HEAT TRANSFER IN LIQUID OXYGEN BOILING IN A LARGE VOLUME

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UDC 536.423.1:546.21

The heat transfer in liquid oxygen boiling in the temperature range –194 to –153°C at pressures of $(0.025\text{-}1.08) \cdot 10^6$ N/m^2 was experimentally investigated. The empirical dependence of the heat-transfer coefficient on thermal flux density and pressure is derived.

At the present time there is no complete theory of the boiling process which permits the calculation of certain heat-transfer characteristics which are important in practical applications. In many cases experimental studies remain the most reliable method of obtaining the quantitative characteristics of the boiling process under different conditions. This is especially true for cryogenic liquids, which are finding wider application in contemporary technology, and for which the boiling process has yet to be adequately studied [1].

This study will be dedicated to an examination of heat transfer in liquid oxygen boiling in a large volume in the region of moderate pressures (to 10^6 N/m^2), since in this region no detailed experimental investigations have been conducted [2, 3].

A schematic diagram of the experimental apparatus is presented in Fig. 1 [4]. The essential part of the apparatus consists of four steel shells placed inside each other and vacuum sealed by lids. These shells form two Dewar flasks of special shape. The shells are provided with observation windows 1. The internal volume 2 of the inner Dewar flask served as the working space. The volume 3 external to the inner flask serves as a buffer zone, being filled with a heat-transfer gas during the experiment by means of valve 4 and pipe 5; valves 6, 7 are mounted on its cover. The internal volume of the outer Dewar flask 8 is filled with liquid nitrogen through pipe 9 and serves as a thermostat, eliminating heat flow to the inner Dewar flask. The condenser 10 is located inside the thermostat volume. In the volume 11, external to the outer flask a high vacuum is maintained.

Boiling studies were conducted with a tubular horizontal heater 12 with polished surface (tube of 1Kh18N9T stainless steel; external diameter $8 \cdot 10^{-3}$ m, wall thickness $3 \cdot 10^{-4}$ m, length 0.1 m), which is attached to copper current leads 13. The current leads pass through the lids of all the cylinders.

The temperature of the heater working surface was measured with a copper – constantan thermocouple, the test junctions of which were placed within the heater in thermal contact with the wall surface. The reference junctions of the thermocouple were located in a brass channel 14, situated within the working space, which allowed measurements of the difference between the temperature of the interior wall and the average volume temperature of the liquid being studied. The temperature head between the external surface of the heater and the liquid volume is found from the measured temperature difference by calculating the temperature drop over the heater wall thickness [5].

To measure the emf of the thermocouple a compensation system was employed, including an R 306 potentiometer and an M 195/1 mirror galvanometer. The temperature of the volume of the liquid oxygen was measured by five thermocouples 15, located at various heights in the working space, as well as a platinum resistance thermometer 16.

Physicotechnical Institute of Low Temperatures, Academy of Sciences of the Ukrainian SSR, Khar'kov. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 21, No. 2, pp. 276-282, August, 1971. Original article submitted November 16, 1970.

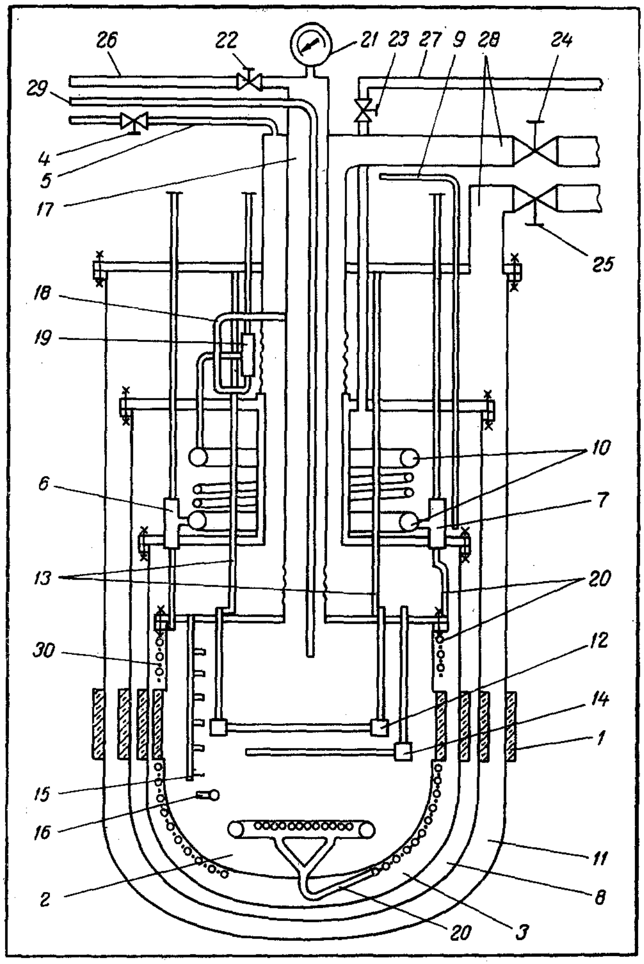

Fig. 1. Schematic diagram of experimental apparatus.

The heater was fed by a VU-12/600A rectifier.

When the liquid oxygen boils, the vapor is fed through pipes 17, 18 and valve 19 to condenser 10 where it is condensed, the condensate being returned to the working space through valve 7 and pipe 20.

The oxygen vapor pressure in the working volume was measured by an MO standard manometer 21, to 10 kgf/cm^2.

Studies were conducted with 99.95% pure liquid oxygen.

Before experiments the working volume of the apparatus was carefully rinsed with ethanol, and then evacuated by heating and exhaust through valves 22, 23, 24, 25 and pipes 26, 27, 28. The working volume is filled to the upper lid with liquid oxygen from pipe 29, while the thermostat volume is filled with liquid nitrogen. By heating the liquid oxygen with the auxiliary heater 30 the necessary temperature and pressure conditions were obtained in the working volume.

Experiments to study the heat exchange in the boiling of liquid oxygen were conducted at thermal flux densities q between 40 and 170,000 W/m^2. During the experiments the temperature of the liquid oxygen varied –194 to –153°C, and the pressure in the range $(0.025\text{-}1.08)\cdot 10^6$ N/m^2.

Allowing for error in measuring the current and voltage drop at the heater, the error in determining q was ±6%. The corresponding error in the determination of the temperature drop Δt was ±20%, and that for the heat-transfer coefficient ±26%.

For 12 pressure values the dependence of the heat-transfer coefficient on the thermal flux density q was determined; the results are shown in Fig. 2. The heat-transfer coefficient was determined from the formula

$$\alpha = q/\Delta t. \tag{1}$$

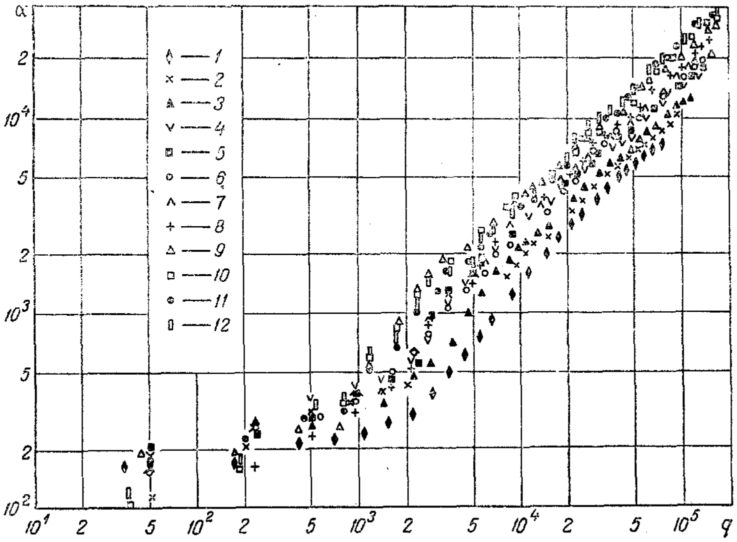

Fig. 2. Dependence of heat-transfer coefficients on thermal flux density: 1) P = 0.025 N/m^2; 2) 0.098 $\cdot 10^6$; 3) 0.196 $\cdot 10^6$; 4) 0.294 $\cdot 10^6$; 5) 0.392 $\cdot 10^6$; 6) 0.49 $\cdot 10^6$; 7) 0.59 $\cdot 10^6$; 8) 0.686 $\cdot 10^6$; 9) 0.784 $\cdot 10^6$; 10) 0.88 $\cdot 10^6$; 11) 0.98 $\cdot 10^6$; 12) 1.08 $\cdot 10^6$.

The dependence of q_{cr}/q_{0cr} on saturation pressure P is given in Fig. 3. For comparison, data from [2, 3] are also shown in Fig. 3. The character of the dependence obtained in the present study is indistinguishable from that calculated using the data of [2, 3]. The departures in values of q_{cr}/q_{0cr} lie within the limits of agreement of the results of the various authors.

The studies were conducted for each of the pressures over the range from pure convection to the first critical thermal flux.

Visual observations showed that, at thermal flux densities q from 50 to 2100 W/m^2 in the pressure range examined, liquid boiling began in particular regions of the heater. With an increase in q to 5000 W/m^2, there appeared new active centers of vapor formation, which generated vapor independently of each other (isolated bubble mode). With further increase in q to 30,000 W/m^2, there occurred a fusion of the separate vapor bubbles, at first at some distance from the heater, and then on the heater itself (mode of fusion of individual bubbles into a vapor structure, "the vapor mushroom"). At q values above 30,000 W/m^2 developed bubble boiling was observed (region of vapor mushrooms [6]).

The function characterizing heat transfer (Fig. 2) does not have the irregularities noted in [3].

The experimental data presented in Fig. 2 can be represented by the following empirical equation found by the method of least squares:

$$\alpha = 10.5 \cdot 10^{-2} P^{0.25} q^{0.75}. \tag{2}$$

The heat-exchange data obtained in our study of the boiling of liquid oxygen at atmospheric pressure were found to be in good agreement with the results of [7], where a horizontal steel pipe served as a heater, while they differed on the average by 10% from the results of [5], where a vertical tubular copper heater was employed. The results of the well-known studies [2, 3] using a planar platinum heater over a wide pressure range are at variance with our results. These departures are evidently connected with the differences in heater geometry and material.

We will compare the results with some semiempirical formulae for heat transfer in bubble boiling*:

1) Kutateladze [10]

$$\frac{\alpha}{\lambda}\left(\frac{\sigma}{g(\rho_l-\rho_v)}\right)^{1/2} = 7.0 \cdot 10^{-4}\left[\frac{q}{L\rho_v a}\left(\frac{\sigma}{g(\rho_l-\rho_v)}\right)^{1/2}\right]^{0.7}\left[\frac{P}{\sigma}\left(\frac{\sigma}{g(\rho_l-\rho_v)}\right)^{1/2}\right]^{0.7} \Pr_l^{-0.35}; \tag{3}$$

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* Unfortunately, they cannot be compared with the results of Tien [8] and Lienhard [9], which include parameters related to the number of active boiling centers, since corresponding observations were not made in our study.

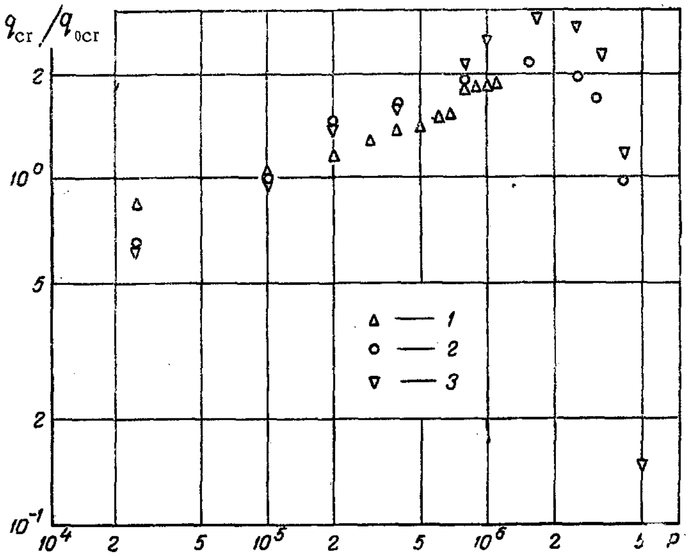

Fig. 3. Dependence of q_{cr}/q_{0cr} on pressure: 1) data of present study; 2) [2]; 3) [3].

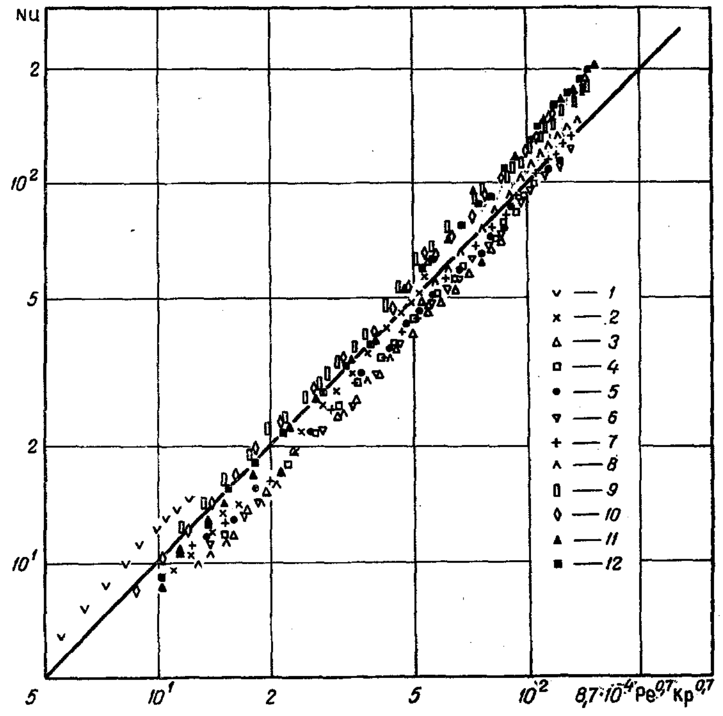

Fig. 4. Generalized experimental data according to Eq. (6) for liquid oxygen boiling in a large volume [$\mathrm{Nu} = (\alpha/\lambda)(\sigma/g(\rho_l - \rho_v))^{1/2}$, $\mathrm{Pe} = (q/L\rho_v a)(\sigma/g(\rho_l - \rho_v))^{1/2}$, $\mathrm{Kp} = (P/\sigma)(\sigma/g(\rho_l - \rho_v))^{1/2}$]. Notation as in Fig. 2.

2) Ronsenow [11]

$$\frac{c_l\,\Delta t}{L} = N_{Tl}\left[\frac{q}{\mu L}\left(\frac{\sigma}{g(\rho_l - \rho_v)}\right)^{1/2}\right]^{0.33}\mathrm{Pr}_l^{1.7}, \tag{4}$$

where $N_{Tl} = 0.013$;

3) Gilmour [12]

$$\frac{L\rho_v}{c_l\rho_l\,\Delta t} = 0.001\left(\frac{\rho_l D q}{\mu L \rho_v}\right)^{-0.3}\left(\frac{P}{\rho_l g \sigma}\right)^{0.425}\mathrm{Pr}_l^{-0.6}; \tag{5}$$

4) Borishanskii and Minchenko [13]

$$\frac{\alpha}{\lambda}\left(\frac{\sigma}{g(\rho_l-\rho_v)}\right)^{1/2}=8.7\cdot10^{-4}\left[\frac{q}{L\rho_v a}\left(\frac{\sigma}{g(\rho_l-\rho_v)}\right)^{1/2}\right]^{0.7}\left[\frac{P}{\sigma}\left(\frac{\sigma}{g(\rho_l-\rho_v)}\right)^{1/2}\right]^{0.7}. \qquad (6)$$

As is evident from Fig. 4, the departure of the average values of our results from Eq. (6) does not exceed 15-20%. Data calculated from Eqs. (3) and (4) depart from ours by ±30%, while the departure of of our results from Eq. (5) is 80%.

Our results can best be described by the following dimensionless relationship, obtained by the method of least squares (numerical values for the physical properties of liquid oxygen were taken from [14]):

$$\frac{\alpha}{\lambda}\left(\frac{\sigma}{g(\rho_l-\rho_v)}\right)^{1/2}=5.763\cdot10^{-4}\left[\frac{q}{L\rho_v a}\left(\frac{\sigma}{g(\rho_l-\rho_v)}\right)^{1/2}\right]^{0.75}\left[\frac{P}{\sigma}\left(\frac{\sigma}{g(\rho_l-\rho_v)}\right)^{1/2}\right]^{0.71} \qquad (7)$$

with change in the limits of the defining criteria

$$1.5\cdot10^3<\frac{P}{\sigma}\left(\frac{\sigma}{g(\rho_l-\rho_v)}\right)^{1/2}<3\cdot10^5,$$

$$1.5\cdot10^3<\frac{q}{L\rho_v a}\left(\frac{\sigma}{g(\rho_l-\rho_v)}\right)^{1/2}<3\cdot10^4.$$

Equation (7) has the same structure as Eq. (6), differing somewhat in the values of the numerical coefficients and exponents.

The dimensional equation (2) and the dimensionless equation (7) describe our data with a divergence of ±10%.

For the calculation of heat-transfer coefficients for liquid oxygen boiling in a horizontal tubular heater in the region of moderate pressures (up to 10^6 N/m^2) the equation of Borishanski and Minchenko, Eq. (6), may be recommended, together with Eqs. (2) and (7).

NOTATION

q	is the heat flux density, W/m^2;
Δt	is the temperature head, deg;
α	is the heat-transfer coefficient, W/m$^2\cdot$deg;
λ	is the thermal conductivity, W/m$\cdot$deg;
g	is the acceleration due to gravity, m/sec^2;
σ	is the coefficient of surface tension;
L	is the latent heat of vaporization, J/kg;
a	is the thermal diffusivity, m^2/sec;
P	is the system pressure, N/m^2;
c	is the specific heat capacity, J/kg$\cdot$deg;
D	is the diameter of the tubular heating surface, m;
μ	is the dynamic viscosity of liquid phase, kg/m$\cdot$sec;
ρ	is the density, kg/m^3;
$\mathrm{Pr} = c\mu/\lambda$	is the Prandtl number.

Subscripts

l	denotes the liquid phase;
v	denotes the vapor phase;
T	denotes the heating surface;
cr	denotes the critical value
^{0}cr	denotes the critical value at atmospheric pressure.

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