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SHORTER COMMUNICATION

SIMULATION OF POOL BOILING HEAT TRANSFER BY GAS INJECTION AT THE INTERFACE

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NOMENCLATURE

A, a dimensionless constant;
g, gravitational acceleration, ft/h²;
g_0, constant in Newton's Second Law of Motion, $4{\cdot}17 \times 10^8$ lbm ft/lbf h²;
h, heat-transfer coefficient between the heated wall and the bulk liquid, Btu/ft² h degF;
k, thermal conductivity of the liquid, Btu/ft h degF;
K_1, Kutateladze's criterion for the critical heat flux, equation (4);
n, exponent of the Reynolds number in equations (1), (2) and (3);
N_{Nu}, Nusselt number; N_{Pr}, Prandtl number; N_{Re}, Reynolds number — see equations (1) and (2);
p, system pressure, lbf/ft²;
P, dimensionless pressure term in equation (2);
$\dot{q}''$, heat flux measured through a control surface just on the wall side of the solid–fluid interface, Btu/ft² h;
$\dot{q}''_{cr}$, critical heat flux measured as for $\dot{q}''$, Btu/ft² h;
$\dot{V}''$, gas volume injected per unit time and unit area of heating surface or superficial gas-injection velocity, ft³/ft² h or ft/h;
$\dot{V}''_{cr}$, critical superficial gas-injection velocity corresponding to the critical superficial vapour velocity in boiling, ft³/ft² h or ft/h.

Greek symbols

α, thermal diffusivity of the liquid, ft²/h;
λ, latent heat of vaporization of the fluid, Btu/lbm;
γ, kinematic viscosity of the liquid, ft²/h;
ρ_G, density of injected gas, lbm/ft³;
ρ_L, density of liquid (saturated for boiling), lbm/ft³;
ρ_V, density of saturated vapour, lbm/ft³;
σ, surface tension for the liquid–vapour interface, lbf/ft;
σ_{LG}, surface tension for the liquid–gas interface, lbf/ft.

INTRODUCTION

In a recent experimental investigation Gose, Acrivos and Petersen [1] simulated nucleate pool boiling at saturation temperature by bubbling a gas through a heated porous or drilled surface into a pool of liquid the gas being insoluble in the liquid.

We are carrying out similar investigations, measuring both heat- and mass-transfer coefficients with a view to' comparing the results with boiling heat transfer in general, and Kutateladze's [2] theory in particular. In connection with this study we have examined the dat of Gose *et al.* in the light of Kutateladze's theory; wit the results contained in the present note.

The comparison of the experimental results with correlations developed for boiling heat transfer will be made in two parts, closely following Kutateladze's presentation. The first part of the comparison will be made for saturation pool boiling at moderate heat fluxes and pressures; the second part for the critical heat flux (burnout).

In this note the following terms require qualification: "porous" will describe only metal plates manufactured by sintering metal powders; "drilled" will describe only solid metal plates with holes drilled through them; "incipient boiling range" will describe the region where the predominant mechanism of boiling heat transfer changes from free convection to nucleate boiling.

MODERATE HEAT FLUXES

Kutateladze obtained the following dimensionless equation for nucleate pool boiling at saturation temperature:

$$\frac{h}{k}\left[\frac{\sigma g_0}{g(\rho_L - \rho_V)}\right]^{\frac{1}{2}} = A\left(\frac{\gamma}{\alpha}\right)^{0\cdot35} \times \left\{\frac{\dot{q}''}{\lambda\rho_V\gamma}\left[\frac{\sigma g_0}{g(\rho_L - \rho_V)}\right]^{\frac{1}{2}}\right\}^{n}\left\{\frac{p g_0^{\frac{1}{2}}\cdot 10^{-4}}{[\sigma g(\rho_L - \rho_V)]^{\frac{1}{2}}}\right\}^{0\cdot7} \quad (1)$$

where $A = 0{\cdot}44$ and $n = 0{\cdot}7$. It will be noted that the group

$$\left[\frac{\sigma g_0}{g(\rho_L - \rho_V)}\right]^{\frac{1}{2}}$$

has the dimension of length so that the dimensionless group

$$\frac{h}{k}\left[\frac{\sigma g_0}{g(\rho_L - \rho_V)}\right]^{\frac{1}{2}}$$

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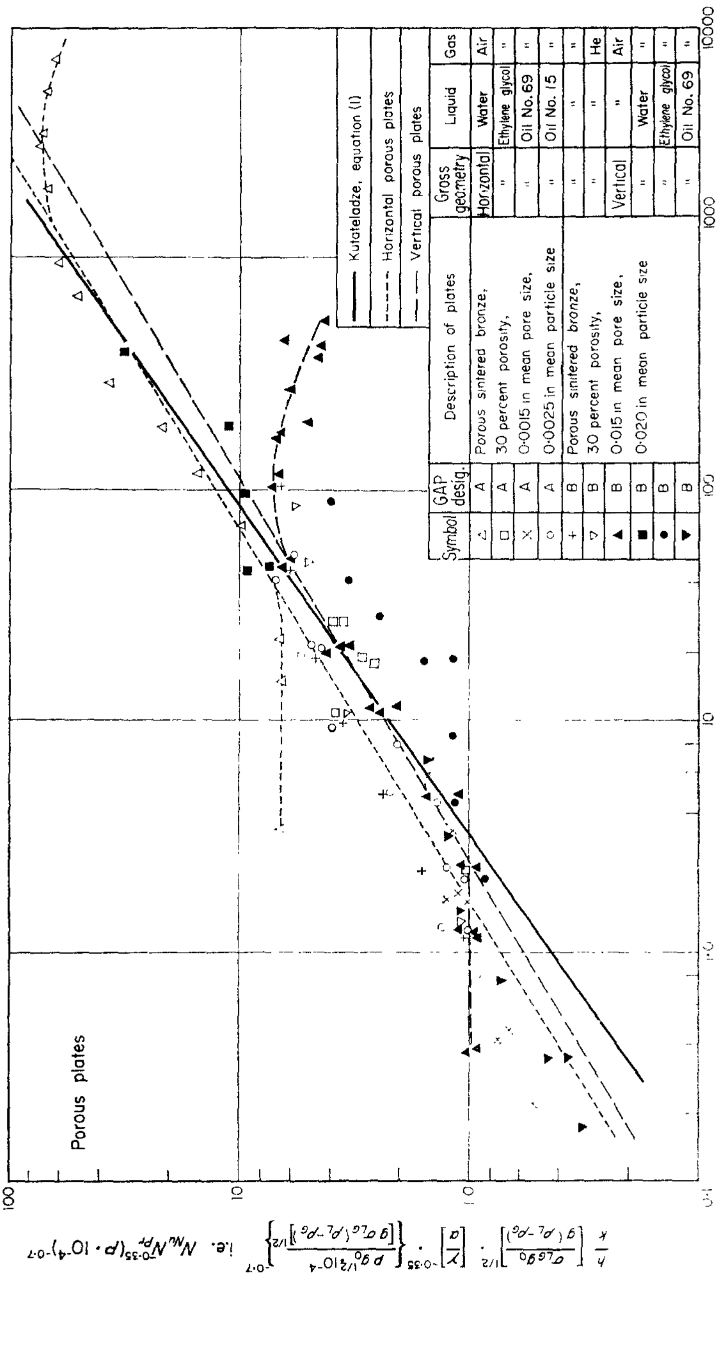

Porous plates
Kutateladze, equation (1)
Horizontal porous plates
Vertical porous plates
Symbol | GAP desig. | Description of plates | Gross geometry | Liquid | Gas
A | Porous sintered bronze, 30 percent porosity, 0·0015 in mean pore size, 0·0025 in mean particle size | Horizontal | Water | Air
A | Ethylene glycol
A | Oil No. 69
A | Oil No. 15
B | Porous sintered bronze, 30 percent porosity, 0·015 in mean pore size, 0·020 in mean particle size | He
B | Vertical | Air
B | Water
B | Ethylene glycol
B | Oil No. 69
i.e. N_{Re}
i.e. $N_{Nu} N_{Pr}^{-0.35} (P \cdot 10^{-4})^{-0.7}$

Fig. 1a.

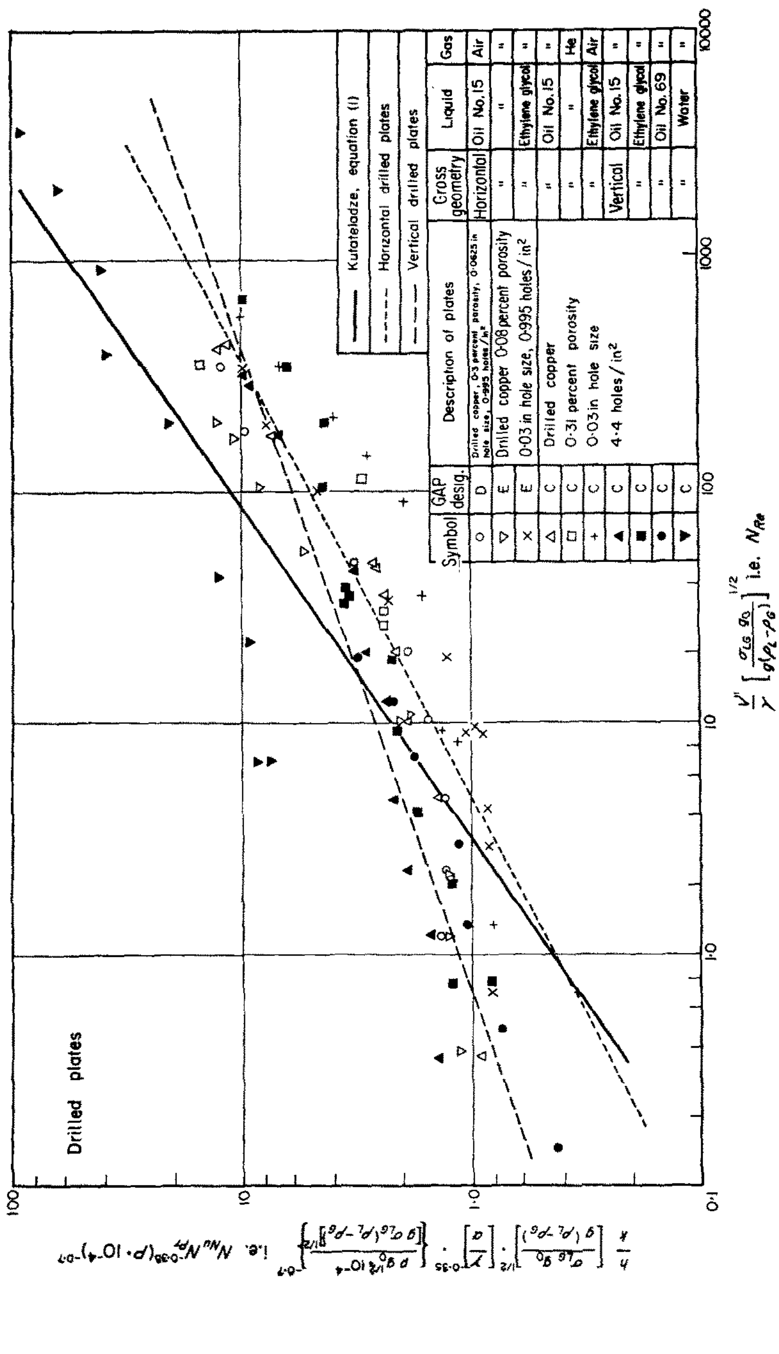

Fig. 1b.

FIG. 1. Gas injection compared to saturation pool boiling at moderate heat fluxes.

is a form of Nusselt number, N_{Nu}, and the dimensionless group

$$\frac{\dot q''}{\lambda \rho_V \gamma}\left[\frac{\sigma g_0}{g(\rho_L - \rho_V)}\right]^{\frac{1}{2}}$$

is a form of Reynolds number, N_{Re}, since the group $\dot q''/\lambda\rho_V$ has the dimensions of velocity. The group γ/a is the usual Prandtl number, N_{Pr}, and the group

$$\frac{p g_0^{\frac{1}{2}}}{[\sigma g(\rho_L - \rho_V)]^{\frac{1}{2}}}$$

is a dimensionless pressure term, P. Equation (1) then, can be rewritten as

$$N_{Nu} = A \cdot N_{Pr}^{0.35} \cdot N_{Re}^{n} \cdot (P \cdot 10^{-4})^{0.7} \tag{2}$$

The group $\dot q''/\lambda\rho_V$ is the volume time rate of vapour production by boiling per unit area of heating surface or the "superficial" vapour velocity; in the gas-injection case it is replaced by the term $\dot V''$, the gas volume injected per unit time and area of heating surface; $\dot V''$ is equal to the "superficial" gas velocity. For the latter case, equation (1) becomes

$$\frac{h}{k}\left[\frac{\sigma_{LG} g_0}{g(\rho_L - \rho_G)}\right]^{\frac{1}{2}} = A\left(\frac{\gamma}{a}\right)^{0.35} \left\{\frac{\dot V''}{\gamma}\left[\frac{\sigma_{LG} g_0}{g(\rho_L - \rho_G)}\right]^{\frac{1}{2}}\right\}^{n}\left\{\frac{p g_0^{\frac{1}{2}} \cdot 10^{-4}}{[\sigma_{LG} g(\rho_L - \rho_G)]^{\frac{1}{2}}}\right\}^{0.7} \tag{3}$$

Equation (3) can also be rewritten as equation (2).

A plot of $N_{Nu} \cdot N_{Pr}^{-0.35} \cdot (P \cdot 10^{-4})^{-0.7}$ vs. N_{Re} is shown in Fig. 1. The various systems of heated surfaces, gross geometry, liquids and gases are given in the key to the symbols. All the tests were performed at atmospheric pressure; the fluid properties were evaluated at the heated surface temperature.

In Figs. 1a and b straight lines have been drawn for the points corresponding to horizontal porous plates, vertical porous plates, horizontal drilled plates and vertical drilled plates. Kutateladze's relationship, equation (1), has also been drawn for the comparison. The values of the constant, A, and the exponent of the Reynolds number, n, appearing in equation (3) were were found from Fig. 1 to be:

	A	n
Porous plates, horizontal,	0·72	0·62
vertical,	0·58	0·60
Drilled plates, horizontal,	0·43	0·53
vertical,	1·14	0·36

Kutateladze used $A = 0.44$ and $n = 0.7$ for nucleate pool boiling at saturation temperature.

Inspection of Fig. 1a shows that Kutateladze's equation for moderate heat fluxes correlates the porous-plate data. On the other hand, it is seen from Fig. 1b that the slopes of the lines for the drilled plates are quite different from that proposed by Kutateladze; there is also considerable scatter of data points.

For the porous plates, the curves of h vs. $\dot V''$ exhibited maxima beyond which h decreased with increasing $\dot V''$. For the drilled plates, no such maxima existed.

In Fig. 1a, the data points in the vicinity of maximum heat-transfer coefficients and beyond them, also these corresponding to the incipient boiling range have not been included. However, the results for the complete range of gas-injection rates for two porous-plate systems have been included in order to illustrate the type of data points rejected, and in particular to illustrate the existence of maximum heat-transfer coefficients. Kutateladze's correlation does not fit, and indeed is not meant to fit, the region corresponding to incipient boiling and the region of maximum heat-transfer coefficients. The complete range of drilled-plate results have been included because the rejection of any data points corresponding to the region of incipient boiling would have not been justified as this region was not well defined; nor did maximum heat-transfer coefficients exist.

The drilled-plate systems are unlike boiling in the existence of very few centres of gas injection (nucleating sites in boiling) and in the constancy of the number of sites throughout the range of injection rates. The absence of maxima in the h vs. $\dot V''$ curves is probably related to this. Gose *et al.* suggest the following tentative explanation "... the velocity of the gas leaving the drilled holes is much greater than the velocity of the gas leaving the pores, and these jets of gas can penetrate the layer of gas tending to form an insulating film near the wall"

CRITICAL HEAT FLUXES

Kutateladze, postulating that the critical heat flux (burnout) is a hydrodynamic phenomenon, derived, by a combination of physical reasoning and dimensional analysis, the following relationship for saturation pool boiling:

$$\frac{\dot q''_{cr}}{\lambda \rho_V^{\frac{1}{2}}[g g_0 \sigma(\rho_L - \rho_V)]^{\frac{1}{4}}} = K_1 = \text{constant} = 0.16 \pm 0.03. \tag{4}$$

The value of the constant was determined from existing experimental data on boiling.

The quantity $\dot q''_{cr}/\lambda\rho_V$ represents the superficial vapour velocity under burnout conditions; in the gas-injection case this group is replaced by $\dot V''_{cr}$, the critical superficial gas velocity. For the latter case, equation (4) becomes

$$\frac{\dot V''_{cr}\,\rho_G^{\frac{1}{2}}}{[g g_0 \sigma_{LG}(\rho_L - \rho_G)]^{\frac{1}{4}}} = K_1. \tag{5}$$

K_1 has been evaluated from the data of Gose *et al.* and the results are shown in Table 1. The values of $\dot V''_{cr}$ used in equation (5) were the superficial gas velocities at which the maximum heat-transfer coefficients occurred.

In Table 1 the values of K_1 are certainly of the correct

Table 1. Kutateladze's critcal heat flux criterion applied to gas injection.

G, A and P plate designation	Gross geometry	Liquid	Injected gas	K_1, equation (4)
A	Horizontal	Water	Air	0·13
A	Horizontal	Shell Tellus oil No. 15	Air	0·14
B	Horizontal	Shell Tellus oil No. 15	Air	0·16
A	Horizontal	Ethylene glycol	Air	0·23
A	Horizontal	Shell Tellus oil No. 69	Air	0·02
B	Vertical	Shell Tellus oil No. 69	Air	0·05
B	Vertical	Water	Air	0·05
B	Vertical	Ethylene glycol	Air	0·10
B	Vertical	Shell Tellus oil No. 15	Air	0·12

NOTE: A description of the porous plates is given in the key to the symbols in Fig. 1.

order of magnitude and three of the values are within the range 0·13–0·19 as determined by Kutateladze. If the effect of heater orientation is taken into account, then the results are even better than they at first appear.

The values of K_1 obtained by Kutateladze were for heaters having a horizontal orientation. Bernath [3], in assessing the effect of heater orientation, found that the critical heat fluxes for heaters with vertical orientation were approximately three-quarters of those for horizontal. The only system tested by Gose *et al.* in the horizontal and vertical positions was that of oil No. 15, air and plate B; K_1 for the vertical position ($K_1 = 0{\cdot}12$) is indeed three-quarters of that for the horizontal position ($K_1 = 0{\cdot}16$). The values of K_1 for the vertical position of heaters could then be expected to fall between $\frac{3}{4}$ (0·13) and $\frac{3}{4}$ (0·19), i.e. between 0·10 and 0·14. Considering the effect of heater orientation, then, three of the five horizontal systems and two of the four vertical systems give values of K_1 within the expected ranges.

However, there were some sources of error in evaluating K_1; for certain systems there was difficulty in assessing the value of $\dot{V}''_{cr}$ because of the lack of data points near the maximum h. This was especially true for the system of vertical plate B, with water and air ($K_1 = 0{\cdot}05$). But, for the system which had the lowest value of K_1 (0·02), the selection of the $\dot{V}''_{cr}$ was comparatively easy as the curve was well defined. This system involved oil No. 69, the most viscous liquid tested, which may account for part of the large discrepancy.

The critical superficial *gas* velocity has been used to correspond to the critical superficial *vapour* velocity. This might have introduced a source of discrepancy since in boiling the superficial vapour velocities at the maximum heat-transfer coefficient and at the critical heat flux are not necessarily the same.

CONCLUSIONS

Kutateladze's relationships for moderate heat fluxes and for the critical heat flux correlate satisfactorily the porous-plate results of Gose, Acrivos and Petersen. Porous-plate systems therefore appear to simulate nucleate pool boiling at saturation temperature.

The results of Gose, Acrivos and Petersen for the drilled plates are not correlated by Kutateladze's relationship for moderate heat fluxes and no phenomenon corresponding to the critical heat flux in boiling occurred. Thus, as a simulation of boiling, the use of drilled plates is not satisfactory.

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