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Recirculation model of kettle reboiler

S. Kumar [a,*], A. Jain [b], B. Mohanty [c], S.C. Gupta [c]

[a] *Department of Mechanical Engineering, Faculty of Mechanical Engineering, R.I.T. Jamshedpur, Jamshedpur 831 014, India*
[b] *Department of Applied Mechanics, M.N.R.E.C. Allahabad, Allahabad, India*
[c] *Department of Chemical Engineering, I.I.T. Roorkee, Roorkee, India*

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Abstract

The present paper deals with the simulation of a kettle reboiler. Considering rectangular tube sheet, concept of internal recirculation developed in a kettle reboiler during boiling, changes in physico-thermal property of liquid and liquid vapour mixture with temperature and pressure and using empirical correlations, a hydrodynamic model has been developed to determine pressure drop, vapour quality, recirculation rate, boiling regime, and heat transfer coefficient at various tube rows of the bundle.

Results show, recirculation rate in a reboiler has been found to vary with the heat flux and pressure. Further, at a given value of heat flux and pressure vapour quality, mass flux, and heat transfer coefficient have been found to increase gradually from bottom to top tube row of the bundle.

Keyword: Interaction factor

1. Introduction

It is a known fact that in a tube bundle, vapour bubbles emerging from lower heating tube interact with upper heating tube vapour bubbles and enhances the heat transfer rate of upper tubes by contributing towards enhancement in turbulence. The enhancement cascades from bottom to top of the bundle. As a consequence of it liquid hold up and vapour fraction and other relevant variables continuously change. Besides, recirculation of liquid also occurs across the tube bundle due to density difference. Some investigators [4–6,11,14,19] have develop models to predicts the occurrence of various flow regimes and thereby heat transfer in each regime inside a tube bundle. Brishbane et al. [4] have developed a method to predict kettle reboiler performance assuming following: (i) liquid starts boiling at the bottom of the bundle even though it is slightly subcooled, (ii) frictional losses in single-phase liquid away from the bundle are neglected, and (iii) the cascading effect of tube interaction is negligible. Fair and Klip [11] have proposed models for the design and analysis of kettle reboiler on the basis of following assumptions: (i) recirculating liquid enters from bottom only, (ii) sensible heating zone at the lower part of the bundle is negligible, (iii) subcooled boiling at the lower part of the bundle is not considered, and (iv) the cascading effect of the tube interaction is negligible. Leong and Cornwell [16] have performed experimental study considering: (i) tubes are heated at constant heat flux and atmospheric pressure, (ii) flow between the inter-tube column is small, and (iii) the mass flow rate in each column at any particular uniform heat flux is approximately constant. Burnside [5] has developed a 2D kettle reboiler model and obtained bundle average heat transfer coefficient using typical superposition and asymptotic flow boiling correlations. Further, Burnside et al. [6] have performed test on a thin slice rig with the help of particle image velocimetry though a complete solution of the problem could not be obtained. However, none of the above models validate experimental observations correctly. This might be due to the absence

* Corresponding author. Tel.: +91-657-200-846.
E-mail address: shal_kumar@yahoo.com (S. Kumar).

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Nomenclature

c_p	specific heat at constant pressure, J/kg K
c_{sf}	liquid surface combination factor
d	diameter, m
h	heat transfer coefficient, W/m^2 K
h'_U	heat transfer coefficient of upper tube when both tubes heated simultaneously, W/m^2 K
k	thermal conductivity, W/m K
p_t	pitch of tube, m
q	heat flux, W/m^2
T_s	surface temperature of tube

Dimensionless numbers

Gr	Grashof number, $\frac{gd^3\beta 1(T_W - T_s)}{\upsilon^2}$
Nu	Nusselt number, hd/k
Nu_B	Nusselt number for boiling, $\frac{h}{k_l}\sqrt{\frac{\sigma}{(\rho_l-\rho_v)}}$
Pe_B	Peclet number of boiling, $\frac{q}{\rho_v\lambda\alpha_1}\sqrt{\frac{\sigma}{g(\rho_l-\rho_v)}}$
Pr	Prandtl number, $\mu c_p/k_l$
Re_B	Reynold number, $\frac{q}{\mu\lambda}\sqrt{\frac{\sigma}{(\rho_l-\rho_v)}}$
Re'_B	modified Reynold number, $\frac{q'_U}{\mu\lambda}\sqrt{\frac{\sigma}{(\rho_l-\rho_v)}}$ where $q'_U = q_U + kq_L$ and $k = (13.77q^{-0.215} - 1)$
K_t	criteria for bubble break-off frequency, $\frac{(\rho_g\lambda_v)^2}{c_{pl}T_s\rho_l[g\sigma(\rho_l-\rho_v)]^{1/2}}$
K_{Sub}	$K_{Sub} = 1 + \left(\sqrt{\frac{\rho_L}{\rho_V}}\right)\left(\frac{T_{Sat}-T}{T_{Sat}}\right)$

Greek symbols

μ	dynamic absolute viscosity, N s/m^2
ρ	density, kg/m^3
σ	surface tension, N/m
λ	latent heat of vapourisation, J/kg

Subscripts

b	bulk, boiling, bundle
B	bubble
L	liquid
L	lower heating tube
O	outer
PL	plain heating tube
PU	plain upper heating tube
S	saturation
U	upper
V	vapour
ef	effective

of interaction factor in the boiling heat transfer correlation used in saturated boiling regime and other inherent assumptions as discussed above incorporated in their model. Thus, a new hydrodynamic model incorporating liquid recirculation from bottom as well as from the side of tube bundle and considering interaction factor is developed for detailed analysis of boiling heat transfer phenomena occurring in multitubular reboilers.

2. Simulation of kettle reboiler

Kettle reboiler is basically a shell and tube type heat exchanger consisting of a tube bundle arranged on a square-in-line pitch enclosed in a shell for easy cleaning. It also contains a vertical oriented weir to ensure sufficient height of liquid pool in the shell. Heating medium, usually steam, flows in the tubes whereas the liquid to be partially vapourised remains in the shell side. Initially, the liquid, usually below boiling temperature, in the bottom-most portion of the bundle is heated by natural convection and then by subcooled followed by saturated boiling regimes when it moves from bottom of the bundle to top. The extent of each regime depends upon composition of fluid as well as parameters affecting performance of distillation column such as type and volume of liquid, operating pressure, heat flux, geometrical parameters etc. From the bottom to top of the bundle the temperature of the liquid increases, reaches to a saturation temperature and then vapour bubble formation on the tube surface takes place leading to two-phase liquid and vapour mixture. This phenomenon continues and vapour fraction in the mixture rises. Thus, recirculation of liquid from top to bottom sets in due to difference in density. The recirculated liquid joins the fresh liquid entering to the reboiler. The combined (fresh + recirculating) liquid attains a velocity depending upon physico-thermal properties, and the quantity of liquid, reboiler geometry and other parameters. Heat transfer in this region is by convection due to velocity induced by recirculation of liquid. Thus, many flow regimes coupled with convection and boiling is observed across the tube bundle. Moreover, the magnitude of each of them depends on velocity of liquid, heat flux, operating pressure, diameter of tubes, spacing between them and other pertinent parameters for a given liquid to be vapourised.

2.1. Development of model

Heat transfer from a tube to fluid in a reboiler basically occurs by two mechanism operating simultaneously—boiling heat transfer and convective heat transfer due to velocity (turbulence due to vapour bubbles) induced in the fluid. However, contribution of each depends upon heat flux, type of fluid, reboiler geometry, operating pressure, etc. Hence, heat transfer coefficient of a tube-row can be written as follows:

$$h = \alpha h_b + \beta h_c \tag{1}$$

where, α and β represent nucleate boiling and two-phase convective correction factors, respectively. Since, two phase convective process dominates over most of the tube length, β may be assumed to be unity [11] so as to get actual contribution of convective boiling in tube bundle. It may be mentioned here that the values of h_b and h_c at a tube row depend upon the physico-thermal properties of fluid, heat flux, operating pressure, velocity of fluid, reboiler geometry and other pertinent variables. Nucleate boiling heat transfer coefficient and convective heat transfer coefficient on a tube row of the reboiler can be computed as follows.

2.2. Convective heat transfer coefficient

The extent of natural and forced convection is determined by the computation of Grashof number, Gr and the Reynolds number, Re of the fluid around the tube row in question. As recommended by Kreith [12], following criteria for the determination of mode of convective heat transfer are used.

$$\text{When natural convection,} \quad \frac{Gr}{Re^2} \geqslant 1 \tag{2a}$$

and

$$\text{When forced convection occurs} \quad \frac{Gr}{Re^2} \leqslant 1 \tag{2b}$$

For the case of natural convection as envisaged by Eq. (2a), conventional method of computing heat transfer coefficient during natural convection by

$$Nu = c(Gr \times Pr)^n \tag{3}$$

is employed.

For the case of forced convection as determined by Eq. (2b), following forced convection correlations as suggested by Zukauskas and Ulinskas [23] are used:

$$Nu = 0.9(Re)^{0.4}(Pr)^{0.36}\left(\frac{Pr}{Pr_w}\right)^{0.25} \quad \text{when } 1 < Re < 100 \tag{4a}$$

$$Nu = 0.52(Re)^{0.5}(Pr)^{0.36}\left(\frac{Pr}{Pr_w}\right)^{0.25} \quad \text{when } 100 < Re < 1000 \tag{4b}$$

$$Nu = 0.279(Re)^{0.63}(Pr)^{0.36}\left(\frac{Pr}{Pr_w}\right)^{0.25} \quad \text{when } 10^3 < Re < 2 \times 10^5 \tag{4c}$$

$$Nu = 0.033(Re)^{0.8}(Pr)^{0.4}\left(\frac{Pr}{Pr_w}\right)^{0.25} \quad \text{when } Re > 2 \times 10^5 \tag{4d}$$

Once boiling starts, fluid becomes a two-phase mixture. Heat transfer coefficient for such a two-phase mixture is computed by the use of above equations, Eqs. (4a)–(4d) with the inclusion of a two-phase multiplier, which is as follows [21]:

$$\phi = \left[1 + \left(\frac{\rho_l}{\rho_v} - 1\right)x\right]^{0.6} \tag{5}$$

2.3. Boiling(nucleate) heat transfer coefficient

Tube sheet of the bundle in reboiler is hypothesised to be of a rectangular shape having its cross sectional area equal to that of an actual tube sheet so that operating conditions of the liquid at a tube row in each column remain uniformly same. Schematic diagram of the assumed rectangular tube sheet in the reboiler is shown in Fig. 1. This portion pertains for identification of flow-regime and computation of heat transfer coefficient associated with the regime. Following assumptions are made for mathematical modelling of reboiler:

- Pressure, temperature and state of fluid entering the reboiler are same as those of recirculating fluid.
- Disengagement of vapour completely occurs in the top space above the bundle and liquid only returns to the bottom portion of reboiler.
- Fluid moves upward from bottom to top of the tube bundle as a single column.

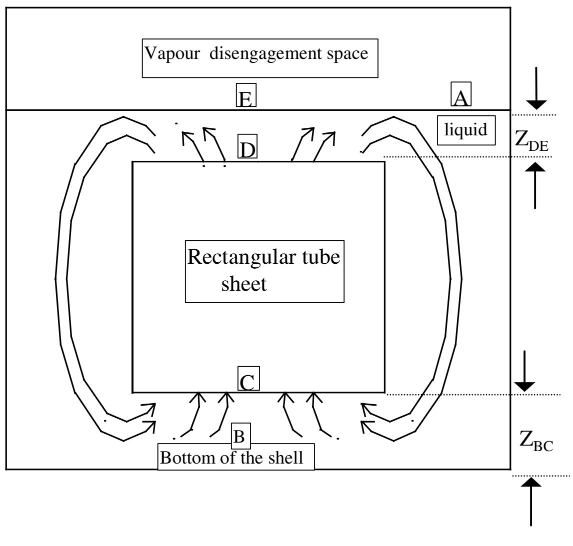

Fig. 1. Approximate configuration of reboiler with assumed rectangular tube sheet.

- Two-phase mixture of liquid and vapour is considered to be homogeneous.
- Loss of heat to surrounding is negligible. It amounts to transfer of the entire quantity of heat to the fluid from tube.
- All the tubes of the bundle are energised with the same value of heat flux. However, in the practical situation, variable heat flux may occurs.

Fluid when moves from point A at liquid vapour interface to point B at the bottom of the shell and then from point B to point C is essentially a single phase liquid. As the fluid further moves up in the bundle its temperature rises, vapour bubbles develop and a two-phase mixture of liquid and vapour is formed. So, the liquid at somewhere between points C and D turns into a two-phase mixture and thereafter, continues to be so up-to point E. The exact location of tube row at which boiling starts and formation of two-phase mixture begins depends upon heat flux, pressure and relevant physico-thermal properties of liquid and vapour. A pressure balance in the flow circuit A–B–C–D–E is made to determine the velocity of liquid recirculating in the reboiler. It is as follows:

$$\Delta p_{\mathrm{AB}} - \Delta p_{\mathrm{BC}} - \Delta p_{\mathrm{CD}} - \Delta p_{\mathrm{DE}} = 0 \tag{6}$$

where, Δp_{AB}, Δp_{BC}, Δp_{CD}, and Δp_{DE} represent pressure drop of circuit legs AB, BC, CD, and DE, respectively.

Pressure drop in leg AB is due to static head available between points A and B. It is as follows:

$$\Delta p_{\mathrm{AB}} = \sum_{j=1}^{N} \rho_{1j} g \left\{ z_{(j)} - z_{(j-1)} \right\} \tag{7a}$$

Similarly, pressure drop in the leg BC is due to static head available between points B and C and can be expressed by following equation:

$$\Delta p_{\mathrm{BC}} = \rho_{\mathrm{l,o}} g Z_{\mathrm{BC}} \tag{7b}$$

where subscript, o refers to the condition at point B.

Pressure drop in the leg CD occurs due to static head, acceleration of the fluid and the frictional force acting on the fluid between points C and D. It is as follows:

$$\Delta p_{\mathrm{CD}} = \sum_{j=1}^{N} \rho_* g \left\{ z_j - z_{(j-1)} \right\} - \sum_{j=1}^{N} G_*^2 \left\{ \frac{1}{\rho_*(j)} - \frac{1}{\rho_*(j-1)} \right\} - \sum_{j=1}^{N} \frac{4 f_* G_{j_*}^2}{2\rho_*} \varphi \tag{7c}$$

where subscript $*$ represents single/two-phase fluid condition occurring at a tube row.

Friction factor f_* is given by the following expression [11]:

$$f_* = \frac{0.63}{Re_*^{0.22}}$$

where

$$Re_* = \frac{d_0 G_*}{\mu_*} \quad \text{and} \quad G_* = \frac{M_{\mathrm{sl}}}{(p_{\mathrm{t}} - d_o) L_{\mathrm{t}} N_{\mathrm{t}}}$$

and φ is a parameter for two-phase pressure drop [21]. It is as follows:

$$\varphi = \frac{\rho_{\mathrm{l}}}{\rho_*}$$

and

$$\rho_* = \left[\frac{x}{\rho_{\mathrm{v}}} + \frac{(1-x)}{\rho_{\mathrm{l}}} \right]^{-1}$$

Fluid is essentially a two-phase liquid–vapour mixture between points D and E. Hence, pressure drop between these points is given by:

$$\Delta p_{\mathrm{DE}} = \rho_{**} g Z_{\mathrm{DE}} \tag{7d}$$

where ρ_{**} represents density of liquid–vapour mixture at the conditions of point D.

Eq. (6) along with Eqs. (7a)–(7d) can be used to calculate recirculation rate of fluid for the vapourisation of a given liquid in a reboiler of specified geometry. A value of mass flow rate of liquid is assumed in the reboiler. Pressure drops in various legs of flow circuit are calculated from Eqs. (7a)–(7d) and substituted in Eq. (6) to examine its validity. The value of assumed mass flow rate of fluid that satisfies Eq. (6) is the recirculation rate in reboiler.

At this junction it is essential to identify the mode of boiling taking place for the prediction of actual heat transfer coefficient in the tube bundle. For the condition when the temperature of tube wall surface is below the value of T_{wONB}, nucleate boiling can not be sustained and the mode of heat transfer in this region is termed as subcooled boiling which may be determined by the following correlation of Smith [21]:

$$T_{\mathrm{wONB}} = T_{\mathrm{s}} + \left[\frac{8\sigma q T_{\mathrm{s}}}{k_{\mathrm{l}} \lambda \rho_{\mathrm{v}}} \right]^{0.5} \tag{8}$$

Correlation due to Alam [1] has been selected here to determine the value of heat transfer coefficient in subcooled boiling region, as this correlation is based on the subcooled boiling data of a large number of liquids over a wide range of heat flux and degree of subcooling. The correlation due to them is as follows:

$$Nu = 0.084 (Pe_{\mathrm{B}})^{0.6} (k_{\mathrm{sub}})^{-0.5} (k_{\mathrm{t}})^{0.37} \tag{9}$$

Once, the temperature of tube wall surface crosses the value of T_{wONB}, nucleate boiling starts and there is plethora of correlations [2,3,18–20,22] available for nucleate boiling regime in literature. But none of them seems to be suitable for calculation of heat transfer coefficient in nucleate boiling regime of a reboiler because they do not account for interaction caused by vapour bubbles of lower heating tube on upper heating tubes which is an important aspect in multitubular bundle. Some investigators [11,19] have used available correlations with modifications to account the interaction of vapour–bubbles amongst heating tubes but could not predict heat transfer rate satisfactorily in reboiler. In the present investigation, correlation based on experimental data [15] for boiling of liquids over a row of two horizontal heating tubes arranged in a vertical grid has been employed which is of the form:

$$Nu_{\mathrm{B}} = c_1 (Re'_{\mathrm{B}})^{0.7} (Pr)^{0.4} \tag{10}$$

It is important to mention here that Eq. (10) is distinctly different from single tube nucleate boiling correlations available in literature as it contains the term, modified Reynolds number, Re'_{B} which considers interaction amongst tube rows of the bundle.

Following correlation due to Fair and Klip [11] for nucleate boiling correction factor, α has been used to determine flow regime in the reboiler:

$$\alpha = 1.1 - \frac{0.00735}{4.88} G \left(\frac{1}{X_{\mathrm{tt}}} \right)^{1.28} \tag{11}$$

where X_{tt} is the flow parameter developed by Martinelli et al. [11]. It is given by the following relationship:

$$X_{\mathrm{tt}} = \left(\frac{1-x}{x} \right)^{0.9} \left(\frac{\rho_{\mathrm{v}}}{\rho_{\mathrm{l}}} \right)^{0.5} \left(\frac{\mu_{\mathrm{l}}}{\mu_{\mathrm{v}}} \right)^{0.1} \tag{12}$$

The value of X in Eq. (12) represents vapour fraction in the mixture. The value of α defines the flow regime. Flow is bubbly for $\alpha = 1$, slug and frothy for $0 < \alpha < 1$, and annular or mist for $\alpha < 0$.

Thus, Eqs. (1)–(12) represent a heat transfer model of a multitubular reboiler which permits the computation of pressure, temperature, flow regime, fluid velocity, void fraction, recirculation rate and heat transfer coefficient at each tube row of the bundle in the reboiler from the knowledge of heat flux, operating pressure, reboiler geometric parameter and physico-thermal property of a given fluid.

To compute the parameters discussed above, a 2500-lines computer code in FORTRAN-77 has been developed to simulate the above physical model of the kettle reboiler. Programme has been run using 32 bit MS FORTRAN POWERSTATION Compiler on a Pentium-133 MHz machine. The algorithm of the programme is given in Appendix A.

2.4. Testing of model

Literature contains only one experimental investigation on heat transfer studies in a reboiler of 241 tubes arranged in a square-in-line pitch arrangement. This investigation is due to Leong and Cornwell [16] for the vapourisation of R-113 for heat flux values of 10, 20, and 50 kW/m^2 at atmospheric pressure. Hence, these data have been used to examine the validity of the model. Figs. 2 and 3 show a plot between heat transfer coefficient computed from present model and the

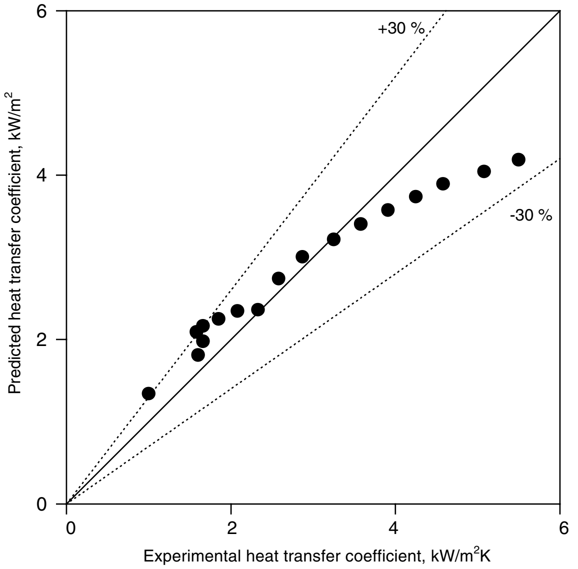

Fig. 2. Comparison of experimental data due to Leong and Cornwell [16] with the present model.

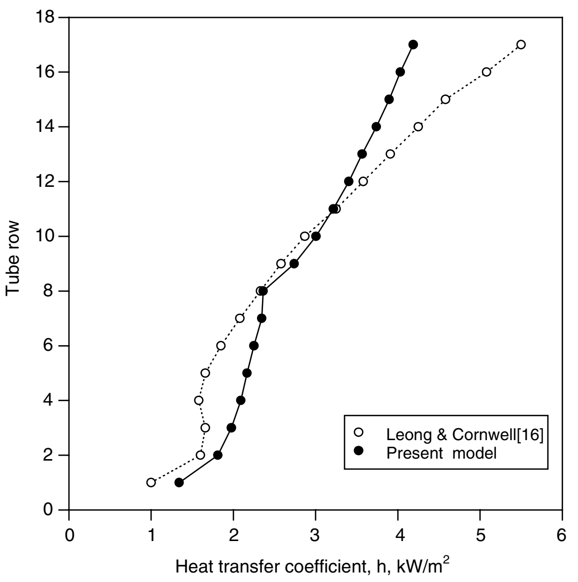

Fig. 3. Variation of heat transfer coefficient with tube row due to Leong and Cornwell [16] and modified model at heat flux of 10 kW/m^2.

experimental values due to Leong and Cornwell [16] at a heat flux of 10 kW/m^2 for the boiling of R-113 at atmospheric pressure. From these figures, it is seen that the predictions due to model do not match well with experimental values. The reasons for deviation between model and experimental values may be attributed to the value of constant, c_1, employed in Eq. (10) and might be due to the fact that in this model the recirculating liquid has been assumed to enter into the tube bundle only as a single column from the bottom of the bundle. As a matter of fact, this situation does not represent a true picture of the phenomenon occurring in the tube bundle. Hence, an improvement of the model is required.

2.5. Improved model

The model developed above has a major drawback. It assumes the whole amount of recirculated liquid to enter into the bottom portion of reboiler as a single column and then to pass through the tubes of the bundle. This situation is far away from real situation of reboiler. The recirculated liquid while moving downward from top and joins the liquid flowing upward at a tube-row depending upon pressure available at that level. In other words, each tube row receives liquids from recirculated stream, in addition to that flowing upward from lower tubes. This is clearly depicted in a schematic block diagram of improved model in Fig. 4. This can be analysed as given below:

Let G_0, G_1, G_2, G_3, …, G_N represent the amount of recirculated liquid entering from bottom, first, second, third, …, nth tube row of the bundle, respectively. Application of law of conservation of mass yields:

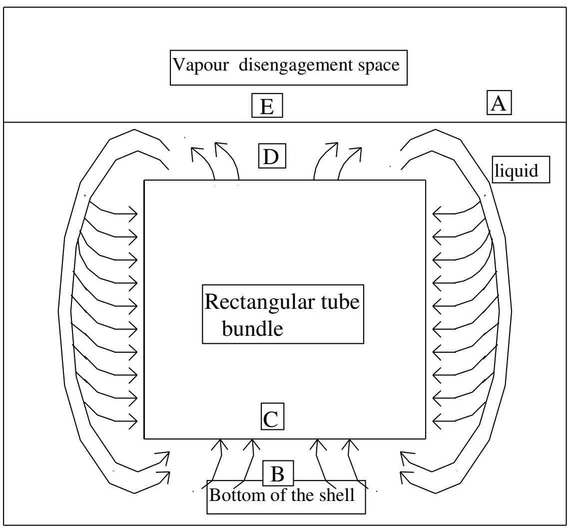

Fig. 4. Schematic representation of the improved model.

$$\sum_{i=0}^{N} G_i = G \tag{13}$$

Further, it is assumed that no frictional loss or acceleration loss in pressure occurs when recirculating liquid joins the liquid flowing upward from lower tubes. With this, pressure drop across ith tube row becomes:

$$\Delta p_i = \rho_* g\{z_{(i)} - z_{(i-1)}\} - \left(\sum_{k=1}^{i} G_k\right)^2 \left\{\frac{1}{\rho_{*_*}(i)} - \frac{1}{\rho_*(i-1)}\right\} - \frac{4f_*\left(\sum_{k=1}^{i} G_k\right)^2}{2\rho_*}\varphi$$

So, pressure drop across the tube bundle, CD becomes

$$\begin{aligned}\Delta p_{\mathrm{CD}} = & \sum_{i=1}^{N} \rho_* g\{z_{(i)} - z_{(i-1)}\} \\ & - \sum_{i=1}^{N}\left(\sum_{k=1}^{i} G_k\right)^2 \left\{\frac{1}{\rho_*(i)} - \frac{1}{\rho_*(i-1)}\right\} \\ & - \sum_{i=1}^{N} \frac{4f_*\left(\sum_{k=1}^{i} G_k\right)^2}{2\rho_*}\varphi\end{aligned} \tag{14}$$

Thus, Eqs. ((1)–(7b) and (7d)–(14)) constitute an improved model of heat transfer in a kettle reboiler. It can be used to predict the values of mass flux, recirculation rate, void fraction, and heat transfer coefficient at each tube row of the bundle at given temperature and pressure.

The heat transfer coefficient predicted by present model have been validated with the experimental data of Leong and Cornwell [16] for the boiling of R-113 at a heat flux of 10 kW/m^2 and atmospheric pressure in a kettle reboiler. The physical property of R-113 has been taken from the handbook [10]. Such a plot is given in Fig. 5. The values of heat transfer coefficient in the subcooled regime are more whereas in saturated boiling regime they are less as compared to experimental values. This might be due to interaction of vapour bubbles of lower tube rows on all tube rows lying above it in the bundle. The present improved model has been formulated on the basis of an equation of nucleate boiling accounting for the interaction of vapour bubbles of lower heating tube on the heating tube lying just above it. With such a scenario the value of interaction factor may not remain constant. In fact, it is likely to vary from tube row to tube row and then model may trace the curve representing the values experimentally observed by Leong and Cornwell [16].

Now, it has been thought proper to compare the improved model with that of Brisbane et al. [4] and Fair and Klip [11] for the boiling of R-113 at a heat flux of 10 and 20 kW/m^2 and atmospheric pressure. The comparison are shown through Figs. 6 and 7. Figs. 6 and 7

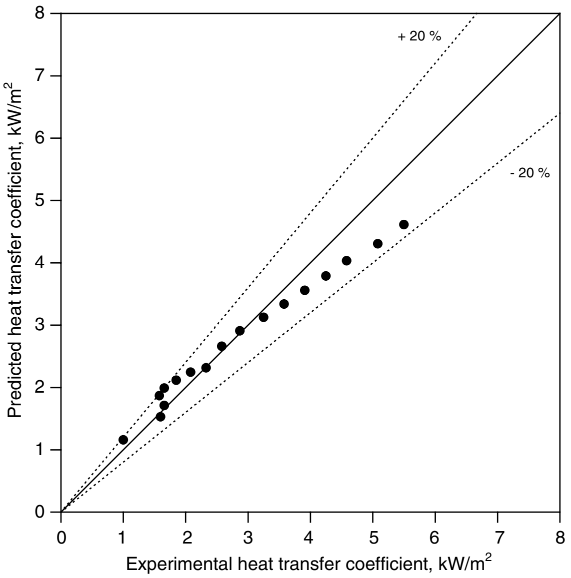

Fig. 5. Comparison of heat transfer coefficient predicted by the improved model with the experimental values [16] for the vapourisation of R-113 at 10 kW/m^2 heat flux and atmospheric pressure.

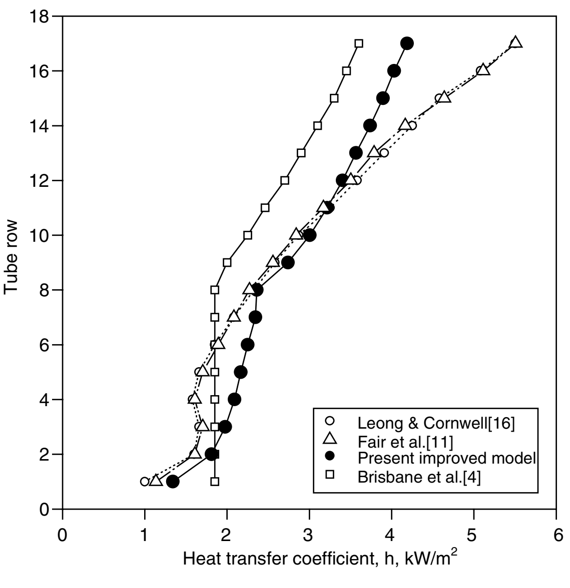

Fig. 6. Variation of heat transfer coefficient with tube row at 10 kW/m^2 heat flux and atmospheric pressure.

clearly reveal that the present improved model predicts the heat transfer coefficient of upper tube of the bundle more accurately as compared to the models of Brisbane et al. [4] and Fair and Klip [11] at heat flux of 10 and 20 kW/m^2 respectively.

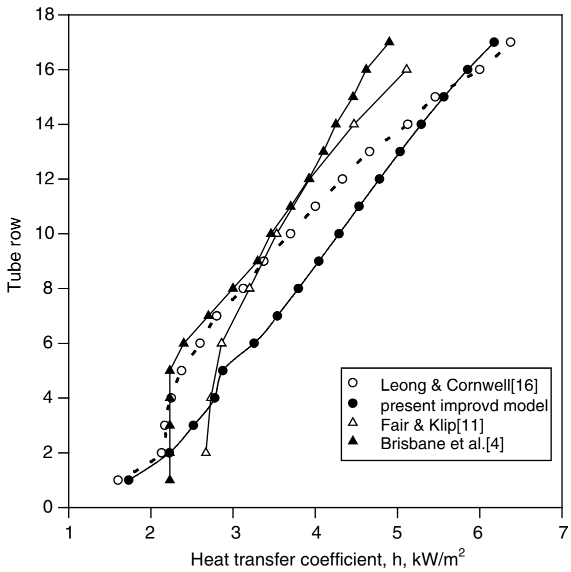

Fig. 7. Variation of heat transfer coefficient with tube row at 20 kW/m^2 heat flux and atmospheric pressure.

2.6. *Effects of operating parameters*

Effect of heat flux and operating pressure in a reboiler on various quantities such as mass flux, recirculation rate, vapour quality, and tube row wise heat transfer coefficient can be analysed by present improved model. The reboiler used for this purpose is of same geometrical configuration as being used by Leong and Cornwell [16] and vapourising fluid is R-113. Heat flux has been considered in the range from 5 to 30 kW/m^2 and operating pressure from 78.278 to 101.325 kPa.

2.7. *Effect of heat flux on recirculation rate*

To demonstrate the effect of heat flux and pressure on the variation of recirculation rate, Fig. 8 has been drawn. It is seen from this plot that at given pressure, recirculation rate increases with increase in heat flux, reaches to a maximum value at a particular value of heat flux and then decreases with increase in heat flux. It may be mentioned here that Fair and Klip [11], and Brisbane et al. [4] have also obtained similar trend. This trend is quite obvious and can be explained as follows: The recirculation rate is dependent on the trade off between frictional, acceleration, and static heads in the bundle. Further, the frictional and acceleration heads are power law function of reciculation rate. At low heat flux values the quality is low, leading to a lower driving force for recirculation. This results in a low recirculation rate in the bundle. With the increase in heat flux (upto a certain limit where recirculation rate is maximum) this driving force increases (due to increase in quality) more rapidly

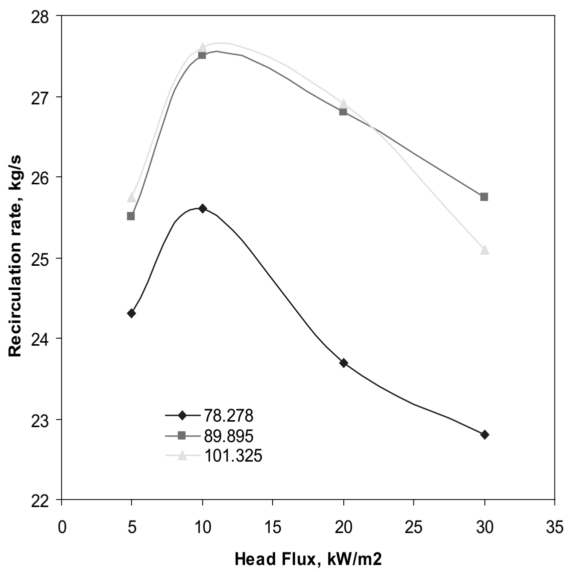

Fig. 8. Variation of recirculation rate with heat flux keeping pressure as a parameter.

in comparison to friction pressure drop—responsible for recirculation rate to decrease. The overall effect is an increase in recirculation rate with heat flux. When heat flux is increased further the frictional pressure drop and to some extent the acceleration pressure drop becomes dominant leading to a decrease in recirculation rate.

However, increase in pressure, at a given value of heat flux, increases recirculation rate. It also shifts the peak value of recirculation rate and the value of heat flux corresponding to peak recirculation rate to higher values. These features are same as has been described by Jensen [14]. Possible reason for this behaviour lies in the fact that pressure affects considerably boiling phenomenon and physical properties of the fluid causing hydrostatic, frictional and acceleration pressure drop components to vary with pressure.

2.8. *Effect of heat flux on vapour quality*

Fig. 9 shows a plot for tube row wise vapour quality in the reboiler for the vapourisation of R-113 at atmospheric pressure. In this plot, heat flux is a parameter. As can be noted from this plot, vapour quality for a given value of heat flux increases continuously from bottom to top of the tube bundle. This is quite natural as vapour bubble population in a tube bundle increases from bottom to top of the bundle due to continuous upward movement of vapour bubbles. Further, an increase in heat flux increases the vapour quality at a tube row. This is in view of the fact that an increase in heat flux multiplies number of vapour bubbles on the tube. Similar behaviour has also been observed at subatmospheric pressures.

2.9. *Effect of heat flux on mass flux*

Fig. 10 shows a plot to represent the variation of liquid mass flux with tube row in the reboiler for vapourisation of R-113 at a pressure of 78.278 kPa. In this plot, heat flux is a parameter. From this plot, following important features are inferred:

1. At a given value of heat flux, liquid mass flux continuously increases from first tube row at the bottom to last tube row at the top of the bundle.

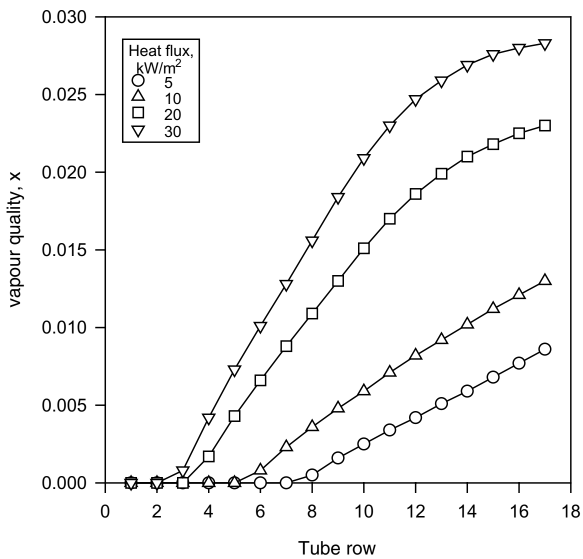

Fig. 9. Variation of vapour quality with tube row keeping heat flux as a parameter at atmospheric pressure.

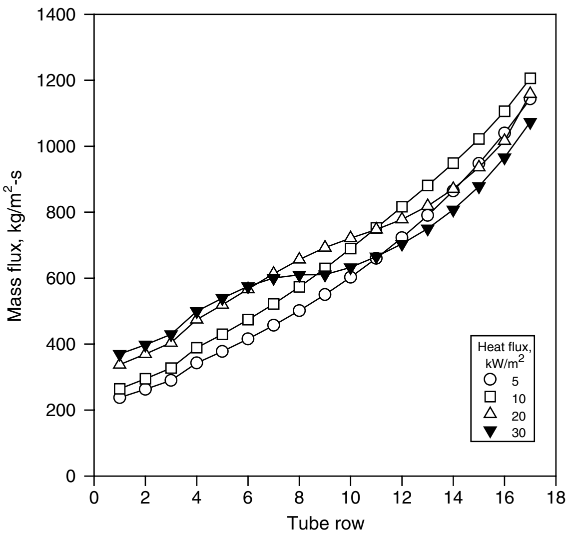

Fig. 10. Variation of mass flux with tube row keeping heat flux as a parameter at a pressure of 78.278 kPa.

2. An increase in heat flux, at a given tube row, shifts the curve of liquid mass flux in upward direction indicating an increase in mass flux. However, it is more evident in the curves of low values of heat flux ranging from 5 to 10 kW/m^2. For 20 and 30 kW/m^2 values of heat flux, liquid mass flux, at a given tube row, are found to be lower than that of 10 and 5 kW/m^2, respectively, especially in the upper region of the reboiler.

Heat transfer from a heating surface to boiling liquid occurs by two mechanisms convective and nucleate boiling operating simultaneously. Consequently, convective heat transfer coefficient continuously increases from bottom to top due to interaction of vapour bubbles of various tubes and causes corresponding decrease in the temperature of heating surface. This in turn leads to decrease the rate of increase of nucleate boiling component. Consequently liquid flow rate undergoing vapourisation decreases with tube row from bottom to top. Besides, the recirculating liquid joining the stream at a tube row also decreases as it move from top to bottom of the bundle. The net result of all this is that mass flow rate of liquid at a tube row is found to increase from bottom to top of the tube bundle. Further, it has also been observed that with the increase in pressure mass flux also increases.

2.10. *Effect of heat flux on heat transfer coefficient*

Fig. 11 represents a plot showing variation of heat transfer coefficient with tube row of the reboiler at various values of heat flux. In this plot, curves have also been

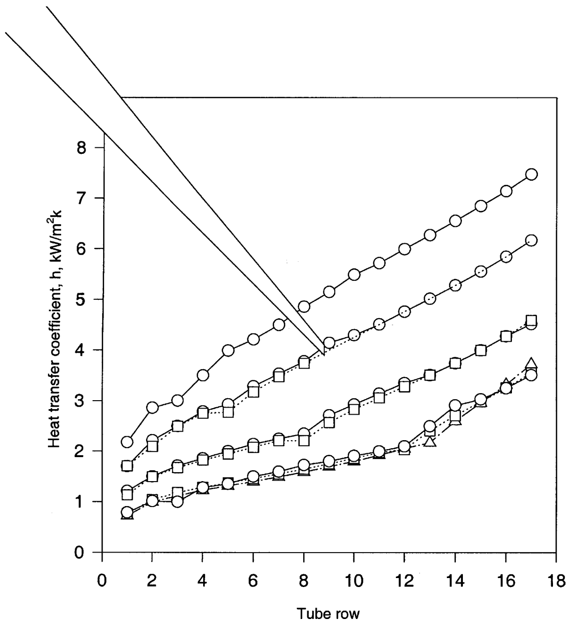

Fig. 11. Variation of heat transfer coefficient with tube row at different heat flux keeping pressure as a parameter.

drawn for different values of pressure so as to determine the effect of pressure on tube row heat transfer coefficient. As can be inferred from this plot, heat transfer coefficient at subatmospheric pressures for a given value of heat flux continuously rises from bottom to top of the reboiler in the same manner as observed at atmospheric pressure. However, pressure decreases heat transfer coefficient at a tube row but its effect is only marginal.

Based on above, it can be concluded that heat flux and pressure are the two important operating parameters, which affect recirculation rate, vapour quality, mass flux, and heat transfer coefficient of a tube row in a reboiler significantly.

3. Conclusions

1. Based on physical phenomenon like recirculation of liquid in the tube bundle and the cascading effect of interaction due to the vapour bubbles generated at different tubes, a mathematical model has been developed to predict tube row-wise heat transfer coefficient, vapour quality, mass flux in the bundle.
2. Tube wise heat transfer coefficient predicted from the model has been found to agree well with the experimental data due to Leong and Cornwall [16] for the vapourisation of R-113 within a maximum error of $\pm 20\%$.
3. Recirculation rate in a reboiler has been found to vary with the heat flux and pressure. Further, at a given value of heat flux and pressure, vapour quality,

mass flux, and heat transfer coefficient have been found to increase gradually from bottom to top tube row of the bundle.

4. The model is capable of predicting the parametric effect of heat flux and pressure on recirculation rate, vapour quality, mass flux, and heat transfer coefficient in a multitubular bundle.

Appendix A. Algorithm of the kettle reboiler

Following algorithm has been used to simulate kettle reboiler through modified model.

Step 1: The geometric parameters, Dto, Dtb, Dsi, Ct, Cb, Lt, Nt, p_t, are collected.
The tube lay out, types of tubes, number of tube pass are identified.
The process data, tube side heating media, shell side fluid are identified.
The physical properties, Ts, ρ_l, ρ_v, μ_l, μ_v, c_{pl}, c_{pv}, λ, σ, k_l, are obtained, and the station points as given in Fig. 1 are identified.

Step 2: Compute saturation temperature of R-113 for the given pressure at liquid vapour interface by correlation:

$$T = -78.38 + 7.817(p)^{0.249} + 273.15$$

Obtain density of liquid at this temperature, T.

Step 3: Compute bottom pressure at station point 'B' from Eq. (7a).

Step 4: Assuming rectangular tube layout obtain no of tubes in each tube row.

Step 5: Assume flow rate and temperature of inlet fluid and recirculation.

Step 6: Carry out Step 7 to Step 18 for each tube row.

Step 7: Assuming fluid to be saturated compute pressure for first tube row.

Step 8: Obtain physical properties at temperature obtained in Step 2.

Step 9: Compute sensible heat.

Step 10: Check $Q - Q_{\text{sensible}}$.
If it is positive, go to Step 13.
If it is equals to zero, go to Step 12.
If it is negative, go to next Step 11.

Step 11: Sensible heating is not completed. Obtain rise in temperature of liquid. Go to Step 8.

Step 12: Sensible heating is just completed. Liquid temperature is saturation temperature. Go to Step 14.

Step 13: Boiling continues, Liquid is at saturation temperature.

$$Q_{\text{vap}} = Q_{\text{supplied}} - Q_{\text{sensible}}$$

Liquid vapourisation rate, $M_{lv} = Q_{\text{vap}}/\text{latent heat}$.

Step 14: Mass flow rate of liquid at current tube row, $M_{SL}(j) =$ Mass flow rate of liquid at previous tube row, $M_{SV}(j-1) -$ Liquid vapourisation rate at this tube row, M_{LV}. Mass flow rate of vapour at current tube row, $M_{SV}(j) =$ Mass flow rate of vapour at previous tube row, $M_{SV}(i) +$ mass flow rate of liquid vapourised, at this tube row, M_{Lv}.

$$\text{quality of liquid,} \quad x_M(j) = \frac{\text{mass flow rate of vapour}, M_{SV}(i)}{\text{mass flow rate of of total fluids}, M_S(i)}$$

Step 15: Compute heat transfer coefficient by Eqs. (3)–(4d) and (9), (10).

Step 16: Compute pressure at liquid vapour interface level.

Step 17: Compare the computed pressure at liquid vapour interface and given *Pr*.
If the above pressure difference is greater than 0.01 %, modify the recirculation and Go to Step 6.

Step 18: If the above computed pressure (Step 16) does not vary with given pressure greater than 0.09%, print the values of heat transfer coefficient, pressure drop, temperature of fluid, quality, recirculation, mass flux, etc. for each tube row.

Step 19: Stop.

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For further reading

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