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HEAT TRANSFER IN SIMULATED BOILING

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Abstract—An experimental study was undertaken to determine the variations of heat-transfer coefficient on a submerged heating surface while air bubbles were injected into the liquid through an orifice in the plate. The results indicated that heat transfer is most intensive during the time that the bubble detaches from the surface. This casts doubts on boiling heat-transfer correlations based on bubble growth or rising phase considerations. In conclusion, it is suggested that the "agitation" and "latent heat" views of boiling heat transfer may be combined in a unified model.

NOMENCLATURE

a, half width of film [cm];
C_p, heat capacity of plate [cal/gdegC];
h, heat-transfer coefficient [cal/cm^2 s degC];
k, heat conductivity of plate [cal/cms degC];
l, distance from bubble site [cm];
q, heat generated in film [cal/cm^2 s];
t, time [s];
T, temperature [degC];
x, distance from film into plate [cm];
y, horizontal distance from film center line [cm].

Greek symbols

α, plate thermal diffusivity [cm^2/s];
β, dimensionless constant ($=2ah/k$);
η, $= h_0\sqrt{(k\rho C_p)}$ [s$^{-\frac{1}{2}}$];
θ, average film temperature [degC];
ρ, plate density [g/cm^3];
$\tilde{v}$, fluctuating component of v;
v_0, steady-state value of v;
v^*, Laplace transform of v, i.e. $v^*(s) = \int_0^\infty v(t) \exp(-st)\, dt$.

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INTRODUCTION

THE PHENOMENON of nucleate boiling derives its importance to the engineer from the extremely high heat-transfer rates to which it gives rise. There exists widespread disagreement, however, on exactly how boiling promotes heat transfer. Many authors have assumed that agitation of the liquid by the bubbles was the cause. Forster and Zuber [1] and Ruckenstein [2] regard the bubble growth phase as the controlling factor, whereas Rohsenow and Clark [3], Nishikawa [4], and Tien [5] credit the rising bubble. Recently, Moore and Mesler [6] and Bankoff [7] have questioned the whole agitation theory, and proposed a latent heat transport mechanism in its place.

The reasons for this confused state of the art are to be sought in the complexity and reciprocity of the dependence of bubble evolution and heat-transfer rate on each other. Heat must be supplied to the bubble to enable it to go through its life cycle; conversely, while going through its life cycle, the bubble promotes heat transfer. It was felt that clarification might be achieved if these dependencies could be severed in one direction—thus enabling one to study more freely the dependence in the other direction.

By substituting inert gas bubbles (injected through orifices in the heating surface) for bubbles produced in boiling, the dependence of bubble growth on heat transfer is eliminated.

There have been previous attempts to simulate boiling by means of other bubble-producing methods. Peterson [8] formed bubbles by the escape of a gas from solution; Mixon *et al.* [9] by electrolysis; Yamagata *et al.* [10] by bubbling air through an orifice; Gose *et al.* [11] by bubbling air through porous and drilled surfaces. In each case, the heat-transfer coefficient from a heated solid surface to a pool of liquid was measured under a variety of bubbling conditions. The data of Gose were correlated by Sims *et al.* [12] and shown to correspond closely with boiling data in the case of porous plates, and within an order of magnitude for drilled plates. Thus, although experiments on injected air bubbles do not in fact constitute boiling, conclusions drawn from them are likely to shed some light at least on the isolated-bubble regime in boiling.

The plan of the present investigation was to determine the effect of a bubble train on heat transfer as a function of both time and distance from the orifice.

EXPERIMENTAL

The core of the apparatus consisted of an 8-in square epoxy resin plate. Orifices of increasing diameter were successively drilled through the center of the plate. At various distances from the center, very thin films were deposited by condensation of nickel vapors on the surface of the plate (Fig. 1). Each film was approximately 0·25-mm wide and 2·5-mm long, and had an electrical resistance of between 1000 and 2000 Ω. For each film, a pair of gold electrodes was also deposited on the plate. These possessed negligible resistance, and permitted electrical contacts to be made with the films.

Each film, when a voltage was applied to it, served two purposes: (1) it acted as a surface heater; and (2) it acted as a resistance thermometer to measure the surface temperature. The use of such films as resistance thermometers has been described by Simpson and Winding [13] and Lummis [14].

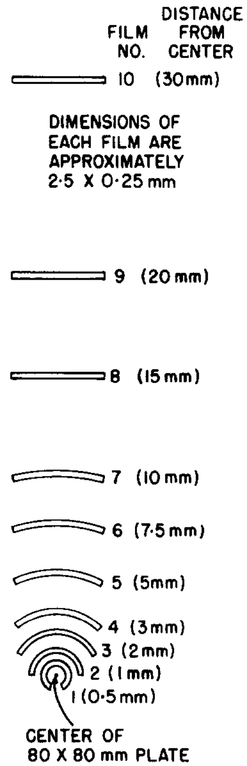

FIG. 1. Layout of thin film resistors.

The experimental procedure was as follows: the plate was horizontally immersed in hexane† at about 25°C. Air, previously saturated with hexane vapor at the same temperature, was introduced into a chamber below the orifice, causing bubbles to rise from the orifice. The films were connected to sources of current, and signals proportional to their resistance fluctuations were simultaneously recorded on a multichannel tape recorder. At the same time, each film's average resistance was measured by means of a Wheatstone bridge. Recordings were made for bubble frequencies between 1 and 20 bubbles/s, and for orifice diameters between 0·37 and 1·5 mm. The analog signals recorded on the tape were then sampled at 1-msec intervals and converted to digital form.

† Water could not be used because its relatively high electrical conductivity would have interfered with film resistance measurements.

DATA ANALYSIS

Since film resistance varied linearly with temperature, the surface temperatures of each film were readily calculable from the recorded signals at the 1-msec sampling intervals. The heat-transfer coefficients, however, could not be calculated simply from the defining formula $h = q/\Delta T$, for two reasons: (1) a significant fraction of the heat generated in each film was not transferred directly to the liquid, but was first conducted into the plate, and then to the liquid at points lying outside the area of the film. (2) When h underwent fluctuations, the plate acted as a heat reservoir which served to attenuate the temperature fluctuations. It is shown in the Appendix that the following relationships apply between the mean film surface temperature θ_0, the mean heat-transfer coefficient h_0, and the time varying components $\tilde{\theta}(t)$ and $\tilde{h}(t)$:

$$\theta_0 = \frac{4qa}{\pi k}\int_0^\infty \frac{1 - \cos \Psi}{\Psi^2(\Psi + \beta)}\,d\Psi \tag{1}$$

$$\tilde{\theta}^*(s) = \left[-\frac{2q\beta^2}{\pi h_0^2}\int_0^\infty \frac{1 - \cos \Psi}{\Psi^2(\beta + \Psi)(\beta + \sqrt{\Psi^2 + (\beta^2 s/\eta^2)})}\,d\Psi\right] h^*(s) \tag{2}$$

where $\tilde{\theta}^*(s)$ and $h^*(s)$ are the Laplace transforms of $\tilde{\theta}(t)$ and $h(t)$, respectively, q is the heat generated in the film per unit area, a is half the width of the film, k is the thermal conductivity of the plate, $\beta = 2ah_0/k$ (a dimensionless parameter), and $n = h_0/\sqrt{(k\rho C_p)}$, with ρ and C_p the density and heat capacity of the plate, respectively.

The assumptions made in deriving these formulae are the following:

(1) Fourier's law applies in the plate.
(2) The film is infinitely long relative to its width, is deposited on an infinitely wide and thick plate, and is infinitesimally thick.
(3) A constant value of h prevails at any moment over the entire area of the film.
(4) The films do not interfere with each other.
(5) The term $\tilde{h}\tilde{\theta}$ is negligible compared to $h\theta + h\tilde{\theta}$.

The error created by assumption (5) has been estimated to be within 10 per cent of the peak value of h.

Equation (2) and assumption (5) may be regarded as defining a linearized "system" whose input is $\tilde{h}(t)$, whose output is $\tilde{\theta}(t)$, and whose transfer function is given by the term in square brackets in equation (2). Since the output $\tilde{\theta}(t)$ is known from the recorded data, and the transfer function can be readily evaluated, it is possible to compute the input $\tilde{h}(t)$. The details of the computation are given by Bard [15].

RESULTS

Figures 2, 3, and 4 represent typical time histories of the heat-transfer coefficient h at various distances from the orifices during those portions of the bubble cycles in which fluctuations occur. In Fig. 5, the h curves at a given distance from the orifice are plotted for various bubble frequencies. The following description summarizes the observed phenomena.

(1) During each bubble cycle, a fairly reproducible signal is generated by each film. This signal indicates a drop in surface temperature, i.e. an increase relative to the steady state value in the heat-transfer coefficient.
(2) Both the onset and termination of most signals are sudden.
(3) In many cases, one or two violent fluctuations occur between signal start and termination.
(4) The signal starts and terminates simultaneously (to within a few milliseconds) at all distances from the orifice, and its general shape varies little from film to film.

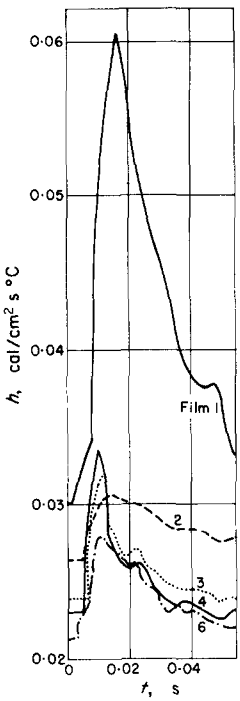

FIG. 2. Variation of h at 5·8 bubbles/s; orifice diameter 0·374 mm.

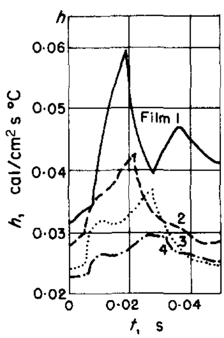

FIG. 3. Variation of h at 4·5 bubbles/s; orifice diameter 0·719 mm.

(5) The intensity of the signal decreases as distance l from the orifice increases. The increase in the average value of h over the steady-state value is roughly proportional to l^{-1}, whereas the peak value of h decreases as $l^{-\frac{1}{2}}$. The signal is observable even at $l =$ 30 mm, but is negligibly small for $l > 10$ mm.

(6) The duration of each signal is relatively unaffected by the bubbling frequency, and is short compared to the bubble rise time.

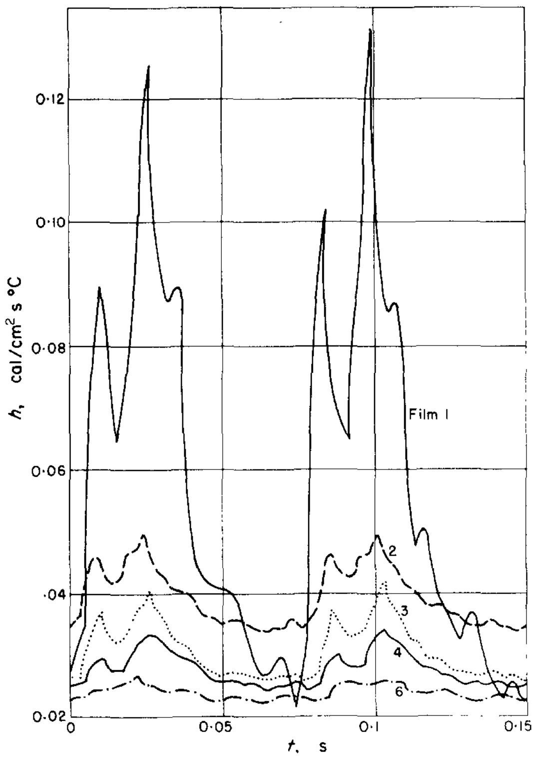

FIG. 4. Variations of h at 13 bubbles/s; orifice diameter 1·016 mm.

(7) The highest value of h observed was 0·136 cal/s cm^2 degC at $l = 0{\cdot}5$ mm, 14·7 bubbles/s, orifice diameter of 1 mm. This value was observed at the rim of the orifice, a point which is "shaded" by the growing bubble throughout most of its growth phase.

DISCUSSION

From the above results it is clear that at some point in the bubble cycle the liquid adjacent to the heating surface is set in violent motion. After possibly undergoing some oscillation, the motion ceases as abruptly as it had started. The view that the motion starts with the birth of the bubble does not fit the facts:

(1) As the bubble grows its base is constrained by the rim of the orifice. A region surrounding

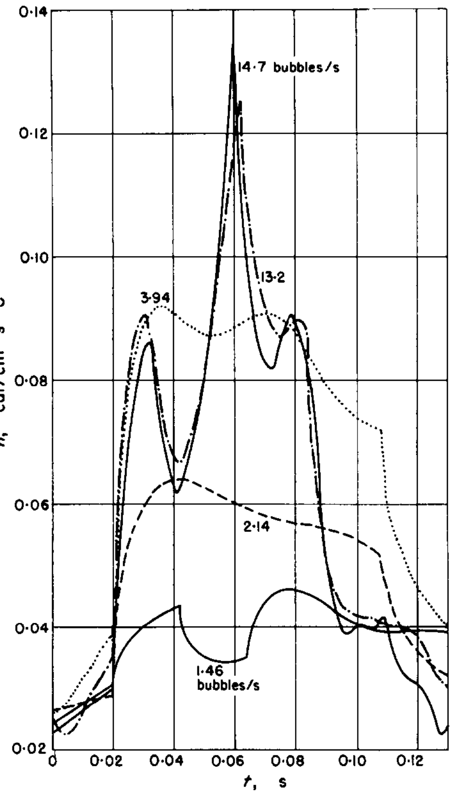

FIG. 5. Effect of bubble frequency on h; orifice diameter 1·016 mm; film No. 1.

the rim is actually shaded by the bubble in the later growth stages. One would expect the liquid in this region to be stagnant during the bubble growth phase—yet it is exactly this region which produces the most intense signals.

(2) A hot wire probe was placed directly above the orifice. During the bubble growth phase its temperature should rise, since then it is partly immersed in air, which has a lower cooling ability than the liquid. Yet the wire temperature was observed to drop at the same instant the film temperatures began to drop.

(3) If the temperature drop occurs at the onset of bubble growth, the signal duration should depend strongly on the bubbling rate. Such was not the case.

(4) The occurrence of violent oscillations during bubble growth is unexpected.

(5) The motion induced by bubble growth should be outward in a radial direction. Yet glass beads placed on the surface of the plate were observed to move inwards towards the orifice in a series of jerky steps.

An explanation consistent with all the above observations is that the bubble growth phase has negligible effect on heat transfer; the signal starts at the moment the bubble begins to detach from the surface, when liquid is suddenly drawn towards the orifice. The motion is centripetal and principally horizontal. Under these conditions the equation of continuity requires that the velocity be proportional to l^{-1}. It is not surprising therefore, that h was found to diminish at a rate ranging from $l^{-0·5}$ to l^{-1}.

It has been observed [16] that during the detaching phase, the bubble may undergo oscillations. These are reflected in the observed temperature fluctuations. As the detachment is completed, the centripetal motion along the plate ceases abruptly, with a consequent sharp rise in temperature.

The facts that liquid depth exercises only a minor influence, and that the signal duration is short compared to the rise time, indicate that the rising bubble has little effect on the heat transfer beyond the departure stage. If motion induced by the rising bubble were the prime agitator, a gradual rather than abrupt signal termination would be expected.

It must be concluded from these remarks that boiling heat-transfer correlations based on bubble growth or rising phase considerations alone cannot be reliable.

As stated earlier, values of h up to about 136 cal/s cm^2 degC (1010 Btu/h ft^2 degF) were observed in the present study in non-boiling experiments. In actual pool boiling of hexane and similar hydrocarbons, values of h between 100 and 3000 Btu/h ft^2 degF were observed by various workers [14, 17, 18, 19], the variation in results being accounted for by differences in surface roughness and degrees of superheat, i.e. by differences in ease of nucleation. Thus, only at the higher heat fluxes does it seem that agitation alone could not account for the observed heat-transfer rates. In these cases, latent heat transfer must contribute significantly. However, even in them, agitation probably plays an important role: as a bubble detaches from its site, the surrounding liquid rushes in, picking up heat from the surface over which it passes. This added heat enables the liquid to reach the degree of superheat which is required for nucleation of the next bubble to occur. Once nucleation has occurred, further evaporation may occur from a liquid microlayer at the base of the bubble, as hypothesized by Moore and Mesler (7).

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APPENDIX

The Response of a Thin Film Surface Thermometer

We seek to establish the relation between the temperature θ and the heat-transfer coefficient h. We assume that a film of infinitesimal thickness, infinite length, and width $2a$ is placed on the upper surface of an infinitely wide and thick plate, and immersed in fluid. Figure 6 shows a

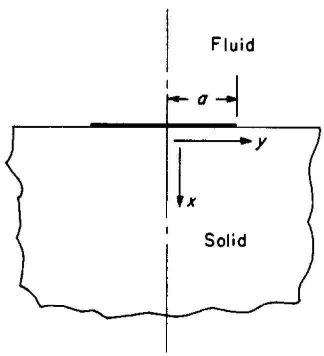

FIG. 6. Cross section of plate and film.

cross sectional view of the plate, and defines the x and y coordinates as used in the ensuing discussion. The center of the film is chosen as the origin.

It is assumed that Fourier's law governs the conduction of heat through the solid, that the bulk fluid temperature is constant at $T = 0$, and that the heat-transfer rate from the solid to the liquid is proportional to the difference between the solid surface and bulk fluid temperatures. Thus, in the solid,

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \tag{3}$$

where $\alpha = k/\rho C_p$ is the thermal diffusivity of the solid. On the surface, the heat generated per unit area $F(y)$ is carried away by conduction into the plate and convection into the fluid, thus:

$$F(y) = hT - k\frac{\partial T}{\partial x}(x = 0). \tag{4}$$

If q is the heat generated in the film per unit area, then

$$F(y) = \begin{cases} q, & y \leqslant a \\ 0, & y > a. \end{cases} \tag{5}$$

Clearly, T must be bounded for all $x > 0$, and must be symmetric in y.

Let $T_0(x, y)$ denote the steady-state temperature in the solid, corresponding to a constant heat-transfer coefficient $h = h_0$. For steady state, equation (3) reduces to

$$\frac{\partial^2 T_0}{\partial x^2} + \frac{\partial^2 T_0}{\partial y^2} = 0. \tag{6}$$

Separation of variables yields the following solution satisfying the boundedness and symmetry conditions, with $A(\lambda)$ an arbitrary function:

$$T_0 = \int_0^\infty A(\lambda)\exp(-\lambda x)\cos\lambda y\,\mathrm{d}\lambda. \tag{7}$$

Differentiation and substitution in (4) yields:

$$\int_0^\infty (h_0 + k\lambda)\,A(\lambda)\cos\lambda y\,\mathrm{d}\lambda = F(y). \tag{8}$$

$F(y)$ is, thus, the cosine Fourier transform of $(h_0 + k\lambda)A(\lambda)$. By the well known inversion formula,

$$(h_0 + k\lambda)\,A(\lambda) = \frac{2}{\pi}\int_0^\infty F(y)\cos\lambda y\,\mathrm{d}y = \frac{2q}{\pi\lambda}\sin a\lambda \tag{9}$$

$$T_0(x, y) = \frac{2q}{\pi}\int_0^\infty \frac{\sin a\lambda\cos\lambda y\exp(-\lambda x)}{\lambda(h_0 + k\lambda)}\,\mathrm{d}\lambda. \tag{10}$$

Let θ_0 be the average value of T_0 on the film, i.e. the measured film temperature. Then

$$\theta_0 = \frac{1}{a}\int_0^a T_0(0, y)\,\mathrm{d}y = \frac{2q}{\pi a}\int_0^\infty \frac{\sin^2 a\lambda}{\lambda^2(h_0 + k\lambda)}\,\mathrm{d}\lambda \tag{11}$$

which, with the substitution $\beta = 2a\ h_0/k$ is easily transformed into equation (1).

Returning now to equation (3) and applying the Laplace transformation to the time variable, we are led to

$$sT^* - T_{t=0} = \alpha\left(\frac{\partial^2 T^*}{\partial x^2} + \frac{\partial^2 T^*}{\partial y^2}\right) \tag{12}$$

where $f^*(s)$ denotes the Laplace transform of $f(t)$. We assume both T and h are subject to fluctuations around their steady-state values T_0 and h_0, i.e.

$$T(t, x, y) = T_0(x, y) + \tilde{T}(t, x, y) \tag{13}$$

$$h(t) = h_0 + \tilde{h}(t) \tag{14}$$

clearly,

$$T^* = \frac{T_0}{s} + \tilde{T}^* \tag{15}$$

$$h^* = \frac{h_0}{s} + \tilde{h}^*. \tag{16}$$

Assuming $T_{t=0} = T_0$, and taking into account the fact that T_0 satisfies (6), we obtain

$$s\tilde{T}^* = \alpha\left(\frac{\partial^2 \tilde{T}^*}{\partial x^2} + \frac{\partial^2 \tilde{T}^*}{\partial y^2}\right). \tag{17}$$

The boundary condition (4) becomes

$$F(y) = h_0 T_0 + \tilde{h} T_0 + h_0 \tilde{T} + \tilde{h}\tilde{T} - k\frac{\partial T_0}{\partial x} - k\frac{\partial \tilde{T}}{\partial x} \qquad (x = 0). \tag{18}$$

We neglect the second order term $\tilde{h}\tilde{T}$, and take into account the fact that h_0, T_0 satisfy (4), to obtain

$$T_0 \tilde{h}^* + h_0 \tilde{T}^* - k\frac{\partial \tilde{T}^*}{\partial x} = 0 \qquad (x = 0). \tag{19}$$

As before, separation of variables yields the following bounded, symmetric solution:

$$\tilde{T}^* = \int_0^\infty B(\lambda) \exp\left[-\sqrt{\left(\lambda^2 + \frac{s}{\alpha}\right)} x\right] \cos \lambda y \, \mathrm{d}\lambda. \tag{20}$$

Applying condition (19), with (10) substituted for T_0, establishes the relation

$$B(\lambda) = -\frac{2q \sin a\lambda}{\pi\lambda(h_0 + k\lambda)[h_0 + k\sqrt{(\lambda^2 + s/\alpha)}]} h^*(s). \tag{21}$$

Whence, after averaging over the width of the film, we obtain

$$\tilde{\theta}^*(s) = -\frac{q\tilde{h}^*(s)}{\pi a}\int_0^\infty \frac{1 - \cos 2a\lambda}{\lambda^2(h_0 + k\lambda)[h_0 + k\sqrt{(\lambda^2 + s/\alpha)}]} \mathrm{d}\lambda. \tag{22}$$

Again, setting $\beta = 2ah_0/k$ and $\eta = h_0/\sqrt{(k\rho C_p)}$, we are led to equation (2).

Résumé—Une étude expérimentale a été entreprise pour déterminer les variations du coefficient de transport de chaleur sur une surface chauffante submergée tandis que des bulles d'air étaient injectées dans le liquide à travers un orifice dans la plaque. Les résultats indiquaient que le transport de chaleur est le plus intense pendant le temps de détachement de la bulle à partir de la surface. Ceci jette un doute sur les corrélations du transport de chaleur par ébullition basée sur des considérations de croissance de bulle ou de phase montante. En conclusion, on suggère que les idées d'"agitation" et de "chaleur latente" pour le transport de chaleur par ébullition peuvent être combinées dans un modèle unifié.

Zusammenfassung—In einer experimentellen Untersuchung wurden Änderungen des Wärmeübergangskoeffizienten an einer beheizten Platte bestimmt, während aus einer Öffnung in der Platte Luftblasen in die umgebende Flüssigkeit austraten. Die Ergebnisse zeigten, dass der Wärmeübergang während der Blasenablösung am grössten ist. Diese Beobachtung lässt Zweifel aufkommen an Wärmeübergangsbezeihungen für das Sieden, die auf Betrachtungen des Blasenwachstums oder einer aufsteigenden Phase beruhen. Abschliessend wird vorgeschlagen, dass Gesichtspunkte der "Rührwirkung" und der "latenten Wärme" in einem einheitlichen Modell zusammengefasst werden könnten.

Аннотация—Проведено экспериментальное исследование по определению измерений коэффициента теплообмена на погруженной поверхности нагрева при вдуве пузырьков воздуха в жидкость через отверстие в пластине. Результаты показывают, что теплообмен наиболее интенсивен во время отрыва пузырька от поверхности. Поэтому можно поставить под сомнение соотношения, описывающие теплообмен при кипении, которые основаны на понятиях роста пузырьков или возникновения фазового перехода. В заключение предполагается, что взгляды на теплообмен при кипении с точки зрения «перемешивания» и «скрытой теплоты парообразования» можно объединить в одной унифицированной модели явления.