Journal of Engineering Physics and Thermophysics, Vol. 65, No. 1, 1993

A STUDY OF THE HEAT TRANSFER MECHANISM IN WATER FILM BOILING USING A LASER

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UDC 536.423.1

The experimental setup, methods, and results of a study of the heat transfer mechanism in film boiling on a horizontal cylinder are described.

Film boiling can take place in various devices during both steady-state and unsteady-state operation. To calculate the heat transfer it is necessary to know the steam film thickness, to have data on the interface variations, and to understand quite clearly the heat transfer mechanism. At present Bromley's theoretical formula [1], numerical calculation results [2], and empirical equations for heat transfer calculation [3] are known.

Bromley's model of film boiling on a horizontal cylinder is similar to Nusselt's model of film condensation. In Bromley's formula for the heat transfer coefficient, heat was assumed to be transferred only by molecular heat conduction through a vapor film whose thickness is independent of time and equal to

$$\bar{\delta}_{av} = \lambda_v/\bar{\alpha}_{pred}. \tag{1}$$

However it is known from [4-6] that the heat flux may be transferred also due to interface variations. Data on the vapor film thickness and interface variations are extremely limited. In [4] heat transfer and the mechanism of film boiling of Freon-113 on a horizontal cylinder were investigated using a continuous laser beam; the distribution functions of the vapor film thickness near the lower and upper elements of the cylinder at different heat flux densities were measured; statistical characteristics of the interface variations were determined; the dependence of the relative contribution of the convective component of the heat flux density on the Reynolds number Re_δ was found. The convective component q_{conv} was found to be as much as 70% of the total specific heat flux under the present conditions. The technique described in [4] was used by Toda and Morie [5] to investigate water film boiling. A 3-mm-diameter wire and a 12-mm-diameter sphere were chosen as the test sections. The dependenceof the vapor film thickness on time and the wall temperature was studied and the relative contribution of the specific heat flux component due to interface variations to the total specific heat flux was determined. It was found that q_{conv}/q_Σ for the wire was as much as 82%. In [6] the subheated water film boiling mechanism on horizontal plates in a large volume of water was investigated. The studies were carried out only in the case of a stable vapor film with a smooth interface. The capacitance method was used to measure the film thickness. The relation between the vapor film thickness and the wall temperature was determined and q_{conv}/q_Σ of 30% was found.

Thus, for the development of more reliable recommendations for calculation of heat transfer in film boiling it is necessary to investigate interface variations, to measure the vapor film thickness, and to analyze the heat transfer mechanism.

Experimental Setup and Method. The test section is a stainless steel tube with an outer diameter of 3 mm and a wall thickness of 0.5 mm; the heated section length is 80 mm. The tube, blazed in copper current feeders, is positioned horizontally in the center of the chamber. Vertical and horizontal displacements of the test section are effected by a micrometer device connected to the working chamber. The tube is heated by continuously passed alternating current. The heat flux is varied by an autotransformer.

The experimental setup consists of a working chamber with two walls of thick glass, a capacitor, and an auxiliary tank. The chamber and the auxiliary tank are equipped with heaters that heat distilled water and keep it at a specified temperature. In the bottom part of the chamber a coiled tube is mounted, through which water flows to cool

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Moscow Power Engineering Institute, Moscow, Russia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 65, No. 1, pp. 76-82, July, 1993. Original article submitted August 11, 1992.

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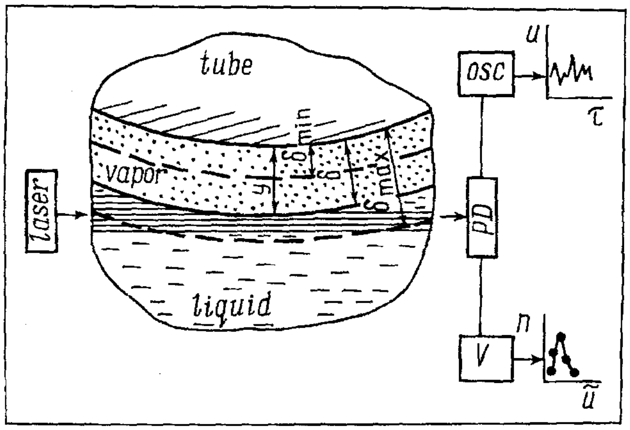


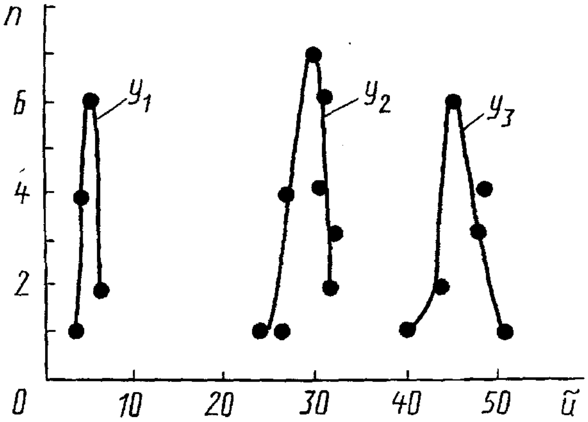


Fig. 1. Schematic diagram of passage of the radiation beam through the region of study.

Fig. 2. The distribution curve of the photodetector signal for different y.

the working liquid to a specified temperature. The temperature of the vapor and liquid phases in the chamber and the auxiliary tank is measured by thermocouples located in thin-walled cases. The test tube temperature is measured by embedded Chromel-Alumel thermocouples. Preliminary measurements showed that in film boiling the temperature of the inner wall of the tube is almost constant along the whole length, slightly decreasing toward the current feeders. Fluoroplastic bushes placed near the current feeders serve to level the temperature along the tube.

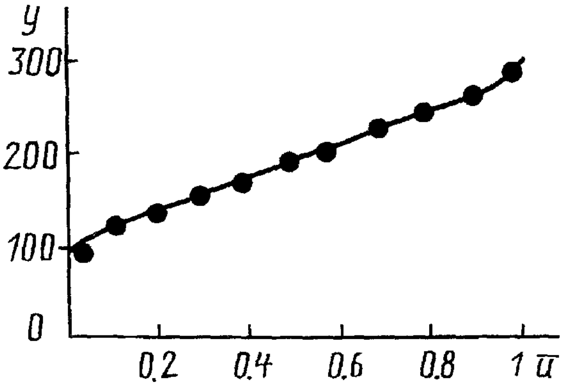
In order to induce film boiling, the test section was heated in vapor to $T_w > T_{cr2}$ and covered with water from the auxiliary tank, heated to the saturation temperature.

Motion of the interface was investigated using an optical method based on probing the near-wall layer by a continuous laser beam [7]. This method has the following advantages: the process studied is not disturbed and the beam position in the test region may be fixed precisely. In this study a He-Ne laser with a wavelength of 632.8 nm and a beam divergence of 1.5 mrad is used. A collimation system consisting of a collimator and a diaphragm located in its focus is used to reduce the beam divergence. The beam, having passed through the collimation system, is brought into focus near the lower cylinder element by a lens, the spot diameter in the focus being about 100 μm. Unlike the technique described in [7], the interface motion is investigated by a beam whose size is comparable with the minimum thickness of the vapor film. The determination of the phase interface position is based on reflection and scattering of the beam incident on the interface. After passing through the working chamber and the test region, the beam falls on a photodetector, whose signal is observed on an oscillograph and recorded by a voltmeter (see Fig. 1). In this technique the photodetector signal is measured at various distances between the beam and the wall. With a preset distance, the photodetector signal is measured several times, and every voltmeter reading is the result of averaging the signal over a selected time interval. Thus, a distribution curve of the time-averaged photodetector signal is obtained for each y_i (Fig. 2). Maxima in the distribution curve are modal values of the signal $\overset{\approx}{U}_i$ for particular y_i. Then, for each y_i the relative modal signal

$$\bar{U}_i = \frac{\overset{\approx}{U}_i(\tau) - \overset{\approx}{U}_{\min}(\tau)}{\overset{\approx}{U}_{\max}(\tau) - \overset{\approx}{U}_{\min}(\tau)}, \tag{2}$$

is calculated, where $\overset{\approx}{U}_{max}$ and $\overset{\approx}{U}_{min}$ are the modal maximum and minimum signals of the photodetector. The distance at which $\bar{U}_i = 0$ corresponds to δ_{min}, the distance at which $\bar{U}_i = 1$ corresponds to δ_{max}.

The measurement results are used to plot the distribution function of the averaged signal from the photodetector $\bar{U}(y)$ (Fig. 3), which is the probability that the interface is located at a specified distance from the wall. The time-average thickness of the vapor film near the lower cylindrical element is determined by integration of the distribution obtained:



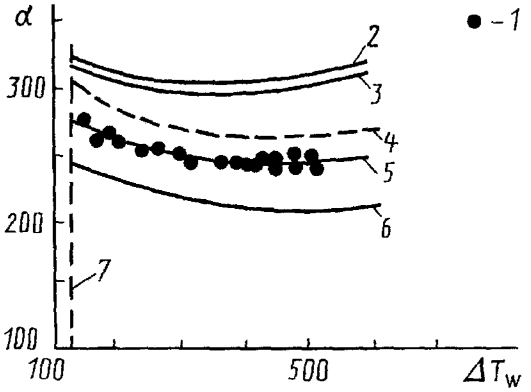


Fig. 3. The distribution function of the signal from the photodetector at $q_{\Sigma} = 107$ kW/m^2; $\Delta T_w = 445$ K. y, μm.

Fig. 4. Heat transfer in saturated water film boiling on a horizontal cylinder at atmospheric pressure: 1) experimental data, d = 3 mm; 2) experimental data [9], d=2 mm; 3, 5, 6) experimental data [10] (d=2, 3, and 4 mm); 4) prediction from Bromley's formula [1], d = 3 mm; 7) predicted ΔT_{cr2} [8]. α, W/(m^{2}K), ΔT_w, K.

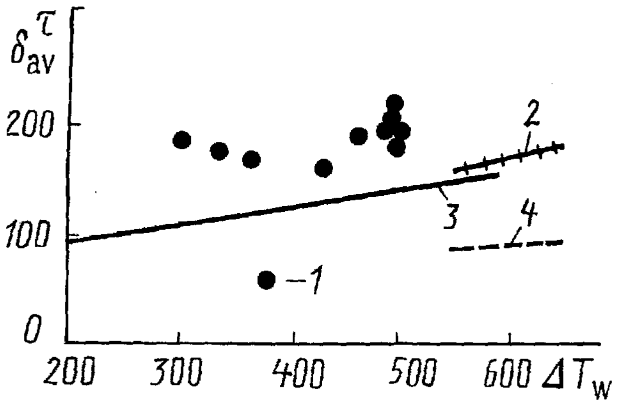
$$\delta_{av}^{\tau} = \int_0^1 y_i d\bar{U}_i. \tag{3}$$

The vapor film thickness averaged over the cylinder perimeter may be obtained from the formula

$$\bar{\delta}_{av} = \frac{1}{\pi} \int_0^{\pi} \delta_{av}^{\tau} d\varphi, \tag{4}$$

where the distribution of δ_{av}^{τ} over φ is the same as in Bromley's formula. The value of δ_{min} is found after cessation of film boiling by measuring the amount of shift of the test section toward the beam that is necessary to minimize the photodetector signal. This position may be found from the plot of $\bar{U}(y)$ by determining the point at which the variation gradient of the signal from the photodetector is quite small. The value of δ_{max} is determined in a similar way. The interface variation amplitude is determined as the difference between δ_{max} and δ_{min}. The largest relative error in determining the vapor film thickness is 30%; the calculation error for the heat load and the heat transfer coefficient is 2 and 4%, respectively.

Experimental Results. As a result of the experiments, data were obtained on heat transfer, the vapor film thickness, and the interface variation amplitude in water film boiling on a horizontal cylinder in a large volume of water at atmospheric pressure. The results of measuring the total heat transfer are presented in Fig. 4. The results agree fairly well with the experimental data of various authors. Heat transfer determined from Bromley's formula is, on the average, 10% higher. The vertical dashed line shows ΔT_{cr2} from [8]. It is found that the present experimental values of ΔT_{cr2} are close to those predicted from the formula of [8]. In Fig. 5 the measured vapor film thicknesses are compared with the experimental data [5] for a wire 0.3 mm in diameter and with the predictions by Bromley's formula. The comparison shows qualitative agreement of the experimental data. However, the values of δ for a tube 3 mm in diameter are substantially higher than those for a wire 0.3 mm in diameter. The vapor film thickness determined from Bromley's formula is substantially lower. This can be ascribed to the fact that in Bromley's model heat is assumed to be transferred only by molecular heat conduction, whereas the interface variations that induce convective transfer of some heat to the vapor film are neglected. In Fig. 6 the amplitude of variation of the vapor film thickness for saturated and subheated water ($\Delta T_{lq} = 10$ K) is plotted versus the heat load. Every vertical line is the amplitude range that results from the fact that variations of the vapor film thickness are a random process. In saturated water film boiling the amplitude of the film thickness variation increases with the heat load. As was found, liquid subheating reduces substantially the amplitude of variation of the vapor film thickness. This is confirmed by measurements [5] which show that the amplitude of the vapor film thickness variation decreases as the heat load decreases and the subheat



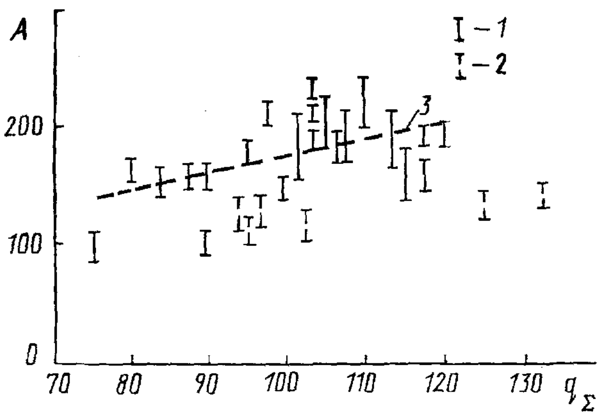


Fig. 5. Time-average vapor film thickness near the lower cylindrical element in water film boiling at atmospheric pressure: 1) experimental data, d = 3 mm; 2) experimental data [5], d = 0.3 mm; 3, 4) prediction from Bromley's formula [1] (d = 3 and 0.3 mm). δ_{av}^{τ}, m.

Fig. 6. Amplitude of the interface variation in film boiling of saturated and subheated water on a horizontal cylinder with d = 3 mm at atmospheric pressure: 1) experimental data, T_{lq} = 0 K; 2) experimental data, T_{lq} = 10 K; 3) the line averaging the experimental data, T_{lq} = 0 K. A, m; q_Σ, kW/m^2.

increases and by observations [6] which revealed practically no interface variations in heated water film boiling (T_{lq} = 15-20 K). The vapor film thicknesses obtained permitted the heat transfer coefficient due to molecular heat transfer to be found:

$$\bar{\alpha}_\delta = \lambda_v/\bar{\delta}_{av}, \tag{5}$$

where λ_v is chosen at the saturation temperature. This value in Eq. (5) was correlated with the total heat transfer coefficient calculated from the supplied power, and the portion of the specific heat flux transferred due to interface vibrations was determined:

$$q_{conv} = q_\Sigma - \bar{\alpha}_\delta \Delta T. \tag{6}$$

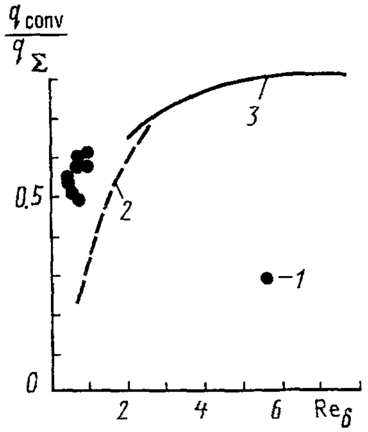
In Fig. 7, the relative contribution q_{conv}/q_Σ of convective heat transfer to the total transferred heat flux versus the Reynold's number is plotted using the present results and those of [4] and [5]. The figure shows that for a cylinder 3 mm in diameter the contribution of the convective heat transfer in boiling of water is larger than that in boiling of Freon-113. The present data and the results of [4] on heat transfer for a cylinder 3 mm in diameter are presented in generalized coordinates in Fig. 8. The abscissa is Re, and the ordinate is $Nu(Pr_{lq}/Pr_v)^{0.19}$. The results on heat transfer for water and Freon-113 in the case of a cylinder 3 mm in diameter are described by the following relation:

$$Nu = 2{,}3\,Re_\delta^{0{,}6}\,(Pr_{lq}/Pr_v)^{-0{,}19}. \tag{7}$$

Figure 8 shows that at $Re_\delta < 0.29$ the contribution of the interface variations is small and heat is transferred through the vapor film by molecular heat conduction. Interface variations and the contribution of convective heat transfer increase with Re_δ, and the convective heat transfer becomes dominant. Thus, when the interface is variable, in calculation of heat transfer in film boiling the convective heat transfer should be included.

NOTATION

α, heat transfer coefficient; λ_v, thermal conductivity of vapor; δ_{av}, vapor film thickness averaged over the perimeter; q_{conv}, convective component of the heat flux; q_Σ, total heat flux; μ_v, vapor viscosity; T_w, tube wall temperature; ΔT_{cr2}, temperature difference at termination of film boiling; r, heat of vaporization ; y, distance from the tube to the radiation beam axis; $\tilde{U}$, time-average signal of the photodetector; n, the number of U_i measurements;



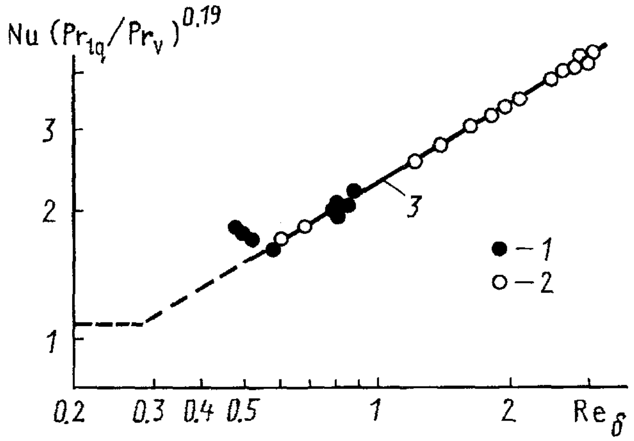


Fig. 7. The relative contribution of convective heat transfer to the total specific heat flux: 1) experimental data, water, d = 3 mm; 2) experimental data [4], Freon-113, d = 3 mm; 3) generalizing relation.

Fig. 8. Generalization of heat transfer data: 1) experimental data, water, d = 3 mm; 2) experimental data [4], Freon-113, d = 3 mm; 3) generalizing relation.

$\overset{\approx}{U}_i$, modal signal of the photodetector at a specific y_i; $\overline{U}$, relative modal signal of the photodetector; δ_{min}, minimum thickness of the vapor film; δ_{max}, maximum thickness of the vapor film; δ^{τ}_{av}, time-average vapor film thickness at the lower cylindrical element; A, amplitude of the vapor film thickness variation; α_δ, coefficient of heat transfer due to molecular heat conduction; ΔT_w, temperature difference; $Re_\delta = q\delta^{\tau}_{av}/r\mu_v$, Reynolds number; $NU = \alpha\delta^{\tau}_{av}/\lambda_v$, Nusselt number.

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