METHOD OF INVESTIGATING FLUCTUATIONS OF THE INTERFACE IN FILM BOILING OF A LIQUID BY MEANS OF A LASER

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A method of investigating fluctuations of the interface by means of a laser is developed and the results of measuring the thickness of the vapor film in film boiling of Freon-113 on a horizontal tube are presented.

According to current concepts, heat transfer from a wall to a liquid in film boiling is accomplished through a laminar vapor film by heat conduction. In the case of high temperatures it is necessary to take into account also heat transfer by radiation. In the relationships obtained by Kutateladze [1] and Bromley [2] it is suggested that the heat transfer coefficient be determined by the time-averaged thickness of the vapor film, and the wave motion on the interface is not taken into consideration.

However, at heat loads insignificantly exceeding the minimum heat flux on a heating surface only several millimeters long the interface in film boiling becomes rough and wave motion is observed almost on the entire interface. Fluctuations of the interface can lead to a change of the heat transfer coefficient. As Kapitsa [3] showed, the coefficient of heat transfer through a film of running liquid should be greater in a wave regime than in a waveless laminar flow.

The need to take into account wave motion on the interface in the case of film boiling is pointed out in the experimental investigation of Coury and Dukler [4]. The authors noted fluctuations of the temperature of the heating surface and heat flux in film boiling of Freon-113 on a vertical plate and showed that they are due to fluctuations of the interface.

At present there are no investigations in which the motion of the interface during film boiling was studied in detail. It is natural that a well-founded consideration of the effect of wave motion on heat transfer is possible if the average thickness of the vapor film and the regularities of the change of amplitude and frequency of the fluctuations as a function of the density of the heat flux are known. Experimental investigations must be conducted to find these characteristics.

High-speed filming and photography are used widely in studying the mechanism of liquid boiling. High-speed filming, for example, was used for studying the motion of a vapor layer during film boiling of various liquids on a vertical surface by Borishanskii and Fokin [5]. However, the experience of using high-speed filming in this study showed that on analyzing the photographs it is not possible to determine the exact position of the heating surface, and so, to find the actual thickness of the vapor film.

To investigate the motion of the interface during film boiling we developed a method based on the use of continuous laser radiation. The method permits, first, observing the behavior of the interface at a quite small distance from the wall (up to 10 μ) and, second, obtaining the characteristics of the fluctuating motion (film thickness, amplitude and frequency of fluctuations). As the experimental section we selected a horizontally positioned tube of diameter 2×0.5 mm which moved relative to the light beam. The position of the fluctuating interface in time was registered due to reflections from it of the beam of continuous laser radiation, whose cross section by means of optical devices was reduced to a size considerably smaller than the minimum thickness of the vapor film. The luminous flux was recorded by a photomultiplier (PM) located at the exit port of the working vessel (Fig. 1).

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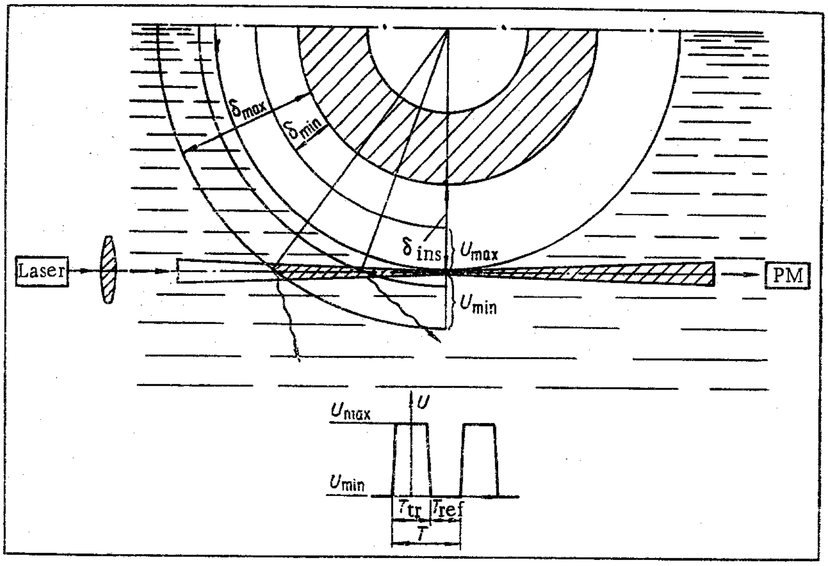

Fig. 1. Scheme of interrupting the light beam.

At a fixed distance from the lower generator of the tube, equal to δ_{ins}, as long as the interface moves from δ_{ins} to δ_{min} and back (T_{tr}) the light beam passes through the liquid and the PM signal is equal to U_{max}. When the interface moves from δ_{ins} to δ_{max} and back the light beam is reflected and scattered from it and the PM signal is equal to U_{min}. In the case of an increase of the distance from the tube δ_{ins} the time of interruption of the light beam by the vapor film decreases. Such a δ_{ins} when the vapor film ceases to interrupt the light beam, which is determined by the constancy of the PM signal, equal to U_{max}, corresponds to the maximum deviation of the interface (Fig. 2a).

To determine the duration of interruption of the light beam by the vapor film, the PM signal was calibrated by mechanical choppers (rotating sector disks) and by an electrooptical light modulator.

During calibration in the case of the mechanical choppers we determined the dependence of the magnitude of the PM signal on the ratio $\varphi/2\pi$ (Fig. 2c). The sum of the angles of the sectors φ was found as $\sum_{i=1}^{n} \varphi_i$. Calibration was done at a chopping frequency equal or close to the experimentally observed frequency of fluctuations of the vapor film.

In Fig. 2c the average beam transmission time through the liquid is laid out on the horizontal line for various distances from the tube, determined so:

$$T_{tr} = (\varphi/2\pi)T,$$

where T, the average period of fluctuations of the vapor film, is found from the recording of the PM signal on a loop oscillograph at a distance between the light beam and tube equal to the average thickness of the vapor film.

The resolution of the method developed depends on the size of the light beam and characteristics of the apparatus. To obtain greater sensitivity of the method the light beam must be focused to a size considerably

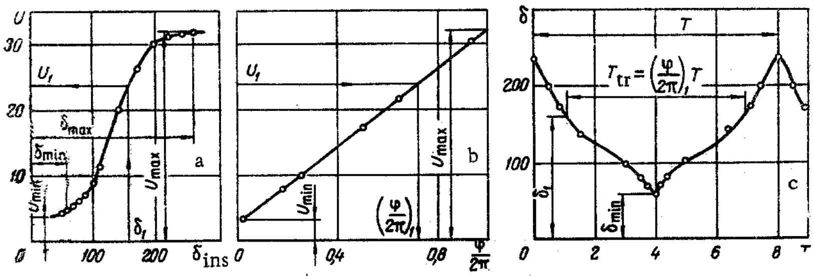

Fig. 2. Treatment of the measurement data: a) change of the PM signal in the experiment; b) calibration curve; c) time of light beam chopping by vapor film. δ_{ins}, μ; U, mV; T, msec.

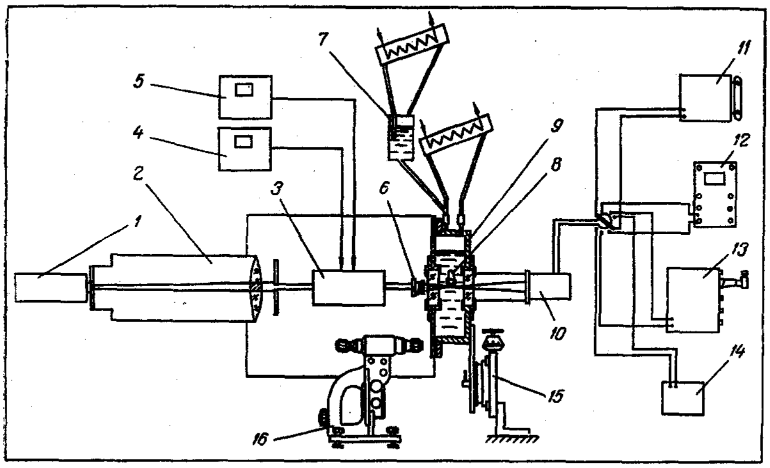

Fig. 3. Basic diagram of device.

smaller than the average thickness of the vapor film, equal to about 60 μ in the case of film boiling of Freon-113 at a mean temperature difference close to Δt_{min} according to Bromley [2].

The diameter of the spot at the focus depends on the focal length of the focusing objective and angular size of the light beam. To reduce the size of the beam at the focus it is advantageous to use an objective with a smaller focal length, for which purpose the working section must be brought up to the entrance port of the working vessel. However, to meet the conditions of boiling in a large vessel the distance between the heating surface and the entrance port was selected equal to 30 mm.

When focusing with the "Industar-50" objective, to obtain a spot at the focus with a diameter of 15 μ, which provides satisfactory accuracy of the method, the divergence of the light beam should be 1'. Of the known light sources, a laser gives minimum beam divergence. In addition, as applied to the given problem the following requirements were taken into account: 1) continuity and stability of operation of the light source; 2) minimum attenuation of the light beam on passing through the liquid in the working vessel; 3) minimum heating of the liquid near the heating surface by the focused light beam.

A gas laser meets these requirements. Therefore, as the light source we selected the LG-55 He–Ne laser with a wavelength of 0.63 μ, whose divergence in single-mode operation was 10'. To reduce this to the necessary value we used a collimation system consisting of the collimator objective of an OSK-2 optical

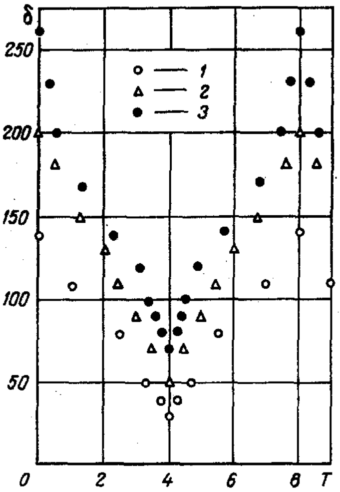

Fig. 4

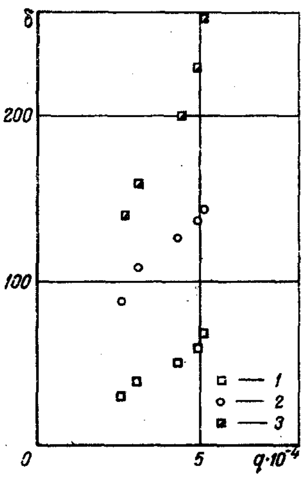

Fig. 5

Fig. 4. Change of the local thickness of the vapor film: 1) $\Delta t = 128°C$, $q = 2.6 \cdot 10^4$ W/m^2; 2) 201.4 and $4.34 \cdot 10^4$; 3) 253.5°C and $5.08 \cdot 10^4$ W/m^2.

Fig. 5. Change of vapor film thicknesses as a function of the heat flux; 1) δ_{min}; 2) $\bar{\delta}$; 3) δ_{max}.

bench with a focal length of 1600 mm and diaphragm installed at its focus at the exit of the beam from the laser. After collimation and focusing of the laser beam the diameter of the spot was measured by means of a microscope without consideration of the nonuniformity of the distribution of the radiation. As the calculation showed, the increase of the temperature of the working liquid as a consequence of the effect of the focused light beam was negligibly small.

The error of determining the minimum thickness of the vapor film depends on the sensitivity of the method, inaccuracy of measuring the movement of the working section, and PM noises. For the minimum value of δ_{min} observed in the study, equal to 30 μ, the error of its determination was about 15%.

Figure 3 shows a diagram of the experimental device. The light beam from the laser 1 passed through the collimation system 2 and was focused in the working vessel 9 near the lower generator of the tube 8. The experimental section, fastened in the side pipe connections of the working vessel, was moved vertically and horizontally by a micrometer device 15 and checked by microscope 16. After passage through the working vessel the light beam struck the PM cathode 10, the signal of which was recorded by potentiometer 14, and observed on the double (SI-16) and storage (SI-29) oscillographs 12, 13. For recording on the loop oscillograph (N004 MI) 11 the PM signal was amplified by a biopotential amplifier (UBPI-02). Mechanical choppers or an electrooptical light modulator (ML-3) were installed in front of the objective 6. A bias voltage was supplied to the modulator 3 from a source (UIP-I) 4 and a modulating voltage from a generator (G5-15) 5.

To monitor the power of the laser radiation a part of its beam was directed by means of a divider plate installed after the collimator to a photodiode, whose signal was measured by a F-116/2 microammeter.

The working circuit of the device consisted of an evaporator with a condenser and an auxiliary vessel with a condenser. To establish a film regime of boiling the working section was heated to a temperature greater than that corresponding to the minimum heat flux for the investigated conditions. After this the liquid located in the auxiliary vessel and heated to saturation temperature was transfered to the working vessel. The experimental section was flooded with the liquid and a film regime of boiling was established. The temperature of the working section was determined by means of a Chromel–Alumel thermocouple installed inside it.

The local thickness of the vapor film was measured during film boiling of Freon-113 on a horizontal tube under conditions of free convection and atmospheric pressure. The measurement results are presented in Fig. 4 in the form of the average time of transmission of the light beam through the liquid at various distances from the lower generator of the working tube. The data on fluctuations of the interface were obtained in the ranges of heat fluxes $2.6\text{-}5.08 \cdot 10^4$ W/m^2 and temperature differences 128-253.5°C.

The curve of the average time of transmission of the light beam through the liquid is plotted on the assumption that the deviations of the interface have a symmetric form. The sharp maxima and minima near δ_{max} and δ_{min} can be conceived as a result of the statistical superposition of fluctuations with a different amplitude. The values of δ_{min}, $\bar{\delta}$, and δ_{max} increase with an increase of the heat flux in the investigated range of q (Fig. 5).

NOTATION

δ_{min}, δ_{ins}, δ_{max}	are the minimum, instantaneous, and maximum deviations of the interface, μ;
U_{min}, U_{max}	are the minimum and maximum signals of the photomultiplier, mV;
φ	is the sum of sector angles;
T_{ref}	is the beam chopping time by vapor film, msec;
T	is the average period of fluctuation of vapor film, msec;
q	is the heat flux density, W/m^2;
T_{tr}	is the transmission time of light beam through liquid, msec;
U	is the average photomultiplier signal, mV;
δ	is the distance from heating surface, μ;
Δt_{min}	is the difference between temperatures of the heating surface and saturation of liquid corresponding to the minimum heat flux, °C;
Δt	is the difference between temperatures of the heating surface and saturation of liquid, °C.

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