A STUDY OF HEAT TRANSFER IN NARROW CHANNELS WITH BOILING NITROGEN

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The coefficient of heat transfer in narrow channels with boiling nitrogen has been determined experimentally.

In recent years researchers have been concerned with the heat transfer during boiling of liquids in narrow channels of diverse geometries. This interest was generated by the multitude of practical applications for the results, especially in the power industry [1-9].

Generally, the heat transfer during boiling and the flow modes of such a common liquid as water have been already studied experimentally in considerable detail.

As to the heat transfer in narrow channels with a boiling liquid, this process will apparently have some specific features distinguishing it from well known boiling modes in large-diameter tubes. In [3], for example, the authors have concluded that boiling in capillaries is a fluctuating process, namely that the liquid heats up while passing through a capillary and at some distance from the inlet begins to effervesce. As a certain superheat level is reached, a vapor bubble nucleates and builds up so as to almost instantaneously cover the entire cross section of the capillary, driving the now isolated slug of liquid toward the capillary outlet. Meanwhile, a backstream appears in the liquid. While the liquid slug is driven out of the capillary, it partly spreads over the capillary walls and forms a boundary film which then evaporates as a result of supplied heat. After complete evaporation, it is replaced by a new portion of liquid and the process repeats itself. The authors have performed over a thousand tests with various liquids, yielding an empirical formula

$$\mathrm{Nu} = 4.4\cdot 10^{-3}\mathrm{Re}_{\mathrm{vap}}^{0.6}\left(\frac{\mathrm{We}}{\mathrm{Re}}\right)^{0.3}\mathrm{Pr}^{0.65}\mathrm{Kp}^{0.55}\left(\frac{d}{l}\right)^{0.6}, \tag{1}$$

which describes the heat transfer between a capillary wall and a boiling liquid on the basis of a data generalization within ±15% accuracy.

The authors studied how the heat transfer is affected by the thermal flux level, the pressure level, the diameter of the capillary, the flow rate of the liquid, and the length as well as the orientation of the capillary. These studies were further extended. On the basis of the model which had been developed in [9] and adopted in [3], the boiling process in small-diameter tubes was evaluated analytically and the results were checked experimentally. The analytical expression for the mean heat transfer coefficient is

$$\bar{\alpha} = q\left\{\frac{qd}{\mathrm{Nu_b}\lambda}\,\frac{l'}{l} + \frac{2}{3}\,\frac{c_\mathrm{b}}{\lambda}\sqrt{\frac{\mu d l}{r\rho'\sigma}}\left[q\left(1-\frac{l'}{l}\right)\right]^{3/2} - \frac{q^2\tau}{2r\rho'\lambda}\left(1-\frac{l'}{l}\right)\right\}^{-1}. \tag{2}$$

Measurements of the heat transfer during boiling in capillaries have shown that, under thermal flux levels within the 10^3-10^4 W/m^2 range, the heat transfer rate during boiling is by one order of magnitude higher in capillaries than in pipes. Owing to the regrettable scarcity of published test data, it is impossible to verify the empirical formula and the analytical relation. For this reason, we resorted to an experiment for the purpose of determining the coefficient of heat transfer in narrow channels with boiling nitrogen or helium.

During the boiling of cryogenic liquids, except helium perhaps, the heat transfer apparently follows the same trends as during the boiling of water [10]. No such analogy has been established between helium

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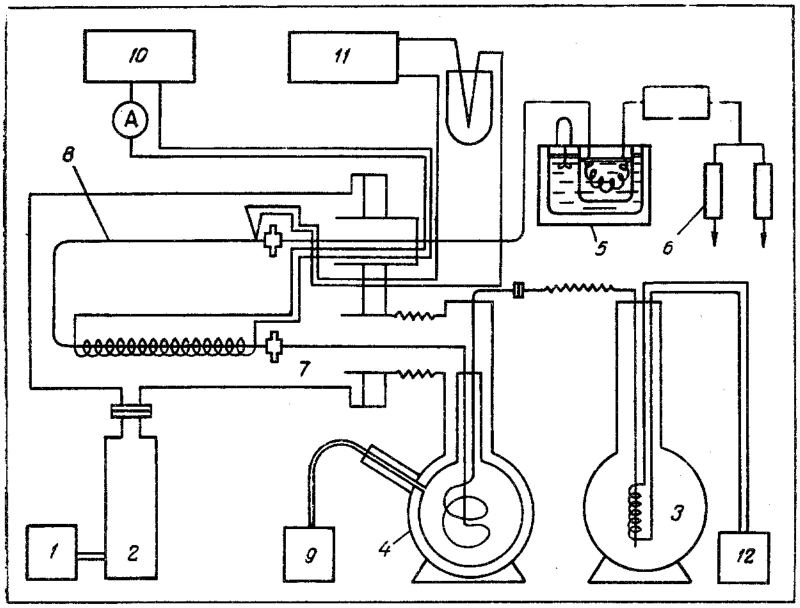

Fig. 1. Schematic diagram of the test apparatus: 1) model VN-2 mechanical pump; 2) model N-2T diffusion pump; 3) main nitrogen container; 4) cooling tank for nitrogen; 5) thermostat; 6) model RS-3 rotameters; 7) vacuum chamber; 8) active capillary; 9) mechanical pump for removing the nitrogen vapor; 10) model U1136° stabilizer; 11) model ÉPP-09 potentiometer; 12) model VSA-5K power supply.

and water, according to the technical literature, but many authors have expressed their doubts as to whether the trends detected in other liquids will be the same in helium with its very narrow temperature range from boiling point (4.2°K) to helium-II transition point (2.17°K)/t = 2.03°K, while there is also no reason to believe that the heat transfer during the boiling of helium should — in principle — be different than during the boiling of other liquids. It seems the process here occurs very fast and without the modal changes noticeable during the boiling of water, but with the technical difficulties in performing the experiment compounded by our imprecise knowledge about the variation of physical properties with temperature and pressure.

For an experimental study of the heat transfer during the boiling of liquid nitrogen, we have developed an apparatus shown schematically in Fig. 1. It included a test tube (Fig. 2), instrumentation for measuring the flow rate and the thermal parameters, a cooling tank for nitrogen, and a main nitrogen container.

For the experiment we used a tube of stainless steel with an inside diameter 1.5 mm and 300 mm long. An acceleration chamber was attached to it at the inlet.

The temperature of the tube wall was measured with 17 copper—constantan thermocouples, their lead wires 0.2 mm in diameter cemented along the tube at equal distances apart with grade BF-2 adhesive. The tube was heated by passing direct electric current through a coil wound around it. The nitrogen flow rate was measured with a model RS-3 rotameter at the tube outlet behind the heater. In order to prevent convective leakage of ambient heat to the tube, we had placed the latter in a vacuum chamber where a pressure of 10^{-5} mm Hg was maintained by continuous suction with a model N-2T diffusion pump in series with a model VN-2 mechanical pump. In order to reduce conductive leakage of heat to the tube from the bearing supports, we had the latter made of thin-walled stainless steel. Radiative heat transfer, the major mode of leakage, was negligible.

The cooling tank for nitrogen was a cryostat consisting of a spherically shaped outer jacket, a vacuum chamber, and a nitrogen vat into which nitrogen was poured periodically from a Dewar flask. The nitrogen in this vat was subcooled by the removal of its vapor. Nitrogen for the test tube was pumped from a Dewar flask at a definite rate through a coil of tubing inside this vat. The nitrogen for the test tube, passing through this coil immersed in subcooled nitrogen, was cooled down to the required test temperature before entering the tube. The flow parameters at the tube inlet were maintained constant.

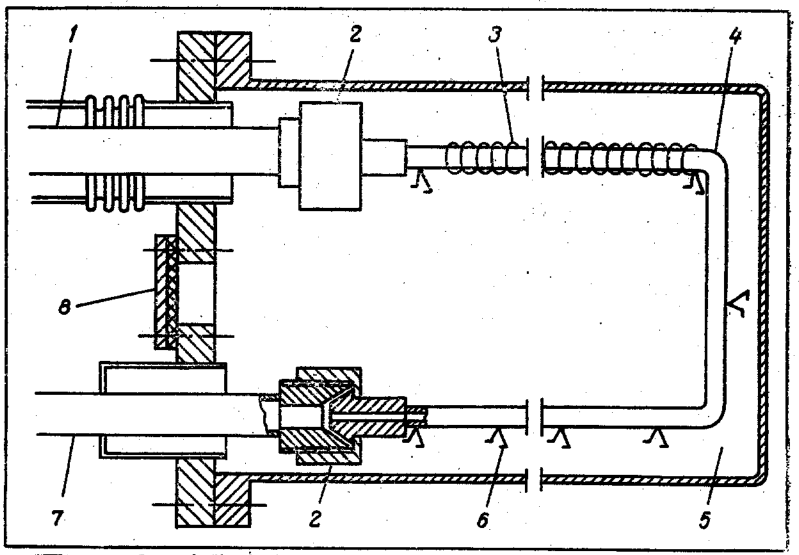

Fig. 2. Schematic diagram of the test segment: 1) acceleration chamber; 2) coupling; 3) heater; 4) active tube; 5) vacuum chamber; 6) thermocouples; 7) outlet stage; 8) socket for thermocouple outlets.

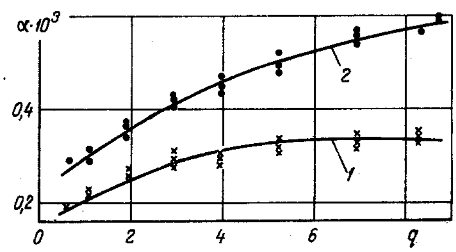

Fig. 3. Heat transfer coefficient α ($W/m^2 \cdot °C$) as a function of the thermal flux density q (kW/m^2), at a flow velocity: 1) w = 0.27 m/sec; 2) w = 0.4 m/sec.

In the course of the experiment, we studied the effect of two parameters on the coefficient of heat transfer during the boiling of nitrogen: the thermal flux over the 0.6-10 kW/m^2 range and the flow velocity over the 0.25-0.4 m/sec range. The test results shown in Fig. 3 represent the heat transfer coefficient as a function of the thermal flux density and of the flow velocity. According to the graph, the heat transfer coefficient increases with an increase in either the thermal flux or the flow velocity. These data agree qualitatively with earlier published data for liquid nitrogen. In addition, a capillary tube with the same inside diameter of 1.5 mm was also used in the experiment and appropriate data pertaining to tubes with smaller diameters (largest diameter 1.13 mm in [5]). A comparison between these values and those in [4] for a tube 0.6 mm in diameter has revealed that our values for $\bar{\alpha}$ are lower within the same range of thermal flux. An explanation for this is that, according to [3, 5], the heat transfer coefficient should regularly decrease as the tube diameter is increased from 0.6 to 1.5 mm. The analytical formula which has been derived in [9] for cryogenic liquids with typically small differences between inlet temperature and boiling point is, unfortunately, valid only for a rather narrow range of thermal flux variation and, therefore, we do not show here the calculated values of $\bar{\alpha}$ — even though these values of $\bar{\alpha}$ calculated according to [2] agree with ours for q = 0.7-1.0 kW/m^2 and w = 0.25 m/sec.

NOTATION

q	is the thermal flux density;
d	is the tube diameter;
λ	is the thermal conductivity;
c_k	is a constant;
l	is the length;
α	is the heat transfer coefficient;
μ	is the dynamic viscosity;
ρ_n	is the density of vapor;
σ	is the surface tension;

τ	is the time;
r	is the latent heat of evaporation;
ρ'	is the density of liquid;
Nu	is the Nusselt number;
Re_{vap}	is the analog of the Reynolds number for a forced flow, with the flow velocity replaced by the evaporation rate;
We/Re_L	is the criterial number for the mass flow rate of liquid;
Pr	is the Prandtl number;
Kp	is the criterial number for the effect of pressure.

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