SURVEY

HEAT EXCHANGE DURING BOILING UNDER CONDITIONS OF INCREASED GRAVITATION

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In connection with the expansion of the area of application of the process of boiling in modern thermal-power engineering the urgent need has arisen for the study of the boiling of liquids under conditions differing from those of normal gravitation. The investigation of the process of boiling under the conditions of reduced and increased gravitation also permits a deeper study of the mechanism of this complex phenomenon and an estimation of the correctness of the available semiempirical equations for the calculation of the basic parameters of the process.

Definite experimental material on the boiling of a number of liquids under the conditions of increased gravitation has presently been accumulated which requires systematic presentation, comparison, and analysis. A brief survey of reports on this problem is made below and some conclusions are drawn.

Merte and Clark [1] studied the boiling of distilled water in a large volume for the conditions of $\eta = 1\text{-}21$ and $q = 1.5 \cdot 10^4$ to $3.2 \cdot 10^5$ W/m^2. The chrome-plated end of a copper cylinder 76 mm in diameter and 25.4 mm high served as the heating surface. The height of the water level above the heating surface was 63.5 mm. The pressure at the free surface level was kept close to atmospheric. The saturation temperature at the heating surface was calculated from the corresponding pressure.

The measurements showed that for the entire indicated range of g-loads and heat flux density the heat transfer from the heating surface is accomplished through free convection. In this case the temperature difference between the wall and the liquid decreased with an increase in η. The liquid temperature was measured at a distance of 6.35 mm from the heating surface. The experimental data for the conditions of $3.6 \cdot 10^9 \leqslant \mathrm{Ra} \leqslant 2 \cdot 10^{10}$ are generalized by the equation

$$\mathrm{Nu} = 0.05\,\mathrm{Ra}^{0.4}. \tag{1}$$

The diameter of the heating surface is used as the determining dimension in Eq. (1).

Undeveloped bubble boiling was observed at the heating surface in the region of $q = 3.2 \cdot 10^4$ to $7.8 \cdot 10^4$ W/m^2. Here the temperature difference $t_w - t_{sw}$ decreased with an increase in the g-load.

With a high heat flux density $q > 1.5 \cdot 10^5$ W/m^2 in the region of developed boiling the temperature difference $t_w - t_{sw}$ increased somewhat with an increase in the g-load.

Costello and Tathill [2] also studied the boiling of distilled water in an increased gravitational field. A Chromel ribbon 75 × 9 mm in size through which an electric current was passed served as the heating surface. The pressure at the free surface level of the liquid was kept close to atmospheric. Tests were conducted for $\eta = 20\text{-}45$ and $q = 3.2 \cdot 10^5$ to $6.2 \cdot 10^5$ W/m^2. The process was photographed during the tests. It was discovered that the separation diameters of the vapor bubbles decrease with an increase in the g-load ($d_0 \sim \eta^{-1/2}$).

The results of the studies on heat exchange showed that for a given heat-flux density the difference between the wall temperature and the local liquid temperature increases with an increase in η: $(t_w - t_l) \sim \eta^{0.1}$.

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Beckman and Merte [3] studied the mechanism of water boiling under the conditions of $1 \leqslant \eta \leqslant 100$ and $q = (5.0\text{-}23) \cdot 10^4$ W/m². A Chromel plate with a size of 6.85 × 146 × 0.05 mm served as the heating surface. The saturation temperature at the heating surface was kept constant for all inertial g-loads through a decrease in the level of the liquid above the heating surface in the range of 25-280 mm with an increase in η. The maximum underheating of the liquid at a distance of 3.2 mm from the heating surface was 5.5°C. High-speed filming was used in performing the experiments.

An analysis of the motion picture data showed that with an increase in η from 1 to 3 the mean separation size of a vapor bubble decreases, while for $\eta > 3$ it remains constant for a fixed heat flux density. At an underheating of 5.5°C the bubble separation sizes were about twice as small as at an underheating of 1.1°C.

The mean bubble separation frequency increases with an increase in $(f \sim \eta^{1/2})$, while the density of the vaporization centers decreases. At the same time, the rate of bubble growth is almost independent of the g-load.

Adelberg and Schwartz [4] performed experiments under the conditions of $\eta = 1$ -134 which provided for the placement of the container with the test element on a centrifuge with a rotation radius of 5.5 m. The test element with a size of 70 × 6.35 × 0.13 mm was made of nickel alloy in the form of a ribbon through which an alternating electric current was passed. The surface of the ribbon was polished before the tests were made.

The pressure at the free water surface was kept equal to 760 mm Hg. The range of variation of the heat flux density was $q = 2.9 \cdot 10^4$ to $4.6 \cdot 10^5$ W/m². Filming of the process was used in performing the experiment.

An analysis of the motion picture data showed that the separation diameters of the vapor bubbles decrease with an increase in the g-load at a fixed heat flux density. Following the separation from the heating surface the condensation of bubbles occurs during their floating upward in the volume of the liquid.

It was discovered that at $q = 1.6 \cdot 10^5$ W/m² and $\eta = 40$ the vapor bubbles are observed only in the immediate vicinity of the heating surface, while there are none in the volume of the liquid. The formation of the vapor phase ceases with a further increase in the g-load.

Turton [5] presents the results of an experimental study of the effect of the g-load and the saturation pressure on the boiling of water and Freon-11 in a large volume. An electrically heated stainless steel tube with an outer diameter of ∿1 mm and a length of ∿32 mm served as the heating surface. The experimental tube was placed in the liquid volume so that the resultant acceleration was perpendicular to the tube axis. The basic parameters of the system for water were varied in the ranges of $P_{s0} = 1.7\text{-}27.8$ bars, $q = (30\text{-}1400) \cdot 10^3$ W/m², and $\eta = 2.5\text{-}65.3$; for Freon-11 $P_{s0} = 1.35\text{-}6.2$ bars, $q = (1.3\text{-}110) \cdot 10^3$ W/m², and $\eta = 2.5\text{-}65.3$.

The results of the measurements showed that in the free convection mode the experimental data for Freon-11 with $\mathrm{Ra} > 10^4$ are generalized by the equation

$$\mathrm{Nu} = 0.725\,\mathrm{Ra}^{1/4}. \tag{2}$$

The results of the measurements for water under analogous conditions could not be generalized. It was noted in the report that the g-loads do not have a marked effect on the relation $q = \varphi(\Delta t)$ in the mode of developed bubble boiling. Only the heat-flux density required to boil the liquid increased with an increase in the g-load.

The results of direct measurements of the heat transfer from an electrically heated Nichrome ribbon with a size of 220 × 1.6 × 0.5 mm to distilled water, obtained for the conditions of $\eta = 11\text{-}1280$ and $q = 3.2 \cdot 10^4$ to $3.6 \cdot 10^6$ W/m², are generalized in [6]. The liquid temperature was measured with thermocouples at several points near the heating surface. The experimental data for the free convection mode are approximated by the equation

$$\mathrm{Nu} = 0.15\,\mathrm{Ra}^{0.36}. \tag{3}$$

Equation (3) corresponds to $2 \cdot 10^7 \leqslant \mathrm{Ra} \leqslant 8 \cdot 10^{10}$. The height of the liquid level above the heating surface, equal to 25.4 mm, is used as the determining dimension.

The results on the boiling, represented graphically in the form $q = \ (t_w - t_{s0})$, showed a decrease in the slope of this line with an increase in the inertial g-load.

Important experimental and analytical studies of the hydrodynamics and heat exchange during the boiling of a number of liquids under the conditions of inertial g-loads have been performed at the Kiev Polytechnic Institute [7-17].

The results of an experimental study of heat exchange during the boiling of Freon-12 at the inner surface of a tube are presented in [8]. The region of the parameters of the system was varied in the following range: $\eta = 1\text{-}5250$, $P_{s0} = 7.5\text{-}9.5$ bars, $q = (26.6\text{-}200)\cdot 10^3$ W/m^2. In this case the maximum thickness of the liquid layer above the heating surface was 3-15 mm. The heat flux density was calculated over the heating surface in contact with the liquid:

$$q = \frac{Q}{2\,Rl \arccos \dfrac{R - \delta_{\max}}{R}}; \tag{4}$$

here Q is the heat flux, R is the inner radius of the tube, $\delta_{\max}$ is the maximum thickness of the liquid layer, and l is the length of the tube.

It was established experimentally that under the conditions of normal gravitation

$$\alpha = 7.96\, q^{0.6} \left(\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \deg}\right). \tag{5}$$

In the presence of inertial g-loads the saturation temperature of the liquid varied over the heating surface owing to the curvature of the test element. In this connection the integral mean saturation temperature over the bathed surface was determined for the calculation of the average heat-exchange coefficients.

The authors of [8] experimentally established the minimum heat flux densities at which boiling of the liquid is observed over the entire heating surface and they obtained the empirical equation

$$q_{\min} = 4.1 \cdot 10^{-3}\, \eta^{1.8} \delta_{\max}^{1.44} \left(\frac{\theta\mathrm{W}}{\mathrm{m}^2}\right). \tag{6}$$

It follows from Eq. (6) that for a given thickness of the liquid layer the minimum heat flux density providing boiling of the liquid on the entire surface of the test element increases considerably with an increase in the g-load.

On the basis of the experimental data obtained, the authors of [8] note that the absolute values of the heat-exchange coefficients increase with an increase in the g-load, while the effect of the heat flux density on α decreases. At the same time the effect of the g-load on α decreases with an increase in the heat flux density. It was found experimentally for $\eta > 10^3$ that

$$\alpha = 14.2\, \eta^{0.6} q^{0.23}. \tag{7}$$

The experimental data corresponding to the conditions $q < q_{\min}$ (boiling not over the entire heating surface) are described by the equation

$$\alpha = 130\, q^{0.4}. \tag{8}$$

Here the heat-exchange coefficient pertained to a temperature head $t_w - t_l$.

The results of an experimental study of the effect of inertial acceleration on the heat exchange during free convection and boiling of Freon-11 and Freon-12 are presented in [9, 10]. The region of g-loads was $\eta = 1\text{-}5000$ with $q > 10^4$ W/m^2.

The tests were performed at saturation pressures $P_{s0} \approx 1.0$ bar for Freon-11 and $P_{s0} \approx 6.2$ bars for Freon-12.

Platinum wires (d = 0.028-0.28 mm), which were simultaneously used as resistance thermometers, served as the heating surfaces. The thickness of the liquid layer above the heating surface was 4-6 mm.

The results of the experiments corresponding to the mode of free convection are in satisfactory agreement with the well-known equations of M. A. Mikheev. In the mode of free convection the heat-exchange coefficient pertained to a temperature head $t_W - t_{s0}$.

It is shown that for the conditions where the heat exchange is determined by free convection the inertial g-loads intensify the process of heat transfer.

The start of bubble boiling was determined by the sharp drop in the temperature of the platinum wire upon an increase in the heat flux density during an experiment. It is noted that with an increase in the g-load higher heat flux densities are required to provide the necessary overheating of the heating surface relative to the local saturation temperature of the liquid. The heat-exchange coefficient for the boiling mode was calculated from the equation

$$\alpha = \frac{q}{t_{\mathrm{w}} - t_{\mathrm{sw}}}. \tag{9}$$

An analysis of the heat-exchange coefficients obtained in the region of g-loads and heat fluxes studied showed that with such a method of analyzing the results of the measurements the g-load does not affect the heat-transfer coefficient. For both liquids it was found that $\alpha \sim q^{0.8}$. Here the absolute values of the heat-exchange coefficients were 45% higher for Freon-12 than the experimental data for Freon-11.

The results of an experimental study of heat exchange during the boiling of water and Freon-12 under the conditions of inertial g-loads are reported in [11, 12]. The parameters of the system were varied in the ranges of η = 1-5250, q = (6.6-200) $\cdot\ 10^3$ W/m², and $P_{s0} \approx 1$ bar for water and η = 1-5250, q = (6.6-200) $\cdot\ 10^3$ W/m², and $P_{s0} \approx 6.5$-9.5 bars for Freon-12.

A flat copper plate 10 × 30 mm in size with a Nichrome heater was used here as the heating surface. The thickness of the liquid layer above the plate was in the range of 10 mm.

An analysis of the results obtained showed that the existence of three characteristic types of heat exchange is possible in an inertial field: 1) the heat transfer is determined only by free convection; 2) nondeveloped boiling, in which free convection has an important effect on the heat transfer; 3) developed boiling, where the effect of free convection is unimportant.

It is recommended that the heat exchange in the investigated regions of variation in heat fluxes and inertial g-loads be calculated by the following equations:

1) region of heat exchange with free convection for water

$$\mathrm{Nu} = 0.75\,\mathrm{Ra}^{1/4}, \tag{10}$$

for Freon-12

$$\mathrm{Nu} = 0.21\,\mathrm{Ra}^{1/3}. \tag{11}$$

The thickness of the liquid layer above the heating surface serves as the determining dimension in Eqs. (10) and (11);

2) region of nondeveloped boiling for water

$$\alpha = 440\, q_0^{0.1} \eta^{0.3}, \tag{12}$$

for Freon-12

$$\alpha = 150\, q_0^{0.15}\, \eta^{0.3}, \tag{13}$$

where $q_0 = q - q_{fc}$, q_{fc} is the density of the heat flux transferred through free convection;

3) region of developed boiling for water

$$\alpha = 4.4\, q_0^{0.68}, \tag{14}$$

for Freon-12

$$\alpha = 3.2\, q_0^{0.68}. \tag{15}$$

Here one must keep in mind that $t_w - t_l$ serves as the temperature head for the mode of free convection, while in the other cases it is $t_w - t_{sw}$.

In [14] an attempt is made to generalize the experimental material corresponding to the modes of free convection and developed boiling by a single equation using the well-known method of S. S. Kutateladze.

The experimental results obtained earlier [11] for Freon-12 were represented in the form

$$\frac{\alpha}{\alpha_{\text{con}}} = \varphi\left(\frac{\alpha_{\text{boil}}}{\alpha_{\text{con}}}\right). \tag{16}$$

Here Eq. (11) was used to calculate α_{con}. The heat-exchange coefficient for developed boiling of Freon-12 was calculated from the empirical equation (15). In both cases the difference $t_w - t_{s0}$ was used as the determining temperature head. The physical constants were determined with respect to the temperature t_{s0}. The experimental data are generalized with an accuracy of ±30% by the equation

$$\frac{\alpha}{\alpha_{\text{con}}} \doteq \left[1 + \left(\frac{\alpha_{\text{boil}}}{\alpha_{\text{con}}}\right)^2\right]^{1/2}. \tag{17}$$

It should be pointed out that Eq. (15) is obtained for $\Delta t = t_w - t_{sw}$ and includes only part of the heat flux density. Therefore its use to obtain Eq. (17) demands special justification.

The reports [15, 17] serve as a definitive summary of the studies discussed. The experiments were performed on two liquids: Freon-11 and Freon-12. The saturation temperature at the free surface level of the liquid was kept in the range of 22-26°C. Platinum wires ($d = 0.028$-0.28 mm) and Permalloy plates 2 and 4 mm wide were used as the heating surfaces. The thickness of the liquid layer above the heating surface was varied in the range of 1-16 mm. The cleanness of the test heating surfaces corresponded to the eighth class of the GOST (All-Union State Standard) 2789-59. The magnitude of the g-load was varied in the range of $\eta = 1$-5000.

It was established experimentally that in the mode of free convection acceleration has an important effect on the heat-exchange intensity. The experimental data were generalized by the following empirical equations:

for a plate

$$\alpha = 1.1 \cdot 10^2\, q^{0.16} g^{0.18}, \tag{18}$$

for a wire

$$\alpha = 5.7\, q^{0.16} g^{0.18} d^{-0.37}. \tag{19}$$

In Eqs. (18) and (19) the heat-exchange coefficients pertained to the temperature head $t_W - t_{s0}$.

The maximum heat flux densities during free convection, which preceded the appearance of the first signs of boiling at the heating surface, were determined.

In the mode of developed bubble boiling the heat-exchange coefficients were calculated by Eq. (9). An analysis of the experimental data showed that with such an analysis of the results of the measurements the acceleration does not affect the heat-exchange coefficient. The acceleration only affects the range of variation in the heat flux density in which developed boiling occurs. With an increase in the acceleration this process is shifted to a region of higher values of q.

The results of the experiments are generalized by the following equations: for Freon-11

$$\alpha = 0.46\, q^{0.8}, \tag{20}$$

for Freon-12

$$\alpha = 0.86\, q^{0.8}. \tag{21}$$

Unfortunately, the conditions of existence of the mode of developed bubble boiling under the conditions of g-loads are not given in [15, 17].

Korner's report [18] is devoted to an experimental study of heat exchange during the boiling of distilled water under the conditions of increased gravitation $\eta = .50\text{-}10$ and $q = 6.2 \cdot 10^4$ W/m². In this case the maximum underheating of the liquid was ∿40°C.

A nickel ribbon 1 mm thick covered by a layer of copper 75 μ thick was used as the heating surface. The liquid temperature was measured at a distance of 2 mm from the heating surface.

It was established experimentally that different types of heat exchange occur depending on the heat flux density and the acceleration: from free convection to developed bubble boiling. For the region of free convection the experimental data are generalized by the equation

$$\mathrm{Nu} = 0.113\, \mathrm{Ra}^{0.375}. \tag{22}$$

The following equation is proposed for the case of boiling with underheating of the liquid up to the saturation temperature:

$$\mathrm{Nu}_* = 300\, \mathrm{Re}_*^{0.67} \mathrm{Pr}^{-0.7} \eta^{-0.48}, \tag{23}$$

where

$$\mathrm{Nu}_* = \frac{\alpha l'_*}{\lambda'}\ ;\ \ l'_* = l_* \frac{t_W - t_{s0}}{t_W - t_{sw}}\ ;$$

$$\mathrm{Re}_* = \frac{q_k l'_*}{r\rho''\nu'}\ ;\ \ q_k = q - q_{fc}\ .$$

With developed saturation bubble boiling Eq. (23) retains its form but the quantity l_* is used as the determining dimension. In accordance with Eq. (23) an increase in the inertial g-loads leads to a decrease in the heat-exchange intensity.

The results of an experimental study of the heat-exchange intensity and the mechanism of the process during the boiling of Freon-113 under the conditions of inertial g-loads are presented in [19]. The principal system parameters of the process were varied in the ranges of $\eta = 1\text{-}100$ and $q = 1.2 \cdot 10^3$ to $1.3 \cdot 10^5$ W/m². The boiling of Freon-113 took place at a glass plate 50 × 33 × 3.2 mm in size coated with an oxide film and with direct electrical heating.

As the experiments were performed the excess pressure at the heating surface was kept constant and equal to $P_{sw} \approx 0.574$ bar. For this the space above the liquid level was filled helium whose pressure was regulated in accordance with the g-load of the system. Thus, the saturation temperature at the heating surface was constant and did not depend on the g-load.

The underheating of the liquid up to the saturation temperature was calculated with respect to the temperature head $t_{sw} - t_l$. In this case the liquid temperature was measured outside the thermal boundary layer. The underheating of the liquid under the experimental conditions was $0 \leqslant t_{sw} - t_l \leqslant 30°C$. High-speed filming was used to study the internal physical characteristics of the process.

The analysis of the experimental material showed that the density of active vaporization centers is a linear function of the heat flux density. It was discovered that with an increase in the g-load the number of vaporization centers decreases and is almost independent of the underheating of the liquid.

The bubble separation frequency increased with an increase in the heat flux density and a decrease in the underheating of the liquid. An increase in the g-load in the range of η = 10-100 leads to an increase in the bubble separation frequency while for η = 1-10 the separation frequency is almost unchanged.

The maximum bubble sizes decreased with an increase in the g-load and in the underheating of the liquid. A considerable reduction in the bubble sizes was observed for the region of η = 1-10. No effect of the heat flux density on the sizes of the vapor bubbles was found.

With an increase in η from 1 to 100 and with underheating of the liquid by $t_{sw} - t_l = 0 - 5°C$ the overheating $t_w - t_{sw}$ of the wall increased by 2°C for $q = 1.3 \cdot 10^5$ W/m^2 and the overheating of the wall decreased by 10°C for $q = 1.2 \cdot 10^4$ W/m^2. In the region of $1.3 \cdot 10^5$ W/m^2 $> q > 1.2 \cdot 10^4$ W/m^2 the overheating of the wall first increased and then decreased with an increase in the g-load.

The experimental data were analyzed in the form proposed by Korner [18]. The following equation was obtained as a result:

$$Nu_* = 150\, Re_*^{0.67} Pr^{-0.7} \eta^{-0.17}. \tag{24}$$

Komarov and Balandin [20] experimentally studied the mechanism and intensity of heat exchange during saturated and underheated bubble boiling of water and ethyl alcohol under the conditions of η = 1-128.

A laboratory centrifuge of the S-52 type was used to produce the g-loads. The boiling took place on flat heaters of nickel foil and of stainless steel plates 5-8 mm wide with direct heating by a direct current.

The experiments were performed with $q = 2 \cdot 10^4$ to 10^6 W/m^2 and P_{s0} = 0.49-0.98 bar.

The measurements showed that the liquid temperature is almost the same over the height of the level. Slight overheating of the liquid was observed at the interface with the vapor. Since under the conditions of a g-load the saturation temperature increases over the height of the level, a certain amount of underheating of the liquid up to the saturation temperature occurred in the volume of the liquid. In the analysis of the experimental data $t_w - t_l$ and $t_w - t_{sw}$ were used as the determining temperature heads.

On the basis of the experimental data obtained it is noted that with an increase in the g-load the heat exchange during free convection increases and the heat flux density at which boiling develops also increases. With nondeveloped bubble boiling an increase in acceleration somewhat improves the heat transfer. With developed bubble boiling, however, the heat exchange worsens with an increase in acceleration.

The principal data on heat exchange during free convection under the conditions of inertial g-loads are presented in Table 1.

Pomerantz [21] studied the effect of acceleration during film boiling of Freon-113 at the surface of a stainless steel tube 4.76 mm in diameter. The pressure at the free surface level of the liquid was kept close to atmospheric.

TABLE 1

Source	Liquid studied	Limits of variation of η	Calculating equation	Determining dimension	Determining temperature head	Characteristic of heating surface
Merte, Clark [1]	Water	1,0–21,0	$Nu = 0{,}05\ Ra^{0{,}4}$ $3{,}6 \cdot 10^9 \leqslant Ra \leqslant 2 \cdot 10^{10}$	Diameter of surface	$t_w - t_l$	Chrome-plated end of copper cylinder 76 mm in diameter and 25.4 mm high
Turton [5]	Water Freon-11	2,5–65,3	$Nu = 0.725\ Ra^{0{,}25}$ for Freon-11 with $Ra > 10^4$	Height of liquid level	$t_w - t_l$	Electrically heated stainless steel tube 1 mm in diameter and 32 mm long
Eschweiler and Benton [6]	Water	11,0–1280	$Nu = 0{,}15\ Ra^{0{,}36}$ $2 \cdot 10^7 \leqslant Ra \leqslant 8 \cdot 10^{10}$	Height of liquid level	$t_w - t_l$	Electrically heated Nichrome ribbon 220 × 1.6 × 0.5 mm in size
Butuzov, Fainzil'berg, Usenko, et al. [11, 12]	Water Freon-12	1,0–5250	$Nu = 0.75\ Ra^{0{,}25}$ (for water) $Nu = 0{,}21\ Ra^{0{,}33}$ (for Freon-12)	Height of liquid level	$t_w - t_l$	Flat copper plate 10 × 30 mm in size with a Nichrome heater
Korner [18]	Water	50–1000	$Nu = 0{,}113\ Ra^{0{,}375}$	Height of liquid level	$t_w - t_l$	Nickel ribbon 1 mm thick coated with a copper film

The experiments were performed for the conditions of $\eta = 1\text{-}10$ and $q = (16\text{-}79) \cdot 10^3\ W/m^2$. High-speed filming of the process was used in performing the experiments. Two different series of experimental results were obtained in the experiments: the thermal characteristics (q, Δt), on the basis of which the heat-exchange coefficients were calculated, and the hydrodynamic characteristics – the distances between bubbles (wavelength), their separation frequency, and the separation sizes of the bubbles.

The experimental data on heat exchange qualitatively confirmed the well-known solutions for the film boiling of liquids.

An analysis of the results of filming of the process showed that with an increase in the g-load the separation sizes of the vapor bubbles decrease while their separation frequency increases.

Leinhard and Kauohwa Sun [22] studied the effect of the force of gravity on the process of film boiling of acetone, isopropanol, and methanol. The experiments were performed on a centrifuge with $\eta = 1\text{-}81$. The boiling of the liquids took place on horizontal Nichrome wires 0.2-2.06 mm in diameter. The heat flux density was varied in the range of $(13\text{-}43) \cdot 10^4\ W/m^2$. The boiling process was photographed.

The properties of the mechanism of removal of the vapor phase from the heating surface as a function of the geometrical size of the surface and the magnitude of the g-load were found. Equations are proposed for calculating the wavelengths and the minimum heat flux.

An experimental study of the effect of increased gravitation on the critical heat flux densities during saturated boiling and boiling with underheating up to the saturation temperature for water, carbon tetrachloride, and ethyl alcohol was performed by Labuntsov and Abdusattorov [23]. The experiments were performed for $\eta = 1\text{-}200$. The pressure at the free surface level of the liquid was close to atmospheric. Nichrome wires from 0.5 to 1.5 mm in diameter, stainless steel tubes with an outer diameter of 2 mm, and stainless steel plates 0.14 mm thick and 3-4 mm wide served as the heating surfaces.

The heating surfaces were placed perpendicular to the inertial acceleration vector. The heating was accomplished by passing an alternating current directly through the working section. The study was performed on clean metal heating surfaces and on heating surfaces with reduced wettability.

Coatings of IP-9 varnish 0.01 mm thick were used in the latter case. The level of the liquid above the heating surface was 15-35 mm in the experiments.

The results of the experiments with saturation boiling of water showed an increase in the critical heat flux density with an increase in η. The critical heat flux density was considerably lower at heating surfaces with reduced wettability than at clean metals.

In the boiling of liquids with underheating up to the saturation temperature the critical heat flux densities depended little on the g-load.

Thus, the experimental data obtained showed that the nature of the effect of increased gravitation on the critical heat flux densities is manifested differently when the conditions of the boiling process differ.

The results of an experimental study of the effect of acceleration on the boiling crisis in liquids at the saturation temperature and in underheated water are presented in [24, 25].

In the study of the boiling crisis at the saturation temperature of the liquids the experimental installation consisted of a circuit with forced circulation of the working liquid, for which water and 96% ethyl alcohol were used. The surface (Armco iron) was heated with a high-frequency current. The experiments were performed for the conditions of $\eta = 1\text{-}2050$.

The results of the measurements showed that the geometrical dimensions of the heating surface do not affect the critical heat flux density. The experimental data are generalized by the equation

$$\mathrm{Re}_{\mathrm{cr}} = 0.135\,(\mathrm{Ar}\,K\rho)^{1/2}. \tag{25}$$

The results of the experimental study of the effect of acceleration on the critical heat flux density in underheated water corresponded to the conditions of boiling in a large volume. The experiments were performed for $\eta = 15\text{-}970$. The height of the water layer above the heating surface was ~15 mm. Atmospheric pressure was maintained above the water level. The temperature difference $t_{sw} - t_{s0}$ was taken as the measure of the underheating of the liquid. The magnitude of the underheating in the experiments was $t_{sw} - t_{s0} \leqslant 65°\mathrm{C}$.

The results of the measurements showed that the critical heat flux density increases with an increase in the underheating of the liquid. The following equation was obtained on the basis of the experimental material:

$$q^{\mathrm{u}}_{\mathrm{cr}} = q_{\text{кр}}\,(1 + 3.8\cdot 10^{-3}\,\mathrm{Ja}). \tag{26}$$

In the analysis of the experimental data the physical properties were related to the total pressure at the heating surface. On the basis of the survey of reports which has been made one can draw the following conclusions.

1. Under the conditions of increased gravitation the mechanism of heat transfer from the heating surface to the liquid differs in important properties. The change in the saturation temperature over the height of the liquid level under the conditions analyzed leads to an important change in the usual representations of the vaporization mechanism.

2. It was established experimentally that the temperature of the liquid in the volume varies insignificantly under the conditions of inertial g-loads. The main temperature variation occurs in the boundary layer of the liquid.

In the case when the temperature difference between the wall temperature and the calculated saturation temperature at the wall is insufficient for the formation of vapor bubbles or this difference is negative the heat transfer from the heating surface will be determined only by pure free convection. This case is observed at relatively low heat flux densities and considerable g-loads. Several empirical equations have now been obtained which determine the region of existence of this mode of heat exchange for certain liquids and specific heat-exchange surfaces. However, these data are extremely limited by the conditions under which the experiments were performed and cannot serve as the basis for general conclusions.

3. The majority of the experimental results showed that in the mode of free convection the heat-exchange intensity increases with an increase in the g-load. In this case the well-known equation $\mathrm{Nu} = \varphi(\mathrm{Ra})$ is used to generalize the experimental material. It should be noted that the experimental results are not always

generalized by this equation or in accordance with well-known functions, and the data of different authors sometimes disagree considerably with each other. These facts may be caused by the different methods of analysis of the experimental material, since arbitrary determining geometrical dimensions and determining temperatures are often used in obtaining the equation of the type $\mathrm{Nu} = \varphi(\mathrm{Ra})$, while the heat-exchange coefficients pertain to different temperature heads.

For example, the size of the heating surface [1] and the height of the liquid level above the heating surface [5, 6] are used as the determining geometrical dimension while the heat-exchange coefficients are referred to $t_w - t_l$ [1, 5, 6] and to $t_w - t_{s0}$ [15, 17].

In our opinion, for the mode of heat exchange under consideration the temperature difference between the wall temperature and the saturation temperature of the liquid at the free interface should be used as the temperature head since the latter enters into the conditions of uniqueness of the problem.

4. The results of the direct measurements showed that at a given g-load the temperature of the heating surface increases with an increase in the heat flux density and the formation of vapor bubbles can be observed under certain conditions. However, because of the large temperature gradient of the liquid near the heating surface the liquid outside the thermal boundary layer remains underheated up to the saturation temperature. Thus, boiling with underheating is observed. In this case the vapor bubbles created at the heating surface condense on contact with the underheated liquid. At the same time the turbulization of the liquid boundary layer, due to the growth and condensation of the bubbles, promotes an increase in the heat-exchange intensity in comparison with pure free convection.

In this mode the role of free convection in the mechanism of heat transfer is still rather large. The heat-exchange coefficients, referred to the difference between the wall temperature and the calculated saturation temperature at the heating surface based on the results of direct measurements, increase with an increase in the g-load of the system. The density of the heat flux providing for the boiling of the liquid also increases with an increase in the g-load.

Reliable quantitative characteristics have not been established for the existence of this mode of heat exchange for a wide range of physical parameters of the process.

5. Saturation bubble boiling begins when the temperature of the liquid outside the thermal boundary layer is higher than the saturation temperature over the entire volume of the liquid.

The results of the cinematographic study of the internal physical characteristics of the boiling process under these conditions showed that with an increase in the g-load the density of the active vaporization centers and the separation sizes of the bubbles decrease while the bubble separation frequency increases. Keeping in mind that $q \sim f d_0^3 r \rho'' n_F$, one should expect a reduction in the heat-exchange intensity in this case. According to the data of different authors, however, the heat-exchange coefficients referred to the temperature head $t_w - t_{s0}$ increase, do not change, or decrease with an increase in the g-load. Such behavior of the heat-exchange coefficient is evidently explained by the fact that the data of the different authors are obtained with different ratios between the g-load and the heat-flux density. Thus, in the experiments cases could occur where free convection has an important effect on the transfer of heat from the heating surface, which is possible at a relatively low heat flux density. In these cases the absolute values of the heat-exchange coefficients increase with an increase in the g-load.

Under conditions where the free convection just compensates for the effect of reduction in the intensity of the vaporization process the heat-exchange coefficients should not depend on the g-load.

In the case where the heat transfer is determined only by the boiling mechanism and the effect of free convection is unimportant, the heat-exchange intensity decreases with an increase in the g-load.

NOTATION

$\mathrm{Nu} = \alpha l/\lambda'$, Nusselt number; $\mathrm{Ra} = g l^3 \beta \Delta t_1/\nu' a'$, Rayleigh number; $\mathrm{Ja} = \rho' c' \Delta t''_u/\rho'' r$, Jacob number; $\mathrm{Ar} = (g l_*^3/\nu'^2)(\rho' - \rho''/\rho')$, Archimedes number; $\mathrm{Pr} = \nu'/a'$, Prandtl number; $\mathrm{Re}_{cr} = q_{cr}l_*/r\rho''\nu'$, critical Reynolds number; $K\rho = \rho'+\rho''/\rho'$; $l_* = [\sigma/(\rho'-\rho'')\,g]^{1/2}$; $\eta = g/g_0$, dimensionless acceleration (g-load); g, inertial acceleration; g_0, acceleration of gravity; α, heat-exchange coefficient; α_{boil}, coefficient of heat exchange during developed bubble boiling; α_{con}, coefficient of heat exchange during free convection; l, determining geometrical dimension; λ', coefficient of thermal conductivity of liquid; β, coefficient of volumetric expansion; ν', kinematic viscosity of liquid; a', coefficient of thermal diffusivity of liquid; ρ', ρ'', densities of liquid and vapor; c', heat capacity of liquid; r, latent heat of phase transition; q, heat flux density; q_{cr}, critical heat flux density; q^u_{cr}, critical heat flux density during boiling with underheating; P_s, saturation pressure of liquid; P_{s0}, saturation pressure of liquid at free interface; P_{sw}, saturation pressure of liquid at heating surface; t_s, saturation temperature of liquid; t_{s0}, saturation temperature of liquid corresponding to saturation pressure at free interface; t_{sw}, saturation temperature of liquid corresponding to saturation pressure at heating surface; t_l, temperature of liquid; t_w, temperature of heating surface; $\Delta t_1 = t_w - t_l$, $\Delta t_2 = t_w - t_{s0}$, $\Delta t_3 = t_w - t_{sw}$, $\Delta t'_u = t_{sw} - t_l$, $t''_u = t_{sw} - t_{s0}$, temperature heads; d_0, bubble separation diameter; f, bubble separation frequency; n_F, density of vaporization centers; δ, thickness of liquid layer.

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