CHARACTERISTICS OF HEAT TRANSFER DURING THE TURBULENT FLOW OF SUPERCRITICAL HELIUM

G. P. Malyshev and V. G. Pron'ko UDC 536 242:536.483

Results are shown of an experimental study concerning the heat transfer during the turbulent flow of supercritical helium through small tubes, as a function of the pressure, the temperature, the velocity, and the thermal flux density.

In certain superconductor devices for power and electrical engineering applications it may be worthwhile to cool and to thermostatize the superconductor with a forced flow of helium at temperatures within the 4.2-10°K range [1-4]. Such apparatus includes various magnetic systems as: energy storage banks, electrical generators, superconducting electrical transmission lines, etc. There helium can circulate through channels inside the stabilized superconductor. The size and the shape of these channels vary, but rather effective channels appear with small diameters [3, 4].

The appropriate thermodynamic state of the coolant is selected not only on the basis of the operating temperature. Several thermodynamic properties of helium, namely its low heat of evaporation ($r = 20.2$ kJ/kg) as well as its relatively lower critical pressure and temperature ($P_{cr} = 2.26 \cdot 10^5$ N/m^2, $T_{cr} = 5.2$°K) than those of other fluids make it most worthwhile to effect the heat removal by circulating helium at above critical pressure and near critical temperature (helium in the supercritical state).

The use of supercritical helium for cooling and thermostatizing a superconductor offers many advantages over the use of gaseous or liquid helium.

These advantages include an increased total heat capacity of the stream, on account of the higher density and the higher specific heat, as well as the absence of clearly defined phase transitions which, if occurring, could result in an appreciable temperature stratification of the helium stream due to the superheating of the vapor phase.

In view of this, a considerable interest has recently developed in studying the heat transfer during a forced flow of supercritical helium through tubes [2-7]. Available test data on that subject [5-7] are extremely limited in scope and contradictory, pertaining mainly to transition modes and to very high velocities (up to $Re = 10^6$). In those references one finds several relations of the $Nu = k \cdot Re^{0.8} \cdot Pr^n$ type, which, unlike the well known relations for one-phase streams with constant thermophysical properties, include various complex parameters accounting for the variation in the thermophysical properties of the stream or for the variation in the temperature of the channel wall. The inevitable discrepancies between estimates on the basis of various proposed formulas are, above all, due to the inadequate research background but also due to the particular thermophysical properties of helium in the supercritical state.

The thermophysical properties of helium are shown in Fig. 1 as functions of the temperature at a $P = 4 \cdot 10^5$ N/m^2 pressure.

In the supercritical range, as is well known, the thermophysical properties of all substances vary rather considerably. This is particularly true of the specific heat at constant pressure, represented by a curve which passes through a sharp peak at definite temperatures and pressures.

Quite recently a few studies have been published concerning the heat transfer in cryogenic fluids: nitrogen and hydrogen [8, 9]. The methods of testing and data evaluation developed for nitrogen and hydrogen cannot be easily applied to helium, however, because the sharp variation in its specific heat (and also

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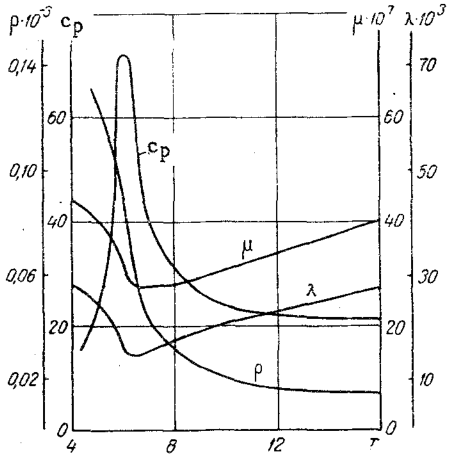

Fig. 1

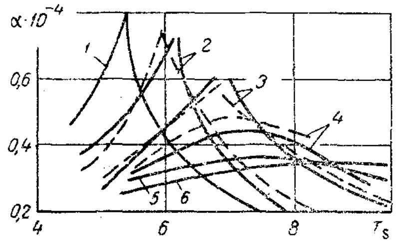

Fig. 2

Fig. 1. Thermophysical properties of helium at a $P = 4 \cdot 10^5$ N/m² pressure, as functions of the temperature T (°K): c_p (J/mole·°K), ρ (kg/m³), λ(W/m·°K), μ (N/sec·m²).

Fig. 2. Heat transfer coefficient α (W/m²·°K) as a function of the stream temperature T_s (°K), at Re = 30,000 and q = 3 kW/m², pressure $P = 3 \cdot 10^5$ N/m² (1), $4 \cdot 10^5$ N/m² (2), $6 \cdot 10^5$ N/m² (3), $8 \cdot 10^5$ N/m² (4), $10 \cdot 10^5$ N/m² (5), $15 \cdot 10^5$ N/m² (6). Solid lines are for the 1.14 × 0.05 mm tube, dashed lines are for the 0.8 × 0.05 mm tube.

in its other thermophysical properties) occurs within a very narrow temperature range overlapping with the range of temperature variation at the channel wall and in the stream. In the case of using supercritical helium, therefore, a characteristic situation arises where the wall temperature T_w and the stream temperature T_s lie on both sides of the temperature T_{max} which corresponds to the maximum specific heat. This peculiarity in the case of supercritical helium makes it imperative, in the authors' opinion, to thoroughly study the variation in the heat transfer rate following a wide variation in the thermophysical properties across a stream section, as a function of the temperature, the pressure, and the velocity.

Such an experimental study was made by the authors, with a turbulent flow of supercritical helium through small tubes under the following conditions: pressure $P = 3 \cdot 10^5$, $4 \cdot 10^5$, $6 \cdot 10^5$, $8 \cdot 10^5$, $10 \cdot 10^5$, and $15 \cdot 10^5$ N/m², stream temperature T_s = 4.5–9.5°K, Reynolds number at the entrance $Re_{en} = 3 \cdot 10^4$–$4.2 \cdot 10^4$, and thermal flux density q = 1.8–5.0 kW/m².

The study was made with an apparatus consisting of a cryostat with liquid helium and a vacuum chamber inside, the latter containing the vertical active test segment. Compressed helium was the working medium fed along a pipe from a tank through a reducer and a nitrogen tub into the cryostat, where it was cooled in two heat exchanger stages by helium vapor in the counterflow mode, then up into the test segment at a temperature within the 4.5–9.5°K range. The stream temperature before the entrance to the test segment was regulated in the second heat exchanger. Along its return path, the compressed helium was heated, throttled, then fed through a gas meter into a gas container. Test data were obtained with two nickel tubes 1.14 mm (dia) × 0.05 mm (thick) and 0.8 mm (dia) × 0.05 mm (thick). The test segment of the first tube was 83 mm long, its hydrodynamic and thermal stabilization segment was 62 mm long. The test segment and the stabilization segment of the second tube were respectively 56 mm and 42 mm long. Along the test segment were installed five model TSG-2 germanium resistance thermometers, while two such probes were installed in the stream at the entrance to and at the exit from the test segment respectively. The temperature was measured by the potentiometer method. The test segment of a tube was heated by passing an electric current through it.

The test data for both tubes have been evaluated in the form of $\alpha = f(T_s)$ curves in Fig. 2 for pressures $P = 3 \cdot 10^5$, $4 \cdot 10^5$, $6 \cdot 10^5$, $8 \cdot 10^5$, $10 \cdot 10^5$, and $15 \cdot 10^5$ N/m² at a Reynolds number Re = 30,000 and a thermal flux density q = 3 kW/m², which corresponded to heat transfer modes at $(T_s, T_w) \leq T_{max}$ and $(T_s, T_w) \geq T_{max}$. The values of the thermophysical properties c_p and ρ were taken from [12], while the missing values of μ and λ were calculated from the data in [13] by the method shown in [14].

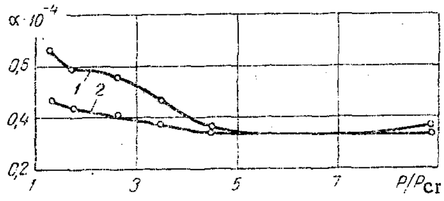

Fig. 3

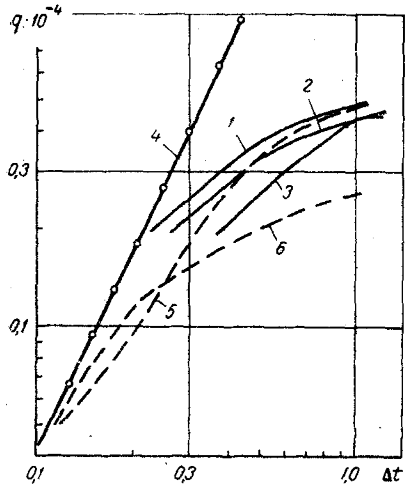

Fig. 4

Fig. 3. Effect of pressure on the heat transfer, within the supercritical range at Re = 30,000 and q = 3 kW/m^2; T^+ = 0.92 (1), 0.83 (2).

Fig. 4. Thermal flux density q (W/m^2) as a function of the temperature difference Δt (°K) in a supercritical stream at $P = 3 \cdot 10^5$ N/m^2: T^+ = 0.92 and Re = 42,000 (1), T^+ = 0.92 and Re = 30,000 (2), T^+ = 0.83 and Re = 30,000 (3), according to the S. S. Kutateladze formula for a large volume [10] (4), for forced flow with X = 0.75 (5) and X = 0.95 (6) [11].

The temperature-dependence of the heat transfer coefficient was considered with reference to the theoretical temperature at a given stream section for which the heat transfer coefficient was measured.

According to the graph, the temperature characteristic of the heat transfer coefficient resembles the temperature characteristic of the specific heat at constant pressure c_p, which indicates a significant effect of the specific heat on the heat transfer rate.

The close correspondence between data for both tubular channels (0.70 and 1.00 mm in diameter respectively) in Fig. 2 suggests that these data may be used for calculating the heat transfer in small channels.

The heat transfer coefficient α as a function of the referred pressure P/P_{cr} is shown in Fig. 3 for referred temperatures T^+ = 0.92 (curve 1) and T^+ = 0.83 (curve 2), corresponding to the range near maximum specific heat and to the range of moderate specific heat respectively.

According to the graph, at $P/P_{cr} \approx 4$ the heat transfer coefficient α is much higher at a near maximum specific heat (curve 1) than at a moderate specific heat (curve 2). The decrease in the heat transfer rate is especially appreciable (curve 1) during an increase of the referred pressure from 3.0 to 4.5, while at referred pressures $P/P_{cr} \geq 4.5$ the heat transfer coefficients at a near maximum specific heat and at a moderate specific heat become almost equal.

Thus, the pressure and the thermophysical properties which depend on it have an appreciable effect on the heat transfer rate at a near maximum specific heat, but only at referred pressures in the $P/P_{cr} \leq 4.5$ range. At a moderate specific heat this effect is negligible over the entire range of referred pressures under consideration here.

The test data have also been evaluated in terms of thermal flux density q from 1.8 to 5.0 kW/m^2 at $P = 3 \cdot 10^5$ N/m^2 as a function of the temperature difference Δt between channel wall and stream, referred to a stream cross section, and are shown in Fig. 4 for Re = 30,000 and for Re = 42.000 at T^+ = 0.92 and 0.83 (curves 1, 2, 3).

It is evident here that the heat transfer rate depends on the thermal flux density, on the thermophysical properties (curves 2, 3), and on the flow velocity (curves 1, 2). The effect of the velocity on the heat transfer rate remains the same here as in the case of a one-phase stream with constant thermophysical properties. The curvature of curves 1, 2, 3 changes at definite points. Such a change corresponds to a transition from the heat transfer mode at $(T_s, T_w) < T_{max}$ to the heat transfer mode at $(T_s > T_{max},$

$T_w < T_{max}$). In the latter mode the heat transfer becomes worse, according to the graph, probably because the boundary layer of a higher-density medium is displaced by a lower-density medium and because the thermophysical properties are poorer at the channel wall.

When the thermophysical properties of supercritical helium vary appreciably along the stream, then the heat transfer rate in every mode will characteristically depend very much on the thermal flux density.

For a comparison between the heat transfer rates in helium under various modes of heat removal (choices of the thermodynamic state), on the same diagram have been plotted $q = f(\Delta t)$ curves for helium boiling in a pool [10] (curve 4) and for helium boiling while forcibly flowing through tubes with various levels of vapor content [11] (curves 5, 6). This comparison indicates that, with the appropriate choice of pressure, temperature, and velocity, the use of supercritical helium yields a sufficiently high rate of heat transfer over almost the entire range of flux densities.

NOTATION

P	is the pressure, N/m^2;
P_{cr}	is the critical pressure, N/m^2;
P/P_{cr}	is the referred pressure;
T_w	is the temperature of channel wall;
T_s	is the temperature of fluid stream;
T_{max}	is the temperature corresponding to the maximum specific heat c_p;
$T^+ = T_w/T_{max}$	is the referred temperature of the stream;
T_{cr}	is the critical temperature;
Δt	is the temperature difference between wall and stream, referred to a stream cross section;
α	is the heat transfer coefficient, $W/m^2 \cdot {}^\circ K$;
c_p	is the specific heat at constant pressure, $J/mole \cdot {}^\circ K$;
$c_{p,max}$	is the maximum specific heat at constant pressure, $J/mole \cdot {}^\circ K$;
q	is the thermal flux density, W/m^2;
ρ	is the density, kg/m^3;
λ	is the thermal conductivity, $W/m^2 \cdot {}^\circ K$;
μ	is the dynamic viscosity, $N/sec \cdot m^2$;
X	is the vapor content in the system.

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