EXPERIMENTAL STUDY OF HEAT EXCHANGE AND HYDRODYNAMICS IN CONDENSATION OF MOVING VAPOR ON THE SURFACE OF A HORIZONTAL CYLINDER

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Results are presented from a study of heat exchange during condensation of moving vapor on horizontal tubes in previously unstudied values of friction on the phase boundary, as well as at vapor velocities leading to droplet breakup and condensate removal.

In the condensation of a vapor flowing over a cylinder within a boundary layer a transverse matter flow exists, directed in the direction of the film, which can be represented as

$$v'' = \frac{q}{r\rho''}. \tag{1}$$

This transverse mass flow has a significant effect on the principles of flow over the body. It is well known that in the asymptotic boundary layer region the tangent stress on a wall with exhaust is equal to

$$\tau = -\rho'' v'' U'' = -\frac{qU''}{r}, \tag{2}$$

i.e., depends on the density and viscosity of the vapor.

The dimensionless laminar boundary layer length on a plate with exhaust can be defined as:

$$X = \left(\frac{v''}{U''}\right)^2 \frac{U''x}{\nu''} = 4. \tag{3}$$

In all solutions of the problem of heat exchange during condensation of a moving vapor known at present [1-5], in the approximation of boundary layer theory with laminar flow of both phases one writes equations of continuity, motion, and energy for each phase, supplemented by boundary conditions on the wall and at infinity, as well as conjugate boundary conditions on the smooth phase separation surface. Such a problem can be solved in general form by numerical methods. Techniques and results of such solutions have been presented in the monographs [6, 7].

In the first case, where friction on the phase boundary surface is completely defined by the momentum transferred upon condensation by the rapidly moving vapor (without consideration of the force of gravity), the heat exchange law obtained in [3, 4] has the form

$$\mathrm{Nu} \to \mathrm{const}\sqrt{\mathrm{Re}'}, \tag{4}$$

which follows directly from Nusselt's solution upon substitution therein of the value of the friction coefficient defined by Eq. (2). It is important to note that in this case heat exchange does not depend on thermal flux. In accordance with [7] the force of gravity may be neglected given the condition

$$Z = [c_f U''^2 \rho''/2g\delta(\rho - \rho'')] \gg 1. \tag{5}$$

For q = idem the relative change in heat exchange can be written in the form

$$\alpha/\alpha_0 = C\,\mathrm{Re}^{1/3}\sqrt{\mathrm{Re}'}\,\mathrm{Ar}^{-1/3} \tag{6}$$

or

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$$\alpha/\alpha_0 = C\frac{q^{1/3}U''^{1/2}}{r^{1/3}\rho^{1/3}\nu^{1/6}g^{1/3}L^{1/6}\overline{\Delta\rho}^{1/3}}. \tag{7}$$

It is evident that the relative change in heat liberation is defined by a number of physical parameters of the liquid, the velocity and density of the vapor, and the thermal flux, and also depends slightly on the characteristic linear dimension of the heat exchange surface.

The second limiting situation is the case in which the effect of the transverse flow in determining friction can be neglected. In this case, for $Z \gg 1$ heat exchange is defined by Nusselt's rules:

$$\mathrm{Nu} \to \mathrm{const}\left(\frac{\mathrm{PrK}}{\mathrm{N}}\right)^{1/3}\sqrt{\mathrm{Re}'}, \tag{8}$$

whence it is evident that $\alpha \sim \Delta T^{-1/3}$. From the limiting expressions (4) and (8) it follows that the intensity of heat liberation for constant vapor velocity varies depending on the exhaust intensity not only quantitatively, but also qualitatively. An experimental confirmation of this change in the character of the dependence of the heat liberation coefficient with change in temperature head during condensation of a rapidly moving vapor was presented in [8].

To calculate heat liberation upon condensation of a moving vapor during flow over an isolated horizontal cylinder [4, 5] presented functions approximating the results of a numerical solution obtained for assumption of undetached overflow, satisfying the limiting relationships (8) and (4), as well as Nusselt's expression for zero vapor velocity.

The majority of studies of heat exchange in condensation of a moving vapor on a cylinder have considered the vapor flow to be undetached. The problem can be solved for boundary conditions t_W = const or q = const. However neither in practical equipment nor in experiments involving condensation on cylinders can these boundary conditions be satisfied, since there always exists a nonuniform distribution of thermal flux and temperature about the perimeter and along the length of the experimental segment.

It was assumed in [9, 10] that the thermal flux changed in steps along the tube perimeter. The vapor boundary layer detachment point was practically independent of the value of the transverse flow, while heat exchange in the lower portion of the cylinder did not change with vapor velocity and was defined by Nusselt's expression for the case of condensation of a nonmoving vapor.

Analysis of experimental data reveals that there exist regimes where the transverse flow component is of the same order of magnitude as the incident vapor flux velocity, i.e., the boundary layer theory approximation becomes incorrect. When the film surface is wavy, the mechanism of interaction with the film becomes extremely complex. Even knowledge of local values of interphase friction is insufficient for solution of such a problem, since additional information on the effect of the condensation process and vapor velocity on critical film motion parameters is required. At high vapor velocities the fraction of liquid removed from the condensate film surface by the vapor flow must be evaluated.

In our opinion the most important factors in analyzing experimental studies are the following:

a) precision in determining the quantity of uncondensed gases;

b) technique for wall temperature measurement;

c) determination of specific thermal flux;

d) clear statement of temperature conditions used for processing experimental data.

The task of our experimental study was to measure heat liberation in the transverse flow of a condensing vapor over a horizontal cylinder and to compare the data obtained with available analytical solutions and experiments of other authors. The experiments were carried out over a wide range of parameters, including vapor velocities leading to breakup of droplets and jets of condensate.

Heat exchange was measured using cylinders 6 and 12 mm in diameter, installed in rectangular channels of various width. The degree of compression of the vapor flow was varied over the range $U''/U''_\infty = 1.4\text{-}2.3$. Saturation temperature varied from 40 to 83°C. In proces-

TABLE 1. Results of Cine Film Processing

Diameter	t'', °C	U'', m/sec	U''_∞, m/sec	$\frac{U''\rho''D_0}{\sigma}$	Results of film analysis and visual observations
$D = 12$ mm	40	0,79	0,34	2	No breakup
	40	1,52	0,66	7,56	»
	40	1,85	0,80	11,1	Beginning of breakup
	55	1,49	0,64	17,5	»
	70	0,61	0,28	3,3	No breakup
	70	1,23	0,53	11,7	»
	70	1,81	0,79	26,0	Beginning of breakup
	83	1,18	0,51	16,6	Atomization
$D = 6$ mm	40	0,55	0,22	0,84	No breakup
	40	0,55	0,39	2,6	»
	40	0,8	0,57	5,6	»
	40	1,4	1,0	17,4	Beginning of breakup
	40	1,4	0,7	8,5	»
	40	1,8	1,28	28,4	Droplet atomiztion
	40	2,2	1,57	42,8	»
	40	2,5	1,8	56,3	»
	40	2,6	1,3	29,3	»
	40	3,0	2,1	76,6	»
	40	3,0	1,5	39,0	»
	40	4,0	2,0	69,0	»
$D = 6$mm	55	1,76	0,89	21,7	Beginning of breakup
	55	3,6	1,8	90,7	Intense atomization
$D = 6$ mm	70	0,4	0,28	3,3	No breakup
	70	0,86	0,62	16	Beginning of breakup
	70	0,86	0,43	7,7	»
	70	1,60	0,80	26,7	Atomization
	70	1,9	0,96	33,7	»
	70	2,2	1,1	50,4	Intense atomiztion
	70	2,5	1,25	65,1	»
	70	2,9	1,45	87,6	»

sing the experimental data the physical properties of the vapor and liquid were taken at the saturation temperature. The mean wall temperature was calculated from the readings of 10 thermocouples installed in two sections along the tube. Systematic chromatographic analyses of the vapor showed that the air content did not exceed 0.03% by volume. The specific thermal flux was determined from the change in enthalpy of the cooling water, and was varied by changing the input temperature to the device. The cooling water was heated from 0.5 to 3°C for minimum and maximum thermal fluxes respectively. The experimental method and equipment used were described more fully in [8, 11].

The maximum uncertainty in determination of the heat liberation coefficient did not exceed 10%, while that in vapor velocity, was no more than 5%.

The heat exchange measurements were supplemented by high speed cine photography of the condensation process. Freon-12 was used as the working fluid. For constant saturation temperature and thermal flux the vapor velocity was raised in steps of 0.2 m/sec, with filming at each step. Results of visual processing of these films are presented in Table 1. Analysis of the films revealed that at even at the low vapor velocity of $U'' = 0.2\text{-}0.4$ m/sec the regularity of the flow existing for condensation of nonmoving vapor is disrupted. The droplets are greatly deformed and perform an oscillatory motion along the tube perimeter before detachment. The amplitude and frequency of these motions increases with increase in vapor velocity. Upon attainment of some velocity, condensate droplet breakup occurs at the moment of detachment from the tube supply zone. The value of the critical vapor velocity was determined for various experimental conditions. Measurements revealed that this process occurred at values of the parameter

$$\frac{U''^2\rho''D_0}{\sigma} > 10. \tag{9}$$

The droplet diameter D_0 was determined by processing films of condensation of nonmoving vapor. This result coincided with Volynskii's study [12], which investigated breakup of liquid droplets by an isothermal gas flow. In our case, as special experiments [13] showed, the condensate drains off in a state supercooled relative to the saturation temperature and the condensation process goes on for some time on the droplets. Apparently the

TABLE 2. Limiting Values of Main Experimental Parameters

U'', m/sec	$q \cdot 10^{-3}$, W/m^2	ΔT, °C	$c_q \cdot 10^3$	α/α_0	$\frac{\chi^4 \mathrm{Fr}}{\mathrm{PrK}}$	$\overline{X} \cdot 10^2$	$\frac{U''^2 \rho'' D}{\sigma}$
Freon-12: $D = 6$ mm; $t'' = 70$ °C; $U''/U''_\infty = 2{,}0$; $B = 12$ mm							
0,4	6,4	2,35	1,31	1,44	0,44	4,04	6,4
0,4	55,0	43,05	11,30	1,19	0,43	300,0	6,4
2,9	163,6	42,17	4,62	3,86	19,64	364,0	336,0
2,9	141,8	1,75	0,4	5,29	22,10	2,73	336,0
Freon-12: $D = 12$ mm; $t'' = 70$ °C; $U''/U''_\infty = 2{,}3$; $B = 21$ mm							
0,61	3,5	1,12	0,47	1,61	0,59	1,59	14,88
0,61	39,5	30,58	5,01	1,17	0,38	202,0	14,88
1,81	5,2	1,28	0,24	2,37	5,23	1,22	131,0
1,81	61,8	32,00	2,80	1,96	3,89	167,0	131,0
Freon-12: $D = 12$ mm; $t'' = 83$ °C; $U''/U''_\infty = 2{,}3$; $B = 21$ mm							
1,18	17,7	8,66	1,03	2,48	1,68	18,10	164
1,18	69,3	37,08	4,00	2,87	1,85	2 74,0	164
Freon-21: $D = 2{,}5$ mm; $t'' = 60$ °C; $U''/U''_\infty = 1{,}3$; $B = 10{,}5$ mm							
0,48	19,5	3,1	8,9	1,46	0,37	26	1,14
0,48	132,0	38,0	60,0	1,45	0,60	1186	1,14
3,81	25,4	2,3	1,5	2,20	24,80	6	70,0
3,81	212,0	34,3	12,2	2,50	36,10	397	70,0
Freon-21: $D = 16$ mm; $t'' = 60$ °C; $U''/U''_\infty = 2{,}6$; $B = 26$ mm							
0,57	7,4	2,1	2,85	1,35	0,088	20,8	1,6
0,57	51,4	22,5	19,80	1,40	0,102	1002,0	1,6
4,30	144,0	29,5	7,30	4,70	6,600	1027,0	91,0
Water vapor: $D = 19$ mm; $t'' = 43$ °C; $U''/U''_\infty = 3{,}1$; $B = 28$ mm							
22,20	121,6	6,4	38,2	1,86	7,00	605,0	2,80
4,96	96,0	6,4	135,0	1,35	0,35	1685,0	0,14
20,80	49,7	2,2	16,7	1,64	3,52	108,0	2,50
2,40	38,0	2,2	110,0	1,15	0,06	541,0	0,03

phase transition does not have a significant effect on droplet stability. The limiting value of vapor velocity at which droplet and condensate jet breakup commences is of special importance in designing a condenser. In this case uncertainty develops in calculating the irrigation density of packets located beneath the tubes. Experiments have shown [8] that at velocities corresponding to condensate atomization, heat exchange occurs with practically the same intensity on the first and tenth tubes of a packet.

Table 2 presents extremal values of the experimental values in the present experiments as well as some from the literature using other working fluids. It is evident from Table 2 that the dimensionless value of the transverse mass flow in our experiments was on the average two orders of magnitude lower than in the water vapor experiments of [14], and one order of magnitude less than the Freon-21 experiments. The dimensionless length of the initial segment for a surface with "exhaust" of the boundary layer in our case was always less than four, in contrast to other studies, i.e., the heat exchange surface was located in the initial segment. This means that a significant contribution to total friction on the vapor–film phase boundary is produced by friction stemming from the transverse mass flow and for an an infinitely small transverse flow. From the theoretical equations of [4, 5] it follows that in the general case where friction is complex in character, the relative change in heat exchange is uniquely determined by the complex parameter $\chi^4 \mathrm{Fr}/\mathrm{PrK}$. For various temperatures and in channels of various widths, experiments were thus planned so that the given parameter was maintained at a prespecified approximately constant values. These results, processed in the coordinates $\mathrm{Nu}^* = f(\mathrm{Re})$ for four values of the parameter $\chi^4 \mathrm{Fr}/\mathrm{Pr} \cdot \mathrm{K}$, are shown in Fig. 1. It is evident that the vapor velocity U" exerts a significant effect on heat exchange. Thus, for increase in vapor velocity from 0.55 to 4 m/sec at t" = 40°C for a tube diameter of 6 mm there is an increase in heat liberation by a factor of approximately three times. The lines averaging the experimental data for a single value of vapor velocity have a slope approximately the same as that given by Nusselt theory for condensation of nonmoving vapor, i.e., $\alpha \sim q^{-1/3}$. The experimental data agree satisfactorily with the approxi-

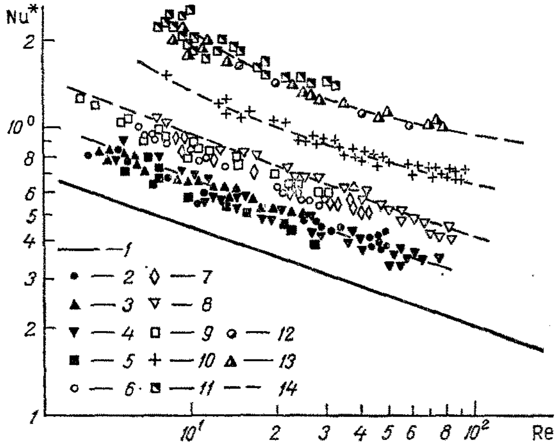

Fig. 1. Comparison of measurement results with calculated function [5]: 1) Nusselt theory calculation; 2) D = 6 mm, t'' = 70°C; U'' = 0.4 m/sec; 3) 6, 40, 0.55; 4) 12, 70, 0.61; 5) 12, 40, 0.79; 6) 12, 40, 1.8; 7) 12, 55, 1.5; 8) 12, 70, 1.25; 9) 6, 40, 1.2; 10) 6, 70, 1.6; 11) 6, 40, 4.5; 12) 6, 55, 3.6; 13) calculation after [5]; 14) lines averaging experimental data.

mation expressions of Shekriladze and Fuji [4, 5], which consider the complex character of friction on the phase separation boundary. Such agreement with computation was not noted in all the regimes studied. At maximum vapor velocity and saturation temperature t'' = 70 and 83°C, the experimental values of the heat liberation coefficient are markedly elevated above the calculated ones. This is evident in Fig. 2. Intensification of heat exchange as compared to calculation reaches 30%.

It may be proposed that in these regimes film removal by the vapor flow occurs. Liquid removal from a surface drafted by an isothermal flow of inert gas was studied in [15-17]. For the parameter characterizing commencement of film removal, [16] presented the following expression:

$$\frac{U''\rho''^{1/2}\delta^{1/2}}{\sigma^{1/2}} > 2. \tag{10}$$

Having performed a quite detailed analysis of studies on film removal, Ishii and Golmes [17] proposed the following expression for the parameter characterizing removal:

$$\frac{U''}{\sigma}\left(\frac{\rho''}{\rho}\right)^{1/2}\left[\frac{\mu\rho^2\sigma^3}{(\rho-\rho'')g}\right]^{1/5} > 1, \tag{11}$$

which can be written in the form $\frac{U''\mu}{\sigma}\mathrm{Ar}_*^{2/5}\left(\frac{\rho''}{\rho}\right)^{1/2} > 1$, where $\mathrm{Ar}_* = \left(\frac{\sigma^3}{\nu^4\rho^3 g\Delta\rho}\right)^{1/2}$.

If in Eq. (10) we express the film thickness with the Nusselt relationship $\delta = \left(\frac{3\nu^2}{g\Delta\rho}\right)^{1/3} \times \mathrm{Re}^{1/3}$, we can then write

$$\left(\frac{\rho''}{\rho}\right)^{1/2}\frac{U''\mu}{\sigma}\mathrm{Ar}_*^{1/3}\mathrm{Re}^{1/6} > 1.75. \tag{12}$$

It is evident that Eqs. (12) and (11) differ only slightly from each other. However, Eq. (12) is the more general, since therein removal depends on the film number Re, although to a low degree. If we assume that upon achieving some value of the film removal parameters the character of the change in the relative heat liberation coefficient changes, then the experimental data can be described in the form

$$\frac{\alpha}{\alpha_0} = f\left[\frac{U''\mu}{\sigma}\left(\frac{\rho''}{\rho}\right)^{1/2}\right]\mathrm{Ar}_*^{1/3}\mathrm{Re}^{1/6} = f(M).$$

Figure 3 presents a processing of the experimental data in these coordinates.

For the scaling factor we use the value of the heat liberation coefficient α_0 for condensation of nonmoving vapor for the condition q = idem. The change in the character of the dependence shown in Fig. 3 at values of the removal parameter greater than 2.0 may indicate the beginning of film removal. In this graph each point corresponds to an averaged series of experiments performed at constant vapor velocity.

Thus, the present study has provided new experimental data obtained in the region of transverse mass flow values where a significant contribution to total friction on the phase

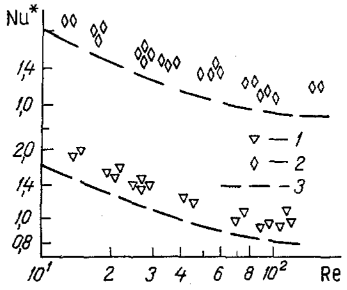

Fig. 2

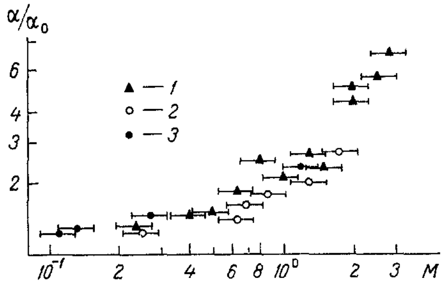

Fig. 3

Fig. 2. Heat exchange for minimum film stability reached in experiments (D = 6 mm, t'' = 70°C): 1) U'' = 2.2; 2) 2.9: 3) lines, averaging experimental data.

Fig. 3. Effect of stability parameter, Eq. (12), on relative heat liberation ($M = \frac{U''\mu}{\sigma}\left(\frac{\rho''}{\rho}\right)^{1/2} \mathrm{Ar}_*^{1/3} \mathrm{Re}^{1/6}$): 1) Freon-12, D = 6 mm; 2) Freon-12, D = 12 mm; 3) Freon-21, D = 16 mm.

separation boundary is produced by friction occurring at infinitely small transverse flow. It has been established that for condensation of "heavy" Freon-12 vapor the process of flow over a cylinder by a vapor occurs completely within the initial segment region for a surface with exhaust. The experiments have shown that the value of the vapor velocity at which droplet and condensate jet breakup occurs can be estimated from Eq. (9), while the velocities at which film removal into the vapor flow is possible will be given by Eq. (10) or (12) at formation values of the defining complex near 2.0.

NOTATION

t'', saturation temperature; U'' and U''_∞, vapor velocity in narrow and full channel section; ρ'' and ρ, vapor and condensate density; σ, surface tension coefficient; D, tube diameter; q, specific thermal flux; α, heat liberation coefficient; δ, condensate film thickness; μ'' and μ, dynamic viscosity coefficients of vapor and liquid; ν, ν'', kinematic viscosities of liquid and vapor; r, heat of vapor formation; $K = r/C_p\Delta T$, Kutateladze number; $Fr = U''^2/gD$, Froud number; $c_q = v''/U''$, relative value of transverse mass flow; ΔT, mean vapor—wall temperature head; B, channel width; $\overline{\Delta\rho} = (1 - \rho''/\rho)$, dimensionless parameter; Pr, Prandtl number; $\varepsilon_t = \left(\frac{\lambda_c^3}{\lambda_H^3}\,\frac{\mu_H}{\mu_c}\right)^{1/8}$, dimensionless complex; $Re' = \frac{U''D}{\nu''}\,\frac{\nu''}{\nu}$, vapor Reynolds number; $Re = \frac{\pi Dq}{\mu r\left(1+\frac{3}{8K}\right)}$, film Reynolds number; $Nu^* = \frac{\alpha}{\lambda}\left(\frac{\nu^2}{g\overline{\Delta\rho}}\right)^{1/3}\varepsilon_t^{-1}$, modified Nussel number $N = \left(\frac{\rho\mu}{\rho''\mu''}\right)^{1/2}$, dimensionless parameter; α_a, heat liberation coefficient for condensation of nonmoving vapor.

LITERATURE CITED

1. G. G. Chernyi, Izv. Akad. Nauk SSSR, No. 12, 38-67 (1954).
2. G. G. Chernyi, Dokl. Akad. Nauk SSSR, 101, No. 1, 39-42 (1955).
3. R. D. Gess, Z. Angew. Math., 426-433 (1960).
4. I. G. Shekriladze, Inzh-Fiz. Zh., 32, No. 12, 221-225 (1977).
5. T. Fujii, H. Uehara, and C. Kurata, Int. J. Heat Mass Trans., 15, No. 2, 235-246 (1972).
6. V. P. Isachenko, Heat Exchange in Condensation [in Russian], Moscow (1977).
7. S. S. Kutateladze, Fundamentals of Heat Exchange Theory [in Russian], Moscow (1979).
8. I. I. Gogonin, A. R. Dorokhov, and V. I. Sosunov, Heat Exchange in Film Condensation of a Moving Vapor (Preprint Inst. Teplofiz., Sib. Otd. Akad. Nauk SSSR, No. 66-80) [in Russian], Novosibirsk (1980).
9. A. A. Nicol and D. J. Wallace, J. Chem. E. Sympos. Ser., No. 38, 1-19 (1974).
10. V. M. Marushkin, Ya. L. Polynovskii, and G. E. Dement'eva, Boiling and Condensation [in Russian], Riga (1981), pp. 45-63.
11. S. S. Kutateladze, I. I. Gogonin, S. I. Lazarev, and V. I. Sosunov, "Heat exchange in phase conversions," in: Collected Scientific Studies [in Russian], Novosibirsk (1983), pp. 5-25.
12. M. S. Volynskii, Dokl. Akad. Nauk SSSR, 68, No. 2, 237-240 (1949).

13. I. I. Gogonin, V. I. Sosunov, S. I. Lazarev, and O. A. Kabov, Teploenergetika, No. 3, 13-17 (1983).
14. L. D. Berman and Yu. A. Tumanov, Energomashinostroenie, No. 5, 24-26 (1964).
15. D. Yang, I. Lorents, and E. Ganich, Teploperedach., Ser. C, No. 1, 17-23 (1980).
16. V. N. Bykov, Study of Foremation and Deformation of Droplet Spectra in Two-Phase Flows by the Holography Method. Author's Abstract, Candidate's Dissertation [in Russian], Leningrad (1975).
17. M. Ishii and M. A. Golmes, AJChE J., 21, No. 2, 308-318 (1975).

BOILING OF NITROGEN AT VARIOUS PRESSURES WITH NONSTATIONARY HEAT INPUT

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Liquid-nitrogen boiling times have been measured at 0.1, 1.3, and 2 MPa by means of a piezoelectric sensor; there is a relationship to the homogeneous nucleation temperature.

The discovery of high-temperature superconductivity has raised interest in research on heat transfer in liquid nitrogen. We have measured the boiling times t_A for liquid nitrogen on step heat input, which simulates the transition to the resistive state in a current-carrying superconductor film on a substrate, where we examined the effects of pressures up to 2 MPa.

The apparatus, including the heater and the boiling recorder, has been described [1]. There was also a pressure-measurement system containing a high-pressure cell made of copper and a Sapfir pressure sensor, together with a thermometer. The cell was placed in liquid nitrogen at atmospheric pressure, i.e., all the measurements were made at 77.4 K. Figure 1 shows the results, where the solid lines correspond to the calculation described in [1]. A step-heated liquid in contact with a fast heater boils in accordance with

$$q\sqrt{t_A} = A\Delta T_*, \tag{1}$$

in which

$$A = \frac{\sqrt{\pi}}{2}\left(\sqrt{(\lambda C\rho)_\ell} + \sqrt{(\lambda C\rho)_s}\right);$$

where ρ is density, C is specific heat, λ is thermal conductivity, and ΔT_* is the limiting attainable superheating for a given liquid at the corresponding pressure. The subscripts ℓ and s relate to the liquid and substrate. The temperature is taken as the average of $T_0 = 77.4$ K and the value T_* corresponding to the pressure in the cell, the limiting attainable temperature, which has been calculated for example in [2].

The pressure was limited to 2 MPa, although the critical pressure for nitrogen is $P_{cr} \approx 3$ MPa, because of the physically obvious reduction in the sensor signal on boiling as the pressure increases, i.e., as the critical point is approached. That reduction can be estimated from the [3] model: explosive growth of a vapor bubble produces an amplitude in the pressure wave $\Delta p \sim (\rho_\ell - \rho_V)(dR/dt)^2$, in which R is radius and ρ_V the vapor density. The growth rate is

$$\frac{dR}{dt} \sim \frac{q\sqrt{(\lambda C\rho)_\ell}}{A\rho_V\,L},$$

in which L is the latent heat of evaporation. The numerical values give $\Delta p_{0.1}/\Delta p_2$ as 300, while the ratio of the signal amplitudes at 0.1 and 2 MPa was 100, i.e., the values agree as to order of magnitude.

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