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EFFECT OF DENSITY RATIO ON CRITICAL HEAT FLUX IN CLOSED END VERTICAL TUBES

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Abstract—An experimental study was conducted to measure the critical axial heat flux in countercurrent two phase flow of liquid and its vapour in a closed-end vertical tube. The experimental results for four different fluids; carbon-tetrachloride, normal hexane, ethyl alcohol and water, were reduced to give a correlation for evaluation of the flooding critical heat flux. Results of other investigators on vertical heated tubes and vertical thermosyphons were also reduced and compared with the present experimental results. The effect of the density ratio of liquid to its vapour on the critical heat flux was shown. The length to diameter ratio of the test section was shown to have an influence on the flooding critical heat flux and was included in the correlation obtained.

INTRODUCTION

Investigation of burn-out condition and estimation of its corresponding critical heat flux are of importance in the design of heat transfer equipment. The effect of burn-out is involved in many practical applications, such as: wickless heat pipes, vertical thermosyphons, the cooling of a hot reactor in case of LOCA, steam generators, the production of natural steam from underground hot rocks and the drying of wet surfaces by applying heat, etc.

An experimental study is made to obtain a correlation for the prediction of the critical heat flux. A liquid substance is flowing down from a reservoir on a tube wall which is heated by a constant heat flux. The vapour generated by the heat input to the tube wall is flowing upwards in the opposite direction to the liquid flow. While increasing the heat input, a condition is reached under which the liquid film flow into the tube from upper reservoir will be controlled by the upward vapour flow and the tube wall at the lower end will become dry. This condition is referred to as the flooding burn-out condition and the corresponding heat flux, which is normally determined in an axial direction is called the critical heat flux. In tubes with small length to diameter ratios where the vapour velocity is small, the liquid film will be controlled by boiling or evaporation and normal film burn-out will occur.

Experimental investigations on the critical heat flux have been reported for vertical heated tubes by Griffith *et al.* (1962) and Nejat (1978), vertical thermosyphons by Kusuda & Imura (1974) and wickless heat pipes by Sakhuja (1973). Nejat (1978) obtained a correlation for the dimensionless critical heat flux of the available data in terms of the Bond number. This correlation was based on the Wallis flooding correlation obtained for the countercurrent two-phase flow of water and air suggested by Wallis (1961), which is generalized by employing Kutateladze number and its limiting value for tubes with large diameters reported by Pushkina & Sorokin (1969). Later a similar flooding correlation for the critical heat flux and for the case of wickless heat pipes was reported by Tien & Chung (1979).

Approximate analytical studies of the burn-out condition were made for large and small length to diameter ratios of the tube by Nejat (1978) and Nejat & Mottaghian (1980) respectively. It was shown that when the length to diameter ratio is large, the critical heat flux will also depend on the kinematic viscosity ratio of the liquid and its vapour.

In this report a correlation is obtained for the critical heat flux based on the Wallis flooding correlation and its dependence on the density ratios of the liquid and its vapour is shown. When experimental results of the present investigation for four substances and data of other investigators on vertical heated tubes and vertical thermosyphons are transformed and compared with the correlation, a good agreement is demonstrated.

CORRELATION FOR CRITICAL HEAT FLUX

An empirical flooding correlation has been obtained by Wallis (1961) for countercurrent two-phase flow of water and air in vertical tubes. This correlation is expressed as:

$$j_G^{*1/2} + m j_L^{*1/2} = C \qquad [1]$$

where j_G^* and j_L^* are dimensionless superficial velocities of gas and liquid respectively and m and C are constants of correlation. Equation [1] has also been employed for the case of countercurrent two-phase flow of liquid and its vapour in closed-end vertical tubes, vertical thermosyphons and wickless heat pipes by Nejat (1978) and Tien & Chung (1979), where a correlation for the flooding critical heat flux has been obtained based on the Wallis correlation. The dimensionless superficial velocities are defined as:

$$j_L^* = j_L \rho_L^{1/2}[g_n D_i(\rho_L - \rho_G)]^{-1/2}$$
$$j_G^* = j_G \rho_G^{1/2}[g_n D_i(\rho_L - \rho_G)]^{-1/2} \qquad [2]$$

where ρ_L and ρ_G are mass densities of liquid and gas and D_i is tube inside diameter. j_L and j_G are superficial velocities of liquid and gas (or vapour for the case of present study) respectively and are evaluated from the following expressions, assuming that liquid and vapour fill the whole cross sectional area of the tube, A_x:

$$j_L = \frac{G'_L}{\rho_L A_x}$$
$$j_G = \frac{G'_G}{\rho_G A_x}. \qquad [3]$$

The mass flow rate of liquid, G'_L and its vapour, G'_G for the case of the closed-end vertical heated tubes can be expressed as:

$$G'_L = G'_G = \frac{Q'}{h_{LG}} \qquad [4]$$

where Q' is heat flow rate and h_{LG} is specific latent heat of vaporization. Equation [4] assumes that at any distance of x from the tube end, the amount of liquid flowing down the tube wall is equal to the amount of vapour flowing upward in the opposite direction. It is assumed that the liquid carryover by vapour is very small and can be neglected and the liquid film contains no vapour bubbles. Equation [4] is also true for wickless heat pipes and vertical thermosyphons, where vapour is generated by a uniform heat flux on the tube wall and a steady state condition is achieved.

The dry-out or burn-out condition due to the flooding mechanism is reached at the lower end of the tube when the flow of fluid into the tube from upper reservoir is controlled by the upward flow of its vapour. The flooding control occurs at the top end of the tube where the maximum flow rate of liquid and its vapour are involved and the heat flow rate in [4] will be equal to the total amount of heat supplied to the tube, Q'_t.

Equation [1] can be written as:

$$j_G^{*1/2} = \frac{C}{1 + m\left(\frac{\rho_G}{\rho_L}\right)^{1/4}}. \qquad [5]$$

Substituting the mass flow rate of vapour, [3] into [2] and introducing the superficial velocity of vapour into [5], the following expression is obtained:

$$\frac{\dfrac{Q_t'}{h_{LG}}}{\rho_G A_x}\rho_G^{1/2}[g_n D_i(\rho_L-\rho_G)]^{-1/2}=C^2\left[1+m\left(\frac{\rho_G}{\rho_L}\right)^{1/4}\right]^{-2}. \qquad [6]$$

The critical heat flux related to flooding is defined as:

$$q_x'=\frac{Q_t'}{A_x} \qquad [7]$$

and it can be non-dimensionalized as follows:

$$q^*=\frac{q_x'}{h_{LG}\rho_G(g_n D_i)^{1/2}}. \qquad [8]$$

Substituting the dimensionless critical heat flux into [6], the following expression is obtained:

$$q^*=C^2\left[\frac{\rho_L-\rho_G}{\rho_G}\right]^{1/2}\left[1+m\left(\frac{\rho_G}{\rho_L}\right)^{1/4}\right]^{-2}. \qquad [9]$$

Equation[9] demonstrates the effect of the density ratio of liquid to its vapour on the dimensionless critical heat flux. The constant m has a value of unity in the present study. Nejat (1978) employed the Wallis flooding correlation and generalized it by introducing the Kutateladze number, K and its limiting value reported by Pushkina & Sorokin (1969). The following expression was obtained:

$$K_L^{1/2}+K_G^{1/2}=(3.2)^{1/2}F(D^*) \qquad [10]$$

where the dimensionless Kutateladze number and Bond number, D^* are defined as:

$$K_L=j_L\rho_L^{1/4}[g_n\sigma(\rho_L-\rho_G)/\rho_L]^{1/4}$$
$$K_G=j_G\rho_G^{1/4}[g_n\sigma(\rho_L-\rho_G)/\rho_G]^{1/4} \qquad [11]$$

and

$$D^*=\frac{D_i}{\left[\dfrac{\sigma}{g_n(\rho_L-\rho_G)}\right]^{1/2}} \qquad [12]$$

and $F(D^*)$ was determined empirically which attains a value of unity when D^* becomes very large. The dimensionless parameter, K represents a balance between the surface tension, σ, the buoyancy forces and the inertial forces in the vapour. The critical heat flux, based on [10] is now expressed as:

$$q^*=\frac{3.2[F(D^*)]^2}{D^{*1/2}}\left[\frac{\rho_L-\rho_G}{\rho_G}\right]^{1/2}\left[1+\left(\frac{\rho_G}{\rho_L}\right)^{1/4}\right]^{-2}. \qquad [13]$$

Equation [13] demonstrates that the critical heat flux is a function of the density ratio of liquid and its vapour and also the dimensionless diameter, D^*. Different forms of $F(D^*)$ have been reported by Nejat (1978) and Tien & Chung (1979).

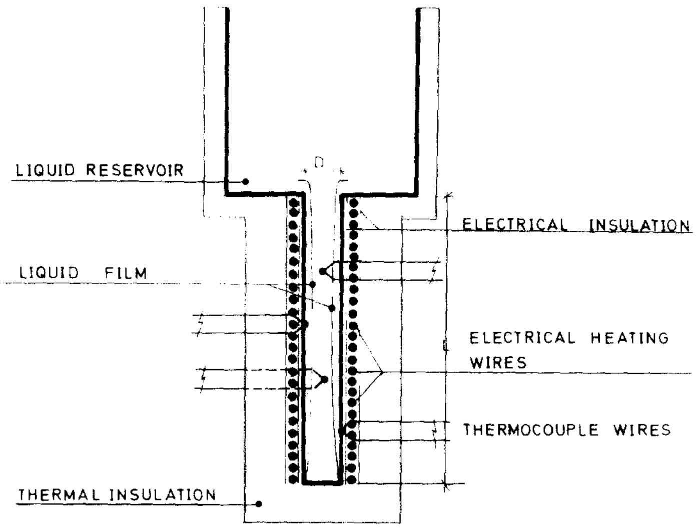

Figure 1. Experimental test rig.

EXPERIMENTAL TEST RIG

A test rig was set up as shown in figure 1. The test section was made of copper tubes having three different i.d's of 8, 10 and 14 mm. The length to diameter ratios had the values of 18.38, 15 and 10.71 respectively. The test section was heated by electrical heating wires by means of supplying of d.c. current from an a.c.–d.c. convertor. The heated section and the upper reservoir were well insulated thermally and although heat loss was negligible, heat loss tests were conducted prior to the experimental investigations. A surface temperature range of 120–380°C was obtained. The surface temperature was measured by four thermocouple wires attached to the heated section. These thermocouple wires were placed on a spiral line to measure the surface temperature variations in axial and radial directions. Tests were made to insure that there was no heating voltage pick ups by the thermocouples. The thermocouples were tested by a digital voltmeter through a selector switch and the heat input to the test section was determined by measuring the voltage and current to the heating wires.

The experiments were conducted with water, carbon-tetrachloride, normal-hexane and ethyl alcohol. The physicsl properties of the fluids employed were obtained from *CRC Handbook of Chemistry and Physics* (1975–76).

DISSCUSSION OF RESULTS

Experimental results of the present tests were first reduced in the form of the dimensionless parameters defined and then shown in figure 2. A correlation was obtained which is expressed as:

$$q^* = C^2\left[\frac{\rho_L-\rho_G}{\rho_G}\right]^{1/2}\left[1+\left(\frac{\rho_G}{\rho_L}\right)^{1/4}\right]^{-2} \qquad [14]$$

Equation [14] represents the present experimental test results to within ±35 per cent, when the constant C in the Wallis flooding correlation is equal to 0.7. The constant C which has been determined empirically, is reported to lie between 0.7 and 1.0. In order to reduce the scatter of the experimental points, the dimensionless length to diameter ratio of the heated tube, L/D was included. Nejat (1978) included the ratio of L/D in the correlation and showed that it is useful in reducing the scatter. Equation [14] is rewritten to give:

$$q^*(L/D)^{-0.1} = C_2^2\left[\frac{\rho_L-\rho_G}{\rho_G}\right]^{1/2}\left[1+\left(\frac{\rho_G}{\rho_L}\right)^{1/4}\right]^{-2}. \qquad [15]$$

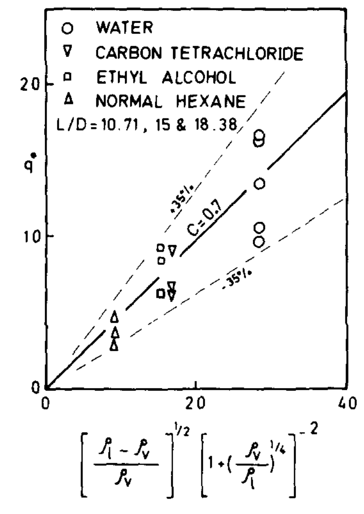

Figure 2. Correlation of experimental results by flooding expression.

Equation [15] correlates better the experimental data of the present study, and the constant C_2 attains a value of 0.6 (figure 3). A possible explanation for the influence of L/D ratio is that, contrary to the case of countercurrent two-phase flow of water and air on which the Wallis correlation is based, here the liquid film and the vapour flow do not have a uniform mass flow rate along the tube length.

Data of Griffith *et al.* (1962) on the vertical heated tube and Kusuda & Imura (1974) on the vertical thermosyphon were also transformed and compared with the present experimental results in figure 4. The experimental results shown in figure 4, were conducted on tubes having the length to diameter ratio of 10.71:35.21.

Tien & Chung (1979) correlated the data of Kusuda & Imura (1974), Sakhuja (1973), Frea (1970) and Cohen & Bayley (1955) employing [10]. It could be concluded from their results that the correlation based on the Wallis flooding expression, will result in better representation of the data. The correlation of experimental data indicates the dependency of the critical flux on the density ratio of liquid and its vapour. Analytical study of the critical heat flux based on the total heat input to the tube and for the case of large length to diameter ratio of the tube made by Nejat (1978), showed that the critical heat flux is a function of the kinematic viscosity ratio of

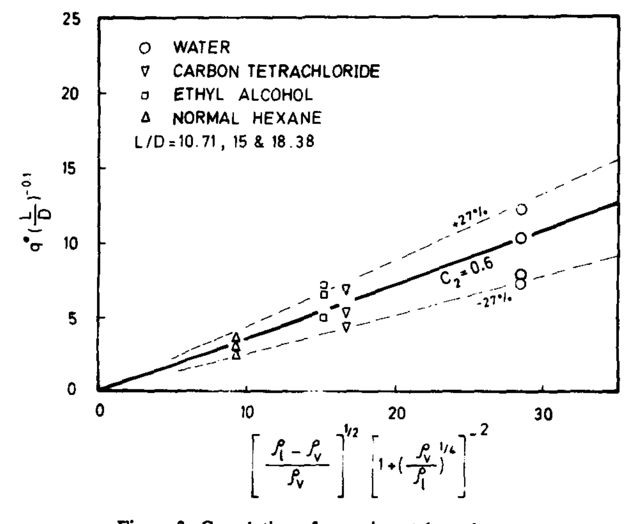

Figure 3. Correlation of experimental results.

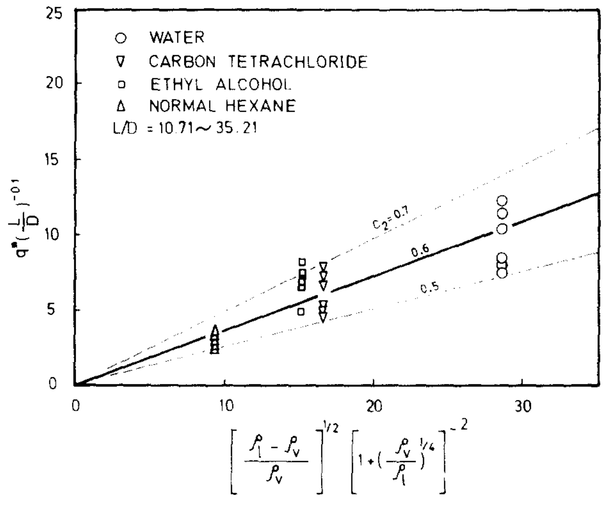

Figure 4. Comparison of present and available data.

liquid and its vapour. This again demonstrates the importance of the density ratio in correlating the experimental data. The appearance of the kinematic viscosity ratio of liquid to its vapour in the result of the analtyical study is due to the fact that the shear stress forces acting on the liauie film and vapour flows are considered, where in the Wallis flooding correlation these forces have been ignored. Analytical study of the burn-our condition for the case of small lenght to diameter ratio of the heated tube has been reported by Nejar & Mottaghian (1980). The vapour velocity in the opposite direction to the liquid film flow was taken to be very small and only the surface tension force has been considered to act on the liquid film. This condition refers to the normal film burn-out, and the density ratio was shown to have no influence on the axial critical heat flux based on the total heat input to the heated tube.

CONCLUSIONS

It can now be concluded that:

(1) The Wallis correlation is in good agreement with the experimental test data for vertical heated tubes and vertical thermosyphons.

(2) The density ratio of liquid substance and its vapour is an important parameter in the correlation of the critical heat flux.

(3) The length to diameter ratio has an effect on the critical heat flux when $10.71 \leq L/D \leq 35.21$ and should be included in the correlation.

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