Int. J. Heat Mass Transfer. Vol. 11, pp. 279–283. Pergamon Press 1968. Printed in Great Britain

ON METHODS OF STUDYING HEAT TRANSFER IN TRANSITION BOILING

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(*Received* 20 *March* 1967)

Аннотация—В статье дан анализ устойчивости переходного режима кипения в условиях большого объема. Предполагается, что режим теплообмена будет устойчивым в том случае, если после случайного малого по величиние изменения температуры поверхности нагрева тепловой баланс стенки изменится таким образом, что начнет восстанавливаться прежнее поле температур. Для пластины, одна сторона которой омывается кипящей жидкостью, а другая — теплоносителем с постоянной температурой, получено условие [уравнение (1)], при выполнении которого режим теплообмена будет устойчивым.

Дано краткое описание экспериментальной установки, методики проведения опытов и приведены результаты измерений зависимости теплового потока от температуры поверхности при кипении воды в зоне переходного режима при атмосферном давлении.

NOMENCLATURE

- q, specific heat flux [kcal/m^{2}h];
- q_{max}, maximum heat flux in nucleate boiling [kcal/m^{2}h];
- q_{min}, minimum heat flux in film boiling [kcal/m^{2}h];
- t, temperature [°C];
- t_{s1}, saturation temperature of testing liquid [°C];
- t_{s2}, saturation temperature of heating liquid [°C];
- θ, $= t - t_{s1}$, temperature difference [°C];
- k, heat-transfer coefficient [kcal/m^2 h°C];
- α, heat exchange coefficient [kcal/m^2 h°C];
- λ, heat conductivity [kcal/m h°C];
- δ/λ, thermal resistance of a wall [m^2 h °C/kcal].

A POOL boiling process is usually divided into three main regimes: nucleate, transition and film. At present the transition regime seems to be the least studied. Steady-state boiling conditions in a transition region may be achieved if a temperature of a heating surface is maintained constant. However, the maintaining of a constant temperature of a heating surface involves certain methodical difficulties. This is probably the reason why transition boiling is not sufficiently studied.

In the present paper are formulated the requirements for a heating method which would make it possible to obtain stable transition boiling.

STABILITY CONDITIONS OF TRANSITION BOILING

As it has been mentioned earlier [1], stable boiling conditions are interrupted by the disturbance of the heat balance of a heat-transfer surface. We shall therefore consider the heat balance of a plate, at whose surface ① liquid is boiling (saturation temperature t_{s1}), and the other surface ② which is heated by saturated steam at temperature t_{s2} (Fig. 1). Assume that the coefficient of heat transfer to boiling liquid is equal to α_1, and that from a heating vapour to a wall, α_2. To simplify the notation, the difference of temperatures $\theta = t - t_{s1}$ will be considered instead of the absolute temperature. The excess temperatures of the surfaces ①, ② and of a heating liquid are designated as: θ_1, θ_2 and θ_0, respectively.

A boiling process is usually accompanied by small temperature variations of the heat-transfer surface. Assume that during a test the plate temperature varies somewhat, and the surface temperature ① becomes equal to $\theta_1 + \delta\theta_1$. Suppose that the deviation $\delta\theta_1$ is very small, but has a finite value and noticeably influences heat transfer to the boiling liquid. Consider the influence of the temperature deviation $\delta\theta_1$ upon the heat balance of a plate.

Under steady-state thermal conditions the amount of heat released by a surface layer of

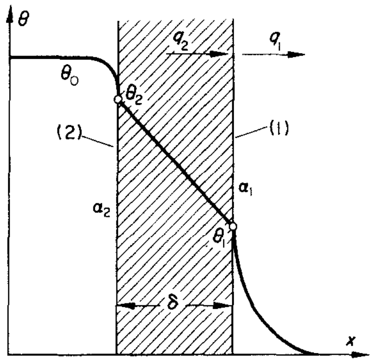

FIG. 1. Character of temperature change.

the plate to the boiling liquid (q_1) is equal to that supplied to this layer $q_1 = q_2$. A change in the temperature of the surface ① leads to that of the heat fluxes q_1 and q_2 which become equal to $q_1 + \delta q_1$ and $q_2 + \delta q_2$. A further change in the surface temperature will depend upon the sign of the difference: $(q_1 + \delta q_1) - (q_2 + \delta q_2) = \delta q_1 - \delta q_2$.

If the surface temperature increases ($\delta\theta_1 > 0$), then cooling of the surface and the return of the process to its initial state are possible provided that $\delta q_1 - \delta q_2 > 0$. Conversely, if the surface temperature decreased ($\delta\theta_1 < 0$), then the conditions may be recovered at $\delta q_1 - \delta q_2 < 0$. Consequently, the surface temperature is recovered if the difference $\delta q_1 - \delta q_2$ and $\delta\theta_1$ have the same signs, i.e. provided

$$\frac{\delta q_1 - \delta q_2}{\delta\theta_1} > 0.$$

Passing to infinitely small deviations of the surface temperature, we have:

$$\frac{d(q_1 - q_2)}{d\theta_1} > 0. \qquad (1)$$

A stable heat-transfer process is possible only when this inequality is satisfied. Inequality (1) is universal since it does not depend upon the mechanism of heat transfer between the liquid and the wall.

Condition (1) may be written somewhat differently. Thus, for a heat flux q_2 we have:

$$q_2 = \frac{\theta_0 - \theta_1}{\frac{1}{\alpha_2} + \frac{\delta}{\lambda}} = k(\theta_0 - \theta_1).$$

Here: λ is the heat conductivity of the plate material; k is the coefficient of heat transfer from the heating liquid to the heat-transfer surface of the plate.

If k and θ_0 are assumed to be independent of θ_1, inequality (1) may be rewritten as:

$$\frac{d[q_1 - k(\theta_0 - \theta_1)]}{d\theta_1} = \frac{dq_1}{d\theta_1} + k > 0 \qquad (2)$$

or

$$k > -\frac{dq_1}{d\theta_1}. \qquad (3)$$

It is of interest to consider some particular cases which may be realized in practice.

1. Thermal resistance of a wall is small,

$$\frac{\delta}{\lambda} \ll \frac{1}{\alpha_2}.$$

In this case condition (3) is of the form:

$$\alpha_2 > \frac{dq_1}{d\theta_1}.$$

2. The heat-transfer coefficient from a heating liquid side is great; the temperature of the surface ② may be considered equal to that of a heating liquid $\theta_2 = \theta_0 = \text{const}$. Although the temperature of the surface ② remains constant, boiling regime will be stable only if

$$\frac{\lambda}{\delta} > -\frac{dq_1}{d\theta_1}.$$

3. Heat flux through a wall is constant; assume $\theta_2 - \theta_1 = \text{const}$. From condition (2) it follows

$$\frac{dq_1}{d\theta_1} > 0.$$

Figure 2 shows approximate variations of the derivative $dq_1/d\theta_1$ with temperature difference for water boiling at atmospheric pressure.

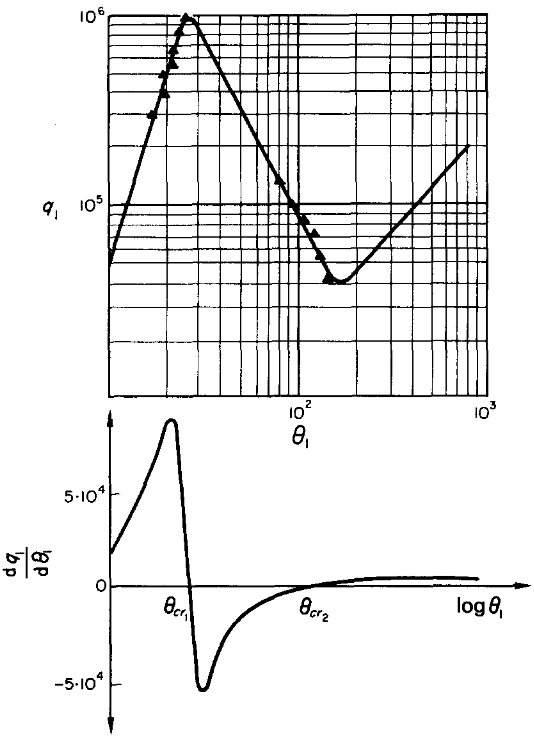

FIG. 2. Change in heat flux (q_1, kcal/m² h) and derivative $dq_1/d\theta_1$, depending on temperature difference between heating wall and boiling liquid (θ_1)

Under the regimes of nucleate and film boiling the derivative

$$\frac{dq_1}{d\theta_1} > 0,$$

and since k is also always positive, then inequality (3) will be satisfied for any k and these boiling regimes will be stable. In the whole transition region the derivative

$$\frac{dq_1}{d\theta_1} < 0,$$

the absolute value of the derivative changes very considerably. This allows us to conclude that when studying different zones of the transition boiling region the requirements of heating (i.e. the quantity k) are not the same. The zone near q_{max} where the derivative

$$\frac{dq_1}{d\theta_1}$$

attains its minimum is the most complicated to investigate.

EXPERIMENTAL APPARATUS

Heating by condensing vapour is frequently used to maintain constant temperature at the surface under investigation. Consider the possibilities of such a heating method applied to the study of heat transfer in transition water boiling at atmospheric pressure.

The experimental apparatus is shown in Fig. 3.* The heating surface ① is made of copper and shaped as a disk (36 mm in diameter) located horizontally. The liquid under investigation is boiling at the disk surface exposed upwards. The disk is heated by a high-pressure water vapour condensing at the lower surface of the disk. To study transition boiling over a wide range of temperature difference it is necessary to have the possibility to increase a heating medium temperature up to 250–300°C, i.e. the heating vapour pressure should achieve ≃ 100 ata. At the disk surface only a part of the heating steam condenses while the remainder, does so in the condenser ②. During the test the pressure of heating steam should be maintained constant. For this purpose the condenser ② is connected with a vessel ③ filled with an inert gas at a prescribed pressure. A certain movable interface exists between the steam continuously entering from the steam generator ④ and the inert gas. An accidental increase in heating

* V. V. Popalov, a student, took part in conducting experiments.

vapour pressure causes the interface displacement upwards, which increases the condensation surface. Conversely with a decrease in heating vapour pressure, the interface displaces downwards and the condensation surface decreases. Since the vessel with the inert gas has a considerable volume (≃ 1 l.), the pressure remains almost constant at small displacements of the interface.

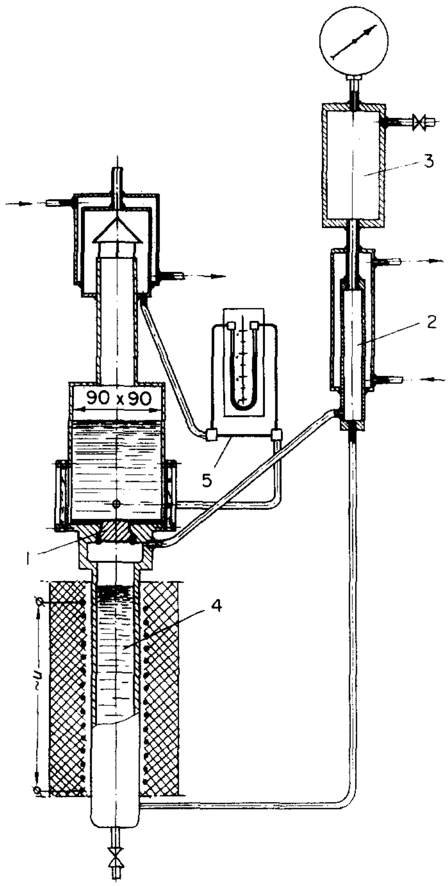

FIG. 3. Experimental apparatus.

During the tests the necessary temperature of heat-transfer surface was achieved by choosing the appropriate saturation temperature θ_0 of the heating vapour; for this the necessary pressure of the inert gas was created in the vessel ③. Heat flux from the heat-transfer surface was calculated from the amount of condensate calculated from the pressure drop over the capillary ⑤. The heat-transfer surface temperature was determined by a thermocouple embedded into a copper disk.

By increasing the heating vapour pressure step by step, it is possible to establish the relation $q_1 = f(\theta_1)$ for nucleate boiling and reach q_{max}. At the point q_{max} the curve $q_1 = f(\theta_1)$ has a rather sharp break. Therefore, when the maximum heat load q_{max} is achieved almost immediately the wall temperature starts to increase quickly and the nucleate regime is replaced by the transition one (point D in Fig. 4).

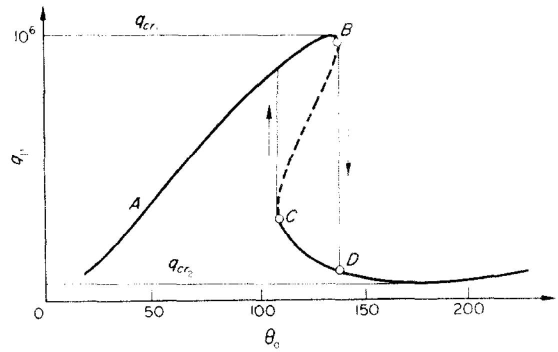

FIG. 4. Character of change in heat flux depending on heating vapour saturation temperature.

By further increasing the vapour pressure one can raise the surface temperature and pass in to the film boiling region; conversely, if the heating vapour pressure is decreased the surface temperature may be lowered, and at point C (Fig. 4) there takes place a reverse transition to nucleate boiling. Points C and B limit the stable boiling region for which the equality

$$\frac{d(q_1 - q_2)}{d\theta_1} = 0$$

is valid.

In Fig. 2 are presented the measured values of q_1 vs. the temperature difference θ_1. The experiments were not conducted over the temperature range 25–80°C since boiling here was unstable. In order to obtain steady-state conditions at any point of the transition region, the condition

$$k > -\left(\frac{dq_1}{d\theta_1}\right)_{min}$$

should be satisfied. With transition water boiling at atmospheric pressure the quantity

$$\left(\frac{dq_1}{d\theta_1}\right)_{min}$$

is $\simeq 6 \, . \, 10^4$ kcal/m^{2}h °C according to our estimates. It is hardly probably to obtain such great values of the heat-transfer coefficient by using water vapour for heating.

REFERENCE

1. S. A. Kovalev, On stability of boiling operating conditions, *Teplofiz. Vysok. Temp.* **2**(5), 780–788 (1964).

Abstract—The paper deals with the analysis of stability of transition pool boiling. Heat transfer is assumed to be stable if after accidental small change in the heating-surface temperature the heat balance of the wall varies in such a way that the initial temperature field begins to recover. For a plate, whose one side is in contact with the boiling liquid and the other, with a constant-temperature heat-transfer fluid, the condition [equation (1)] is obtained such that when this condition is satisfied heat transfer is stable.

A short description is given of the experimental apparatus and the methods for conducting experiments. Results are presented of the measurements of the heat-flux vs. surface-temperature relation for transition water boiling at atmospheric pressure.

Résumé—L'article traite de l'analyse de la stabilité de l'ébullition en réservoir en régime de transition. On suppose que le transport de chaleur est stable si après un petit changement accidentel de la température de la surface chauffante, le bilan de chaleur de la paroi varie de telle façon que le champ de température commence à revenir à sa configuration initiale. Pour une plaque, dont une face est en contact avec le liquide en ébullition et l'autre avec un fluide caloporteur à température constante, on obtient la condition de l'équation (1) de telle façon que le transport de chaleur est stable lorsque cette condition est satisfaite.

On donne un brève description de l'appareillage expérimental et des méthodes de conduite des expériences. Les résultats des mesures du flux de chaleur en fonction de la température pariétale sont présentés pour l'ébullition en régime de transition de l'eau à pression atmosphérique.

Zusammenfassung—Die vorliegende Arbeit behandelt eine Analyse der Stabilität beim Übergangssieden bei freier Konvektion. Der Wärmeübergang wird als stabil angesehen, wenn sich das Gleichgewicht des Wärmestroms der Wand nach einer zufälligen kleinen Änderung der Heizflächentemperatur so verschiebt, dass sich das ursprüngliche Temperaturfeld wieder auszubilden beginnt. Für eine Platte, deren eine Seite mit der siedenden Flüssigkeit und deren andere Seite mit einer wärmeübertragenden Flüssigkeit konstanter Temperatur in Beziehung steht, wird eine Bedingung [Gleichung (1)] erhalten, derart, dass der Wärmeübergang stabil ist, wenn diese Bedingung erfüllt wird.

Die Anordnung und die Durchführung der Versuche werden kurz beschrieben. Die Messergebnisse der Wärmestromdichte über der Oberflächentemperatur für Übergangssieden von Wasser bei Atmosphärendruck wurden angegeben.