6. A. V. Gulakov, Thermophysics and Hydrogas Dynamics of Boiling and Condensation Processes. Abstracts of Proceedings of an All-Union Conference [in Russian], Vol. 1, Riga (1982).
7. E. Ya. Tarat, A. N. Khoze, and Yu. I. Sharov, Khim. Khim. Tekhnol., No. 8, 1141-1146 (1969).

EXPERIMENTAL STUDY OF THERMALLY INDUCED OSCILLATIONS AND HEAT TRANSFER IN AN ASCENDING FLOW OF SUPERCRITICAL HELIUM IN A VERTICAL TUBE

V. A. Bogachev, V. M. Eroshenko, and E. V. Kuznetsov

UDC 536.24

An experimental study of the conditions for the onset of thermally induced oscillations and their influence on heat transfer in an ascending flow of supercritical helium in a heated vertical tube is reported.

One of the distinctive characteristics of heat transfer near the critical point is the existence of regimes with low- and high-frequency oscillations of the temperature and pressure together with the usual stable regimes. This fact is indicated by the results of numerous experiments with different liquids, including helium at supercritical pressure subjected to pure forced convection in tubes [1-3]. It has been established [2, 3] that the onset of low-frequency temperature and pressure oscillations is associated with the values of the heat input and flow rate and with the position of the pseudocritical temperature T_t within the limits of the heated section of the tube. Oscillations of the wall temperature T_w set in when it attains the value T_t, and pressure oscillations set in when the bulk temperature T_f of the fluid reaches the level T_t [3].

For the determination of the stability thresholds of the regimes, it has been proposed [2] that the parameters $R = (\rho_{in} - \rho_{out})/\rho_{in}$ and $\psi = (\Delta p_1 + \Delta p_{1t})/(\Delta p_2 + \Delta p_{2t})$ be used, where ρ_{in} and ρ_{out} are the densities of the fluid at the inlet and outlet of the heated tube, Δp_1 and Δp_2 are the pressure drops at valves located at the inlet and outlet of the tube, Δp_{1t} is the pressure drop along the section of the tube from the inlet valve to the cross section where the bulk temperature T_f of the fluid is equal to T_t, and Δp_{2t} is the pressure drop along the section of the tube from the cross section with $T_f = T_t$ to the outlet valve. The parameter R characterizes the quantity of heat admitted to the tube and the compressibility (elasticity) of the circulating fluid. The parameter ψ is an analog of the well-known criterion proposed by Petrov for two-phase flows [4].

Despite the considerable number of articles that have been published on the stability problem, it is still not clear how the flow stability is affected by thermogravitation or how the heat transfer is influenced by thermally induced oscillations in the mixed convection of a supercritical fluid. The solution of this problem is important for the design of various cryogenic energy devices. In the present article we report an experimental investigation of the influence of these factors on the thermohydraulic stability and heat transfer in supercritical helium.

For the analysis we used experimental data from [5], along with our own results obtained on an arrangement described in [3], in which certain modifications were introduced. The experiments were carried out in a cryostat filled with liquid helium. After reduction and cooling in a liquid-nitrogen cryostat to ~80°K, the direct flow of helium from the ramp was first directed into the main heat exchanger, where it was further cooled down to 8-10°K by heat transfer with the reverse helium flow, and then into a heat exchanger immersed in liquid helium, where it was cooled to 4.2-5.2°K. The direct flow at this temperature was admitted into the working section. The reverse helium flow from the working section, prior to

---

G. M. Krzhizhanovskii Power Institute, Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 51, No. 5, pp.719-723, November, 1986. Original article submitted September 20, 1985.

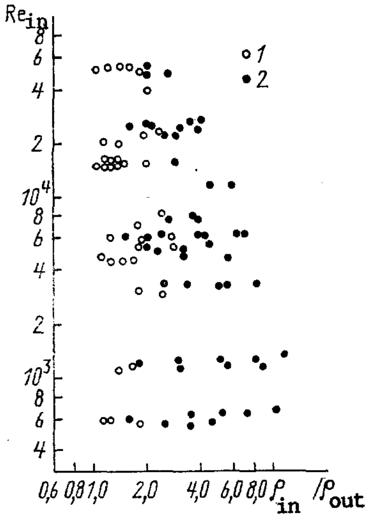

Fig. 1. Map of helium flow stability. 1) Regimes without pressure oscillations; 2) regimes with pressure oscillations.

its entry into the main heat exchanger, was directed into a heat exchanger immersed in liquid helium, where it was cooled down to 5-6°K. The processed helium flow leaving the main heat exchanger was dumped into a gas holder.

The working section comprised a stainless steel tube with an inside diameter of 1.8 mm, a wall thickness of 0.1 mm, and a length of 510 mm, in which a constant electric current was passed. The length of the heated section was 400 mm. Mixing chambers with an inside diameter and length of 5 mm were set up at the inlet and outlet of the working section, and TSG-2 thermometers were placed in them to measure the bulk temperatures. Similar thermometers were used to measure the wall temperature of the working section. The pressure in the helium flow was determined by a standard manometer. The pressure in the working section was sampled after the inlet mixing chamber through a small copper tubing [6], which was then soldered to a stainless steel tube. This measure was aimed at lowering the temperature gradient along the length of the pressure-sampling tube and thus decreasing the probability of the onset of thermally induced oscillations in the manometer line with low-temperature helium flowing in it.

The experiments were carried out at a pressure p = 0.23-0.4 MPa, a heat input q = 7-1770 W/m², a helium temperature at the inlet to the working section T_{in} = 4.21-5.14°K, an inlet Reynolds number $Re_{in} = 600\text{-}5\cdot10^4$, a thermogravitation parameter $Gr_A/Re^2 = 2.6\cdot10^{-7}\text{-}1.1\cdot10^{-1}$, and temperature ratios T_f/T_t = 0.7-2.6 and T_w/T_t = 1.01-1.69.

The investigation of heat transfer to the helium in an ascending flow under mixed-convection conditions disclosed temperature and pressure oscillations with a frequency of 1-2 Hz and an amplitude up to 1-2%. The situation in which they occurred was similar to that described in [3], except that the helium temperature at the inlet to the working section was ∿4.2°K. Pressure oscillations could not set in at higher values of T_{in}, even when the bulk temperature of the helium attained the value T_t within the limits of the heated section of the tube. Consequently, the condition $T_f = T_t$ within the limits of the working section still does not determine the onset of the pressure oscillations. We note that the pressure oscillations in these investigations were always accompanied by fluctuations of the thermometer readings at the tube wall and in the outlet mixing chamber. Fluctuations of the thermometer readings in the inlet mixing chamber were not observed.

Our analysis showed that pressure oscillations occurred, as a rule, when the ratio $\rho_{in}/\rho_{out} \approx 2$ (the parameter R ≈ 1). Figure 1 illustrates the stable and unstable regimes of heat transfer to the helium in coordinates Re_{in}, and ρ_{in}/ρ_{out} (stable heat-transfer regimes are interpreted here as those without pressure oscillations, and the unstable regimes as those with pressure oscillations). We see that the quantity $\rho_{in}/\rho_{out} \approx 2$ can be used for the threshold of the onset of pressure oscillations over the entire investigated range of Re_{in}. Since a large part of the heat-transfer regimes in the experiments at $Re_{in} < 2\cdot10^4$ is referred to the mixed-convection domain, i.e., $Gr_A/Re^2 > 10^{-5}$ [5], it is reasonable to conclude that thermogravitation does not significantly affect the onset of the oscillations.

We call attention to the fact that the threshold of stability of the heat-transfer regimes in the experiments reported in [2] for the forced convection of helium in a horizontal

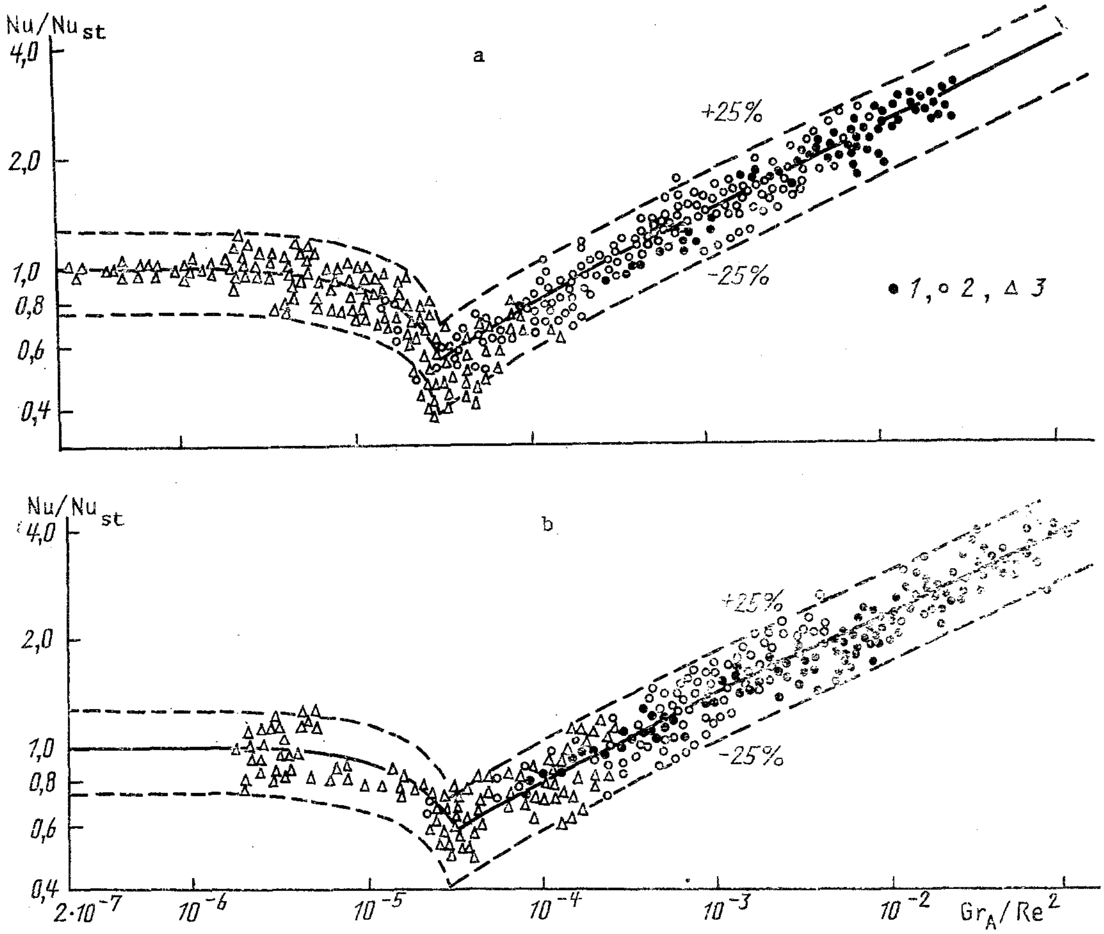

Fig. 2. Relative heat transfer vs thermogravitation parameter in regimes without (a) and with (b) pressure oscillations. 1) Re < 2300; 2) 2300 < Re < 10^4; 3) Re > 10^4. The solid curves represent the equations in [5].

tube of length 184 m was determined by the quantity $(\rho_{in}/\rho_{out})_{min} = 3.5$, which does not agree with the data for an ascending helium flow. The shift of the stability threshold toward smaller values of ρ_{in}/ρ_{out} in our experiments is evidently attributable to the significant departure from isothermicity ($T_w/T_f = 1.01$-1.69), the shorter working section, and the design features of the heat-exchanging and ducting section of the experimental apparatus. For example, the reverse helium flow from the working section was not utilized to cool the direct flow in the apparatus of [2]. The presence of feedback through the main heat exchanger in our apparatus could result in amplification of the perturbations at the inlet to the working section and a loss of flow stability.

The experimental data in [5] for supercritical helium in an ascending flow in the case of regimes with and without temperature and pressure oscillations were generalized within ±25% error limits by the ratio of the measured Nusselt number Nu to its value Nu_{st} for pure forced convection as a function of the thermogravitation parameter Gr_A/Re^2. The measured heat-transfer coefficients in regimes with oscillations were averaged over the time in this case. The influence of oscillations on the heat transfer was not analyzed in [5]. According to present-day notions, the occurrence of oscillations in a fluid flow usually tends to increase the heat-transfer coefficient. To determine the magnitude of the possible increase in the heat transfer in an ascending flow of supercritical helium under the influence of thermally induced oscillations, it is instructive to plot these regimes separately in the coordinates Nu/Nu_{st}, Gr_A/Re^2 (see Fig. 2). It is evident from the figure that the experimental points in both cases are clustered about the graphs of the equations in [5]. The somewhat larger scatter of the points for the regimes in Fig. 2b can be attributed to the fact that the readings of the thermometers and the manometer in these regimes have been averaged over the time with a certain error. Similarly, the departure from isothermicity in the pressure-oscillation regimes was considerably greater than in the regimes of Fig. 2a. Consequently, the onset of thermally induced oscillations of the temperature and pressure at a frequency of 1-2 Hz and amplitude of 1-2% did not induce any appreciable intensification of heat transfer in the investigated regimes associated with the ascending flow of supercritical helium in a vertical tube.

LITERATURE CITED

1. P. J. Giarratano, V. D. Arp, and R. V. Smith, Cryogenics, 11, No. 5, 385-393 (1971).
2. D. E. Daney, P. R. Ludtke, and M. C. Jones, Trans. ASME, Ser. C; J. Heat Transfer, 101, No. 1, 9-14 (1979).
3. V. A. Bogachev, V. M. Eroshenko, and L. A. Yaskin, Inzh.-Fiz. Zh., 44, No. 4, 544-548 (1983).
4. P. A. Petrov, Hydrodynamics of Once-Through Boilers [in Russian], Moscow—Leningrad (1960).
5. V. A. Bogachev, "Heat transfer in an ascending flow of single-phase helium with near-critical parameters in a vertical tube," Author's Abstract of Candidate's Dissertation, Engineering Sciences, Moscow (1983).
6. V. M. Eroshenko and E. V. Kuznetsov, Inventor's Certificate No. 798521, "Device for measuring the pressure of cryogenic media," Byull. Izobret., No. 3 (1981).

THE FINAL STAGE OF DEGENERATION IN THE TURBULENT PATTERN FOR A PASSIVE TRACE COMPONENT IN A WAKE

N. N. Luchko and I. I. Kovalev

UDC 532.517.4

A multiparameter differential model has been used to derive asymptotic formulas for the behavior of a passive component in the final stage of degeneration in a turbulent wake.

Recently, considerable experience has been accumulated in calculating the characteristics of turbulent shear flows on the basis of multiparameter $u_i u_j - \varepsilon_u$ differential models [1]. The advances in this area have provided a stimulus to constructing differential models for the transport of a passive component, which one can take as being the temperature if there is a slight temperature rise and buoyancy effects are negligible.

The passive scalar is a transportable substance , so that in most free flows the turbulent Peclet number P_λ varies along with R_λ from $P_\lambda \gg 1$ in the near region to P_λ in the far one. A study has been made [2] of the features in the final stage of degeneration in the pattern for a passive component by applying a Fourier transformation to the Navier—Stokes equations and then expanding the Fourier transforms as series, taking the first few terms in the expansion. The multiparameter differential model has been proposed [3, 4] to describe the scalar field.

A distinctive feature is that it contains functions of the turbulent Reynolds and Peclet numbers instead of the traditional empirical constants and incorporates the evolution of the scalar field as a function of R_λ and P_λ. In the zones of strong turbulence ($R_\lambda \gg 1$, $P_\lambda \gg 1$) and weak turbulence ($R_\lambda < 1$, $P_\lambda < 1$), one can replace the empirical functions by constants, which determine the damping of the model characteristics of the wake in the asymptotic cases R_λ, $P_\lambda \to \infty$ and R_λ, $P_\lambda \to 0$.

The following is the closed system of equations in a Cartesian coordinate system [4]:

$$\frac{D\overline{T}}{D\tau} = \varkappa\frac{\partial^2\overline{T}}{\partial x_k^2} - \frac{\partial\overline{u_k t}}{\partial x_k},$$

$$\frac{D\overline{u_i t}}{D\tau} = \frac{\partial}{\partial x_k}\left[\alpha_{ut}\frac{q^2}{\varepsilon_u}\left(\overline{u_i u_l}\frac{\partial\overline{u_k t}}{\partial x_l} + \overline{u_k u_l}\frac{\partial\overline{u_i t}}{\partial x_l} + \overline{u_l t}\frac{\partial\overline{u_i u_k}}{\partial x_l}\right) + \frac{\nu+\varkappa}{2}\frac{\partial\overline{u_i t}}{\partial x_k}\right] - b_{ut}\overline{u_k t}\frac{\partial\overline{U}_i}{\partial x_k} - \overline{u_i u_k}\frac{\partial\overline{T}}{\partial x_k} - c_{ut}\frac{\varepsilon_t}{\overline{t^2}}\overline{u_i t},$$

Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 51, No. 5, pp. 723-728, November, 1986. Original article submitted November 7, 1985.

0022-0841/86/5105-1268$12.50