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BRIEF COMMUNICATION

CRITICAL HEAT FLUX OF SATURATED NATURAL CONVECTION BOILING IN A SPACE BOUNDED BY TWO HORIZONTAL CO-AXIAL DISKS AND HEATED FROM BELOW

Y. KATTO and Y. KOSHO†
Department of Mechanical Engineering, University of Tokyo, Hongo, Bunkyo-ku, Tokyo, Japan

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1. INTRODUCTION

Studies have been made of critical heat flux (CHF) of natural convection boiling in horizontally confined geometries. Katto & Yokoya (1966) performed experiments on boiling of saturated water at atmospheric pressure in a space bounded by two horizontal co-axial disks with lower-disk heating, but no correlations of CHF data were presented. Jensen *et al.* (1976) carried out CHF experiments for natural convection boiling of saturated water at atmospheric pressure in horizontal annular geometries with inside-rod heating, and presented a generalized equation correlating their own data of water together with the data of refrigerant 113 obtained by others. Their correlation was derived on the basis of Reynolds number referenced to viscous flow of vapor in the confined space. The effect of gravitational acceleration g was not taken into account. On the other hand, Smirnov *et al.* (1976) and Smirnov (1976) measured the critical heat flux q_{co} for saturated boiling of water at 0.5–5 bar and that of ethyl alcohol at 1 bar in a horizontal rectangular slot of length b and clearance s. Their data were correlated by the following equation:

$$q_{co} = q^*_{co}\frac{1}{\sqrt{\left(1 + C_3\frac{\rho_v}{\rho_l}\left(\frac{b}{s}\right)^3\right)}} \qquad [1]$$

where q^*_{co} is the critical heat flux in ordinary pool boiling on an open heated surface, C_3 a constant, ρ_v the density of vapor, and ρ_l the density of liquid. Agreement between [1] and experimental data is not good with noticeable error extending from −33 to +70%.

In the present study, experiments were made to obtain CHF data for natural convection boiling in a space bounded by two horizontal co-axial disks in a pool of saturated liquid at atmospheric pressure. The fluids used were water, R-113, ethyl alcohol and benzene. A generalized correlation equation was derived for the CHF data thus obtained.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

The main part of experimental apparatus employed is shown in figure 1. The test liquid (distilled water, ethyl alcohol of purity higher than 99.5%, R-113 of purity higher than 99.99%, and benzene of purity higher than 95%) stored in a boiling vessel (1) at atmospheric pressure is kept at saturation temperature by means of an auxiliary heater (5). The generated vapor is returned through a condenser to the boiling vessel. The flat, end surface of the upper cylindrical part of a copper block (2), mounted with electric heaters of plate type (4) and insulated by a Bakelite sleeve (5), as well as glass wool (7),

†Present address: Department of Mechanical Engineering, Miyazaki University, Miyazaki, Japan.

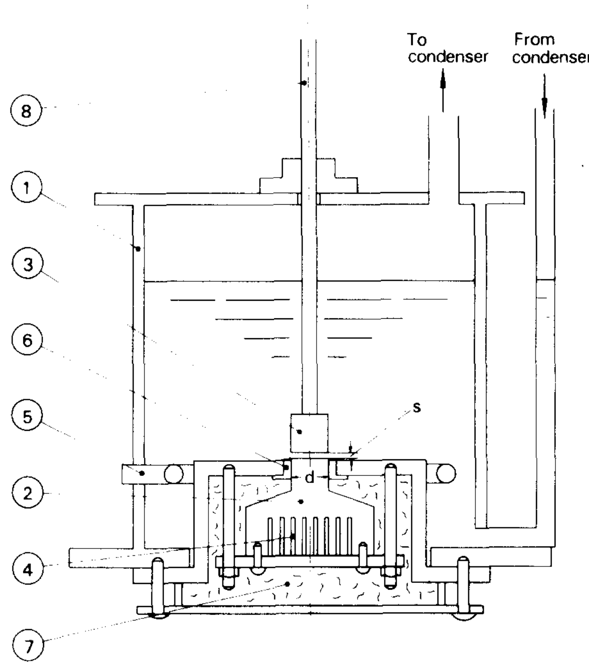

Figure 1. Main part of experimental apparatus.

provides a heated disk surface for boiling. The heat flux across the heated surface is determined by the temperature gradient, measured with three copper-constantan thermocouples placed at regular intervals along the axis of the cylindrical part of the copper block. The thermal conductivity of each copper block employed, which is required for an accurate estimate of the heat flux, has been carefully determined in preliminary experiments. Two diameters of heated surface, 10 and 20 mm, are employed. The axial length of the cylindrical part is 15 mm for the runs with water, which has a comparatively high CHF, and 40 mm for the experiment with the other fluids which have a comparatively low CHF. The unheated Bakelite cylinder (3), which is supported co-axially above the heated disk surface at a distance s, has a thickness and a diameter of the same length as the diameter of the heated surface d. A rod (8) supporting the unheated cylinder (3) is movable up and down by means of a screw system, and the distance s between the heated and unheated disk surface is measured by a dial gauge, not shown in figure 1.

In order to estimate the distance s correctly, the displacement of the heated surface level due to the thermal expansion of the copper block must be taken into account. Therefore, when boiling becomes steady at a heat flux which is a little lower than the presumed value of CHF for a prescribed distance s, the unheated cylinder is rapidly lowered until coming in contact with the heated surface. In this case, the heated surface temperature begins to rise if the surface becomes dry, but it is actually possible to avoid the disturbance by a prompt reading of the dial gauge at the moment of contact. The origin of s effective near the CHF point is thus determined. Immediately after the reading of the dial gauge, the unheated cylinder is lifted and can be fixed at a prescribed distance s above the heated surface. Then, the heat flux is raised stepwise by Δq leading to the corresponding steady state boiling, and thereafter, the procedure is repeated for the increment of heat flux until the occurrence of CHF. In the present study, each increment of heat flux Δq is limited to less than 5% of the preceding heat flux q. When an increment of heat flux brings about the condition where the heated surface temperature cannot have a steady state, critical heat flux q_{co} is determined with an error less than about 5%.

3. CORRELATION OF EXPERIMENTAL DATA

In order to get a clue for correlating the experimental data obtained, dimensional analysis is utilized. Postulating that the hydrodynamic condition of two-phase vapor-liquid flow is responsible for the occurrence of CHF in the present boiling system, the superficial vapor velocity $q_{co}/\rho_v H_{fg}$ at a critical heat flux of q_{co}, where ρ_v is the density of vapor and H_{fg} the latent heat of evaporation, is governed by physical quantities, such as the density of liquid ρ_l and that of vapor ρ_v—relating to the force of inertia; the surface tension of the interface σ; the gravitational force $g(\rho_l - \rho_v)$ relating to the buoyancy; the diameter of heated disk surface d; and the normal distance between parallel disk surfaces s. At present, the effect of viscous force on CHF is ignored because it is presumed to be negligibly small. Applying dimensional analysis to the physical quantities mentioned above, yields the following relation:

$$\frac{q_{co}}{\rho_v H_{fg}} \bigg/ \sqrt[4]{\left(\frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2}\right)} = f\left(\frac{\rho_v}{\rho_l}, \frac{g(\rho_l - \rho_v)d^2}{\sigma}, \frac{s}{d}\right). \quad [2]$$

Now, in the light of [2], the experimental data for q_{co} is plotted in the following form:

$$\sqrt[4]{\left(\frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2}\right)} \bigg/ \frac{q_{co}}{\rho_v H_{fg}} \text{ vs } \frac{d}{s}.$$

Figure 2 is obtained for the case of d = 10 mm and figure 3 for that of d = 20 mm. In these figures, it is noted that experimental data at d/s = 0, which corresponds to the reciprocal of the constant

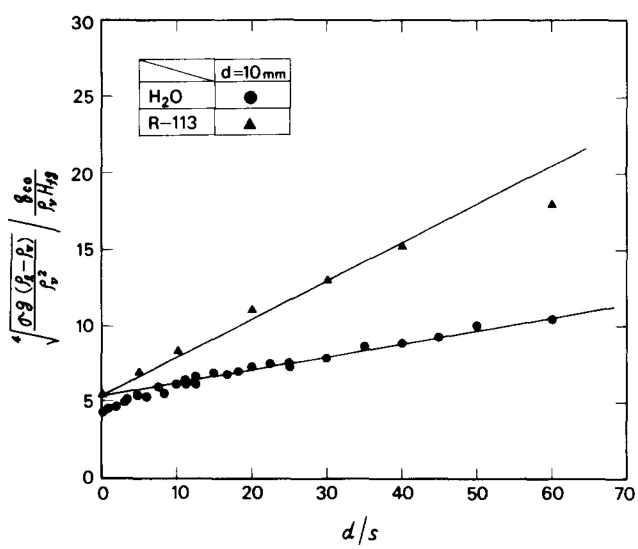

Figure 2. Critical heat flux q_{co} for boiling on a 10 mm dia. heated surface.

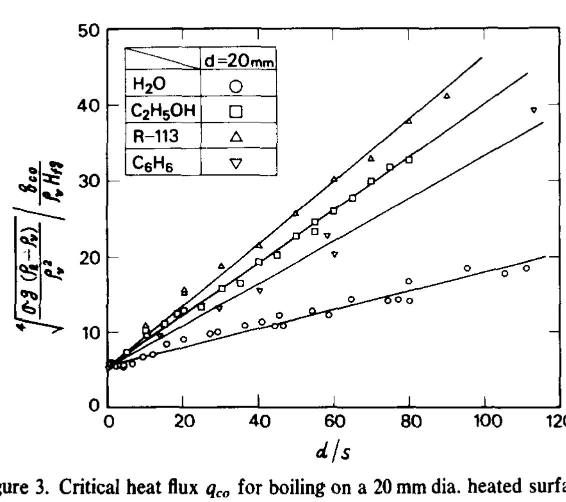

Figure 3. Critical heat flux q_{co} for boiling on a 20 mm dia. heated surface.

C included in Kutateladze (1952) or Zuber (1959) correlation equation of CHF for ordinary pool boiling, shows nearly the same values for all liquids and heated surface diameters. Taking an average,

$$\frac{1}{C} = 5.5 \quad \text{or} \quad C = 0.18. \qquad [3]$$

This value of C agrees with the constant in Zuber correlation recommended by Rohsenow (1973).

Next, the following form of CHF correlation may be assumed for the data for $d/s > 0$ in figures 2 and 3:

$$\sqrt[4]{\left(\frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2}\right)} \Big/ \frac{q_{co}}{\rho_v H_{fg}} = \frac{1}{C}\left(1 + \Psi \frac{d}{s}\right) \qquad [4]$$

where Ψ/C (that is, 5.5Ψ) denotes the gradient of every straight line drawn for every group of experiments in figures 2 and 3 so as to pass the point 5.5 on the ordinate axis. Of course, Ψ takes a different value for every combination of test liquid and heated surface diameter. Experimental values of Ψ are listed in table 1.

According to [2], Ψ may be regarded as a function of ρ_v/ρ_l and $g(\rho_l - \rho_v)d^2/\sigma$. A test of this possibility is shown in figure 4 where the values of Ψ listed in table 1 are plotted against $g(\rho_l - \rho_v)d^2/\sigma$. It may be noted that there is a close relation between Ψ and $g(\rho_l - \rho_v)d^2/\sigma$, but a slight deviation seems to exist between the group for water for which ρ_l/ρ_v is comparatively high and the group of other liquids for which ρ_l/ρ_v is comparatively low. In fact, as shown in figure 5, improvement is obtained if the effect of ρ_v/ρ_l on Ψ is taken into account and the result of figure 5 is expressed as follows:

$$\Psi = 0.00918 \left(\frac{\rho_v}{\rho_l}\right)^{0.14} \sqrt{\left(\frac{g(\rho_l - \rho_v)d^2}{\sigma}\right)}. \qquad [5]$$

Substituting C and Ψ on the RHS of [4] by [3] and [5] respectively, yields a generalized correlation equation as follows:

$$\frac{q_{co}}{\rho_v H_{fg}} \Big/ \sqrt[4]{\left(\frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2}\right)} = 0.18 \frac{1}{1 + 0.00918\left(\frac{\rho_v}{\rho_l}\right)^{0.14} \sqrt{\left(\frac{g(\rho_l - \rho_v)d^2}{\sigma}\right)} \frac{d}{s}}.$$

Table 1. Experimental data of Ψ and magnitude of d'

Fluid	d (mm)	Ψ	d'
H_2O	10	1.53×10^{-2}	4.05
H_2O	20	2.45×10^{-2}	8.10
R-113	10	4.55×10^{-2}	9.93
R-113	20	7.31×10^{-2}	19.9
C_2O_5OH	20	5.93×10^{-2}	12.9
C_6H_6	20	4.44×10^{-2}	12.3

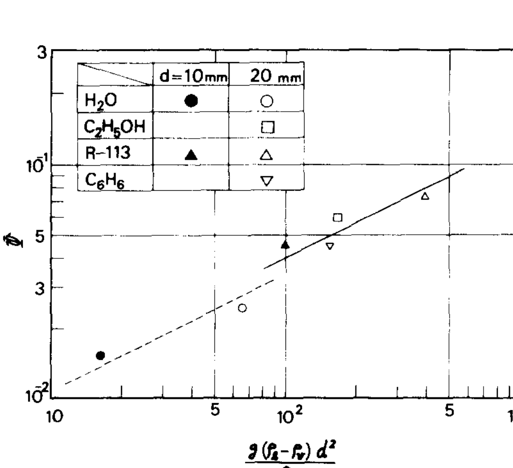

Figure 4. Relation between Ψ and $g(\rho_l - \rho_v)d^2/\sigma$.

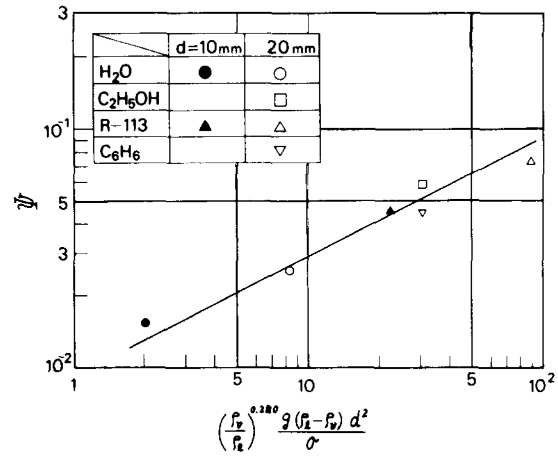

Figure 5. A generalized correlation of Ψ.

Figure 6 shows a comparison of $q_{co}/\rho_v H_{fg}$ obtained experimentally in the present study with the prediction of [6]. It is noted in figure 6 that a part of the water data, indicated by black circles, exhibits somewhat larger deviations than other data, but it must be remembered that these data are in the vicinity of $d/s = 0$ in figure 2. In other words, the above deviation has arisen in connection with the fact that the boiling of water on a 10 mm dia. heated surface exhibits somewhat higher critical heat flux than usual in the vicinity of $d/s = 0$. In this respect, it may be useful to note that for the test liquids employed the magnitude of $d' = d\sqrt{(g(\rho_l - \rho_v)/\sigma)}$ as shown in table 1 is lowest for water for $d = 10$ mm. According to Lienhard & Dhir (1973), when d' is as small as 4.05, there is a possibility of generating such a deviation of CHF as above, that is, to give somewhat higher CHF than usual.

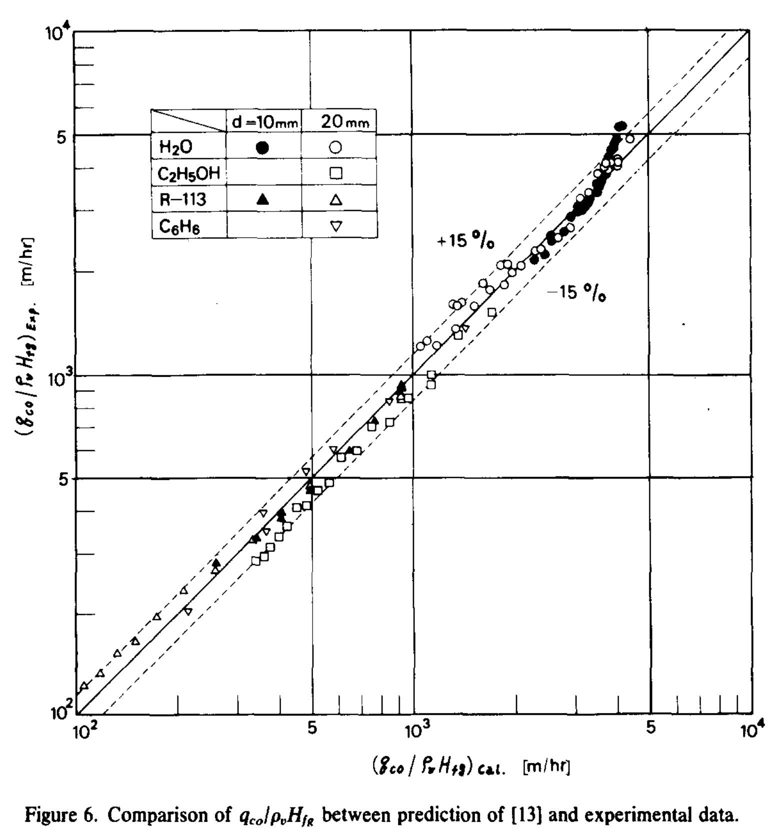

Figure 6. Comparison of $q_{co}/\rho_v H_{fg}$ between prediction of [13] and experimental data.

4. CONCLUSIONS

(i) CHF experiments in boiling at atmospheric pressure have been made for disk diameters of $d = 10$ and 20 mm, the distance between the parallel disks s in a range of $d/s = 0 \sim 120$, and four different fluids (water, R-113, ethyl alcohol and benzene). The CHF data obtained is correlated in a generalized form by [6] with an uncertainty of about $\pm 15\%$.

(ii) In employing[6], if the condition considered is in the vicinity of $d/s = 0$, it is recommended to ascertain that the magnitude of $d' = d\sqrt{(g(\rho_l - \rho_v)/\sigma)}$ is not less than, say, 6.0.

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