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BOILING FROM A MERCURY SURFACE

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Abstract—An investigation has been made of nucleate boiling of liquids (water, alcohol) from a smooth quiet horizontal mercury surface. Measurements were made of heat flux and superheating and the heat-transfer coefficient has been found. The results have been correlated with the physical parameters of the boiling liquid by:

$$Nu = 1{\cdot}90 \times 10^{-4} \times Pr^{-0{\cdot}35} \times Pe^{0{\cdot}81} \times Kp^{0{\cdot}7} \qquad (4)$$

The formation and development of vapour bubbles were recorded by a high-speed cine-camera (6000 frames/s), see Fig. 1, and these results are discussed.

NOMENCLATURE

a,	thermal diffusivity [m^2/h];
C,	specific heat of the liquid at constant pressure [kcal/kg degC];
P_s,	saturation pressure [kg/m^2];
q,	heat-flux density [kcal/m^{2}h];
r_s,	latent heat of vaporization [kcal/kg];
T_s,	absolute saturation temperature [°K];
t_s,	saturation temperature [°C];
t_p,	temperature of the heating surface [°C];
$\Delta t = t_p - t_s$,	liquid superheat temperature difference [degC];
α,	heat-transfer coefficient [kcal/m^{2}h degC];
γ,	specific weight of the liquid [kg/m^3];
γ',	specific weight of the vapour [kg/m^3];
λ,	thermal conductivity of the liquid [kcal/m h degC];
μ,	viscosity of the liquid [kg/m h].
ν,	kinematic viscosity of the liquid [m^2/h];
σ,	surface tension [kg/m];

INTRODUCTION

BOILING from a liquid surface is of interest from the point of view of the investigation of boiling phenomena under ideal conditions. A liquid surface from which another liquid boils is extremely smooth and it can be kept clean during heat-transfer processes, thus enabling the observation of the phenomena in conditions approaching the ideal. Boiling from liquid surfaces may also be of interest for the construction of apparatus for heat exchange. The investigation was made to study nucleate boiling from an extremely smooth surface and to determine the heat-transfer coefficient. To correlate the results with physical parameters of the boiling liquid, investigations of the nucleation of water and ethyl alcohol were carried out.

The problem of heat transfer between immiscible liquids has been little studied, especially in the case of one liquid boiling. Trefethen [1] has studied nucleation from the interface of two liquid phases, but he did not measure heat fluxes and heat-transfer coefficients. K. F. Gordon *et al.* [2] measured heat transfer between a mercury surface and boiling water, methyl and ethyl alcohol. They found that for a superheated mercury surface with $\Delta t = 7$–103°F one obtains a heat flux $q = 1500$–$110\,000$ Btu/ft^{2}h and the heat-transfer coefficient $\alpha = 200$–1800 Btu/ft^{2}h degF. Their results can be expressed by

$$q = C\Delta t^n$$

where n is constant for water ($n = 1{\cdot}43$) and ethyl alcohol ($n = 1$), while it decreases for methyl alcohol from $n = 2{\cdot}2$ to $n = 1$. The study of the same problem of boiling heat transfer from a liquid interface was started some time ago in this laboratory but reproducible results could not be obtained because of experimental difficulties (contamination of mercury and boiling from the walls of the vessel) which have now been overcome. Since this mode of heat transfer can be widely applied for improving heat apparatus and for the analysis of nucleation phenomena which are not sufficiently well understood it should be studied in detail.

2. EXPERIMENTAL TECHNIQUE

The experimental vessel (Fig. 2) consisted of a glass cylinder connected to a steel bottom by means of a rubber ring. The connexion was made at a relatively cold place and the mercury was isolated from the rubber, by a water layer. The vessel was covered with a stainless steel top with an opening for air, an opening for water and mercury, and a travelling thermocouple. The top of the cylinder was provided with a tube for conducting vapour.

The thin layer above the convex middle part of the bottom was heated by an electric heater. The vapour produced was conducted by a pipe which reached a few millimeters above the mercury. Thus, boiling from the surface of the vessel (glass cylinder) was avoided because it was kept at a temperature below the boiling point. The influence of the ends was also avoided by extracting vapour from the central part only. (The tube for conducting vapour had a smaller diameter than the heater.)

In the mercury layer, temperatures were measured with a chromel–mercury travelling thermocouple. A single 0·3 mm diameter chromel wire was inserted into a capillary tube with a 1 mm outer diameter so that only 0·5 mm of the end of the wire was free. The position of this tube, which projected horizontally into the mercury layer, could be adjusted by a micrometer screw so that vertical temperature traverses could be made. The layer of mercury in contact with chromel served as the other thermocouple metal. Mercury in a P.V.C. hose was led from the vessel to the cold junction where a mercury–chromel contact was made and kept in melting ice. Thermocouple e.m.f.'s were measured by the zero method.

Pure mercury distilled in a special apparatus before the experiment, was poured into the experimental apparatus. From the distillation apparatus the mercury was conducted through water so that it did not absorb air. The mercury

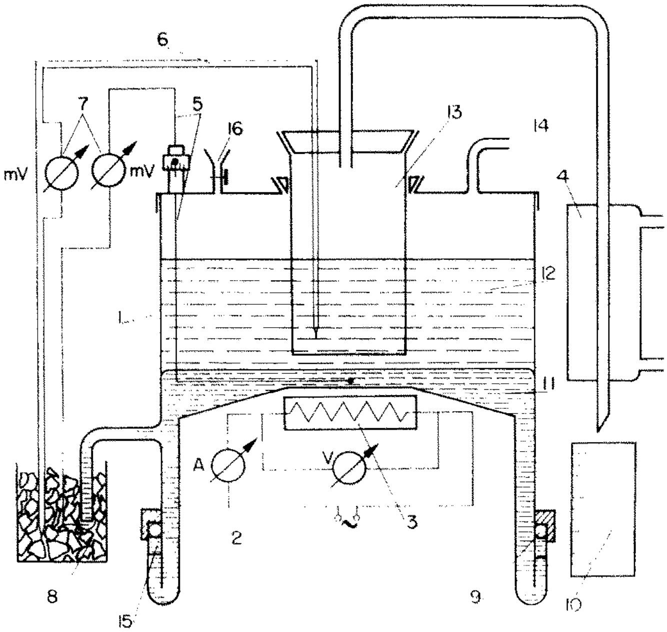

Fig. 2. Experimental apparatus.

1. Glass cylinder (boiling vessel); 2. stainless steel bottom of vessel; 3. heater; 4. condenser; 5. chromel–mercury thermocouple; 6. copper–constantan thermocouple; 7. instruments for measuring e.m.f.; 8. vessel with ice (cold point); 9. rubber ring; 10. vessel for taking the condensate; 11. mercury; 12. boiling water; 13. tube for conducting vapour; 14. opening for air; 15. water layer; 16. opening for water and mercury.

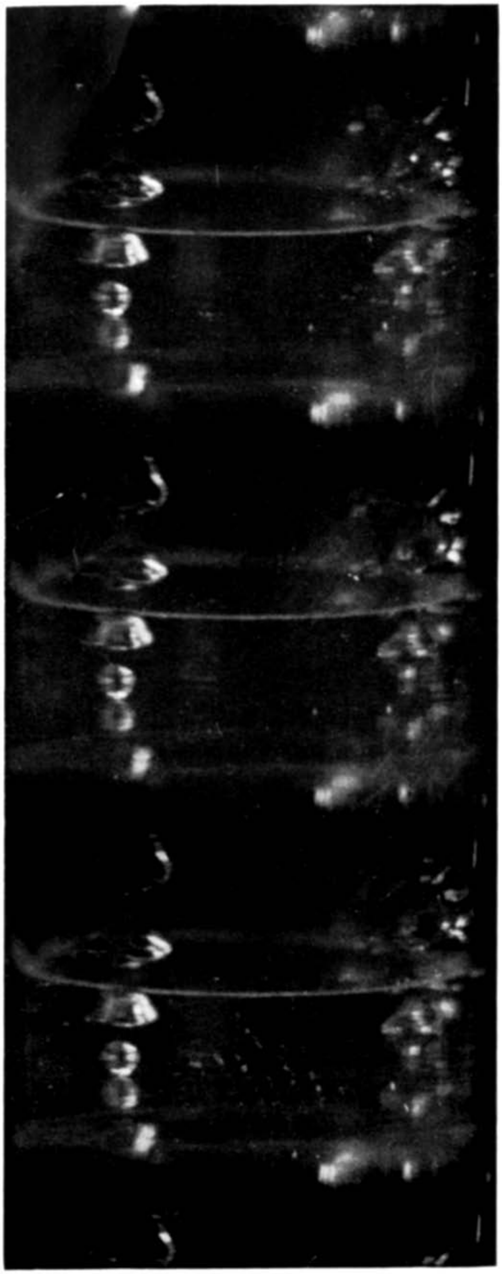

FIG. 1. The formation and development of vapour bubbles—some frames from the high-speed cine-camera film.

layer above the central convex part of the bottom was about 3–7 mm thick. Water or ethyl alcohol was poured over the mercury. Double distilled water was boiled immediately before the experiment to eliminate air.

In the first experiments with mercury in a glass tube, boiling started at the convex meniscus where the glass cylinder broke the mercury surface, and at the place where the thermocouple penetrated into the mercury.

In the final apparatus this difficulty was avoided by heating only the central part of mercury while the thermocouple penetrated the mercury surface outside the test region.

To reduce heat losses, thinner mercury layers were used. This was also useful for more precise temperature determinations of the heating surface by extrapolation because of the reduced convection within the thin mercury layer. However the mercury layer would break if it were thinner than a certain value. The mean thickness of the mercury layer which was stable was about 6 mm for water and about 3 mm for alcohol. The thickness increased with an increase of heat flux.

Measurements were made with water or with ethyl alcohol boiling from the mercury to the other liquid surface at atmospheric pressure. With water the heat flux varied from $q = 2{\cdot}5 \times 10^4$ kcal/m^{2}h to $q = 1{\cdot}08 \times 10^5$ kcal/m^{2}h. In this case the superheating of the heating surface obtained ranged from $\Delta t = 13{\cdot}5\,^\circ\mathrm{C}$ to $\Delta t = 23\,^\circ\mathrm{C}$ and the heat-transfer coefficient from $\alpha = 1{\cdot}9 \times 10^3$ kcal/m^{2}h degC to $\alpha = 4{\cdot}7 \times 10^4$ kcal/m^{2}h degC.

With boiling alcohol the heat flux varied from $q = 5 \times 10^3$ kcal/m^{2}h to $q = 6 \times 10^4$ kcal/m^2, the superheating obtained ranged from $\Delta t = 26\,^\circ\mathrm{C}$ to $\Delta t = 44\,^\circ\mathrm{C}$, and the heat-transfer coefficients from $\alpha = 5 \times 10^2$ kcal/m^{2}h degC to $\alpha = 1{\cdot}26 \times 10^3$ kcal/m^{2}h degC. No measurements were made at smaller heat fluxes because of the difficulty of getting the system into a stationary state. No measurements were made at higher heat fluxes because the strong boiling prevented exact temperature measurement in the mercury layer.

For experiments with water the boiling heat flux was determined by measuring the condensate at set time intervals and was calculated on the basis of the test surface covered by a glass pipe opening ($A = 10$ cm^2). The temperature of the heating mercury surface was determined by extrapolating the temperature distributions measured in the mercury layer.

For boiling of alcohol the heat flux was determined by measuring the temperature gradient in the mercury layer.

The heat-transfer coefficient α (kcal/m^{2}h degC) was computed as the ratio of heat flux to driving temperature difference (or superheating) Δt (degC) which was defined as the difference between the mercury surface and saturation temperatures.

3. THE EXPERIMENTAL RESULTS AND OBSERVATION

Results of the measurements for water are presented in Fig. 3 as the dependence of heat flux on surface superheating.

In the graph one can easily discern two boiling regions similar to those with solid surfaces, one in which the ratio $\mathrm{d}q/\mathrm{d}(\Delta t)$ is small so that it can

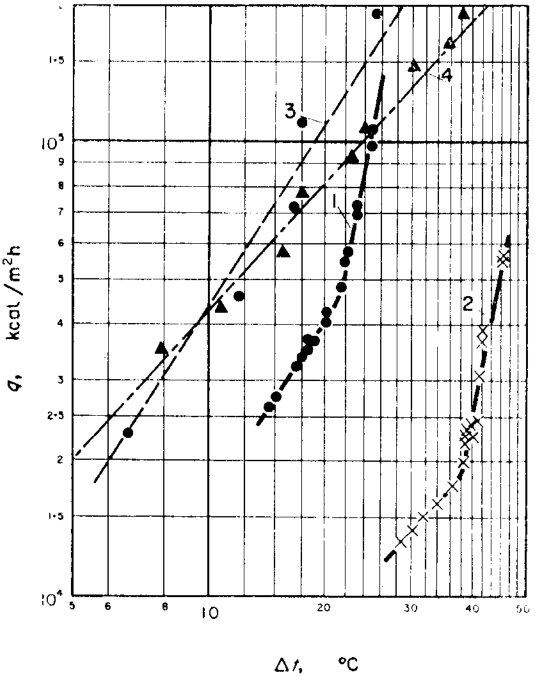

FIG. 3. Dependence of the heat flux on heating.

1. Results for water (Novaković and Stefanović);
2. results for alcohol (Novaković and Stefanović);
3. results for water (Gordon *et al.*); 4. results for alcohol (Gordon *et al.*).

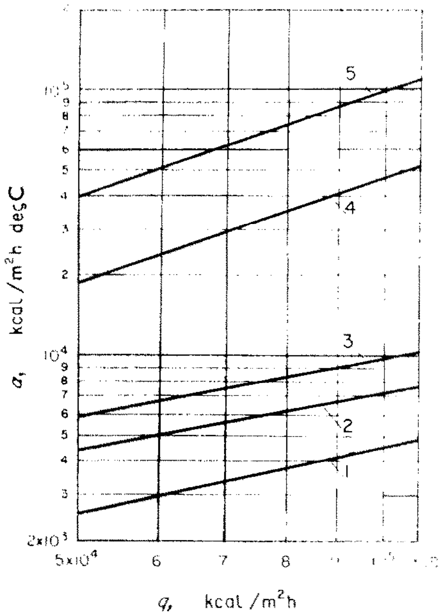

FIG. 4(a). Correlation for boiling of water.
1. Boiling from the mercury surface (Novaković and Stefanović); 2. Kutateladze's correlations; 3. Kruzhilin's correlation; 4. Rohsenow's correlation for boiling from brass; 5. Rohsenow's correlation for boiling from platinum.

be considered as convective boiling, the other with a much higher gradient corresponding to developed bubble boiling. The slopes of the lines for both water and alcohol are the same in both conditions. The broken lines on the graph show the results of Gordon *et al.* [2]. It can be seen that, in the experimental range of this investigation, higher superheating was obtained for the same heat flux.

It is of interest to note that the broken lines showing Gordon's results [2] have the same slope as the lines representing convection boiling in our experimental results.

It is evident from the graph that the results for bubble boiling show a linear dependence on a log–log graph, i.e. they have the form

$$\alpha = Cq^{n} \tag{1}$$

A similar dependence can be obtained for other pairs of parameters (q, Δt and α, Δt). From the experimental results, using the method of least squares, the following values for the constants in equation (1) are obtained: $n = 0{\cdot}81$ for both water and alcohol; $C = 0{\cdot}395$ for water and $C = 0{\cdot}189$ for alcohol, if α is in kcal/m²h degC and q in kcal/m²h.

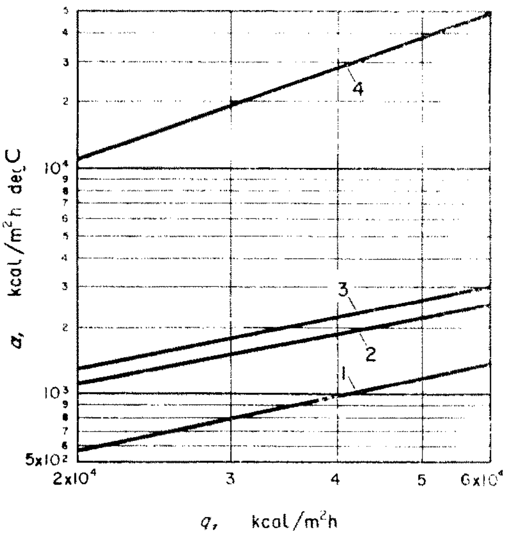

FIG. 4(b). Correlation for boiling of alcohol.
1. Boiling from the mercury surface (Novaković and Stefanović); 2. Kutateladze's correlation; 3. Kruzhilin's correlation; 4. Rohsenow's correlation for boiling from chromium.

The graphs in Figs. 4(a) and 4(b) show our experimental relations and those based on Kutateladze's [3], Kruzhilin's* [3, 4] and Rohsenow's† [5] well-known boiling equations.

It is clear that Kutateladze's equation of the form

$$Nu = A\,Pr^{n_1} \times Pe^{n_2} \times Kp^{n_3}\ddagger \tag{2}$$

correlates our results best for both fluids.

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* Kruzhilin's equation

$$Nu = 0{\cdot}082\,Pr^{0{\cdot}5}\,Pe^{0{\cdot}7}\,Kt^{0{\cdot}377}$$

† Rohsenow's equation

$$\frac{c\,(t_p - t_s)}{r_s} = c_1\left[\frac{q}{\mu\,r_s}\sqrt{\left(\frac{\sigma}{\gamma - \gamma'}\right)}\right]^{0{\cdot}35} Pr^{1{\cdot}7}$$

$$\text{or } Nu = C_1\,Pr^{1{\cdot}35}\,Pe^{1{\cdot}35}$$

‡ Nusselt's number:

$$Nu = \alpha\sqrt{[\sigma/(\gamma - \gamma')]}/\lambda$$

Peclet's number:

$$Pe = q\sqrt{[\sigma/(\gamma - \gamma')]}/r_s\gamma' a$$

Kutateladze's number:

$$Kp = P_s/\sqrt{[\sigma/(\gamma - \gamma')]}$$

Kruzhilin's number:

$$Kt = (r_s\gamma)'^2/ACT_s\gamma\sqrt{[\sigma/(\gamma - \gamma')]}$$

The graph in Fig. 5 shows our experimental results in dimensionless forms and the dependences obtained on the basis of Kutateladze's equation

$$Nu = 7 \times 10^{-4} \times Pr^{-0{\cdot}35} \times Pe^{0{\cdot}7} \times Kp^{0{\cdot}7} \quad (3)$$

Kutateladze's curve is less steep than ours but it gives somewhat higher values for heat-transfer coefficients in the range investigated. From Fig. 5 we note that although the results for water and alcohol give the same slope the values of Nusselt numbers for water and alcohol differ by about 6 per cent. Since we worked with two fluids only we could not attempt a correction of exponents n_1 and n_3 which would reconcile these discrepancies. In agreement with experiments for both fluids the exponent n_2 was chosen as $n_2 = 0{\cdot}81$, so that our dependence has the following form:

$$Nu = 1{\cdot}90 \times 10^{-4} \times Pr^{-0{\cdot}35} \times Pe^{0{\cdot}81} \times Kp^{0{\cdot}7} \quad (4)$$

for both water and alcohol.

Photographs of the appearance and development of bubbles were taken with a high-speed cine-camera (6000 frames/s) for heat fluxes ranging from 25×10^3 to 50×10^3 (kcal/m^{2}h).

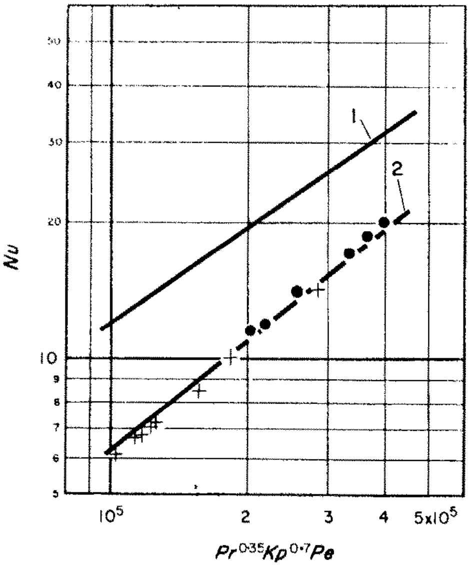

FIG. 5. Dimensionless correlations for boiling.
● Experimental results for water (Novaković and Stefanović); + Experimental results for alcohol (Novaković and Stefanović); 1. Kutateladze's dependence; 2. correlation (Novaković and Stefanović) [equation (4)].

From visual and photographic study it was observed that nucleation took place at preferred points called nucleation centres, from which bubbles were released at almost regular intervals similar to those from solid surfaces. Unlike boiling from solid surfaces, nucleation centres are mobile and they move irregularly.

Since the analysis of the films is still in progress, only some preliminary observations can be given. The film proves some observations reported earlier; it can be seen that the number of nucleation centres increases with heat flux, as was already known for the boiling from solid surfaces. But even at constant flux, new centres

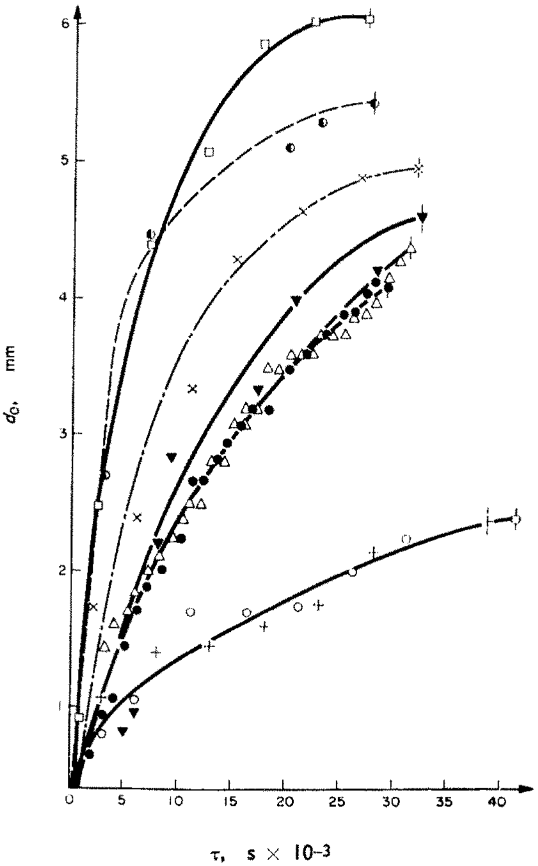

FIG. 6. Diagram of bubble growth. (The moments of departure of a bubble from the heating surface are marked by vertical lines for eight individual bubbles.)

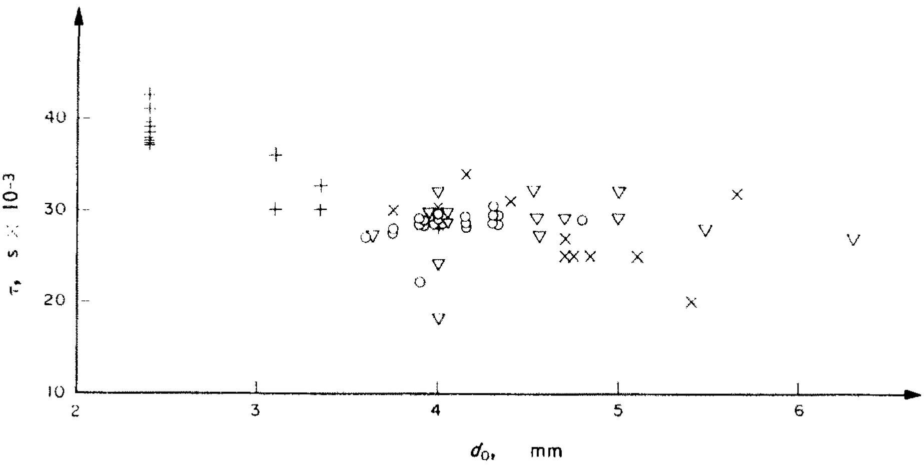

FIG. 7. The time during which bubbles remain on the heating surface as a function of the bubble diameter at the moment of breaking off, + 9 ≈ 25 × 10^3 kcal/m^2h; ○ 9 ≈ 30 × 10^3 kcal/m^2h; × 9 ≈ 40 × 10^3 kcal/m^2h; ▽ 9 ≈ 50 × 10^3 kcal/m^2h.

are formed by sudden explosion of a new bubble followed by characteristic crackling. This bubble grew much faster and when it escaped its size was bigger than that of the bubbles appearing at a centre already formed. Below the centre a very slight concavity of the mercury was observed.

Figure 6 presents the results for the development of several typical bubbles. It is apparent that the diameter of the bubble increases with time and that, with an increasing flux, the development rate of the bubble also increases.

Figure 7 shows the time for which bubbles remain on the heating surface τ_0 as a function of the diameter of the bubble at separation d_0 for various fluxes. For our values of the heat flux and boiling conditions the values lie within the range 2 mm $< d_0 <$ 6 mm, 50 $s^{-3} > \tau_0 >$ 20 s^{-3}. The graph also illustrates that, with increasing flux, the time τ_0 for which bubbles remain on the surface is shortened while d_0 increases. Thus, bubbles escaping with a larger diameter d_0 remained a shorter time on the heating surface, i.e. their τ_0 was shorter. These results are not in agreement with observations of Fritz, Ende and Jakob for solid surfaces. This can be explained by different physical conditions of the boiling (a considerably higher superheating of the heating surface for the same heat fluxes).

4. CONCLUSION

The results of the measurement are very reproducible and conclusive. The scattering of results is slight because of improved and accurate measuring techniques and careful avoidance of secondary effects. There is considerable disagreement between the results of our investigations and those of Gordon *et al.* [2]. In our opinion the disagreement originates in the experimental conditions. Our results concern only boiling heat transfer from a liquid interface, i.e. from a mercury surface, not heat transfer in a complex system consisting of liquid to liquid interfaces and liquid to solid interfaces (such as between the fluids and vessel). We think that nucleation from the edge of liquid interface—(the convex meniscus to solid surface contact) and nucleation at the thermocouple penetration through mercury–water interface in Gordon *et al.*'s experiment caused lower superheatings of their interface as reported. We have found that penetration of mercury surface of a thermocouple in the test region caused an increase in measured heat flux up to 200 per cent (due to redistribution of heat flux) with a simultaneous decrease in surface temperature of several degrees centigrade.

In our opinion this method of heat transfer is of much interest and our work has only touched on this problem. Further work on this is in progress in our laboratory.

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Résumé—Une recherche sur l'ébullition par germes des liquides (eau, alcool) à partir d'une surface de mercure horizontale lisse et au repos a été faite. On a fait des mesures de flux de chaleur et de surchauffe et on a trouvé le coefficient de transport de chaleur. On a corrélé les résultats avec les paramètres physiques du liquide en ébullition à l'aide de:

$$Nu = 1{,}90 \times 10^{-4} \times Pr^{-0{,}35} \times Pe^{0{,}81} \times Kp^{0{,}7} \tag{4}$$

La formation et le développement des bulles de vapeur furent enregistrés par une caméra à grande vitesse (6000 images par seconde), voir Fig. 1, et ces résultats sont discutés.

Zusammenfassung—Das Blasensieden von Flüssigkeiten (Wasser, Alkohol) an einer waagerechten, glatten, unbewegten Quecksilberoberfläche wurde untersucht. Gemessen wurden Wärmestrom und Überhitzung; der Wärmeübergangskoeffizient liess sich daraus berechnen. Die Ergebnisse können mit den physikalischen Parametern der siedenden Flüssigkeit nach

$$Nu = 1{,}90 \times 10^{-4} \times Pr^{-0{,}35} \times Pe^{0{,}81} \times Kp^{0{,}7} \tag{4}$$

wiedergegeben werden.

Die Bildung und das Anwachsen der Dampfblasen wurde mit einer Hochgeschwindigkeitskamera (6000 Bilder/Sekunde) registriert, siehe Fig. 1; diese Ergebnisse werden diskutiert.

Аннотация—Проведено исследование пузырькового кипения жидкостей (воды, спирта) с гладкой горизонтальной поверхности ртути. Проводились измерения теплового потока и перегрева, а также определен коэффициент теплообмена. Результаты связываются с физическими параметрами кипящей жидкости следующим соотношением:

$$Nu = 1{,}90 \times 10^{-4} \times Pr^{-0{,}35} \times Pe^{0{,}81} \times Kp^{0{,}7} \tag{4}$$

Образование и развитие пузырьков пара регистрировалось высокоскоростной кинокамерой (6000 кадров/сек) (см. Рис. 1). Обсуждаются полученные результаты.