ESTIMATING THE INTENSITY OF HEAT TRANSFER TO SUPERCRITICAL HELIUM WHEN THE SPECIFIC VARIATION OF THE THERMOPHYSICAL PROPERTIES IS TAKEN INTO ACCOUNT

V. G. Pron'ko* and G. P. Malyshev

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We carry out an analysis of the rational choice of the rules for averaging the thermophysical properties of helium, and on the basis of this analysis we propose a generalizing function for calculating the intensity of heat transfer.

Earlier, in [1], on the basis of an analysis of a large amount of experimental data on heat transfer to helium in the supercritical state in vertical cylindrical channels, we established the existence of regimes with "normal" and "impaired" heat transfer and proposed, for determining the intensity of the heat transfer, a function of the type

$$\mathrm{Nu} = \mathrm{Nu}_0 F, \tag{1}$$

where F is the heat-transfer impairment factor.

The amount of experimental data obtained, the analysis of those data, and the specific form of the structural relation (1) have been discussed in detail in [1, 2] and therefore will not be repeated here.

However, owing to the accumulation of experimental data on heat transfer by purely forced convection in tubes of small diameter [1-9], it became necessary to generalize the experiment further. The existing empirical formulas [1, 5, 10], including a function of the type (1), do not generalize the data over the entire range of investigated regimes of heat transfer in the supercritical region of helium — the "normal," "impaired," and "improved" regimes — or else generalize them with insufficient accuracy (Fig. 1, curves I-III).

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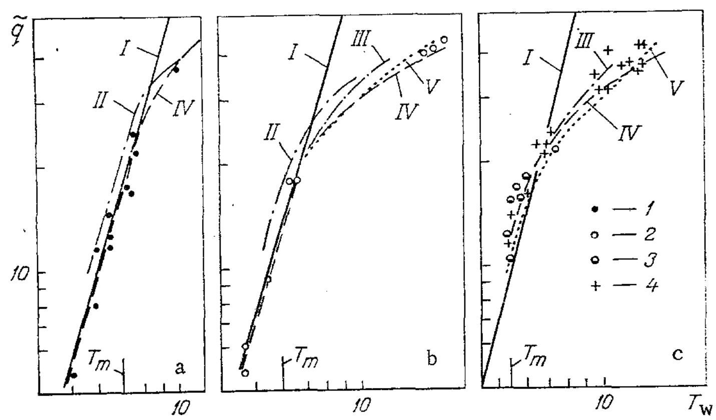

Fig. 1. Comparison of experimental and calculated data ($T_n < T_m$): a) $6 \cdot 10^5$; b) $4 \cdot 10^5$; c) $2.5 \cdot 10^5$ Pa; I) calculation according to [5]; II) according to [1]; III) according to [10]; IV) according to formula (3); V) according to [12]. Experimental data: 1-3) from [3]; 4) from [6]. $\tilde{q}$ in SI units; T in °K.

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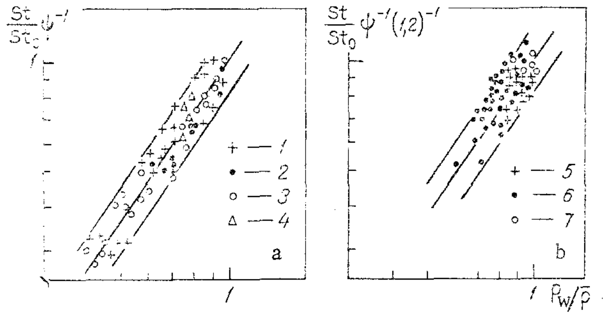

Fig. 2. Generalization of the experimental data: 1) d = 1.40 mm, P = 2.5-6.0·10^5 Pa [3]; 2) d = 1.09 mm, P = 3-15·10^5 Pa [7]; 3) d = 2.13 mm, P = 2.5-20·10^5 Pa [5, 6]; 4) annular channel, d_{eq} = 0.8 mm, P = 3-4·10^5 Pa [2]; 5) d = 1.04 mm, P = 6, 8, and 15·10^5 Pa [1]; 6) d = 0.7 and 1.04 mm, P = 4·10^5 Pa [1, 4]; d = 1.04 mm, P = 3·10^5 Pa [1]; 7) d = 3.0 mm, P = 3-6·10^5 Pa [8].

Taking account of the foregoing, we undertook a search for a new form of a more general function describing the heat transfer in the supercritical region, and the results of that search are given in the present article.

In a number of theoretical studies [11-13], the use of various models (methods) for determining the coefficients of turbulent transfer yielded results which agreed at least qualitatively, and in many cases quantitatively as well, with the experimental data. We shall not discuss in detail the individual shortcomings of these studies or the difficulties of using the recommended methods in practical engineering calculations. The important thing is that agreement with the experimental data was obtained without introducing and taking into account any new physical phenomena which might explain the reasons for the "impairment" or "improvement" of the heat exchange.

In [14] it was shown that even when relatively simple rules are used for the integration (averaging) of the thermophysical properties over the core of the flow, it is possible to obtain a good agreement between the experiment and the approximate estimates in the range of supercritical parameters. This gives us reason to suppose that it is possible to make a rational choice of the rules for averaging the thermophysical properties over the cross section of the flow with respect to supercritical helium.

We made an attempt, on the basis of an analysis of the available experimental data in accordance with the model of the process, to work out a function which would take into account the averaging of the thermophysical properties expressed in terms of fundamental parameters [3]. The search for a new form of function was conducted on the basis of Reynold's analogy: In particular, for the relevant range of variation of the parameters, we used the relations

$$\mathrm{St}_0 \equiv \frac{\alpha}{\overline{\rho u} C_p} \cong \frac{\xi_0}{8}, \quad \frac{q_\mathrm{w}}{\overline{\rho u}} = (i_\mathrm{w} - i_\mathrm{f}) \frac{\xi_0}{8}. \tag{2}$$

The function was obtained in the form

$$\mathrm{St} = \mathrm{St}_0 \left(\frac{\rho_\mathrm{w}}{\overline{\rho}}\right)^{1.45} \psi, \tag{3}$$

where

$$\mathrm{St} = \frac{q_\mathrm{w}}{\overline{\rho u} \Delta i}; \quad \mathrm{St}_0 = \frac{\xi_0}{8}; \quad \overline{\rho} = \int_{T_\mathrm{f}}^{T_\mathrm{w}} \rho_{(T)}\, dT \approx$$

$$\approx \frac{1}{n} \sum_{n=1}^{n \geqslant 10} \rho_\mathrm{w} + \rho_1 + \ldots + \rho_\mathrm{f}; \qquad \psi = \frac{0.60}{(P/P_\mathrm{cr})^4} + 1.$$

Here

$$\xi_0 = 0.3164\,\mathrm{Re}_f^{-0.25} \quad \text{for} \quad \mathrm{Re}_f = 5\cdot 10^3 - 5\cdot 10^4,$$

$$\xi_0 = (1.82\,\lg \mathrm{Re}_f - 1.64)^{-2} \quad \text{for} \quad \mathrm{Re}_f > 5\cdot 10^4$$

$$(T_f < T_m, \quad T_w \gtrless T_m).$$

In the proposed formula (3) the factors $\rho_w/\bar{\rho}$ and $\psi = \frac{0.60}{(P/P_{cr})^4} + 1$ determined the law used for averaging the thermophysical properties.

In Fig. 2a we show the results of generalizing the experimental data of [2, 3, 5-7] using formula (3). It can be seen that the accuracy of approximation is within ±18%. This formula generalizes a set of data in stainless-steel channels for ascending and descending flows of supercritical helium in tubes and in an annular channel.

In Fig. 2b, where the material of the channel is nickel [1, 4] or monel metal [8], the data are generalized with a systematic 20% excess of the calculations carried out according to (3) (a coefficient of 1.2 was used in the processing). We should include in this group the data of [9], where the channel was made of copper.

This result of the generalization is probably the consequence of the way in which the heat exchange is affected by the high axial thermal conductivity of the channel material or the low-frequency oscillations of the flow, which was not discovered during the experiments.

In addition to curves I-III, Fig. 1 also shows curve IV, calculated according to formula (3), and curve V, obtained by means of an analytic expression from [12] based on a theoretical model of surface renewal and penetration. It can be seen that the best agreement with experiment over the entire range of variation of the parameters is found in curve IV, with curve V close to it.

NOTATION

T, temperature; P, pressure; ρ, density; i, enthalpy; $\overline{\rho u}$, mass velocity; q_w, heat flux density at the wall; ξ, resistance coefficient; d, diameter of tube; $\tilde{q} = q_w d^{0.2}/\overline{\rho u}^{0.8}$, reduced heat flux density. Subscripts: f, flow; w, wall; m, pseudocritical; cr, critical; 0, initial conditions.

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CHARACTERISTICS OF DIODE-TYPE HEAT PIPE IN FORWARD MODE AND IN REVERSE MODE OF OPERATION

M. G. Semena, V. M. Baturkin, and B. M. Rassamakin

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Results of an experimental and theoretical study are reported pertaining to a diode-type heat pipe with a liquid plug of the vapor channel in the reverse mode of operation.

Diode-type heat pipes are used in thermal stabilization systems [1-3]. Such heat pipes operating in the forward mode dump heat efficiently into the ambient medium and, for all practical purposes, insulate the object thermally whenever the ambient temperature exceeds its permissible level.

Several experimental studies have dealt with the laws governing the operation of basic thermodiode circuits [1-4]. Theoretical studies have been limited to consideration of a simplified model of transient heat propagation through a diode-type heat pipe with a liquid trap [5], a model which disregards conductive heat transfer in the axial direction. According to some studies [1, 3, 4], diode-type heat pipes designed without moving parts should be most widely used. These include diode-type heat pipes with a coolant trap [4-6] and with a liquid plug in the vapor channel in the reverse mode of operation [1-3].

Selection and application of any particular design version of diode-type heat pipe are largely determined by the transient characteristics. Transient conditions, however, have so far hardly been studied at all. Only the authors of study [6] have discovered that the transient characteristics of a diode-type heat pipe with a coolant trap depend on the magnitude of the initial heat load and on the instant this load has been applied.

These authors made a study of diode-type heat pipes with liquid plugging of the vapor channel under steady and transient conditions in the forward mode and in the reverse mode of operation.

The terminology of zones used in description of the forward mode of operation (thermal resistance R_{hp} minimum) is also used in description of the reverse mode of operation (thermal resistance R_{rev} approaching its maximum) (Fig. 4).

For the experimental part of the study, earlier equipment [7], adapted for tracking transients in a diode-type heat pipe, namely capable of producing a pulse change of ambient temperature and of heat transfer intensity within the heat transfer zone and at the reservoir surface was used.

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