THERMALLY INDUCED OSCILLATIONS OF HELIUM IN CRYOGENIC APPARATUS

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The results of an experimental study of thermally induced oscillations are presented. Relations are given for the determination of the stability limit and amplitudes of the oscillations.

In work with liquid and near-critical helium one often observes peculiar and little-studied interference which is absent in nitrogen—oxygen apparatus and at a higher temperature level [1, 5-11]. For example, in the pressure transfer of boiling liquid helium from one Dewar vessel to another its flow frequently becomes unstable and the flow process is disrupted. In the measurement of small pressure drops in apparatus containing low-temperature helium, and in the measurement of the height of the liquid helium level in particular, entirely incorrect instrument readings are frequently obtained owing to spontaneously developing oscillations. With smaller oscillations the measurements prove to be distorted, with the errors being difficult to notice here, as a consequence of which one loses confidence in the instrument readings. In the storage and use of liquid helium the development of unstable oscillations leads to an increase in evaporability because of the intensification of heat exchange and to the appearance of internal heat sources. These and other analogous phenomena are connected with the process of self-excitation of helium oscillations. The fact is that all apparatus of low-temperature helium technology contain the elements of oscillating systems: elastic elements in the form of cavities containing gaseous helium and inertial elements containing a mass of gaseous or liquid helium, whereas the damping elements are very weak because of the negligible kinematic viscosity of the cold (liquid and gaseous) helium. At the same time there is always a supply and transfer of energy to the helium because of imperfection of the thermal insulation or the heating during its use as a coolant. In this connection the self-oscillations of the working medium (helium) which develop are called thermally induced.

In a more detailed analysis the thermally induced oscillations of a liquid or gas are subdivided into: a) gravitationally unstable motions (with the predominant supply of heat to the lower part of the apparatus or a component of it); b) oscillations connected with the boiling front and its instability; c) oscillations connected with a given forced motion of the boiling liquid; d) gas oscillations in unevenly heated pipes.

The indicated interference during the pressure transfer of helium from vessels and in the measurement of the height of its level and of pressure drops is due precisely to oscillations of the latter type. Such oscillations were described long ago by Sondhaus [12], who observed the humming of blowpipes and of incandescent bottles which had just been blown. However, no reliable methods for calculating such oscillations have been developed up to now, and models of the oscillations which have been proposed by different authors differ considerably from each other. A typical diagram (Fig. 1) of the stands for the experimental study of such oscillations has been developed [10, 11]. The basis here is the Dewar vessel 1 containing liquid helium and the pipe 2 communicating with it, one end of which emerges into the warm (room) zone. The pressure gauge 3 is usually placed here.

We worked with different modifications of such stands, using both metal and transparent glass Dewar vessels and pipes of different lengths and different diameters equipped with

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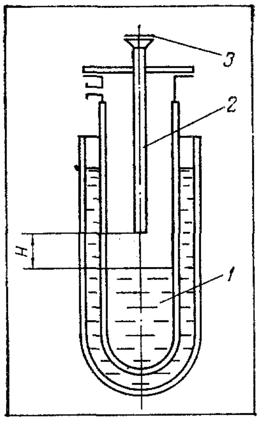

Fig. 1

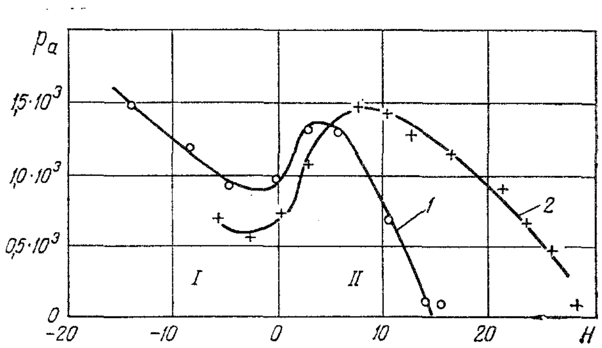

Fig. 2

Fig. 1. Stand for the study of thermally induced oscillations.

Fig. 2. Variation in amplitude of pressure p_a (N/m²) of thermally induced oscillations (gauge 3 in Fig. 1) as a function of distance H (cm) of end of pipe from helium level based on observations: 1) on a stand with a spherical Dewar vessel with a long neck; 2) on a stand with a cylindrical transparent Dewar vessel (I: below level; II: above level).

membrane tensometric pressure gauges. We used thermometric and photographic apparatus as well as various damping devices, particularly inserts. In all the experiments the more or less sudden spontaneous development of oscillations of the gas in the pipe was observed during the lowering of the pipe into the vessel and the corresponding reduction of the temperature of its lower end. The frequency of these oscillations proves to be close to the fundamental tone of the free oscillations of the gas column in the pipe with allowance for the temperature variation of the velocity of sound along its length. The amplitude of the established self-oscillations of pressure increases in proportion to the decrease in the temperature of the open cold end of the pipe and its approach to the free surface of the liquid helium (Fig. 2). It reaches the highest value (up to 8% of the ambient pressure) in the immediate vicinity of this surface (from 8 to 1 cm). In this case the surface of the helium is sometimes (but not in all devices) strongly disturbed and also undergoes oscillations, with the inner and outer surfaces of the pipe being washed by drops of liquid helium. The self-oscillations continue even when the free end of the pipe is submerged in the liquid helium. In this case the frequency of the fundamental oscillations decreases, components with higher frequencies appear, and the amplitude can either decrease or increase as the pipe is submerged in the liquid helium.

An unstable equilibrium, without oscillations of the state of the helium in the pipe and the vessel, can be observed under very quiet conditions: with good thermal insulation and weak boiling, in the absence of external vibrations and bumps, and with very smooth movement of the pipe. However, a very slight flick on any part of the apparatus is enough for intense thermally induced oscillations to develop in it.

Self-oscillations are not excited if both ends of the pipe are fully closed or well throttled. According to our experience and the data of other authors, apparatus containing cold (liquid or gaseous) helium react very sharply to external vibrations or random disturbances of pressure or flow rate. When this happens there develop intense (up to 10^4 $N \cdot m^{-2}$) forced or free oscillations of pressure which die out very slowly, and the damping is weakened with an increase in the temperature gradients and as the state of the helium approaches the limit of stability.

Good reproduction of the experimental data in different series of tests was observed on each stand or apparatus tested when the experimental conditions were maintained (same level of liquid helium, same working pipe, etc.).

The thermally induced oscillations under consideration pertain to type d) by the classification given above. In accordance with the acoustical theory of small oscillations of a gas, its containment in a pipe is imitated in the form of a solid elastic rod. Then thermal actions only produce changes in the distribution of the elastic and inertial forces along the length of the pipe without affecting the energy expenditure in the oscillations. In this case randomly excited free oscillations die out with time t by the exponential law exp $(-\delta t)$.

The oscillations with the lowest frequency Ω_1 die out most slowly, and then $\delta = \delta_1 \approx 0.5c\Omega_1$, where c is the coefficient of relative hydrodynamic friction of the gas against the wall of the pipe, which has the value [3, 4]

$$c = \sqrt{\frac{16\nu L}{\pi D^2 v_*}} = \sqrt{\frac{8\nu}{D^2\Omega_1}} \text{ for } c < 0.1, \tag{1}$$

where v_* is the average velocity of sound in the gas.

Such gas oscillations which are damped independently of the heating actually occur in pipes with both ends closed. If the end of the pipe is open, however, the ejection of gas in the process of the oscillations is accompanied by observable vortical motions during which intensive mass exchange with the surrounding gas occurs. Because of this the rod analogy is violated near the open end of the pipe. Friction increases because of irreversible losses of kinetic energy [3]. Along with this, at a moment of reduction in pressure during acoustical oscillations a colder portion of gas than would be expected from the rod analogy enters the pipe through the cold open end. Such an effect is especially noticeable if the open end of the pipe is not far from the surface of the liquid helium in the vessel. The cold gas which has entered the pipe is heated, as a consequence of which the pressure is increased with a phase shift with respect to its main component. Then the gas is ejected with an increased amplitude, which leads to a subsequent increase in the amplitude of the cold helium sucked into the pipe with an increased evaporation of the liquid phase. Here the thermal action plays the role of a sort of negative nonlinear friction, and the oscillations are driven until their increase is stopped by the nonlinearly increasing forces of velocity resistance (generalized friction).

The thermal action on the gas is determined by the relative thermal head

$$\Delta = T_{\max} T_{\min}^{-1} \tag{2}$$

and by the Fourier number Fo, which characterizes the relative heat transfer during some part of the oscillation period:

$$\mathrm{Fo} = \pi^2\lambda(\vartheta D^2\Omega_1)^{-1}. \tag{3}$$

Here $T_{\max}$ is the maximum temperature (near the closed end of the pipe) and $T_{\min}$ is the temperature (near its open end). Besides this, the heat transfer depends to a certain extent on the geometrical characteristic L/D of the pipe, on the initial temperature distribution function $T_0(x)$ along the length of the pipe, on the distance from the mouth of the pipe to the liquid surface, on the vortices during the movement of the gas, and on other less important parameters and effects. The gas vortices strongly intensify the heat transfer, so that in place of the coefficient of thermal conductivity λ in Eq. (3) one must use an effective value $\lambda_e = \lambda\mathrm{Nu}$ much larger than it, which unfortunately is not reliably known for such a case. In the oscillations of the gas near the closed end of the pipe, where the velocity is small, its motion is undoubtedly laminar, whereas near the open end it is turbulent or strongly turbulized. In this case one can take Nu as equal to the quantity

$$f_l(\mathrm{Re},\ \mathrm{Pr}) + f_t(\mathrm{Re},\ \mathrm{Pr}),$$

an integral average over the longitudinal x coordinate, which with allowance for the recommendations in [2] and the conclusions in [4] is equal to

$$\mathrm{Pr}^{0.43}(k_1\mathrm{Re}^{n_1} + k_2\mathrm{Re}^{n_2}),$$

where $k_1 \approx 0.15$, $n_1 \approx 0.33$, $k_2 \approx 0.02$, and $n_2 \approx 0.8$.

In the apparatus under consideration the velocity of sound in the gas near the open end of the pipe is small because of the relatively low temperature there, which means an increased elastic compliance of the gas in comparison with the warm region near the closed end. This effect, as well as the fact that the section of the pipe near its open end is the main zone of excitation of the oscillations, leads to the fact that here the velocities of gas motion increase and the entry of the energy of the oscillations increases, whereas in the rest of the pipe (toward the closed end) the velocity of the gas oscillations and the dissipation of energy are reduced. This can be represented by introducing into the expression for the energy entering into the oscillations the coefficient $k_L = L \cdot L_{\min}^{-1}$ in the form of the ratio of the length of the pipe to the length of its section with the temperature $T_{\min}$. Then the balance of the energy entering and dissipated during a cycle of the oscillations under consideration is expressed by the approximate relation

$$k\,\mathrm{Nu}\,\mathrm{Fo}\Delta s p_0 a^2 L_{\min}^{-1} = 0.5\pi^2\varkappa(c + 1.33\,aL^{-1})\,sp_0a^2L^{-1}. \tag{4}$$

Both the limit of formation of thermally induced self-oscillations of the gas and their amplitude a are determined explicitly by this relation through the function Nu = Nu(a). Self-oscillations do not develop at relatively small values of the criteria Fo and Δ. When they are large enough the amplitude a has two values, of which the smaller a_1 determines the size of the initial impulse needed for the formation of self-oscillations while the larger a_2 is the amplitude of an established limiting cycle of self-oscillations. The quantity a_1 decreases and the quantity a_2 increases in proportion to the increase in the numbers Fo and Δ. All this reflects rather well the observed qualitative properties of the self-oscillations.

The self-oscillations are excited in a similar but still more complicated way when the gas interacts with a nearby layer of boiling liquid (helium) and when the pipe is submerged in the liquid helium. Here masses of the boiling liquid are involved in the oscillations, which leads to a decrease in the frequency of the oscillations. In addition, higher forms of oscillations are excited in which the gas in the pipe is reflected from the surface of the boiling liquid. Polyharmonic oscillations take place as a result. It is noteworthy that after passing through the zone of strong excitation when the end of the pipe is located near the liquid surface the parameters of the self-oscillations change relatively little with the further submergence of the pipe.

Under the conditions of our test apparatus the thermally induced oscillations under consideration could be eliminated by damping them. For this we used throttles in the section of the pipe near the open end and more effective damping inserts of porous material. When such inserts are used the oscillations are suppressed with a lower hydraulic resistance than in the throttles. By using such devices we obtained fully reliable barometric detectors of the helium level. Flattening the temperature gradient at the wall of the pipe in the vicinity of the open end by increasing the length of its cold section enclosed in a special sleeve has a certain stabilizing effect.

Forced oscillations of helium and thermally induced self-oscillations of other types are considerably more difficult to combat. Because of the exceptionally low kinematic viscosity of liquid helium and its saturated vapor their pulsations generated by outside sources or by vibrations of the apparatus propagate a long way along pipelines, with local resonances being possible. Therefore, in setting up cryogenic equipment it is recommended that such oscillations be monitored using low-inertia tensometric pressure gauges and an oscillograph. When it is necessary to reduce such oscillations one can use damping inserts and other quieting devices, including the construction of components with flattened temperature gradients.

NOTATION

a, amplitude; c, coefficient of viscous resistance; D, diameter; Fo, Fourier number; k, coefficient; L, length; Nu, Nusselt number; n, exponent; $\Pr = \nu\vartheta\lambda^{-1}$, Prandtl number; p, pressure; $\mathrm{Re} = a(x)\Omega_1 D\nu^{-1}$, Reynolds number; s, area; T, temperature; t, time; v, velocity; x, coordinate; Δ, relative temperature drop; δ, damping coefficient; ϑ, coefficient of heat capacity; $\varkappa$, adiabatic coefficient; λ, coefficient of thermal conductivity; ν, kinematic viscosity; Ω, circular frequency. Indices: l, laminar mode of flow; t, turbulent mode of flow.

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DISSIPATIVE HEATING OF A MEDIUM DURING ROTATION OF A DISK IN A BOUNDED SPACE

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A method is proposed for calculating dissipative heating of a medium in a model of a turbine stage. Results of the calculation are compared with experiment.

Consideration of the problem of flow thermodynamics around rotating axisymmetric bodies grew out of the requirements of power-machine construction to a considerable extent. In the literature up to now the principal attention has been given to problems of hydrodynamic resistance and heat transfer during rotation of bodies in free and bounded spaces [1-3] without analysis of the changes in the parameters of the medium during the irreversible conversion of mechanical energy into heat. At the same time, the enclosure of a rotating body in a bounded chamber presupposes a significant intensification of the effect of dissipation on the thermal state of the medium. There is great interest in the consideration of the rotation of a disk in a cylindrical chamber from this viewpoint, since the flow portion of various turbines contains as a required element alternately arranged rotating and fixed flat surfaces perpendicular to the axis of rotation.

Theoretical and experimental studies of flow hydrodynamics in rotating systems yield only qualitative results in most cases because of the extreme complexity of the processes. Calculations are possible with a number of important simplifications and assumptions which significantly reduce the accuracy of the results.

A rotating disk acts like a centrifugal fan and creates a suction that causes radial motion of the medium from a center near the disk to a center near the chamber walls. In addition to rotation around the axis of the disk and vortex motion in the meridional plane, a certain flow rate of the medium, G_s, ordinarily occurs in the gap between a rotating disk of the turbine and the cylindrical chamber; this is associated with the flow or with the need

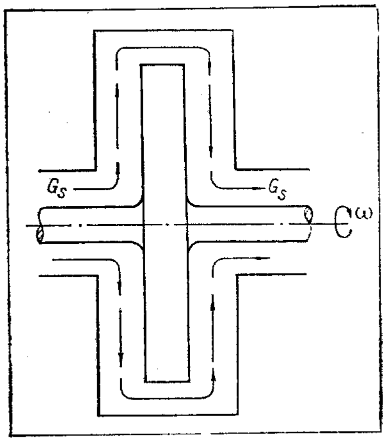

Fig. 1. Diagram of medium flow in gap between surfaces of disk and chamber.

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