NOTATION

P, total porosity; P_0, open porosity; r_M, maximal pore radius; K, coefficient of permeability; r_T, mean hydraulic pore radius; $\underline{a}$, coefficient of sinuosity; r_p, mean equivalent particle radius; D, equivalent particle diameter; M, percent content of fraction on the distribution curve.

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EVAPORATIVE LOSS OF CRYOGENIC LIQUIDS DURING VIBRATION AND TRANSPORT IN VESSELS AND CISTERNS

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It is shown that the cause of increased evaporative loss of cryogenic liquids during transportation is scattering of oscillation energy within the liquid. The dependence of the increase in loss on oscillation parameters and transportation conditions is determined.

When cryogenic vessels and cisterns are transported the rate of cryogenic liquid evaporation is several times greater than under steady-state conditions, for example, 3-8 times greater for liquid helium in a 10-liter vessel [1]. The causes and principles of this increased loss have yet to be studied thoroughly. In [2] experiments were performed involving vibration of a 5-liter liquid helium vessel, and it was found that the increase in loss depended quadratically on vibration amplitude.

The problem of the interaction between an oscillating body and a liquid is quite complex and has been studied by many researchers. A quite complete theoretical analysis of the perturbed motion of a body containing liquid in cavities, with consideration of the liquid's viscosity, was presented in [3]. As the body oscillates, energy is partially scattered in the liquid. The oscillation energy scattering is characterized by an absorption coefficient ψ_0:

$$\psi_0 = \Delta E / E. \tag{1}$$

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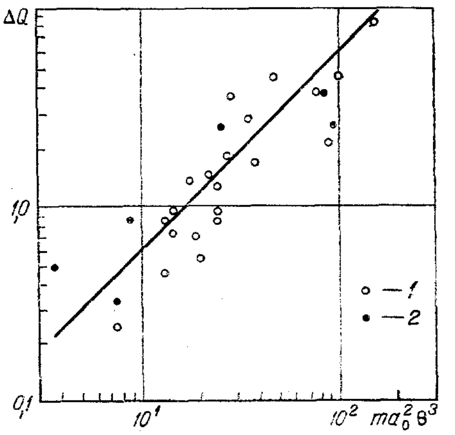

Fig. 1

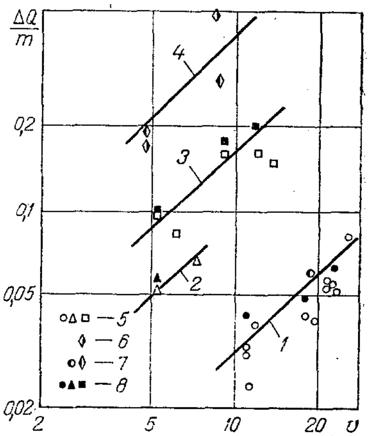

Fig. 2

Fig. 1. Heat liberation in liquid nitrogen ΔQ (W) for vibration in vessels: 1) VÉDS-200 vibrostand; 2) SIT vibrostand. $ma_0^2\theta^3$, W.

Fig. 2. Specific heat liberation ΔQ/m (W/kg) in liquid nitrogen and helium vs transport rate v (m/sec) of vessels in ZIL-130 automobile: 1) high-speed road; 2) dirt road; 3) flat cobblestone; 4) profiled cobblestone; 5) TsTK-1.6/0.25 cistern; 6) ASD-16 vessel; 7) SDS-20 vessel; 8) STG-10 vessel.

When the oscillations are slightly damped by the liquid (damping coefficient $\beta \ll \omega$) the absorption coefficient is related to the logarithm of the decrement by the expression

$$\psi_0 = 2\delta. \tag{2}$$

Results of theoretical and experimental determination of the value of δ for vessels of various form were presented in [3]. In particular, the logarithmic decrement for the fundamental oscillation mode can be calculated with the expression

$$\delta_1 = \frac{C}{\sqrt{\mathrm{Re}_1}}, \tag{3}$$

where the coefficient C is equal to 5.78 for a circular cylinder with plane bottom and 4.0 for a spherical vessel over a wide range of liquid levels.

As is well known, the maximum value of forced-oscillation kinetic energy stored by the beginning of a period (given the condition that the construction of the container and its attachments to the vibrostand are absolutely rigid) is determined by the expression

$$E = \frac{1}{2} ma_0^2\theta^2. \tag{4}$$

Scattering of oscillation energy produces heat liberation in the cryogenic liquid and a corresponding increase in its evaporation from the vessel. The energy scattered per period ΔE and the heat liberation per unit time ΔQ are related by the expression

$$\Delta E = \Delta QT = \Delta Q\frac{2\pi}{\theta}. \tag{5}$$

Substituting Eqs. (1) and (4) in Eq. (5), we find

$$\Delta Q = \frac{\psi_0}{4\pi} ma_0^2\theta^3. \tag{6}$$

An experimental study was performed of the increase in loss of liquid nitrogen and helium in vessels upon vibration on vibrostands and transportation over various types of roads. The containers used for liquid nitrogen on the vibrostand were the 16-liter spherical ASD-16 and the 20-liter vertical cylindrical SDS-20. A VÉDS-200 electrodynamic vibrostand was used to create harmonic oscillations with amplitude of 0.1-10 mm and frequency of 5-80 Hz. An SIT stand was used to emulate vibration conditions found in road transport, at frequencies of 4 and 9 Hz with mean amplitude of 6 mm. The amount of liquid nitrogen used was varied from 7 to 16 kg.

Evaporative losses were determined from the quantity of gas formed, using gas counters. Tests were performed with the gas exhaust open and closed. In the first case the gas discharge was measured directly during vibration. In the second case the gas exhaust was opened after vibration was completed and the increase in loss was determined by relating the increase in quantity of gas formed to the vibration time. Measurements in both cases produced coinciding results, which indicates, in particular, the absence of mechanical removal of cryogenic liquid by gas leaving the vessel during vibration.

The test results indicate that the increase in evaporative loss is proportional to the square of the amplitude and the cube of the frequency of the oscillations. The experimental data obtained are presented in Fig. 1. They are described satisfactorily by Eq. (6). Thus, it can be maintained that the cause of increased evaporative loss of cryogenic liquids upon vibration is scattering of oscillation energy in the liquid.

Calculation with Eq. (3) gives a value of $\delta_1 \approx 0.1$ and corresponding value of $\psi_0 = 0.2$. Equation (6) correctly expresses the qualitative dependence of ΔQ on oscillation parameters with the empirical value of the coefficient $\psi_0 = 0.8$.

Aside from the vessels noted above, a TsTK-1.6/0.25 1.6-m^3 liquid nitrogen cistern, an STG-10 10-liter liquid helium vessel, and a TsTG-0.5/0.7 500-liter liquid helium cistern were tested in a ZIL-130 automobile over roads of four types. These conditions were characterized by a wide frequency and amplitude spectrum, which complicated comparison of the test results with Eq. (6).

The results of the transport tests (Fig. 2) permit the following conclusions. First ΔQ is proportional to the liquid mass over a 50-100 times variation in mass. Second, for identical test conditions the ratio $\Delta Q/m$ is a constant, rather than the ratio of increased loss to mass, so that the cause of the increased evaporative loss is transformation of mechanical oscillation energy into thermal energy (not mechanical removal of liquid).

The TsTG-0.5/0.7 cistern was tested by transport over an asphalt road with gas discharge closed and open. In the latter case, the helium loss decreased by a factor of more than 10 times. This can be explained by the use of the coldness of the vapors formed upon absorption of oscillation energy by the liquid helium in the efficient thermal insulation system of the cistern.

Third, as follows from Fig. 2, the ratio $\Delta Q/m$ changes approximately in proportion to the velocity of the automobile carrying the vessel, which makes it simple to estimate liquid losses during transportation. The total quantity of heat liberated during transport is determined only by the distance traversed and is independent of the automobile velocity. In particular, the increase in loss of liquid nitrogen over 100 km is $7.5 \cdot 10^{-3}$ kg/kg for a cobblestone road, $4.5 \cdot 10^{-3}$ kg/kg for a dirt road, and $1.5 \cdot 10^{-3}$ kg/kg for an asphalt high-speed roadway. For an ordinary asphalt road we can estimate the loss at $(2.0\text{-}2.5) \cdot 10^{-3}$ kg/kg per 100 km. In helium vessels without nitrogen cooling (using the cold of the vapors) with gas exhaust open the liquid helium losses are close to those in nitrogen vessels. The increase in liquid helium loss in vessels without nitrogen cooling with gas exhaust closed and in vessels with nitrogen cooling is approximately 10 times higher.

NOTATION

a_0, amplitude of forced vibrations, m; E, energy of forced vibrations accumulated to start of period, J; ΔE, energy scattered in one oscillation period, J; m, liquid mass, kg; ΔQ, oscillation energy scattered in liquid (heat liberation), W; r_0, vessel radius; $Re = \omega r_0^2/\nu$, Reynolds number; v, velocity of motion over road, m/sec; δ, logarithmic oscillation decrement; ψ_0, oscillation energy absorption coefficient in liquid; θ, circular frequency of forced oscillations, sec^{-1}; ν, kinematic viscosity, m^2/sec; ω, circular frequency of free oscillations, sec^{-1}.

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