# EXPERIMENTAL INVESTIGATION OF HEAT TRANSFER IN BOILING OF SOME CRYOGENIC LIQUIDS AND CONDENSATION OF THEIR VAPORS

I. G. Shekriladze and D. G. Rusishvili

UDC 536.423

The results of an experimental investigation of heat transfer in the boiling and condensation of nitric oxide, carbon monoxide, and boron trifluoride are given.

Heat transfer in the boiling and condensation of cryogenic liquids has been the subject of numerous investigations. A sufficiently complete body of results has been compiled in [1]. These investigations, however, have not included such cryogenic liquids as nitric oxide, carbon monoxide, and boron trifluoride. An experimental investigation of heat transfer in the boiling and condensation of these compounds, which are used as working fluids in several technological processes, is the subject of the present paper.

The experimental investigation of heat transfer in the boiling and condensation of CO, NO, and $BF_3$ was conducted on the apparatus shown schematically in Fig. 1. Boiling took place in a cylindrical vessel 1, at the bottom of which was the boiling test section in the form of a horizontal stainless steel tube 2 of class 7-8 surface finish, diameter 4.5 mm, and length 53 mm. Condensation took place on the outer surface of the vertical experimental tube 3, which was connected to a liquid nitrogen tank 4. In the middle of tube 3 there was a cloth condensate drain 5 for removal of the condensate formed at the top of the condensation surface. The investigated gas was admitted to vessel 1 through a branch 6, and an inert gas, for creation of the required pressure in the apparatus, was admitted through branch 7. The cryogenic-liquid vapor—inert gas interface during the experiments was always kept much higher than the level of the condensate drain 5, which was above the condensation test section. Branch 8 served for removal of the liquid. The wall of vessel 1 carried a sleeve 9 which contained a thermocouple for measuring the vapor saturation temperature. The saturation pressure was measured with a standard pressure gauge 10. The entire apparatus was encased in a layer of foam-plastic heat insulation 11. The tube 2 was heated by direct passage through it of a current supplied from the electric system through an RNO-250/10 voltage regulator, an OSU-20/05 stepdown transformer, and leads 12.

Figure 1 also shows the setup of the thermocouples A and B on the boiling and condensation test sections. Tube 2 contained a porcelain tube 13 with a copper—Constantan thermocouple 14. The temperature of the outer surface of tube 2 with internal heat release was calculated from the known relation [2]. A truncated cone 15 of the same material as the condensation section wall 3 (stainless steel) was soft-soldered into this wall 50 mm below the cross section at which the condensate drain was attached. Constantan and stainless steel electrodes were welded to the inner surface and formed the thermocouple 16. Another Constantan electrode, which passed through a thin porcelain tube 17, was welded to the outer surface. Thus, thermocouple 18 measured the temperature of the outer surface of tube 3, while thermocouple 16 measured the temperature of the inner surface. From the temperature drop in the wall of tube 3 we calculated the specific heat flux into the boiling liquid nitrogen coolant due to condensation of the investigated substance. To determine the heat flux on the boiling section we measured the current and voltage drop on the experimental tube 2. The emf's of the thermocouples were measured in a compensation circuit incorporating an R306 potentiometer, an M195/3 galvanometer, and a second-class standard element.

Before the start of the experiments we calibrated the thermocouples at the evaporation temperature of nitrogen and the melting points of pentane, ethyl alcohol, acetone, and propanol-2.

The maximum error in determination of the heat-transfer coefficients in the conducted experiments did not exceed 15%.

---

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 33, No. 3, pp. 486-490, September, 1977. Original article submitted July 19, 1976.

0022-0841/77/3303-1079$07.50

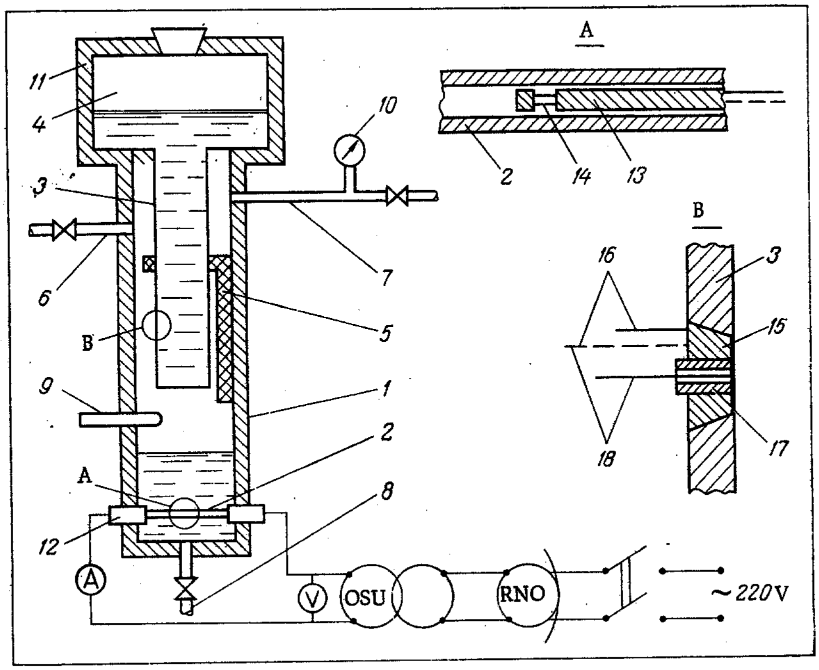

Fig. 1. Diagram of experimental apparatus: 1) cylindrical vessel; 2) boiling section; 3) condensation section; 4) liquid-nitrogen tank; 5) condensate drain; 6, 7, 8) branches; 9) thermocouple sleeve; 10) standard pressure gauge; 11) heat insulation; 12) current leads; 13, 17) porcelain tubes; 14, 16, 18) thermocouples; 15) truncated cone.

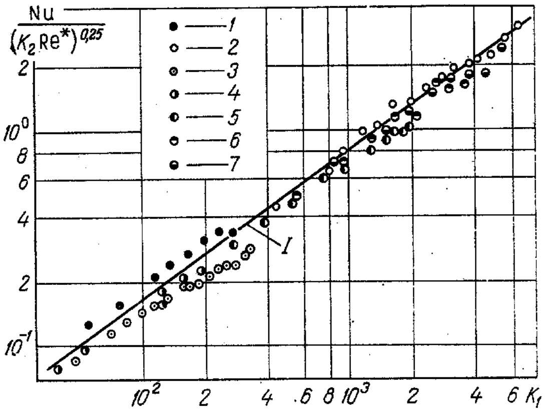

Fig. 2. Correlation of experimental boiling data: 1) $N_2$, 0.1 MPa; 2) CO, 0.45; 3) NO, 0.185; 4) $BF_3$, 0.1; 5) $BF_3$, 0.57; 6) $BF_3$, 0.85; 7) $BF_3$, 1.25 MPa. I indicates $Nu = 0.7 \cdot 10^{-2} K_1^{0.7} (K_2Re^*)^{0.25}$.

To test the accuracy of the investigation technique we first made experimental determinations of the heat-transfer coefficients in the boiling of distilled water and nitrogen at atmospheric pressure. A comparison of the experimental data with known relationships for these liquids [3, 1] gave satisfactory results.

The main experiments, in which we investigated carbon monoxide at a pressure of 0.45 MPa, nitric oxide at 0.185 MPa, and boron trifluoride at 0.1, 0.57, 0.85, and 1.25 MPa, covered the whole region of nucleate boiling up to the critical heat loads. The values of these loads were $0.32 \cdot 10^6$ W/m$^2$ for CO (at 0.45 MPa); $0.35 \cdot 10^6$ W/m$^2$ for NO (at 0.185 MPa); $0.325 \cdot 10^6$ W/m$^2$ for $BF_3$ (at 0.1 MPa), $0.38 \cdot 10^6$ W/m$^2$ (at 0.57 MPa), $0.415 \cdot 10^6$ W/m$^2$ (at 0.85 MPa), and $0.43 \cdot 10^6$ W/m$^2$ (at 1.25 MPa).

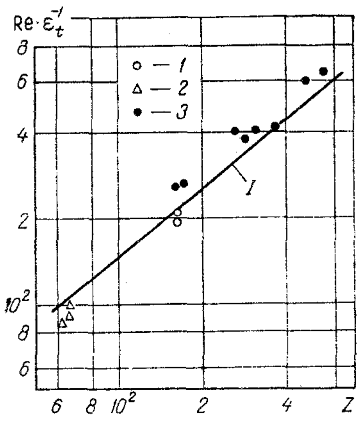

Fig. 3. Correlation of experimental film condensation data: 1) CO, 2) NO, 3) $BF_3$; I) $\varepsilon^{-1}Re = 3.8Z^{0.78}$.

The experimental data for the critical heat fluxes were satisfactorily predicted by Kutateladze's well-known equation [4].

The obtained experimental data on boiling heat transfer were compared with the critical equations most frequently recommended at present. Kutateladze's equation [4] satisfactorily correlated the data for the boiling of carbon monoxide and was consistent, though not so well, with the results for boiling boron trifluoride (the deviation of the experimental data lay in the range —35% to +40%, depending on the pressure). The difference between the experimental and theoretical data for nitric oxide, however, reached 70%. Borishanskii's equation [5] satisfactorily correlated the experimental data for boron trifluoride. The deviation of the experimental data from theory for nitric oxide, however, reached 40%, and for carbon monoxide reached 70%. The experimental data agreed less well with Labuntsov's equation [3] (the difference between the experimental and theoretical data for all three liquids reached about 80%). On the whole, the best agreement for all three liquids was obtained when the heat transfer was calculated from Eq. (22) in [6]. The results of treatment of the experimental data in the coordinates of this equation are shown in Fig. 2. In this treatment the mean effective radius of the nucleation sites on the surface of the experimental tube was taken as 20 $\mu$, in accordance with [6]. The comparison showed that Eq. (22) in [6] agreed sufficiently accurately with the obtained experimental data. The results of this comparison demonstrate once more the universality of this equation, which is valid for practically all heat-transfer media, including liquid metals [6].

The results of investigation of the local heat-transfer coefficients in film condensation on the vertical tube showed that the film flowed in a wavelike manner on the test section. The Reynolds number of the film was 200 for CO, 100 for NO, and 250-650 for $BF_3$. This was reflected in the rate of heat transfer: The experimental values of the heat-transfer coefficients were 10-40% greater than the values calculated from the Nusselt equation [3]. In view of this we treated the experimental data in the coordinates of Labuntsov's criterial equation [3], which takes into account the effect of the wavelike flow of condensate film. As Fig. 3 shows, this equation predicts the experimental results with satisfactory accuracy.

It should be noted that the slightly greater deviation (on the average) of the experimental data from the equations representing boiling and condensation for NO and $BF_3$ in comparison with CO is partly due, in our opinion, to the fact that in the treatment of the results we had to use calculated values for some of the physical parameters of liquid NO and $BF_3$ owing to the lack of experimental data. The calculations were made from the equations recommended in [7, 8].

## NOTATION

$\lambda$, thermal conductivity; $\rho'$, $\rho''$, densities of liquid and vapor, respectively; $v'$, $v''$, reciprocals of liquid and vapor densities; $\nu$, kinematic viscosity; $C_p$, heat capacity of liquid; r, latent heat of evaporation; $\sigma$, surface tension; g, gravitational acceleration; $T_s$, saturation temperature; $T_w$, temperature of heat-transfer surface; $\Delta T = T_s - T_w$; P, absolute pressure; q, specific heat flux; $\alpha$, heat-transfer coefficient; $\varepsilon_t$, correction factor; $\rho_0$, mean effective radius of nucleation sites; x, length of condensation region to point of measurement;

$$\mathrm{Nu} = \frac{\alpha\rho_0}{\lambda}; \qquad K_1 = \frac{q\rho_0^2 r\rho''}{\sigma\lambda T_s};$$

$$K_2 = \frac{\rho'\sigma T_s C_p}{(r\rho'')^2\rho_0}; \qquad \mathrm{Re}^* = \frac{\sqrt{P(v''-v')}}{\nu}\rho_0;$$

$$\mathrm{Re} = \frac{4qx}{r\rho'\nu}; \qquad Z = x\left(\frac{g}{\nu^2}\right)^{1/3}\frac{\lambda\Delta T}{r\rho'\nu}.$$

## LITERATURE CITED

1. M. P. Malkov et al., Manual of Physicotechnical Fundamentals of Cryogenics [in Russian], Énergiya, Moscow (1973).
2. V. A. Osipova, Experimental Heat-Transfer Research [in Russian], Énergiya, Moscow (1969).
3. V. P. Isachenko et al., Heat Transfer [in Russian], Énergiya, Moscow (1969).
4. S. S. Kutateladze, Theory of Heat Transfer [in Russian], Nauka, Moscow (1970).
5. V. M. Borishanskii et al., in: Convective Heat Transfer in Two-Phase and One-Phase Flows [in Russian], Énergiya, Moscow–Leningrad (1964), p. 71.
6. G. V. Ratiani and I. G. Shekriladze, in: Questions of Convective Heat Transfer and Purity of Water Vapor, Metsniereba, Tbilisi (1970), p. 44. [Heat Transfer–Soviet Research, 4, No. 4, 126 (1972).]
7. A. Misnar, Thermal Conductivity of Solids, Liquids, Gases, and Composite Substances [in Russian], Mir, Moscow (1968).
8. R. C. Reid and T. K. Sherwood, The Properties of Gases and Liquids, McGraw-Hill, New York (1966).

---

# EFFECT OF THERMAL DIFFUSION ON PHOTOPHORETIC MOTION OF AEROSOL PARTICLES

Yu. I. Yalamov, E. R. Shchukin, V. B. Kutukov,
A. V. Myagkov, and A. V. Gretskii

UDC 533.7

Expressions for the strength and velocity of photophoresis of moderately large and large nonvolatile aerosol particles in binary gas mixtures are obtained. The effect of thermal diffusion on the photophoretic motion of aerosol particles is taken into account.

The papers on photophoresis that have been published so far (see [1-2], for instance) have ignored the effect of thermal diffusion on the photophoretic motion of aerosol particles, although it is known that thermal diffusion can greatly affect the nature of the motion of aerosol particles in gas mixtures that are inhomogeneous in temperature and concentration [3]. In the present paper we take into account the effect of thermal diffusion on the photophoresis of moderately large and large aerosol particles in binary gas mixtures.

In the construction of the theory we took into account all kinds of slipping of the gas over the particle surface [4], temperature discontinuities [5], and bulk thermal diffusion [6].

As in the other studies of photophoresis, the theory is constructed for spherical particles. The distributions of temperature T, concentration $c_j$ of the gas mixture components, pressure p, and mass velocity $\vec{U}$ of the gas mixture were found by solution of the linearized system of equations (1)-(6). The solution of this system was obtained in a spherical coordinate system (r, Θ) with the origin at the center of the particle and the polar axis directed along the flux of electromagnetic radiation (Θ = 0). With this choice of coordinate system the velocity of the gas flow at infinity is equal, but opposite in sign, to the velocity of photophoretic motion of the particle:

---

Kalinin State University. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 33, No. 3, pp. 491-494, September, 1977. Original article submitted July 27, 1976.

0022-0841/77/3303-1082$07.50