EXPERIMENTAL STUDY OF THERMOHYDRAULIC STABILITY AND HEAT TRANSFER IN THE DESCENDING FLOW OF SUPERCRITICAL HELIUM IN A VERTICAL TUBE

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The conditions for the onset of thermally induced oscillations and their influence on heat transfer in low-temperature helium in forced and mixed convection are investigated.

The assurance of high reliability on the part of cryogenic equipment cooled by the circulation of supercritical helium at a temperature level of 4.2-10 K requires investigations of the interrelated processes of heat transfer and thermohydraulic stability. The need for such investigations is underscored by the results of numerous experiments with various fluids, including helium at supercritical pressure in pure forced convection [1-3]. It has been established in these studies that fluctuation flow regimes with periodic oscillations of the flow rate, pressure, and temperatures of the helium and the tube wall can set in for a certain combination of regime parameters and hydraulic characteristics. The parameters $\psi = (\Delta p_1 + \Delta p_{1m})/(\Delta p_{2m} + \Delta p_2)$ and $R = (\rho_{in} - \rho_{out})/\rho_{out}$ are used in [2] to find the stability threshold. Here Δp_1 and Δp_2 are the pressure drops at inlet and outlet valves located at the ends of the heated tube, and Δp_{1m} and Δp_{2m} are the pressure drops in the sections of the tube from the inlet valve to the cross section where the bulk temperature T_f is equal to the pseudocritical temperature T_m and from this cross section to the outlet valve. The parameter R is associated with the quantity of heat admitted to the tube; ψ characterizes the hydrodynamics of the circulation system in pure forced convection and is an analog of the familiar criterion proposed by Petrov for assessing the stability of two-phase flows [4].

The loss of thermohydraulic stability in heated lines that include vertical sections is known to be more complicated than in the case of pure forced convection. For example, in tests of the first high-power subcritical- and supercritical-pressure steam boilers [5, 6] it was found that two types of instability occur in the ascending and descending legs of boiler lines with a multiple-valued hydraulic characteristic. In one case, stable periodic oscillations of the pressure and temperature, like those in pure forced convection, occur as the heat input is increased at a relatively large mass flow rate of the coolant (water). In the other case, a sudden change in the direction of flow and an increase in the wall temperature ("flow reversal") are noted when boilers are fired at a constant heat input and relatively small mass flow rates of the coolant. An analysis of the characteristic features of this phenomenon shows that it can be regarded as an aperiodic instability. An aperiodic instability can go over spontaneously to a stabilized or constant-amplitude fluctuation regime under the action of nonlinear factors. The action of gravity forces causes the pressure drop to vary along the length of a vertical duct by the amount of the level head Δp_L. The level head in power equipment is often much greater than the pressure losses in overcoming friction and acceleration of the heated coolant flow. Since the parameter ψ is expressed in terms of the ratio between the heat losses in the individual sections of the duct, its application under the condition $\Delta p_L \gg \Delta p_{1m} + \Delta p_{2m}$, which governs the multiple-valuedness of the hydraulic characteristic of the line, is problematical. On the other hand, it is adequately justified to use the ratio of the coolant densities at the duct inlet and outlet (the parameter R) if $\Delta p_L \ll p$.

Oscillations of the flow rate, pressure, and temperature are undesirable in many respects because they promote the formation of local hot spots on the wall or fatigue cracks, which result in fracture of the tube.

The objective of the present study is to determine experimentally the domain of inception of thermally induced oscillations and to estimate their influence on the heat transfer associated with a descending flow of supercritical helium in a vertical tube.

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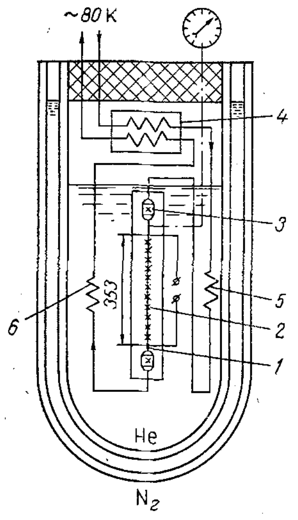

Fig. 1

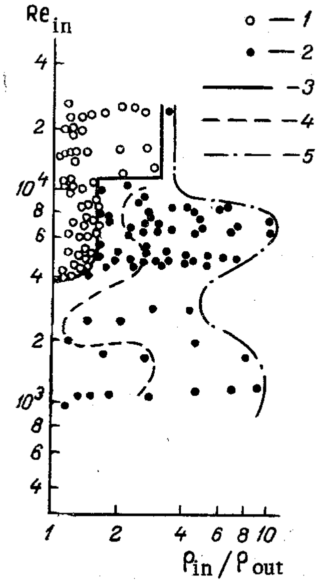

Fig. 2

Fig. 1. Experimental apparatus. 1) Working section; 2) resistance thermometers; 3) mixing chamber; 4) main heat exchanger; 5, 6) liquid helium heat exchangers.

Fig. 2. Stability diagram of the helium flow. 1, 2) Regimes without oscillations and with pressure oscillations, respectively; 3) stability threshold; 4) demarcation line between regions with stable small and large pressure oscillations; 5) demarcation line between regions of stable and unstable fluctuation regimes.

For the analysis we used experimental heat-transfer data [7] and data that we obtained on thermally induced oscillations, using the apparatus described in [3] with certain design modifications, viz.: The working section was a stainless steel tube with an inside diameter of 1.8 mm and a heated length of 353 mm; after the reverse flow of helium was heated in the working section and before it entered the main heat exchanger, it was directed into a secondary heat exchanger immersed in boiling helium, in which it was cooled to ∿4.2 K. The layout of the apparatus with these modifications is shown in Fig. 1. The pressure takeoff in the working section occurred after the inlet mixing chamber by means of a copper tube [8], which was then soldered to the stainless steel tube. The purpose of this arrangement was to lower the temperature gradient along the pressure-takeoff tube and thus to diminish the probability of the onset of thermally induced oscillations in the low-temperature helium manometer line. The helium pressure in the working section was measured with a standard manometer; the wall temperature of the tube and the bulk temperature of the helium were measured with a TSG-2 germanium resistance thermometer. The errors of the pressure and temperature measurements were $1.5 \cdot 10^{-3}$ MPa and $5 \cdot 10^{-2}$ K.

The experiments were carried out at a pressure $p = 0.25$–0.4 MPa, a heat input $q = 9$–1290 W/m^2, a helium temperature at the inlet to the working section $T_{in} = 4.2$–4.6 K, a mass flow rate $G = (0.15$–$1.2) \cdot 10^{-1}$ g/sec, an inlet Reynolds number $Re_{in} = 10^3$ to $2.4 \cdot 10^4$, a Prandtl number $Pr = 0.7$–6, a thermogravitation parameter $Gr_A/Re^2 = 2 \cdot 10^{-6}$ to $3 \cdot 10^{-2}$, and a ratio $T_L/T_m = 0.7$–2.1. The Grashof number is given by the equation $Gr_A = g\beta q d^4/(4\lambda\nu^2 Re Pr)$, where d is the diameter of the tube, g is the acceleration of gravity, β is the isobaric coefficient of cubical expansion, λ is the thermal conductivity, and ν is the kinematic viscosity.

Temperature oscillations with a frequency of 1-2 Hz and an amplitude up to 1-2% were observed in the investigation of heat transfer to helium in descending flow under the conditions of forced and free convection. The situation in which they occurred was similar to the situation in an investigation [3] of heat transfer to supercritical helium in ascending flow in a vertical tube.

In the stability analysis we investigated the threshold for the onset of thermally induced oscillations of the pressure and temperature of helium at the tube inlet as a function

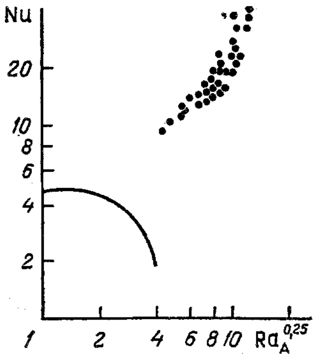

Fig. 3. Heat transfer vs thermogravitation parameter, calculated theoretically (curve) and determined experimentally (dots).

of the helium density. We found that this threshold can be determined from our experimental results in the coordinates ρ_{in}/ρ_{out} and Re_{in} in Fig. 2. Several characteristic domains are noted in the stability diagram. Line 3 is the stability threshold. In the domain of numbers $Re_{in} > 4000$ the threshold for the onset of oscillations is practically independent of the number Re_{in} and the parameter Gr_A/Re^2 except in regimes near $Re_{in} = 1.1 \cdot 10^4$. The abrupt transition from unstable to stable flow near $Re_{in} = 1.1 \cdot 10^4$ at a constant heat input can be attributed to the specific features of the multiple-valued characteristic of the U-shaped line formed by the stainless steel tube and the heat exchanger 6, which was used to cool the reverse helium flow (see Fig. 1). A variation of the ratio of the level heads in the individual sections of the line during the heating of helium in the descending leg (working section) and during cooling in the ascending leg can induce an aperiodic instability, which is outwardly manifested in the form of a sudden change in the stability threshold. For $Re_{in} > 4000$, exclusive of the vicinity of $Re_{in} = 1.1 \cdot 10^4$, the stability threshold depends only on the ratio of the helium densities at the tube inlet and outlet, as in the case of pure forced convection for a fixed ratio of the fluid friction coefficients at the inlet and outlet of the working section. The stability threshold is determined by the ratio $\rho_{in}/\rho_{out} = 1.7$ in the domain $4000 < Re_{in} < 1.1 \cdot 10^4$ and by the ratio $\rho_{in}/\rho_{out} = 3.7$ in the domain $Re_{in} > 1.1 \cdot 10^4$. The flow regimes are always stable for numbers $Re_{in} < 4000$ and any heat inputs. Experiments with water [9] flowing through an asymmetrically heated U-shaped tube with heat input to the descending leg at numbers $Re_{in} < 1000$ have also shown that steady motion is obtainable only in the interval $\rho_{in}/\rho_{out} < 1.1$. In unstable regimes, the amplitude of the oscillations increases until the flow changes direction. We did not observe a change of direction of the flow in our experiments. This is possibly attributable to the fact that the transition from one branch of the multiple-valued hydraulic characteristic to the other through the section with a negative value of the derivative $d(\Delta p)/dG$ is of a random nature, which was perceived in the experiments as an oscillatory process. The instability of the flow regimes in the domain $Re_{in} < 1000$, $\rho_{in}/\rho_{out} < 1.1$ in comparison with the water experiments can be explained by the destabilizing action of heat withdrawal in the ascending leg of the U-shaped line, as indicated in [9].

The amplitudes of the pressure oscillations are less than 1% of p near the stability threshold in the domain between lines 3 and 4 for $Re_{in} < 1.1 \cdot 10^4$. The amplitude of the pressure oscillations increases monotonically to 2% as the heat input is increased. This law is observed in the domain between lines 4 and 5, except for regimes with numbers $Re_{in} = (5-7) \times 10^3$, where the amplitudes of the pressure oscillations increase initially to 1% of p as ρ_{in}/ρ_{out} is increased and then gradually decrease to 0.1% up to line 5. Regimes with a large heat input (to the right of line 5) are characterized by an abrupt monotonic growth of the amplitude, which is accompanied by an increase in the helium temperature at the inlet to the working section, warming of the heat exchangers, and an intensification of the evaporation of liquid helium.

It is evident from Fig. 2 that the most abrupt transition from regimes with weak pressures oscillations (less from 1%) to strong oscillatory regimes (greater than 2%) with increasing value of ρ_{in}/ρ_{out} takes place in the domain $Re_{in} > 10^4$. Under the experimental conditions, this corresponds to $Gr_A/Re^2 < 6 \cdot 10^{-5}$, i.e., the domain of weak influence of the thermogravitational process on heat transfer [7]. At small Reynolds numbers ($Re_{in} < 2000$) under the conditions of appreciable influence of gravity forces on heat transfer ($Gr_A/Re^2 > 10^{-4}$), the amplitudes of the oscillations increase much more slowly, attaining values of the order of 2% of p at $\rho_{in}/\rho_{out} = 10$.

Experimental data for supercritical helium in descending flow have been generalized [7] by a dependence using the turbulent heat-transfer equations. An analysis of the previously obtained and new stable and fluctuation-type regimes shows that temperature and pressure oscillations of the indicated amplitude and frequency do not have any appreciable influence on heat transfer in the transition and turbulent domains of Reynolds numbers. We note that the dependence in [7] also generalizes experimental data referring to the laminar domain of Reynolds numbers. This result requires a specific interpretation. Heat transfer is known to decrease with increasing value of the thermogravitation parameter (third Rayleigh number) $Ra_A = Gr_A Pr$ in the case of descending flow in vertical tubes in the laminar domain of Reynolds numbers, and the Nusselt number Nu drops below its value of 4.36 for stabilized heat transfer. This fact has been established by experiments with water in the domain $Ra_A \leqslant 119$ [10]. Hydrodynamic stability is lost for values of $Ra_A \geqslant 168$ and the flow becomes turbulent in the domain $Ra_A > 250$. However, heat transfer in a flow with loss of hydrodynamic stability was not investigated.

The minimum value of Ra_A in the helium experiments at Re < 2300 was 400, i.e., the experiments were carried out in a domain where the flow is hydrodynamically unstable. It is important, therefore, to establish the validity of the recommendations for heat-transfer calculations in stable flows under these conditions. Figure 3 shows data on heat transfer to supercritical helium in the coordinates (Nu, Ra_A) in the region far from the inlet. The boundary of this region is taken as $(RePr)^{-1}x/d \geqslant 0.04$, for which the number Nu becomes equal to 4.36 (x is the length from the start of the heated section of the tube) within 5% error limits. Also shown in this figure is Ostroumov's theoretical curve [11] for descending laminar flow. We see that the experimental heat-transfer data lie far above the theoretical curve. Moreover, the experimental data in the domain of appreciable influence of the thermogravitational process do not exhibit the slightest tendency toward the theoretically established heat-transfer law. This result can be explained by bearing in mind the loss of stability of laminar flow.

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