HEAT EXCHANGE IN FILM BOILING OF CRYOGENIC LIQUIDS UNDER NATURAL CONVECTION CONDITIONS

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Heat exchange is studied in stationary and nonstationary cooling of vertical cylinders by hydrogen and nitrogen. An empirical function generalizing the experimental results is presented.

Film boiling of cryogenic liquids under natural convection conditions was studied in [1-4]. The majority of experiments have been performed with nitrogen. Experimental data on hydrogen have been obtained for the saturated liquid in an experimental section with 25-mm-wide ribbon heater [1]. Use of these data for vertical surfaces of a different geometry requires additional experimental verification. Data obtained in various studies on the effect of subcooling of the liquid upon heat transfer in film boiling diverge markedly from each other. Thus, the hydrogen studies of [4] indicated that heat liberation is self-similar with respect to subcooling of the liquid in stationary cooling of a vertical tube. However, in the experiments of [3] with subcooled nitrogen under nonstationary cooling conditions, subcooling was found to have a significant effect on heat transfer.

Therefore, the goal of the present study is to investigate the effect on heat liberation of various parameter regimes in film boiling of nitrogen and hydrogen under conditions of stationary and nonstationary cooling of vertical surfaces.

The experiments were performed with vertical tubes 10, 12, 19, and 20 mm in diameter with wall thickness of 0.5 mm and lengths to 0.54 mm. The tube sections were placed in the lower portions of cryogenic containers and heated by an electric current. The inner cavities of the tube sections were evacuated and temperature of the inner tube wall was measured in four sections. Under stationary conditions the measurements for nitrogen were performed with Chromel—Copel thermocouples, while for hydrogen, platinum resistance thermometers were used. For the nonstationary cooling regimes Chromel—Copel thermocouples were used for both hydrogen and nitrogen. The liquid temperature within the cryogenic containers was measured at three sections along the vertical with platinum resistance thermometers, and pressure was measured by potentiometric sensors. Voltage drop along the heated cylinders was determined by a voltmeter of at least class 0.5 accuracy, and current was read by a current transformer and class 0.5 accuracy ammeter. The temperature of the heat producing surface was determined from the measured inner wall temperature by solving the thermal conductivity problem with consideration of internal heat liberation. The thermal load density was calculated in the stationary regimes from the results of current and voltage measurements with consideration of the dependence of the wall material resistivity on temperature, while in the nonstationary regimes the change in enthalpy of a tube wall element was used [5]. The maximum error in determination of the temperature of the heat-producing surface was 1%, with thermal load accuracy of 6% for stationary regimes, while in the nonstationary regimes the corresponding values were 3 and 12%.

The experimental data are presented in Fig. 1 in the form of a graph of heat-liberation coefficient vs temperature head for various nitrogen and hydrogen pressures. The heat-liberation coefficient increases with increasing temperature head, more significantly for hydrogen than for nitrogen. The greatest growth can be seen for hydrogen at temperature heads of 60-180°K. However, [1] found a reduction in heat-liberation coefficient with increase in temperature head in this range. This can be explained by unique features of the experimental construction used in [1]. With decrease in temperature head the effect of lateral heater

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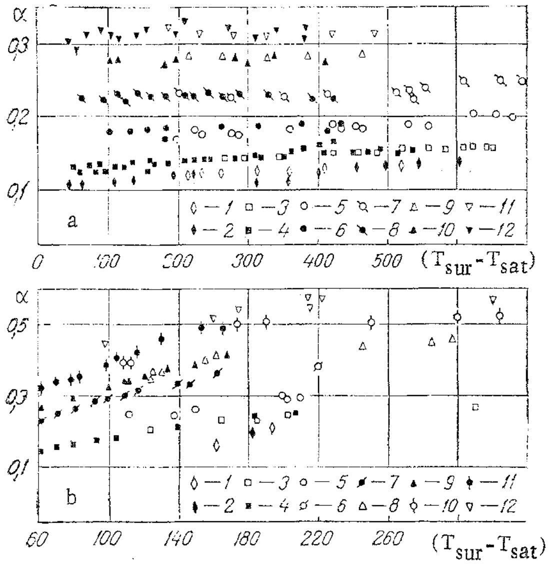

Fig. 1. Heat-liberation coefficient vs temperature head: a) nitrogen: 1, 2, P = 0.75 bar; 3, 4, 0.98; 5, 6, 2; 7, 8, 4; 9, 10, 8; 11, 12, 12; 1, 3, 5, 7, 9, 11, stationary regimes; 2, 4, 6, 8, 10, 12, nonstationary; b) hydrogen: 1, 2, P = 0.28 bar; 3, 4, 0.56; 5, 0.98; 6, 7, 2.1; 8, 9, 3.1; 10, 11, 4.7; 12, 6.9; 1, 3, 5, 6, 8, 10, 12, stationary regimes; 2, 4, 7, 9, 11, nonstationary. α, kW/m²·deg K; (T_{sur} − T_{sat}), °K.

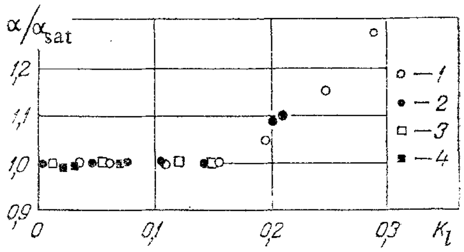

Fig. 2. Ratio of heat-liberation coefficients for subcooled and saturated liquids vs dimensionless subcooling: 1) P = 12 bar; 2) 8; 3) 4.7; 4) 3.1; 1, 2) nitrogen; 3, 4) hydrogen.

surfaces on vapor film formation increases, leading to an increase in heat-liberation coefficient, in contrast to cylindrical heaters. At temperature heads greater than 180°K the character of the heat-liberation coefficient dependence agrees with the present data. Therefore, in the present generalization the experimental data from [1] obtained at high-temperature heads were included. In both the nitrogen and hydrogen experiments, with increase in pressure the heat-liberation coefficient increased for fixed temperature head.

Analysis of the experimental data revealed that the heat-liberation coefficient is independent of the longitudinal coordinate. The good agreement between stationary and nonstationary experiments should be noted, this indicating the absence of any effect on heat-liberation coefficient produced by the actual cooling rate.

As shown in Fig. 2, subcooling of the liquid at $K_l \leq 0.18$ does not affect the ratio of the heat-liberation coefficients for the subcooled and saturated cases. At $K_l > 0.18$ there

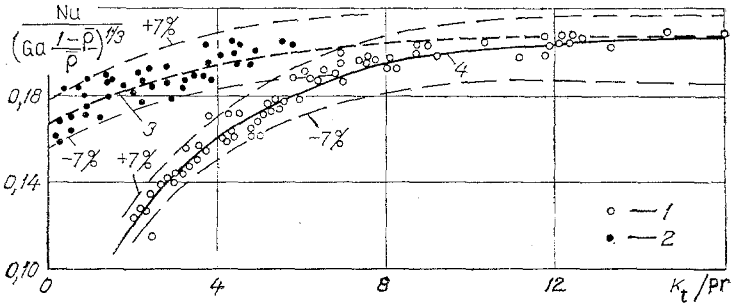

Fig. 3. Generalization of experimental data in coordinates $Nu\Big/\left(Ga\frac{1-\bar{\rho}}{\bar{\rho}}\right)^{1/3} - \frac{K_t}{Pr}$: 1) hydrogen; 2) nitrogen; 3) calculation by Eq. (1) with K = 0.2; 4) calculation by Eq. (1) with K = 0.8.

is an increase in the heat-liberation coefficient. All experiments were performed with hydrogen at K_l = 0-0.18, and for nitrogen at K_l = 0-0.29; these values correspond to absolute liquid supercoolings of 0-10 and 0-22°K. Thus, for the liquid considered, in the range $K_l \leqslant 0.18$ in cases of practical interest the heat liberation may be considered self-similar relative to subcooling. The absence of any effect of subcooling on heat liberation can be explained by the fact that in film boiling a greater vapor film thickness is realized, and superheating of the vapor is concentrated in a layer near the wall, the thickness of which is much less than the total film thickness. As was shown in [4], the state of this layer depends to a significant degree on the intensity of heat liberation. In the dimensionless subcooling range $0 \leqslant K_l \leqslant 0.18$ the vapor film thickness is significant and the observed oscillations of the interphase surface have no effect on the turbulent structure of the vapor layer near the wall, and consequently, no effect on heat liberation. With increase in subcooling the film thickness decreases, but the amplitude of interphase surface oscillations decreases also. At $K_l > 0.18$ the ratio of the film thickness and the amplitude is such that oscillations of the interphase boundary reach the layer near the wall, additional turbulization of the latter occurs, and heat liberation increases in comparison to heat liberation with boiling of the saturated liquid.

In the region where heat liberation is self-similar relative to dimensionless subcooling the experimental data were compared to well-known computed functions obtained in various studies for the boiling of saturated liquids. At dimensionless temperature head values $K_t \geqslant 3$ the experimental data for hydrogen are described satisfactorily by the criterial dependence of [4]. However, the latter does not generalize the experimental data on heat liberation at low temperature heads, or the experimental data on nitrogen boiling. The divergence of the experimental data from values calculated with the functions of [5-8] reaches: 200% [5], 45% [6], 50% for nitrogen, 200% for hydrogen [7], and 200% [8]. The function recommended in [3] generalizes the experimental data for nitrogen to an accuracy of 15%, and that for hydrogen to an accuracy of 60%. The maximum deviation between calculation and experiment is founded at low temperature head values.

Analysis of the experimental data revealed that heat liberation is essentially determined by two basic criteria: $Ga((1-\bar{\rho})/\bar{\rho})$ and K_t/Pr. The results of the generalization presented in Fig. 3 can be described satisfactorily by the following empirical expression:

$$Nu = 0.205\left(1 - K\exp\left(-0.32\frac{K_t}{Pr}\right)\right)\left(Ga\frac{1-\bar{\rho}}{\bar{\rho}}\right)^{1/3}, \tag{1}$$

where K = 0.2 for nitrogen and 0.8 for hydrogen.

The scattering of the experimental data relative to this expression comprises ±7%. The generalization was obtained over the following parameter ranges: nitrogen, P/P_{cr} = 0.03-0.36; K_t = 0.5-3.6; K_l = 0-0.29; hydrogen, P/P_{cr} = 0.019-0.66, K_t = 2-18, K_l = 0-0.18. In calculating the vapor parameters the mean temperature T_m was used, while for the liquid the temperature T_l was employed.

NOTATION

$K_l = C_{pl}(T_{sat} - T_l)/r$, dimensionless liquid subcooling; $K_t = C_{pv}(T_{sur} - T_{sat})/r$, dimensionless temperature head; $l = \sqrt{\sigma/(g(\rho_l - \rho_v))}$, capillary constant; $Nu = ql/((T_{sur} - T_{sat})\lambda_v)$, Nusselt number; $\Pr = \mu C_p/\lambda$, Prandtl number; $Ga = gl^3\rho_v^2/\mu_v^2$, Galileo number; T, temperature; g, acceleration of gravity; ρ, density; $\bar{\rho} = \rho_v/\rho_l$, density ratio; μ, dynamic viscosity; C_p, specific heat at constant pressure; q, thermal load density; λ, thermal conductivity; σ, surface tension coefficient; r, specific heat of vaporization; K, constant. Subscripts: l, liquid; v, vapor; m, parameter determined at mean temperature $T_m = 0.5(T_{sur} + T_{sat})$; sat, on saturation line; sur, on heat liberation surface.

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