EXPERIMENTAL STUDY OF THE HEAT-TRANSFER MECHANISM FOR A SINGLE BUBBLE-GENERATING CENTER

V. Z. Borisov and P. L. Kirillov

UDC 536.423.1

It is shown that in the development of boiling the main quantity of heat is transferred from the surface into the vapor volumes due to the latent heat of vaporization.

Following are the most widely accepted physical models of the heat-transfer mechanism associated with boiling [1-3]: it is postulated that the bubbles generate vigorous turbulence of the thermal boundary layer, thus creating large heat-transfer coefficients. According to another hypothesis [4-6], the vapor phase acquires a considerable quantity of heat from the liquid even during the buildup period on the heating surface due to the latent heat of vaporization; the fraction of this "latent heat transfer" in the total energy balance of the surface increases to 100% as the thermal load approaches the critical value.

In order to obtain additional information about the heat-transfer mechanism in boiling we have conducted some investigations on a plane surface of small dimensions with a single bubble-generating center. The heat transfer on this type of surface corresponds to the process in an individual element of the cellular model [7, 8].

The working section was fabricated from a copper rod 50 mm in length and 3 mm in diameter. The rod was silver-soldered to a nickel diaphragm 0.05 mm thick. Boiling took place on a plane horizontal surface of nickel foil of GOST (All-Union State Standard) purity class 8. The heat source was a heater situated at the lower end of the rod. Four grooves were cut into the upper part of the rod, separated by a distance of about 2.5 mm, and copper–Constantan thermocouples were pressed into the grooves. The heat flux and temperature of the boiling surface were determined from the readings of the thermocouples. Once-distilled water was used for the working surface. The physical process was filmed with a Fastax motion picture camera at a speed of 2500 frames/sec in transillumination. The quantity of heat withdrawn from the bubble vapor volume was determined from the equation

$$q_{\mathrm{lat}} = \frac{\Sigma V_i r \gamma_2}{A\tau}.$$

The volume of each bubble, which had a nonspherical shape, was calculated by addition of the volumes of 15 to 20 cylinders into which the bubble was partitioned.

A comparison of the experimental boiling data for a single vaporization center with the bubble-boiling curve for a large surface shows that both processes are similar in terms of their main characteristics. Agreement is also observed with respect to the parameters D_0, f, and D_0f. We note certain features of the heat-transfer processes on a small surface. Thus, boiling is initiated at thermal loads [(35 to 50) $\cdot 10^3$ W/m^2] higher than on the well-developed surface. This result is possibly attributable to the fact that the probability of the inception of a vaporization center on the small surface is also small (all other conditions being equal).

The results of the tests in which the latent heat transfer was determined are presented in Table 1. It is seen that the latent heat-transfer fraction q_{lat}/q varies from 0.25 to 1.15. This parameter is observed to depend on: a) the time during which the surface is covered with vapor; if the surface is free of growing bubbles some of the time, i.e., if there is a large time between bubbles or series of bubbles, heat transfer

---

Physics and Power Institute, Obninsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 18, No. 5, pp. 910-915, May, 1970. Original article submitted March 20, 1969.

TABLE 1. Experimental Data on the Boiling of Water for a Single Vaporization Center

Test No.	$q\cdot 10^{-2}$ W/m^2	ΔT, °C	$\alpha\cdot 10^{-3}$ W/m$^2\cdot$°C	D_0, mm	f, sec^{-1}	D_0f, mm/sec	q_{lat}, 10^{-3} W/m^5	$\frac{q_{lat}}{q}$	$\tau_{lps}/\tau_{gr}+\tau_{lps}$	$\frac{D_0}{d_{hs}}$	v, cm^3/sec	$p\cdot 10^{-5}$, N/m^2
22	39	4,3	9	2,92	13,3	39	44	1,14	0	1,12	0,173	1,01
23	70	6,2	11,2	2,31	41	91	68	0,97	0	0,89	0,59	
24	93	7,8	11,9	3,32	19	63	93	1,00	0	1,28	1,21	
38	43	5,6	7,7	1,63	80	131	22	0,51	0,05	0,43	0,183	
39	78	8,4	9,3	2,17	92	200	60	0,77	0	0,57	0,50	
40	106	10	10,6	2,85	65	185	94	0,90	0	0,75	0,786	
65	242	13	18,6	4,15	4,9	20	78	0,32	0,9	2,07	0,182	
72	64	8,4	7,6	3,53	7,9	28	35	0,56	0,85	1,18	0,184	
73	102	8,4	12,2	2,74	39	107	80	0,79	0,55	0,91	0,417	
74	132	9,2	14,3	2,53	70	176	114	0,87	0,15	0,85	0,59	
75	85	10	8,5	2,22	34	76	37	0,44	0,66	0,74	0,192	
77	170	11,4	14,9	2,91	66	192	164	0,97	0	0,97	0,853	
86	97	7	14	1,82	54	98	84	0,86	0	0,75	0,327	
87	152	9,6	15,9	2,37	68	162	126	0,83	0,04	0,91	0,492	
88	231	12,7	18,2	3,04	50	150	187	0,81	0	1,17	0,73	
106	80	5,5	14,5	0,93	103	96	68	0,85	0	0,55	0,442	3,0
120	105	6	17,4	0,9	62	56	26	0,25	0,1	0,53	0,237	2,0

is realized during this time by convection alone; b) the ratio of the diameters of the bubble and heating surface. It may be assumed that heat transfer is realized beneath the bubble by "latent" heat transfer, while on the rest of the surface heat is withdrawn by convection of the liquid, i.e., if $D_0 < d_{hs}$ (diameter of the heating surface), then $q_{lat}/q < 1$.

Taking these dependences into account, we calculated the thermal balance of the heating surface. The results of the calculation are given in Fig. 1; the points fit the straight line $(q_{lat} + q_{conv})/q = 1$ with $\pm 15\%$ deviation. For the calculation of q_{conv} we used the value of the heat-transfer coefficient from our experimental data on natural convection on a small surface. Thus, the thermal balance of the surface is given without regard for the turbulence effects created by the bubbles.

In several series of tests the lapse time was roughly equal to zero, and the mean bubble diameter at detachment was equal to the heater diameter. In this case there is no convective heat transfer, and all the heat from the heating surface must be contained in the vapor volumes of the bubbles. The test results indicate that indeed $q_{lat} = q$ in this case.

We draw the following conclusions on the basis of our experiments on the role of latent heat transfer: 1) all the heat generated by the surface over an area equal to the projection of the mean bubble diameter at detachment is spent in the formation of bubbles at each vaporization center when $\tau_{lps} \approx 0$; 2) the latent heat-transfer fraction increases with the thermal load, and at each vaporization center the ratio q_{lat}/q attains a value of unity with the buildup of a continuous vapor-jet regime.

A second group of tests was carried out to study the turbulence-generating effects of the bubbles through the simulation of boiling by gas bubbling. During the growth of the gas bubble there is no latent heat of vaporization spent in its formation (at a liquid temperature well below the saturation temperature); on the other hand, the turbulence effects of the gas bubble do not differ from those created by a vapor bubble in boiling, i.e., all the heat flux near the bubble-generating center is withdrawn by turbulent convection.

The boiling simulation tests were conducted on a working section different from the one described above in that now the rod had a lengthwise bore running through it, 0.9 mm in diameter, to deliver the gas to the surface. On this working section we first obtained data on natural convection at distillate temperatures of 17, 55, and 75°C, along with boiling data for identification with the "solid rod" apparatus (the boiling curves are similar in both cases, differing by 10 to 15%); then in the nickel diaphragm we punched a hole 0.65 mm in diameter at the center of the inner duct and conducted our gas bubbling experiments.

In the boiling simulation tests the range of gas volumetric flow rates spanned the entire vapor-rate interval obtained in boiling; the parameters D_0, f, D_0f, and $dR/d\tau$ also concurred, i.e., similarity conditions were preserved by and large between the processes.

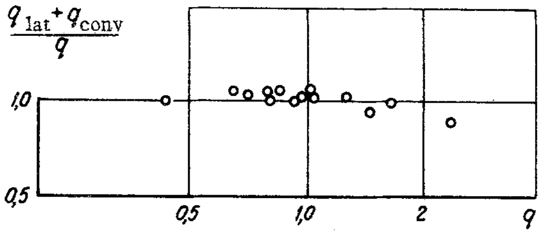

Fig. 1

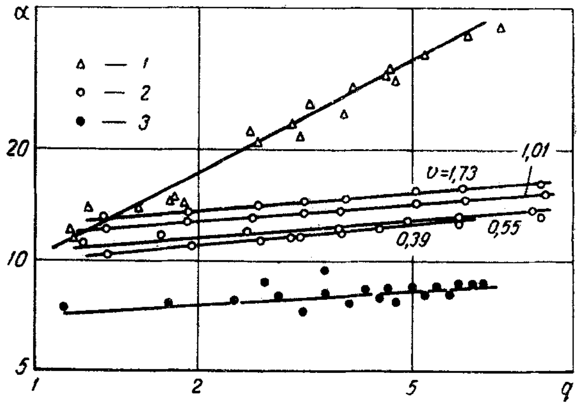

Fig. 2

Fig. 1. Sum of latent heat transfer (measured) and heat flux (calculated) due to natural convection versus measured total heat flux ($q \cdot 10^{-5}$, W/m^2).

Fig. 2. Heat-transfer coefficient ($\alpha \cdot 10^{-3}$ W/m$^2 \cdot$deg) versus heat flux ($q \cdot 10^{-5}$, W/m^2) in the simulation of boiling by gas bubbling; liquid temperature 17°C; v is the gas volumetric flow rate, cm^3/sec: 1) boiling; 2) gas injection; 3) free convection.

The results of the bubbling tests at a liquid temperature of 17°C are given in Fig. 2; similar results were obtained at T = 55 and 75°C.

Analyzing the experimental data, we note the following: an increase in the gas flow rate improves the heat transfer, but only within definite limits (no more than 20 to 100% over natural convection conditions); the graphic dependence $\alpha(q)$ for gas bubbling is parallel to the line representing heat transfer in natural convection. The experimental results definitely imply that the creation of turbulence in the boundary layer by bubbling does not yield as high heat-transfer coefficients as in boiling. For a quantitative determination of the agitating efficiency of the bubbles we need to introduce into the heat-transfer equation the parameter $D_0 f$, which is common to the bubbling and boiling processes. It is apparent from Fig. 3 that the product $D_0 f$ increases with the gas flow rate, and simultaneously the heat transfer improves. Consequently, $D_0 f$ must enter into the numerator of the dimensionless complex, which may be represented in the form

$$\frac{qD_0f}{\sigma g} = \frac{(qD_0^2)\left(\frac{D_0f}{g}\right)}{(\sigma D_0^2)} = \frac{\text{(heat flux)} \times \text{(time)} = \text{work of thermal forces}}{\text{work of surface formation}}$$

The simulation results are generalized by the equation

$$\mathrm{Nu} = 3050\left(\frac{qD_0f}{\sigma g}\right)^{0.15}. \qquad (1)$$

The deviation from the average line is ±15%. The bubble-boiling data appear to obey two relations in the adopted dimensionless coordinates (the experimental results were processed only for p = 1 atm,

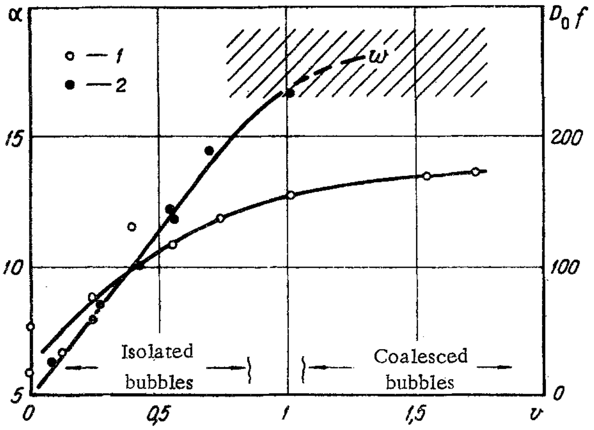

Fig. 3. Heat-transfer coefficient ($\alpha \cdot 10^{-3}$, W/m$^2 \cdot$deg) (1) and bubble growth rate ($D_0 f$, mm/sec) (2) versus gas volumetric flow rate (v, cm^3/sec) in gas bubbling; w is the bubble ascent rate.

because the boiling simulation study was carried out at this pressure). For low heat fluxes (in the isolated-bubble regime) the boiling data are generalized by Eq. (1). When the regime of vertical coalescence of the bubbles sets in ($q \approx 1.5 \cdot 10^5$ W/m^2 at $p = 1$ atm), the growth rate attains a maximum under the given conditions (Fig. 3), and the results of the boiling tests are described by the relation

$$\mathrm{Nu} = 415 \left(\frac{qD_0 f}{\sigma g} \right)^{0.7}, \tag{2}$$

in which $D_0 f$ = const and is equal to half the bubble ascent rate under the given conditions (0.15 m/sec in water at $p = 1$ atm).

We conducted an experiment with a constant surface thermal load, but a variable gas flow rate. The results are given in Fig. 3. It is seen that the heat-transfer coefficient attains a maximum in transition from the isolated-bubble regime to the coalesced-bubble regime. It is clear that a limit is imposed on the enhancement of the role of turbulence generation by the bubble ascent rate, i.e., each vaporization center can withdraw only a limited quantity of heat from the surface by turbulent convection. A further increase in the thermal load induces an abrupt change in the density of active vaporization centers and, hence, in the heat-transfer coefficient. The foregoing discussion explains why the experimental data on boiling follow the two dependences (1) and (2).

Consequently, the creation of turbulence in the boundary layer by bubbles, being proportional to the growth rate $D_0 f$, is nevertheless bounded and small (as compared, say, with the action of forced convection of the liquid). Our experiments with the simulation of boiling by gas bubbling support the conclusions drawn from the experiments involving direct measurements of the latent heat transfer.

LITERATURE CITED

1. M. Jakob, Heat Transfer, New York (1949).
2. G. N. Kruzhilin, Izv. Akad. Nauk SSSR, OTN, Énergetika i Transport, No. 7 (1948).
3. S. S. Kutateladze, Heat Transfer in Condensation and Boiling [in Russian], Mashgiz (1952).
4. C. Rallis and H. Jawurek, Internat. J. Heat Mass Transfer, 7, No. 10 (1964).
5. N. Zuber, Appl. Mech. Rev., 17, No. 9 (1964).
6. R. Gaertner, Teploperedacha, 87, No. 1 (1965).
7. S S. Kutateladze, et al., Inzh.-Fiz. Zh., 8, No. 1 (1965).
8. A. I. Leont'ev and A. G. Kirdyashkin, Inzh.-Fiz. Zh., 9, No. 1 (1965).