HEAT TRANSFER DURING FILM BOILING OF A SUBCOOLED LIQUID UNDER CONDITIONS OF FORCED FLOW THROUGH CHANNELS

É. K. Kalinin, I. I. Berlin,
V. V. Kostyuk, Yu. S. Kochelaev,
and S. A. Yarkho

UDC 536.423.1:532.542

An experimental study of heat transfer during the film boiling of subcooled liquid nitrogen in pipes with the Reynolds number Re = 80,000-1,500,000 and ψ = 0.20-0.95 is reported.

Film boiling during flow through channels has been studied mainly on saturated liquids [1-4] and slightly subcooled liquids [5]. In this article, the essential points of which have already been covered in an earlier survey [7], the authors present the results of a study concerning the film boiling of a highly subcooled liquid ($\psi \leq 0.95$). Film boiling in this range is characterized by large thermal fluxes in the liquid, necessary for maintaining the saturation temperature T_S at the vapor–liquid interphase surface.

The test apparatus is shown schematically in Fig. 1. As the operating medium we used liquid nitrogen. In order to ensure the supply of single-phase liquid into the operating segment, all pipeline segments with a high thermal capacitance were enclosed inside adiabatic jackets. The appropriate temperature of the liquid at the entrance to the test segment was attained by either heating or depressurizing the liquid in the tank.

The operating segment was placed in a vertical position with the liquid flowing downward.

Prior to the beginning of the experiment, the entire apparatus, except the test segment, was cooled down to the temperature of liquid nitrogen. The test segment was heated up to the appropriate initial temperature. The liquid was let into the operating segment by opening a cutoff valve. While the pipe was in the transient state of cooling, we measured the following parameters and recorded them as functions of time on a model OT-24 and on a model N-700 oscillograph:

1) flow rate, pressure, and temperature of the liquid at the entrance;

2) temperature of the outside surface at 8-12 sections along the pipe.

The temperature of the inside pipe surface and the thermal flux were determined by solving the reverse problem of heat conduction [6]. The maximum calculation errors were 15% in the thermal flux, 2.5°K in the pipe wall temperature, 1°K in the nitrogen temperature, $0.1 \cdot 10^5$ N/m^2 in the pressure, and 1% in the flow rate.

The test results have shown that, within the given range of operating parameters, the thermal flux is proportional to the amount of subcooling of the liquid below its saturation temperature ($T_S - T_L$) and to the flow rate of the liquid, but is independent of the temperature excess ($T_W - T_S$). Physically this can be explained as follows. When the liquid enters a pipe whose temperature is far above the critical point of the liquid, the liquid becomes separated from the pipe wall by a layer of vapor. If the liquid is subcooled below the saturation temperature, then the thermal flux from the wall q_W passes through the vapor film toward the interphase boundary, where it is then spent on heating the liquid core and evaporation. The thermal flux into the liquid q_L does not depend on the temperature excess ($T_W - T_S$), because the temperature

S. Ordzhonikidze Moscow Aviation Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 22, No. 4, pp. 610-613, April, 1972. Original article submitted July 20, 1971.

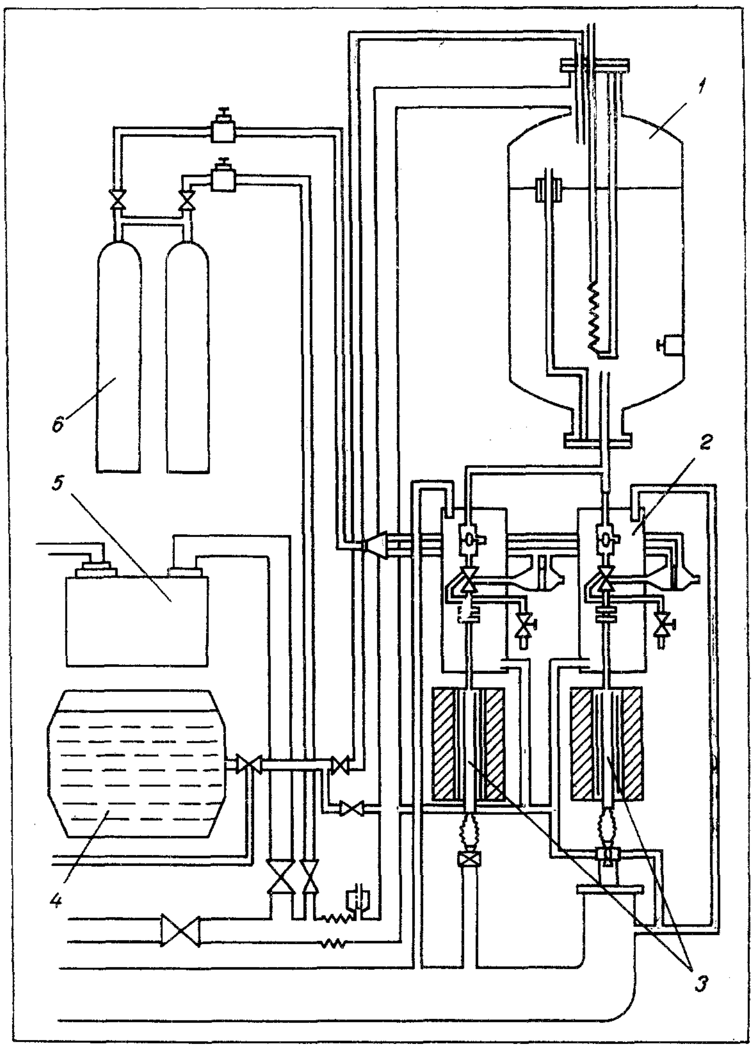

Fig. 1. Basic diagram of the test apparatus: 1) operating container; 2) cooling jacket; 3) operating segments; 4) transporting tank; 5) vacuum pump; 6) pressurizing system.

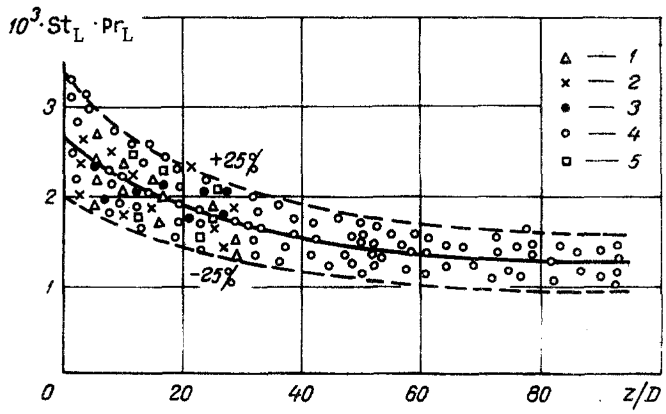

Fig. 2. Variation of the dimensionless thermal flux along a segment where film boiling occurs: 1, 4, 5) steel; 2, 3) copper; 1) D = 4 mm and δ = 1 mm; 2) D = 10 mm and δ = 1 mm; 3) D = 10 mm and δ = 5 mm; 4) D = 9.7 mm and δ = 2 mm; 5) D = 20 mm and δ = 1 mm.

at the interphase boundary stabilizes at the saturation point T_s. As the amount of subcooling ($T_s - T_L$) increases, the thermal flux into the liquid q_L increases too, while the thickness of the vapor film decreases and the thermal flux spent on evaporation becomes negligibly small; thus $q_W \approx q_L$.

An increasing flow rate causes the thermal flux in the liquid to increase, as a result of a higher turbulent thermal conductivity of the latter.

The thermal flux decreases along a channel, because the amount of subcooling of the liquid decreases along it and the structure of the turbulent liquid core changes.

The test results can be generalized by the following criterial relation (Fig. 2):

$$\mathrm{St}_L = 0.0012\,\mathrm{Pr}_L^{-0.6}\left[1 + 1.22\exp\left(-0.036\frac{z}{D}\right)\right]. \tag{1}$$

Here z is the distance of a given section from the point where film boiling begins, calculated with the consideration that the film boiling juncture point moves along the channel.

Formula (1) applies to the following ranges of parameter values:

$$\mathrm{Re} = 8\cdot 10^4 - 1.5\cdot 10^6;\quad \frac{z}{D} = 7 - 100;\quad \mathrm{Pr}_L = 1.9 - 3.3;\quad P/P_{crit} = 0.06 - 0.63;$$

$$\psi = 0.02 - 0.95;\quad \Theta \leqslant \frac{0.0115\psi^{0.5}}{1 + 0.3\Psi + 1.3\exp(-0.4\Psi)}\left(\frac{\mathrm{Re}}{\bar{\rho}\bar{\mu}}\right)^{0.25}.$$

NOTATION

c	is the specific heat at constant pressure;
D	is the outside diameter of the pipe;
P	is the pressure;
Pr	is the Prandtl number;
q	is the specific thermal flux;
r	is the heat of evaporation;
$\mathrm{Re} = \rho_L u_L D/\mu_L$	is the Reynolds number;
$\mathrm{St}_L = q_L/[\rho_L u_L c_L (T_s - T_L)]$	is the dimensionless thermal flux into the liquid;
T	is the temperature;
u	is the velocity;
z	is the distance from the point at which film boiling begins;
δ	is the pipe wall thickness;
$\Theta = c_V(T_W - T_s)/r$	is the dimensionless temperature excess;
μ	is the dynamic viscosity;
$\bar{\mu} = (\mu_V/\mu_L)_s$;	
ρ	is the density;
$\bar{\rho} = (\rho_V/\rho_L)_s$;	
σ	is the coefficient of surface tension;
$\Psi = 10^{-5}\psi(\rho_V \sigma D/\mu_V^2)^{0.7}/\bar{\rho}$;	
$\psi = c_L(T_s - T_L)/r$	is the dimensionless subcooling.

Subscripts

L	denotes the liquid;
crit	denotes the critical point of the substance;
s	denotes the saturation line;
V	denotes the vapor;
W	denotes the wall.

LITERATURE CITED

1. Z. L. Miropol'skii, Teploénergetika, No. 5 (1963).
2. A. A. Gukhman et al., in: Heat and Mass Transfer [in Russian], Vol. 1, Minsk (1968), p. 192.
3. W. Laverti and W. Rosenow, Teploperedacha, 89C, No. 1 (1967).
4. J. Chi, J. Spacecraft and Rockets, 3, No. 1, 150 (1966).

5. V. K. Koshkin, É. K. Kalinin, et al., in: Heat and Mass Transfer [in Russian], Vol. 2, Minsk (1968), p. 153.
6. O. Burggraf, Teploperedacha, 86C, No. 3 (1964).
7. É. K. Kalinin et al., Proceedings of the Fourth International Conference on Heat Transfer, Versailles (September 4-5, 1970).