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BURNOUT IN A HIGH HEAT-FLUX BOILING SYSTEM WITH AN IMPINGING JET

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Abstract—An experimental study has been made on the fully-developed nucleate boiling at atmospheric pressure in a simple forced-convection boiling system, which consists of a heated flat surface and a small, high-speed jet of water or of freon-113 impinging on the heated surface. A generalized correlation for burnout heat flux data, that is applied to either of water and freon-113, is successfully evolved, and it is shown that surface tension has an important role for the onset of burnout phenomenon, not only in the ordinary pool boiling, but also in the present boiling system with a forced flow.

NOMENCLATURE

C, constant;
c_{pl}, specific heat of liquid at constant pressure;
D, diameter of a heated surface;
d, inside diameter of a nozzle of impinging jet at the exit;
G_0, mass flow rate of an impinging jet;
G, mass flow rate of splashed droplets;
G', mass rate of evaporation of liquid;
g, gravitational acceleration;
K, constant;
L, latent heat of evaporation;
q, heat flux;
$q_{B.O}$, burnout heat flux;
T_{liq}, temperature of supplied liquid;
T_{sat}, saturation temperature;
T_w, temperature of heated surface;
u_e, exit velocity of liquid jet.

Greek symbols
β, thermal coefficient of volume expansion;
ε_{sub}, correction factor for the effect of subcooling on burnout heat flux;
λ_l, thermal conductivity of liquid;
μ_l, viscosity of liquid;
μ_v, viscosity of vapor;
ρ_l, density of liquid;
ρ_v, density of vapor;
σ, surface tension.

1. INTRODUCTION

As is generally known, burnout in pool boiling has been studied rather extensively, and generalized correlations, that apply to the burnout heat flux data for many kinds of fluid and thermodynamical condition, have been derived by Kutateladze [1], Rohsenow and Griffith [2], Zuber [3], Chang and Snyder [4], Zuber *et al.* [5], and others.

In the case of forced-convection boiling, many studies have also been made for correlating the burnout or critical heat flux data, particularly in boiling with flow inside of tubes, annuli, outside of rod bundles, etc. In this case, however, it is probably close to the truth to say that due to the complexity of included phenomena, no correlation for burnout heat flux has yet been evolved that is applied universally to the data for various kinds of fluid and conditions. As an inevitable consequence, it has been impossible to examine whether the mechanism of burnout in pool and forced-convection boiling is quite different.

On the other hand, one of the authors of this paper, starting from the studies on the mechanism of burnout in pool boiling [6, 7], entered into an attempt [8] to raise the burnout heat flux by holding a small impinging jet through which the liquid is forcibly supplied to the heated surface. Then, it was followed by the authors' preceding study [9], in which the burnout heat flux was observed to vary as a very simple function of the velocity of jet.

As the next step, the present study has been planned to make a more extensive study of nucleate boiling and to search for a possibility of obtaining a generalized correlation of burnout heat flux in the boiling system with an impinging jet, which can be regarded as one of the simplest systems associated with the forced-convection boiling.

2. EXPERIMENTAL APPARATUS

The whole system of experimental apparatus, which is shown schematically in Fig. 1, consists of three cardinal portions; the loop for circulating a test fluid, the electric system for heating the test fluid, and the main part where the nucleate boiling with an impinging jet is generated on a heated surface. The experiment is made in the present study on saturated and subcooled boiling of pure water and freon-113 at atmospheric pressure on the heated surface (2) in a boiling vessel (1). These two fluids with different physical properties have been chosen in order to avert the danger of fire during the experiment. Liquid, coming

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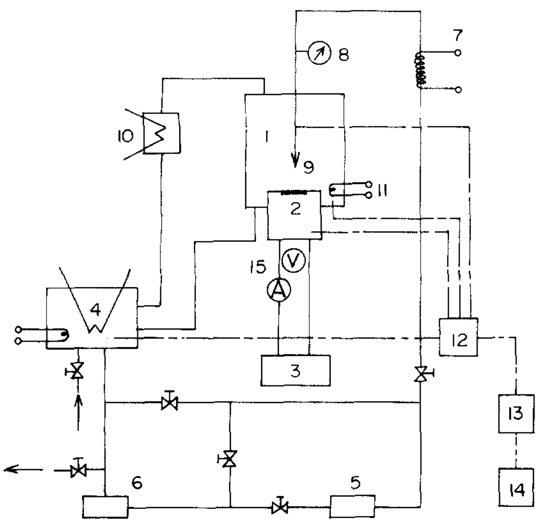

FIG. 1. Whole system of experimental apparatus. 1. Boiling-vessel; 2. Heated surface; 3. Transformer; 4. Heating and subcooling apparatus; 5. High-pressure pump; 6. Low-pressure pump; 7. Temperature-regulator; 8. Pressure gauge; 9. Nozzle; 10. Condenser; 11. Auxiliary heater; 12. Ice-box; 13. Self-registering thermometer; 14. Digital volt meter; 15. AC meter.

out of the heating and subcooling apparatus (4) which consists of a main electric heater, an automatic electric heater for controlling the temperature of liquid and a heat exchanger for subcooling the liquid, is pressurized by two pumps of regenerative type (5) and (6), and is regulated to be kept at a desired temperature by means of a temperature-regulator (7) before flowing out of a nozzle (9). The piping for the liquid is thermally insulated. Liquid and vapor flowing out of the boiling vessel (1) are returned to the heating and subcooling apparatus (4) through either a drain pipe or a condenser (10).

Figure 2 shows the main part of the apparatus in the case of the upward-facing heated surface, and this part can be replaced by another alternative with a downward-facing heated surface in order to make an experiment to check the effect of gravitational force on heat transfer as well as on burnout. The end surface of the conical part of the copper block (3) located at the central position in a boiling vessel (1) is a circular heated surface of 11 mm to 21 mm in diameter. The heated surface is polished with the emery paper (No. 0) and cleaned with acetone and pure water in every experiment. The electric heater (10), which is composed of eleven heating elements of plate type mounted in the grooves of the lower part of copper block, is capable of providing the maximum heat flux of 2×10^7 W/m^2 across the heated surface. The temperature of the heated surface T_w as well as the heat flux across the heated surface q is measured by employing the temperature distribution determined with three Chromel–Alumel thermocouples of 0.1 mm-dia. set up along the axis of copper block.

In the preliminary experiment, the vapor, which is generated on the heated surface in the nucleate pool boiling at sufficiently high heat flux of 5×10^5 to 1×10^6 W/m^2, is accumulated in a collector to measure the heat flux across the heated surface, and by this means the thermal conductivity of copper block is determined. When the heat flux, thus determined, is compared with the electric input to the heater mounted in the copper block, it is found that the heat loss from the copper block is less than 10% of the total input.

The nozzle (4) in Fig. 2 has been designed to be able to make a circular liquid jet of laminar flow within the range of jet velocity in the present study. The liquid jet

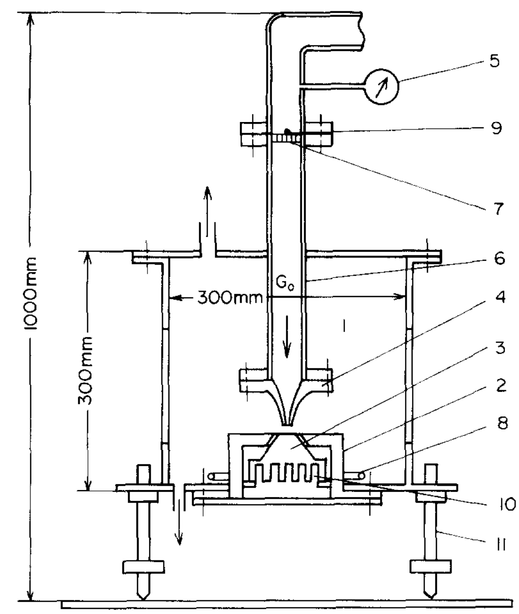

FIG. 2. Main part of experimental apparatus. 1. Boiling-vessel; 2. Heating-equipment; 3. Copper block; 4. Nozzle; 5. Pressure gauge; 6. Feed pipe; 7. Filter; 8. Auxiliary heater; 9. C-A thermocouple; 10. Electric heater; 11. Height adjustment screw.

is held vertically at the center of heated surface (3), and thereby the heated surface is covered with a radially flowing thin liquid film. In this connection, it should be mentioned that the cross-sectional area of the liquid jet used in the present study is only 6–10% compared with the total area of the heated surface, and therefore the rise of saturation temperature as well as the rise of static pressure which appears in the so-called impinging zone near the center of the heated surface, has little effect on the boiling taking place all over the heated surface (cf. [9]). The mass flow rate of liquid flowing out of the nozzle (4) G_0 is determined by means of a pressure gauge (5). Calibrations made with water at temperatures ranging from 30 to 80°C and with freon-113 at temperatures ranging from 20 to 25°C show that the error is less than a few percent if the thermal variation of density of liquid is taken into account. The temperature of liquid flowing out of the nozzle is measured by a Chromel–Alumel thermocouple (9) of 0.3 mm-dia. set up in the feed pipe.

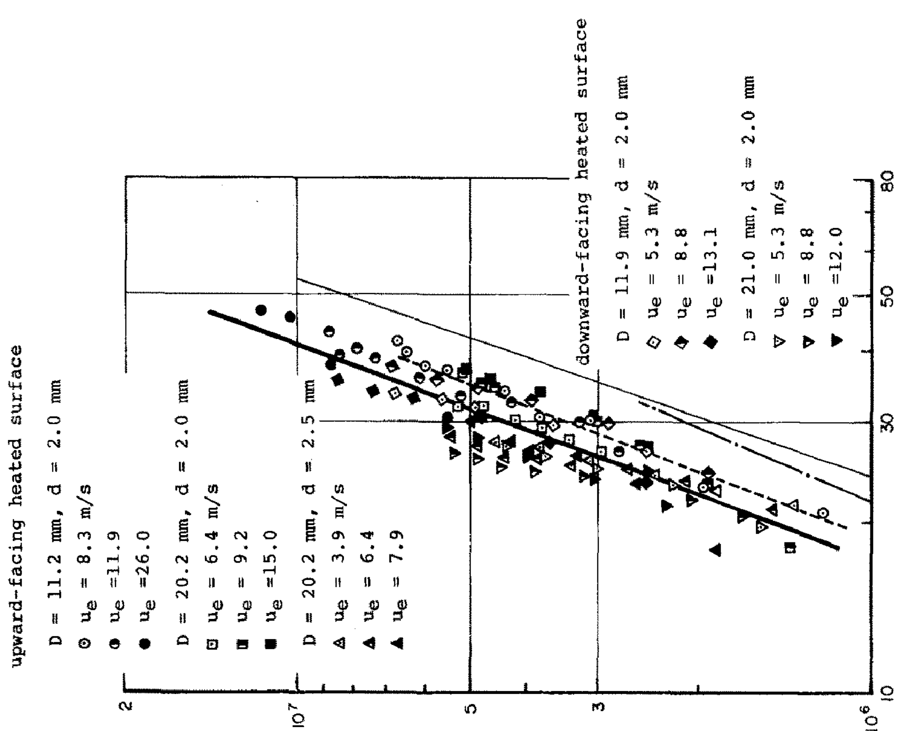

FIG. 3. Saturated nucleate boiling data for water.

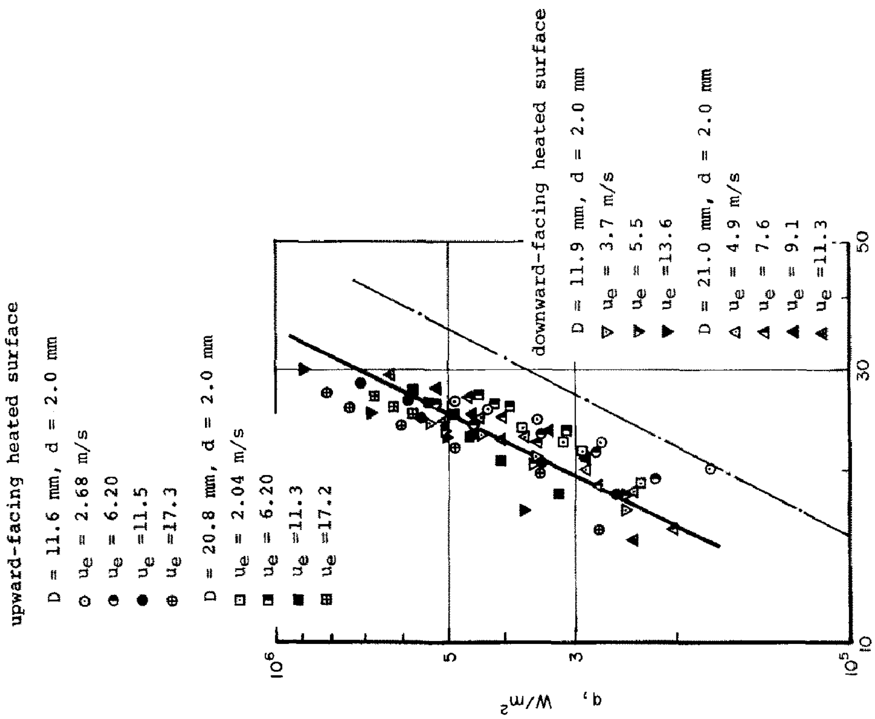

FIG. 4. Saturated nucleate boiling data for freon-113.

3. SATURATED NUCLEATE BOILING HEAT TRANSFER

Figures 3 and 4 show the typical data of fully-developed nucleate boiling obtained in the range of high heat flux for the respective cases of supplying saturated water and freon-113. In Fig. 3, a heavy solid line is the mean nucleate boiling curve, while a broken line is the result of nucleate boiling curve obtained by Katto and Kunihiro [8] for the boiling system with an impinging jet of water of velocity $u_e = 2.0$–2.7 m/s including the state mixed with pool boiling. In this connection, it may be of use to refer the authors' preceding study [9] reporting the empirical fact that approximately speaking, the nucleate boiling curve of the boiling system with an impinging jet is in accord with the monotonous extension of the nucleate boiling curve obtained in the region of high heat flux of the ordinary pool boiling.

Apart from the scattering of data inherent in nucleate boiling, it may be concluded from Figs. 3 and 4 that the boiling curves obtained under different conditions coincide with each other independently of the jet velocity u_e, the ID of nozzle d, the diameter of the heated surface D, and the orientation of the heated surface. Then the following assumption can be made from the afore-mentioned characteristics of boiling curve. Namely, the motion of fluid activated by nucleate boiling on the heated surface is so active in the nucleate boiling at high heat flux, that the state of fluid motion near the heated surface hardly changes even if the forced convection is applied to the bulk fluid. In addition, it can be presumed that almost all the quantity of heat transferred from the heated surface is spent on the latent heat of evaporation at the active nucleation sites distributed on the heated surface in case of the nucleate boiling at high heat flux. Therefore, an active, self-supporting boiling layer may be assumed to cover the heated surface and to govern the nucleate boiling heat transfer at high heat flux. The thin layer above-mentioned will be called nucleate-boiling liquid layer in the present paper.

Finally, for reference, the light solid line in Fig. 3 is the prediction of Nishikawa–Yamagata's equation [10] correlating the nucleate boiling heat transfer of water and some organic liquids in ordinary pool boiling. On the other hand, the respective dot-dash-lines in Figs. 3 and 4 represent the nucleate boiling curves obtained experimentally by Copeland [11] for water and by Ruch and Holman [12] for freon-113 on the boiling system with an impinging jet.

4. BEHAVIOR OF FLUID IN THE PRESENT BOILING SYSTEM

4.1. *Observation of behavior of fluid*

Figure 5, dealing with the case of water supplied with the jet velocity $u_e = 8.8$ m/s from a nozzle of $d = 2.0$ mm to the downward-facing flat surface that includes the heated surface of $D = 11.9$ mm in it, shows the typical aspect of saturated boiling.

Now, Fig. 5(a) represents the special case of heat flux $q = 0$, that is non-boiling, in which the water dischar-

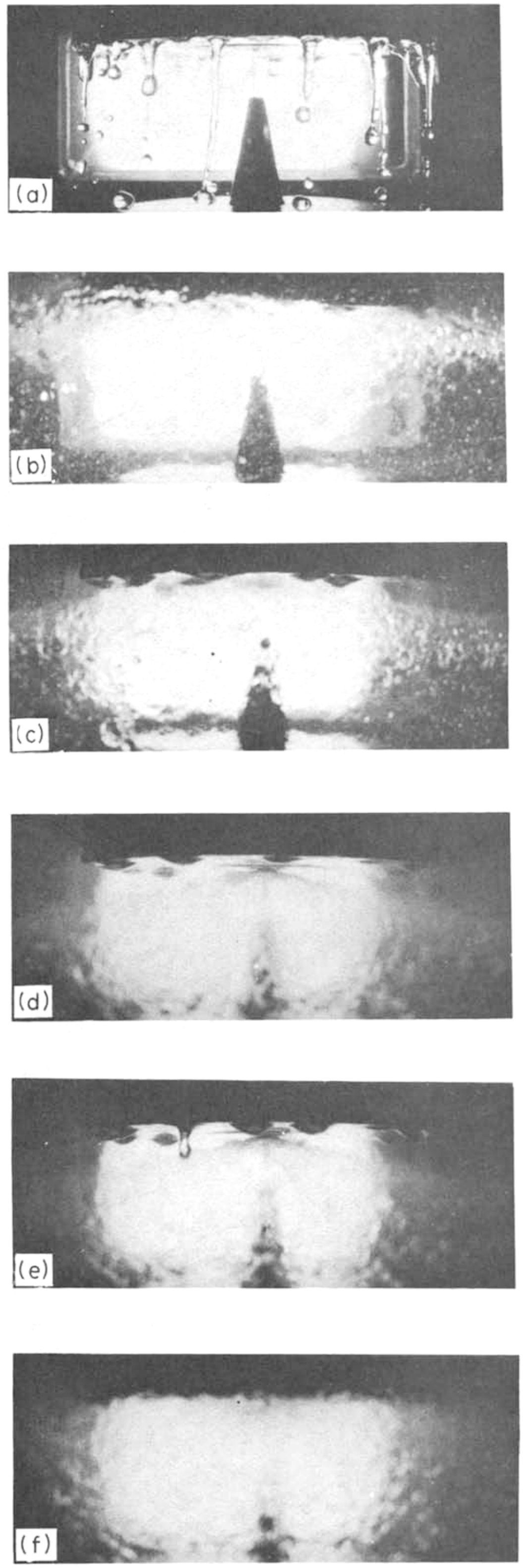

FIG. 5. State of saturated boiling of water downward-facing heated surface ($u_e = 8.8$ m/s, $D = 11.9$ mm, $d = 2.0$ mm).

ged upwardly from the nozzle impinges on the center of the downward-facing surface and then flows radially over the surface without boiling until it loses kinetic energy resulting in the natural falling of waterdrops at the position far away beyond the outer edge of the heated surface. Then, Figs. 5(b–e) represent the state of $q = 1.97 \times 10^6$, 3.66×10^6, 5.70×10^6 and 6.80×10^6 W/m^2 respectively. In these cases, the splash of water from the heated surface appears due to the strong ejection of vapor from the nucleate-boiling liquid layer [notice the conical envelop of splashing flow clearly observed in Fig. 5(d) and (e)], but still there is a non-vanishing, residual water flowing over the heated surface, which is verified by the observation of successive formation of waterdrops falling down at the position beyond the outer edge of the heated surface [see Fig. 5(e) for example]. Here, it should be mentioned that the burnout dealt with in the present study, has been observed to appear always with the non-vanishing, residual liquid, flowing over the heated surface and maintaining the nucleate boiling there. Once the burnout has occurred, however, the liquid flowing over the outer edge of the heated surface disappears and all the quantity of liquid impinging on the heated surface is splashed out as shown in Fig. 5(f) [notice no trace of the residual water to make the natural falling of waterdrops].

In the case of the upward-facing heated surface, the same behavior of fluid as afore-mentioned is observed only except that the phenomenon of hydraulic jump appears, instead of the falling of waterdrops, at the position far beyond the outer edge of the heated surface [cf. Fig. 7(b)].

4.2. *Variation of the rate of splashing with heat flux*

In order to measure the mass flow rate of droplets splashed from the heated surface, the droplet-catcher similar to that used in the preceding study [9] is installed in the boiling vessel in case of the upward-facing heated surface. Figure 6 shows typical results thus obtained for the variation of the rate of splashing G/G_0 with the heat flux q, where G is the mass flow rate of droplets splashed depending on q, while G_0 is the total mass flow rate of an impinging jet. As q is raised, G/G_0 increases rapidly; and it has been observed in the experiment that when G/G_0 in Fig. 6 reaches its highest value of data shown near $G/G_0 = 0.8 \sim 1.0$ in each experiment, a little increase of q leads to the occurrence of burnout. In this connection, it should be mentioned that the rate of evaporation G'/G_0, where G' is the mass of liquid evaporated on the heated surface per unit time, is readily estimated from q, and G'/G thus determined has been found to be always smaller than $1-(G/G_0)$ at a burnout point. Of course, the residual quantity $G_0-(G+G')$ is nothing but the mass flow rate of the residual liquid flowing over the outer edge of the heated surface which has been mentioned in the preceding section.

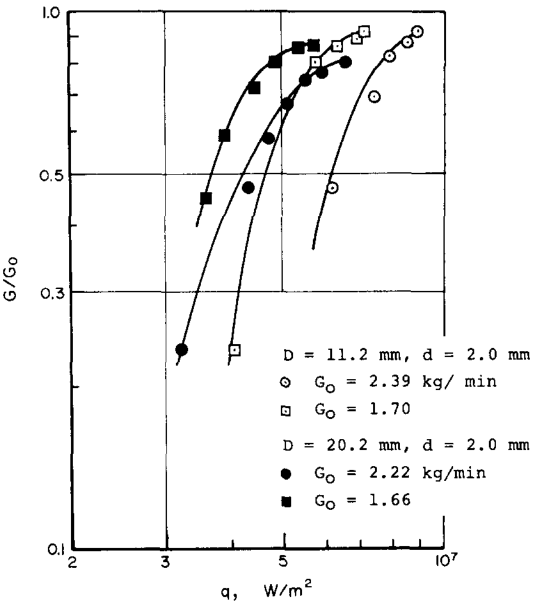

FIG. 6. Rate of splashing vs heat flux (saturated boiling of water).

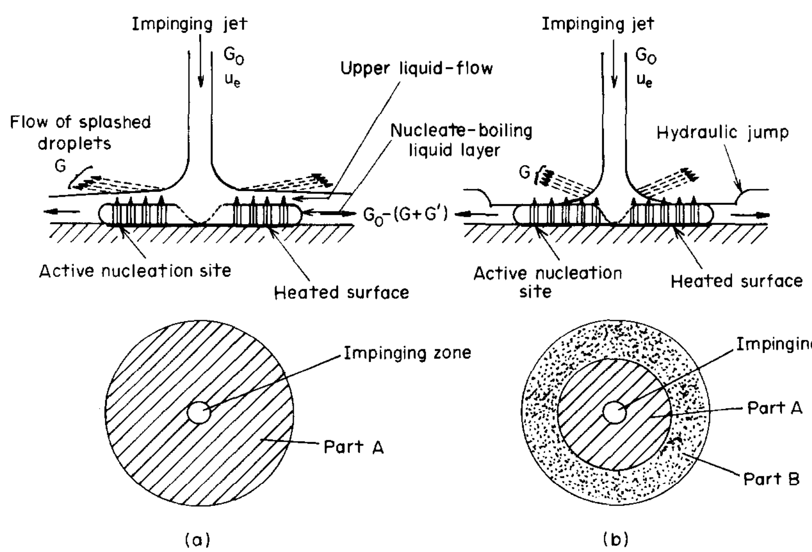

FIG. 7. A model of flow (upward-facing heated surface).

4.3. *A flow model*

On the basis of experimental facts represented by Figs. 3–6, we may assume such a model as shown in Fig. 7 for the flow of liquid and vapor in the fully-developed nucleate boiling at high heat flux with an impinging jet, which is a slight revision of that presented in the authors' preceding study [9]. Self-supporting violent nucleate boiling independent of the external effect is kept in a nucleate-boiling liquid layer on the heated surface, and the thin layer is covered with an upper liquid-flow, from which the splash of droplets is produced due to the ejection of vapor jets from the underlying boiling layer as shown in the part A of Fig. 7(a). As heat flux is far raised, however, the splashing becomes very violent and the upper liquid-flow is splashed out near the impinging zone so that the clear conical envelop of splashing flow such as seen in Fig. 5(d) and (e) is developed, and the downstream part of nucleate-boiling liquid layer is exposed to the surrounding atmosphere of vapor, yielding the state of the part B in Fig. 7(b). Even in the case of Fig. 7(b), the flow rate of the residual liquid flowing over the outer edge of the heated surface $G_0-(G+G')$ does not vanish (cf. Section 4.2), so that the nucleate-boiling liquid layer is maintained on the heated surface.

4.4. *Flow state at the onset of burnout*

According to the observation employing the colour photography and the high-speed photography, the burnout takes place in the state of Fig. 7(b), as far as the boiling of water is concerned. However, in the case of the boiling of freon-113, it seems likely that the flow still remains in the state of Fig. 7(a) when the burnout occurs. Consequently, if there are no particular phenomena inherent to the substance of liquid, it may be concluded that the burnout can occur in either state of Fig. 7(a) and (b). In other words, the change of the state of flow shown in Fig. 7(a) and (b) cannot be the cause for the onset of burnout.

In addition, the observation shows that once burnout takes place, in either state of Fig. 7(a) and (b), the dry-out starts from the outer edge of the heated surface to extend up to the vicinity of impinging zone, being accompanied by the state that all the liquid is splashed out immediately after impinging on the heated surface.

5. BURNOUT HEAT FLUX IN SATURATED BOILING

5.1. *Experimental result*

In the authors' preceding study [9], the burnout heat flux $q_{B.O}$ was measured by varying the velocity of impinging jet u_e alone, to give the empirical and tentative result:

$$q_{B.O} = \text{const. } u_e^{0.39}.$$

In the present study, however, not only the jet velocity u_e but also the various factors such as the diameter of heated surface D, the inside diameter of nozzle d, the orientation of heated surface (i.e. the direction of gravitational force), and the kind of boiling liquid are changed, yielding the result of Figs. 8 and 9. Namely, Fig. 8 shows all the experimental data of burnout heat flux obtained for the upward-facing heated surface, and similarly Fig. 9 shows the data obtained for the downward-facing heated surface. In addition, Fig. 8 includes the data of authors' preceding study [9] obtained for the burnout on a square, stainless plate (8 × 8 mm) heated by the conduction of alternating current, for which the diagonal of square plate ($=\sqrt{2}$ × 8 mm = 11.3 mm) is taken as D and the time-averaged value of heat flux observed at burnout is taken as $q_{B.O}$ in Fig. 8.

From Figs. 8 and 9, it may be noticed that $q_{B.O}$ can be correlated as a function of u_e/D, and the solid lines inserted tentatively in both figures represent the relation of

$$q_{B.O} = \text{const. } (u_e/D)^{1/3} \tag{1}$$

where the value of constant differs between water and freon-113, and the comparison of Fig. 8 and Fig. 9 shows that there is no effect of gravitational force on $q_{B.O}$ in the present forced-convection boiling system. Besides, it may be noticed from Fig. 8 that there is no effect of d on $q_{B.O}$. The above-mentioned fact that $q_{B.O}$ is not governed by d but is governed by u_e, suggests that $q_{B.O}$ is unaffected by the mass flow rate of impinging jet G_0, because $G_0 = (\pi/4)d^2u_e\rho_l$ where ρ_l is the density of liquid.

5.2. *Dimensional analysis and correlation of burnout heat flux data*

In order to search for dimensionless groups for correlating the data of Figs. 8 and 9, a dimensional analysis will be attempted on burnout in the saturated boiling with a forced flow in a gravitational field. Since the burnout in the case of saturated boiling can be regarded as a phenomenon independent of heat transfer (i.e. the thermal conductivity and the specific heat of liquid have no effect on burnout), it may be assumed that there are ten physical quantities concerned: that is, $q_{B.O}$: burnout heat flux, L: latent heat of evaporation, ρ_v: density of vapor, ρ_l: density of liquid, μ_v: viscosity of vapor, μ_l: viscosity of liquid, σ: surface tension, $g(\rho_l-\rho_v)$: difference of specific weight between liquid and vapor, u_e: velocity of forced flow, and D: representative length of heated surface. On the other hand, there are four fundamental units (mass, length, time and quantity of heat). Therefore, according to pi theorem, there are six (that is ten minus four) independent dimensionless groups, to give the relation:

$$\frac{q_{B.O}/(\rho_v L)}{u_e} = C\cdot\left(\frac{\rho_l}{\rho_v}\right)^{\alpha_1}\left(\frac{\mu_v}{\mu_l}\right)^{\alpha_2}\left(\frac{\sigma}{\rho_l u_e^2 D}\right)^{\alpha_3} \times\left(\frac{\mu_l}{\rho_l\cdot u_e D}\right)^{\alpha_4}\left[\frac{g(\rho_l-\rho_v)D}{\rho_l\cdot u_e^2}\right]^{\alpha_5} \tag{2}$$

where C and the five exponents α_1 to α_5 are constant respectively. All the dimensionless groups included in equation (2) can be regarded as of hydrodynamic character.

Now, it may be of interest to note that equation (2) can also be applied to the burnout in ordinary pool

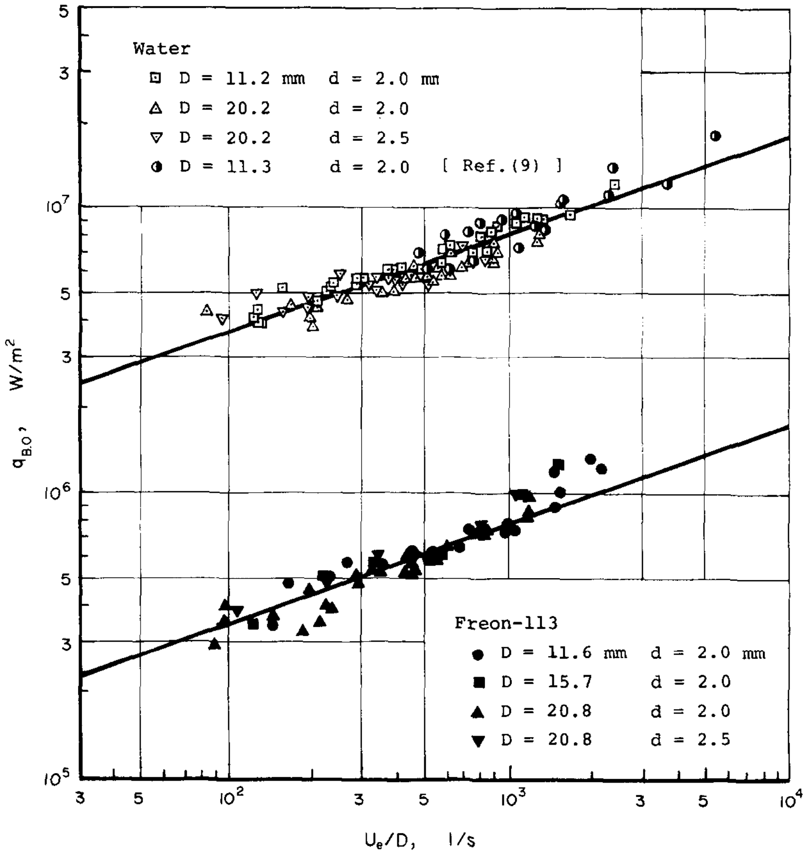

FIG. 8. Burnout heat flux vs u_e/D (saturated boiling, upward-facing heated surface).

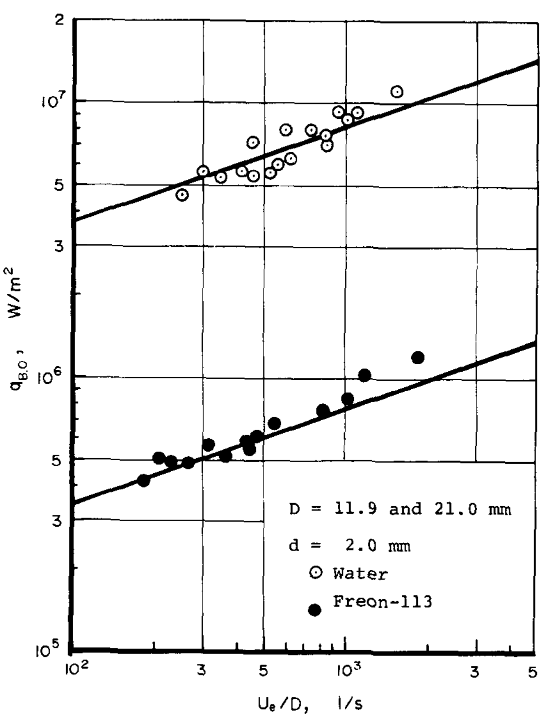

FIG. 9. Burnout heat flux vs u_e/D (saturated boiling, downward-facing heated surface).

boiling if the case of heated surface of extremely small size is excluded. Namely, assume that none of μ_v, μ_l, u_e, and D affects $q_{B.O}$, and all the exponents of equation (2) except α_1 are immediately determined as:

$$\alpha_2 = 0,\ \alpha_3 = 1/4,\ \alpha_4 = 0,\ \alpha_5 = 1/4.$$

Then, equation (2) is rewritten as:

$$\frac{q_{B.O}/(\rho_v L)}{(\sigma g(\rho_l-\rho_v)/\rho_v^2)^{1/4}} = C\left(\frac{\rho_l}{\rho_v}\right)^{\alpha_1-1/4} \quad (3)$$

where C and α_1 can be determined, for example, so as to accord with the correlation proposed by Kutateladze [1] to give $C = 0.16$ and $\alpha_1 = 1/4$.

Next, let us apply equation (2) to the burnout in the present study. In this case, presuming that μ_v has no effect on $q_{B.O}$ and recalling the empirical fact that equation (1) holds and g has no effect on $q_{B.O}$ (cf. Section 5.1), it yields immediately:

$$\alpha_2 = 0,\ \alpha_3 = 1/3,\ \alpha_4 = 0,\ \alpha_5 = 0.$$

Then equation (2) is rewritten as:

$$\frac{q_{B.O}/(\rho_v L)}{u_e} = C\left(\frac{\rho_l}{\rho_v}\right)^{\alpha_1}\left(\frac{\sigma}{\rho_l u_e^2 D}\right)^{1/3} \quad (4)$$

and the exponent α_1 in equation (4) can be determined so as to combine the two groups of data (water and freon-113) of Figs. 8 and 9 into a single group to give $\alpha_1 = 0.725$. Then, the constant C in equation (4) can be determined from the solid straight line in Fig. 10, correlating the data of Figs. 8 and 9 in the form of equation (4) with $\alpha_1 = 0.725$, to give $C = 7.45 \times 10^{-2}$. As the result, the burnout heat flux for the nucleate boiling with an impinging jet of saturated liquid is

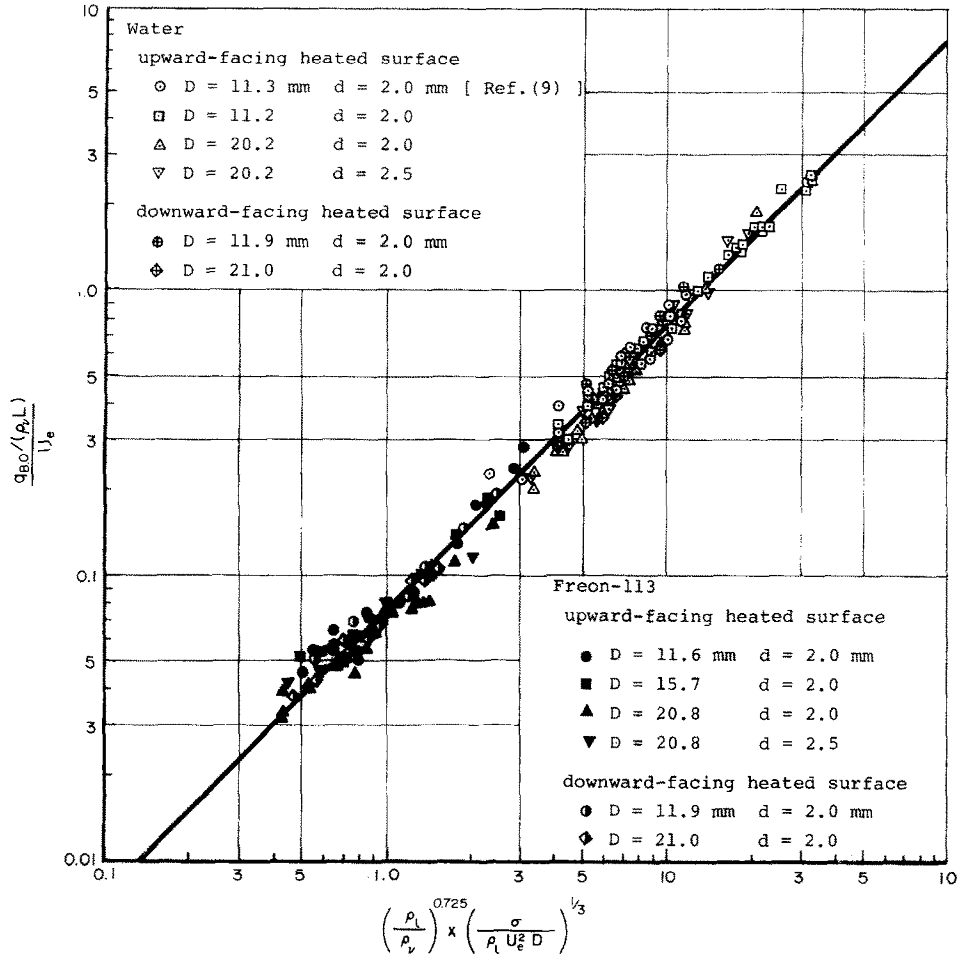

FIG. 10. Nondimensional correlation of burnout heat flux (saturated boiling).

correlated by

$$\frac{q_{B.O}/(\rho_v L)}{u_e} = 7.45 \times 10^{-2}\left(\frac{\rho_l}{\rho_v}\right)^{0.725}\left(\frac{\sigma}{\rho_l \cdot u_e^2 D}\right)^{1/3} \quad (5)$$

keeping such a fine accord with the data as is shown by the heavy solid line in Fig. 10. It should be noted that the burnout is regarded as a phenomenon originated mainly under the effect of the surface tension σ in either case of equations (3) and (5).

5.3 *Appendix*

In connection with the fact that both equations (3) and (4) can be derived from the general equation (2), it may be of use to give the following note. For the conventional heat transfer in a forced flow of single phase in a gravitational field, there are eight quantities concerned (h: heat-transfer coefficient, D: length, λ: thermal conductivity, μ: viscosity, c_p: specific heat, ρ: density, u: velocity of forced flow, $g\rho\beta\Delta T$: difference of specific weight due to thermal expansion) against four fundamental units (mass, length, time, and heat divided by temperature), so that four independent dimensionless groups appear to give the relation:

$$\frac{hD}{\lambda} = C\left(\frac{\mu c_p}{\lambda}\right)^{\alpha_1}\left(\frac{\mu}{\rho u D}\right)^{\alpha_2}\left(\frac{Dg\beta\Delta T}{u^2}\right)^{\alpha_3}. \quad (6)$$

For pure free convection, the exponent of u in equation (6) should vanish, so that $\alpha_2 = -2\alpha_3$, and thereby equation (6) is rewritten as:

$$\frac{hD}{\lambda} = C\left(\frac{\mu c_p}{\lambda}\right)^{\alpha_1}\left(\frac{D^3 g\beta\Delta T}{\nu^2}\right)^{\alpha_3} \quad (7)$$

where ν is the kinematic viscosity. On the other hand, for pure forced convection, the exponent of g in equation (6) should vanish, so that $\alpha_3 = 0$ to give

$$\frac{hD}{\lambda} = C\left(\frac{\mu c_p}{\lambda}\right)^{\alpha_1}\left(\frac{uD}{\nu}\right)^{-\alpha_2}. \quad (8)$$

It is unnecessary to say that either of equations (7) and (8) is a very popular expression in the field of single-phase heat transfer.

6. EFFECT OF LIQUID SUBCOOLING

6.1. *Experimental result*

Experiment of subcooled boiling on the heated surface of 11–21 mm in diameter has been made for the impinging jet of 2 mm in diameter with subcooling ($T_{sat} - T_{liq}$) up to 30°C for water and up to 16°C for freon-113.

As for the heat transfer of nucleate boiling, it is found that when the heat flux q is plotted against $(T_w - T_{sat})$, the data deviate from the saturated nucleate boiling curve in the range of low $(T_w - T_{sat})$, and the deviation increases as the liquid subcooling becomes higher. As $(T_w - T_{sat})$ is raised, however, the effect of subcooling on heat transfer disappears rapidly and the data begin to fall on the saturated nucleate boiling curves shown in Figs. 3 and 4, indicating that $(T_w - T_{sat})$ is the effective driving force for heat transfer. At the same time, the similar behavior of fluid as described in Section 4.1 can be observed, that is, the splash of liquid takes place all over the heated surface except near the impinging zone. Accordingly, it may be presumed that the heated surface is covered with the self-supporting nucleate-boiling liquid layer, while the upper liquid-flow (cf. Fig. 7) is probably subcooled in this case, so that a part of the vapor rising from the underlying boiling layer may be condensed into liquid.

Then, if $(T_w - T_{sat})$ is raised further, it finally results in the onset of burnout. As for the burnout heat flux $q_{B.O}$ in the subcooled boiling, it is found that $q_{B.O}$ increases as the liquid subcooling $(T_{sat} - T_{liq})$ is increased. Besides, what is of more interest is that the relation of equation (1) still holds in the case of subcooled boiling if $(T_{sat} - T_{liq})$ is kept constant.

6.2. *Correlation of burnout heat flux data*

On the basis of equation (5), let us assume the following expression for the burnout in subcooled boiling:

$$\frac{q_{B.O}/(\rho_v L)}{u_e} = 7.45 \times 10^{-2}\left(\frac{\rho_l}{\rho_v}\right)^{0.725} \times \left(\frac{\sigma}{\rho_l u_e^2 D}\right)^{1/3}(1+\varepsilon_{sub}) \quad (9)$$

where ε_{sub} is the correction factor for the effect of liquid subcooling on the burnout heat flux. Of course, ε_{sub} vanishes for the saturated liquid, while ε_{sub} increases as the liquid subcooling is increased.

Now, it may be assumed that the specific heat of liquid c_{pl}, the subcooling of liquid $(T_{sat} - T_{liq})$, and thermal conductivity of liquid λ_l join the six quantities included in equation (9) but $q_{B.O}$, to exert respective effects on ε_{sub}. Dimensional analysis, such as employed in Sections 5.2 and 5.3, can be applied to the above-mentioned nine quantities to give:

$$\varepsilon_{sub} = K\left(\frac{\rho_l}{\rho_v}\right)^m\left[\frac{c_{pl}(T_{sat} - T_{liq})}{L}\right]^n \times \left(\frac{\sigma}{\rho_l u_e^2 D}\right)^r\left[\frac{\lambda_l(T_{sat} - T_{liq})}{\rho_l u_e L D}\right]^s \quad (10)$$

where K is constant. Then, according to the empirical fact described in the preceding section that equation (1) still holds in the subcooled boiling, the exponents of u_e and D should vanish in equation (10) to give $r = s = 0$, so that equation (10) is written as:

$$\varepsilon_{sub} = K\left(\frac{\rho_l}{\rho_v}\right)^m\left[\frac{c_{pl}(T_{sat} - T_{liq})}{L}\right]^n.$$

Then K, m and n in the above expression can be determined from the experimental result as follows:

$$\varepsilon_{sub} = 2.7\left(\frac{\rho_l}{\rho_v}\right)^{0.5}\left[\frac{c_{pl}(T_{sat} - T_{liq})}{L}\right]^{2.0} \quad (11)$$

and Fig. 11 shows the comparison between the experimental data of $q_{B.O}$ in subcooled boiling and the prediction of equation (9) with the correction factor ε_{sub} of equation (11). In addition, Table 1 shows the rate of increase of burnout heat flux $(1+\varepsilon_{sub})$, calculated by equation (11) for the range of subcooling $(T_{sat} - T_{liq})$ experienced in the present study.

Table 1. Rate of increase of burnout heat flux due to liquid subcooling

Water		Freon-113	
$T_{sat} - T_{liq}$ (°C)	$1+\varepsilon_{sub}$	$T_{sat} - T_{liq}$ (°C)	$1+\varepsilon_{sub}$
3	1.004	3	1.015
10	1.038	10	1.159
20	1.151	16	1.407
30	1.341		

Finally, in connection with the form of equation (11), it may be of interest to note that the correction factor ε_{sub} suggested by Ivey and Morris [13] in the case of subcooled pool boiling is of the following form

$$\varepsilon_{sub} = 0.1\left(\frac{\rho_l}{\rho_v}\right)^{3/4}\left[\frac{c_{pl}(T_{sat} - T_{liq})}{L}\right]^{1.0}$$

which is of the form similar to equation (11).

7. CONCLUSIONS

1. Experimental study has been made on the fully-developed nucleate boiling at very high heat fluxes in a forced-convection boiling system, combining a heated disk surface with a steady, cylindrical liquid jet, which is of a small diameter compared with the diameter of heated surface and impinges on the center of the heated surface at a right angle.

2. As for the flow of vapor and liquid in the above-mentioned boiling system, an idealized flow model may be assumed so as to accord with the observations on the heat transfer as well as on the fluid behavior. However, it seems very difficult to explain the onset of burnout by means of such a superficial flow model alone.

3. It has been found that if a conventional, dimensional analysis is applied to the burnout heat flux in a boiling with a forced flow in a gravitational field, it provides a dimensionless, generalized equation capable of correlating the experimental data, not only in the case of the ordinary pool boiling, but also in the case of the present boiling system with an impinging jet. In addition, surface tension is a common factor for originating the burnout, and it suggests a possibility that there may be a common, hydrodynamic principle for the onset of burnout in the two cases above-mentioned, in spite of the quite different model of flow.

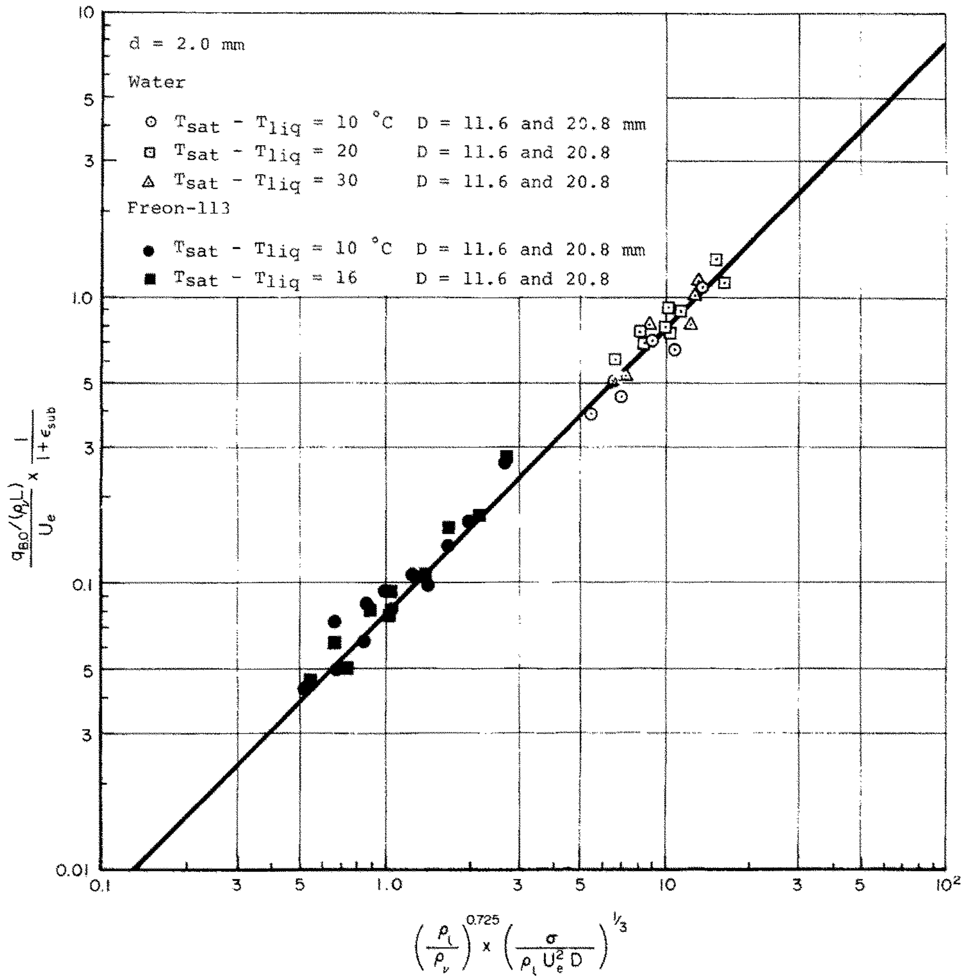

FIG. 11. Nondimensional correlation of burnout heat flux (subcooled boiling).

4. The generalized correlation of the burnout heat flux data in the present boiling system with an impinging jet has been determined as:

$$\frac{q_{B.O}/(\rho_v L)}{u_e} = 7.45 \times 10^{-2} \left(\frac{\rho_l}{\rho_v}\right)^{0.725} \times \left(\frac{\sigma}{\rho_l u_e^2 D}\right)^{1/3} (1+\varepsilon_{sub})$$

where ε_{sub}, the correction factor for liquid subcooling, is given as:

$$\varepsilon_{sub} = 2.7 \left(\frac{\rho_l}{\rho_v}\right)^{0.5} \left[\frac{c_{pl}(T_{sat} - T_{liq})}{L}\right]^{2.0}$$

and the above correlation preserves a fairly good agreement with the experimental data.

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BURNOUT DANS UN SYSTEME BOUILLANT A HAUT FLUX THERMIQUE AVEC UN JET INCIDENT

Résumé—Une étude expérimentale porte sur l'ébullition nucléée pleinement développée à la pression atmosphérique dans un système à ébullition en convection forcée qui consiste en une surface chauffée plane et un petit jet à grande vitesse d'eau ou de fréon 113 frappant la surface. On obtient une formule généralisée, pour le flux de crise, appliquée aussi bien à l'eau qu'au fréeon 113 et on montre que la tension superficielle joue un role important sur la mise en place du phénomène de crise non seulement dans l'ébullition en réservoir ordinaire mais aussi dans le cas présent avec un écoulement forcé.

BURNOUT IN EINEM SIEDESYSTEM HOHER WÄRMESTROMDICHTE MIT EINEM AUFPRALLENDEN STRAHL

Zusammenfassung—Es wurde das voll ausgebildete Blasensieden unter Atmosphärendruck an einem einfachen Siedesystem, das aus einer ebenen Heizfläche und einem, mit hoher Geschwindigkeit aufprallenden, kleinen Wasser- oder R 113-Strahl bestand, experimentell untersucht. Für die Burnout-Wärmestromdichte wird eine allgemeine Beziegung aufgestellt und mit Erfolg auf Wasser und R 113 angewandt. Es wird gezeigt, daß die Oberflächenspannung nicht nur beim gewöhnlichen Behältersieden sondern auch bei dem hier betrachteten Siedesystem mit erzwungener Konvektion von großem Einfluß auf das Einsetzen des Burnout ist.

КРИЗИС КИПЕНИЯ В СИСТЕМЕ С ПАДАЮЩЕЙ СТРУЕЙ ПРИ БОЛЬШОЙ ПЛОТНОСТИ ТЕПЛОВОГО ПОТОКА

Аннотация — Проведено экспериментальное исследование полностью развитого пузырькового кипения при атмосферном давлении и вынужденной конвекции в простой системе, состоящей из нагреваемой плоской поверхности и падающей на неё с большой скоростью струйкой воды или фреона-113. Выведено соотношение, обобщающее данные по критическому тепловому потоку, которое является справедливым как для воды, так и для фреона. Показано, что как и при обычном кипении в большом объеме, поверхностное натяжение оказывает большое влияние на наступление кризиса в рассматриваемой системе с вынужденным течением.