illustrates the lack of soundly based design methods.

This paper presents a calculation method, which can place design, particularly regarding the occurrence of coking, on a sounder footing. The many encumbrances associated with the characteristic of fired reboilers are therefore described. These include: (1) occurrences of upward and downward flows; (2) the type of flow pattern encountered due to the nature of gas–liquid flows; (3) the influence of bends on the dynamics of flow; and (4) the problem with multi-component mixtures. Because of the geometry found in the fired reboiler, the channel shall be called a serpentine channel throughout the paper.

BACKGROUND

At the flow rates and qualities used in fired reboilers, the flow pattern that will occur over the majority of the length of a heated tube, both upward and downward flow, was found to be annular by Chong (2003). Annular flow is characterised by a liquid film flowing in a channel with a central gas core that may or may not contain droplets entrained from the film due to the shearing action of the gas on periodic structures on the wall film that are usually called disturbance waves. Dryout during annular flow in heated systems is usually considered to occur when the integral effect of entrainment of liquid plus evaporation from the wall film less deposition of drops results in a zero film flow rate.

Phenomenological models have been relatively successful at predicting the occurrences of dryout in straight tubes such as those by Whalley *et al.* (1982), Hewitt and Govan (1990) and Azzopardi (1996). All have adopted a three-field concept which takes into account the liquid film at the wall, the gas core and the droplet field. The flow can be described by mass balances on the three interacting fields:

$$\frac{d\dot{m}_{\mathrm{lF}}}{dz} = \frac{4}{D_{\mathrm{t}}}(R_{\mathrm{D}} - R_{\mathrm{A}} - Ev_{\mathrm{F}}) \tag{1}$$

$$\frac{d\dot{m}_{\mathrm{lE}}}{dz} = \frac{4}{D_{\mathrm{t}}}(R_{\mathrm{A}} - R_{\mathrm{D}} - Ev_{\mathrm{p}}) \tag{2}$$

$$\frac{d\dot{m}_{\mathrm{g}}}{dz} = \frac{4}{D_{\mathrm{t}}}(Ev_{\mathrm{F}} + Ev_{\mathrm{p}}) \tag{3}$$

The processes of annular flow in vertical tubes were first modeled by Whalley *et al.* (1974) who took into account entrainment of drops, evaporation from the wall film and redeposition of drops back onto the film. The critical heat flux was well predicted by this model. Bennett *et al.* (1967) were one of the first to model the post dryout region. However, only steam–water mixture flowing in uniformly heated tubes were investigated. Problems associated with the post dryout region were described earlier, which stamps the importance of accurately predicting the wall temperature. Bennett *et al.* (1967) identified heat transfer from the wall to the vapour and evaporation of the droplets in the superheated vapour as the important mechanisms in determining wall temperature for which knowledge of position of dryout and droplet sizes is required.

Whalley *et al.* (1982) combined the models by Whalley *et al.* (1974) and Bennett *et al.* (1967) to form a dryout and post dryout model for flows with thermodynamic and hydrodynamic non-equilibrium. A major innovation of the model