11. A. A. Boshe and I. B. Palatnik, "Experimental determination of the critical value of Weber's number for drop fragmentation in accelerating gas flow under quasistatic conditions," Alma-Ata (1984); VINITI 21.06.84, No. 4215-84.
12. B. E. Gel'fand, S. A. Gubin, and S. M. Kogarko, "Various forms of drop fragmentation in shock waves and their special characteristics," Inzh.-Fiz. Zh., 27, No. 1 (1974).

APPARATUS FOR INVESTIGATING THE LIQUID-NITROGEN DISTRIBUTION IN THE SPRAY CONE OF A JET FLOWING OUT OF A NOZZLE INTO AN AIR FLOW

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In systems which cool the flow in cryogenic wind tunnels liquid nitrogen is injected into the flow through spray nozzles. In using this method it is of interest to have information about the distribution of liquid in the flow, the penetration depth of the drops into the flow, and the evaporation time of the drops. Optical methods are widely employed for studying these processes [1], but often the accuracy of these methods is too low.

In the present paper we present data on an apparatus for measuring the amount of liquid nitrogen present in a two-phase flow. The operation of the apparatus is based on the extraction of a sample of the liquid. The construction and the measurement system were made so that the sample is analyzed in the dynamic regime. The apparatus was employed for studying the spraying and evaporation of liquid nitrogen out of a spray nozzle perpendicular to the flow in the working part of a cryogenic wind tunnel. The mass of the liquid nitrogen entering the receiver is measured with an accuracy of ±5%.

A diagram of the apparatus and the system of measurements is presented in Fig. 1 (a: 1 – feed path of the liquid nitrogen, 2 – nozzle, 3 – Pitot tube, 4 – adapter for extracting liquid from a gas–liquid mixture, 5 – feed path of helium, 6 – regulator, 7 – variable hydraulic resistance, 8 – calibration tube, 9 – flowmeter orifice, 10 – thermocouple; b: 1 – input slit of adapter, 2 – helium inflow, 3 – mixture of helium and evaporating nitrogen, 4 – flow of nitrogen drops, 5 – jet of excess helium; DF – direction of air flow).

The inner channel of the nozzle used for injecting liquid nitrogen has a smooth profile and the output diameter of the nozzle is equal to 1.5 mm. The attachment was constructed in two variants. In the first variant, a jet of helium, blocking the path of the air flow into the adapter, is injected into the receiving channel (through a 1 × 10 mm slit) perpendicular to the direction of the incident flow. Because helium has a low density the drops of liquid pass through the zone of the helium jet and evaporate in the cavity of the adapter in a helium atmosphere. The mixture of evaporating nitrogen and helium is extracted through a path in which the density and flow rate of the mixture and thereby the amount of liquid entering the adapter are measured. The volume flow rate of the helium jet is set at a value 1.5-2 times greater than the volume flow rate of the mixture through the channel.

In the second variant the adapter consists of a tube with an inner diameter of 4 mm and an outer diameter of 5 mm into which helium is introduced. A 0.7 × 7 mm input slit is cut in the tube 60 mm from the point of helium entry. At the location of the slit the tube is flattened to an oval cross section with inner dimensions of 1.5 × 5 mm. The slit is oriented along the generatrix of the tube and is located on the crest of the flattened section. The mechanism of the processes occurring in this adapter is the same as in the first adapter.

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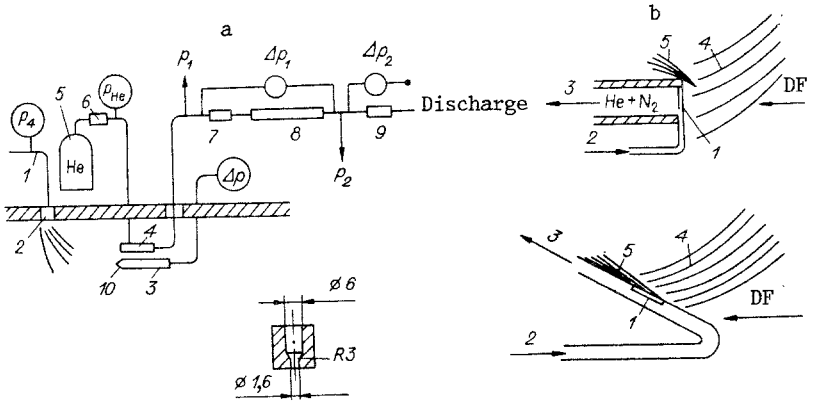

Fig. 1

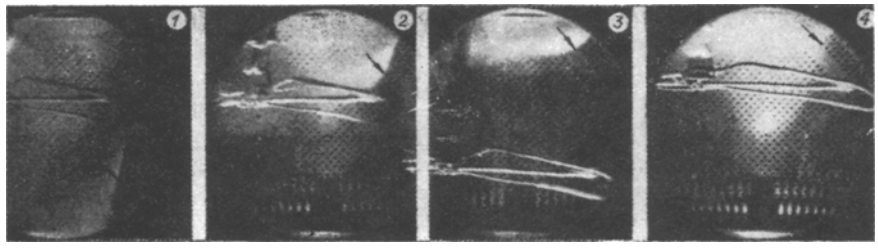

Fig. 2

The amount of liquid flowing into the adapter is measured with the help of the following operations: After separation at the input the liquid in the adapter evaporates in a helium atmosphere, and the mixture of vapor and helium is passed successively through two hydraulic resistances in which the character of the friction is different. In the first resistance a Poiseuille type flow is established. This resistance consists of a constant part (8 in Fig. 1a), consisting of a cylindrical tube with an inner diameter of 2 mm and a length of 300 mm, into which four 0.7 mm in diameter wires are inserted tightly against one another, and a variable regulated part (7 in Fig. 1a), consisting of a rubber tube with a regulatable cross section, into which a bundle of polyethylene filaments, 0.4 mm in diameter and 20 mm long, is inserted. The second hydraulic resistance (9 in Fig. 1a) is made in the form of a flowmeter orifice with an inner diameter of 1 mm with a 2 mm in diameter and 5 mm long tube at the outlet.

The Reynolds number $\mathrm{Re}_1 = \rho_1 u_1 \ell_1/\mu_1$ (ρ is the density, u is the velocity, and μ is the viscosity), estimated from the dimensions of the inner channels of the first hydraulic resistance under the conditions of the experiments, does not exceed 120 for pure helium flow and 1000 for air flow. The resistance coefficient for these values of Re_1 is proportional to Re_1^{-1} (Poiseuille's law). The the variation of the pressure p along the channel (first resistance) can be written in the form

$$dp/dx = -C\,\mathrm{Re}_1^{-1}\rho u^2/2, \tag{1}$$

where the constant C depends only on the geometry of the channels. As gas flows through the long input channel to the resistances, the temperature of the gas reaches room temperature and remains constant. Then, using Eq. (1) and the equation of state $p = \rho RT/m$, we can write for the first resistance

$$(m/\mu^2)\left(p_1^2 - p_2^2\right) = C_1\,\mathrm{Re}_1. \tag{2}$$

Here the constant C_1 depends on the geometric dimensions of the channel and the temperature of the gas, and m is the molecular weight. The presence of an additional regulatable resistance (with different values of Re) does not change the form of the relation (2), because the flow rate in the channel is constant.

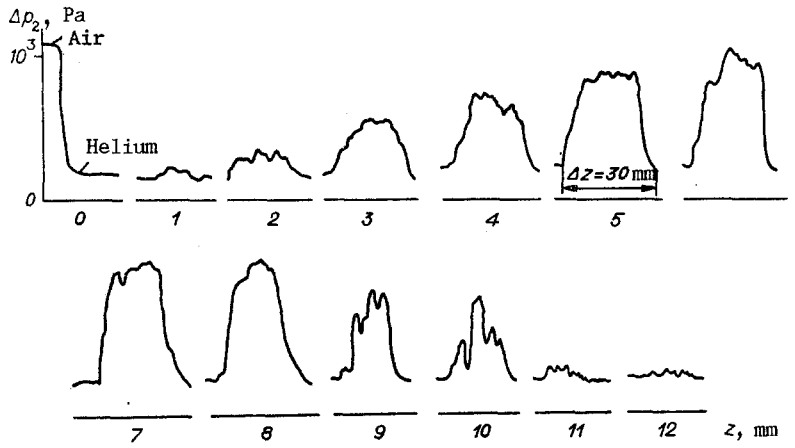

Fig. 3

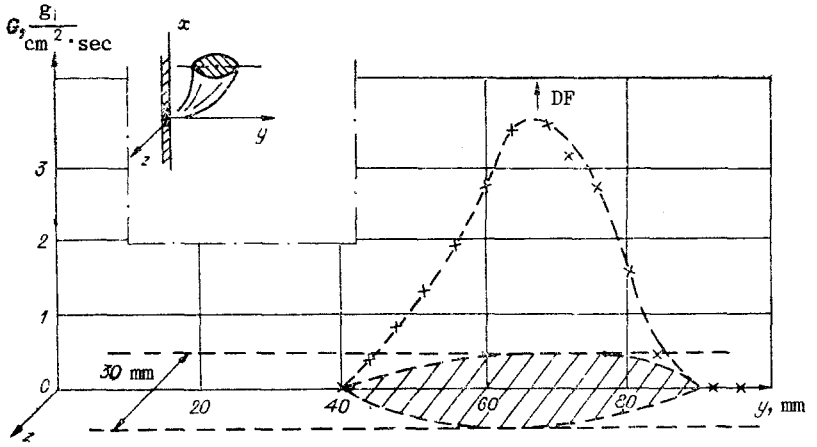

Fig. 4

If C depends on Re_1, the form of the relation (2) also remains the same, except that C_1 now depends on Re_1. In checking (2) experimentally the quantity $p_1^2 - p_2^2$ for the pure gas is proportional to the flow rate (i.e., it is also proportional to Re_1) within the limits of error of the measurements, and hence C_1 can be only a weak function of Re_1.

The pressure drop on the flowmeter orifice relative to atmospheric pressure p_3 has the form $\Delta p_2 = p_2 - p_3 = \xi(Re_2)\rho_2 u_2^2/2$ (ξ is the resistance coefficient).

Using the equation of state $p_2 = \rho_2 RT/m$ we write the last relation as

$$(m/\mu^2)\,\Delta p_2 p_2 = Af(\mathrm{Re}_2), \tag{3}$$

where the constant A depends only on the geometric parameters and the gas temperature, but not on the type of gas, the pressure, and the flow rate.

Since $Re_1 \sim Re_2$ (the flow is constant), it follows from Eqs. (2) and (3) that for fixed temperature and geometric dimensions there exists a functional dependence between the quantities $q = (m/\mu^2)\Delta p_2 p_2$ and $r = (m/\mu^2)(p_1^2 - p_2^2)$ (i.e., $q = q(r)$), which can be determined with the help of preliminary calibration. In this manner it was established that under the conditions of the experiments $q \sim r^n$, $n \approx 1.72$. Then

$$m/\mu^2 = B\left(p_1^2 - p_2^2\right)^{-n/(n-1)} (\Delta p_2 p_2)^{1/(n-1)}. \tag{4}$$

Here the constant B is determined from measurements using pure helium (the constants appearing in Eqs. (1)-(4) are dimensional).

From Eq. (4) and the relations $4(1-\alpha)+28\alpha=m$, $\mu=\mu(\alpha)$ we determined the molar fraction α of nitrogen in the mixture. Since the viscosity of pure helium and nitrogen differ by only 10%, to a first approximation it can be assumed that the viscosity μ is equal to the viscosity of helium, and μ can be determined in subsequent iterations using the theoretical dependence $\mu(\alpha)$.

Since $Re_2 \sim g/\mu$, we construct the calibration curve for finding the flow rate g on the basis of Eq. (3) and the relation $r \sim q^{1/n}$: $g/\mu \sim [(m/\mu^2)\Delta p_2 p_2]^{1/n}$. The amount of nitrogen in the mixture is αg. The main error in finding αg is related with the error in constructing the calibration curves and is estimated to be ±5%.

The experiments were performed on the apparatus of [2]: a cryogenic induction wind tunnel with a 200 × 200 × 740 mm working part. The conditions of the experiments were as follows: the static pressure in the flow $p_\infty = (1.2\text{-}1.5)\cdot 10^5$ Pa, the Mach number of the flow M = 0.1-0.6, the temperature T_∞ = 250-130 K, the pressure in the channel for injecting liquid nitrogen into the nozzle being studied $p_4 = (3\text{-}9)\cdot 10^5$ Pa, and the temperature of liquid nitrogen T_4 = 80 K. The efflux velocity of the jet from the nozzle was determined from the relation $u_4 = k\sqrt{2(p_4 - p_\infty)/\rho_4}$, where the flow rate coefficient k = 0.9 [3].

We measured the pressure p_0 and the temperature T_0 in the forechamber of the wind tunnel, the static pressure p_∞ in the flow (Point tube in the zone of the input opening of the adapter), the atmospheric pressure p_3, the nitrogen pressure p_4, and the pressure differences $(p_1 - p_2)$ and $\Delta p_2 = p_2 - p_3$. Simultaneously with the measurements we photographed the jet in scattered light from a spark source (flash duration $\sim 10^{-3}$ sec).

Figure 2 shows photographs of the liquid nitrogen jet with u_4 = 40 m/sec, T_∞ = 145 K. The velocity head for frames 1-4 corresponds to $1.1\cdot 10^3$, $7.2\cdot 10^3$, $2.3\cdot 10^4$, $3\cdot 10^4$ N/m^2 (the arrow marks the outer boundary of the jet). Both the penetration depth of the jet into the flow and the arrangement of the zones of breakdown and atomization of the jet depend on the velocity head.

Figure 3 shows a sequence of oscillograms for measuring Δp_2. This sequence was obtained by scanning with the adapter along the z direction (coordinates in Fig. 4) the region of atomization of the jet for different values of the coordinate y (the step Δy = 4 mm, y_1 = 44 mm, and y_{12} = 88 mm) at a distance x = 65 mm from the axis of the nozzle. Since the measurements were performed with $p_1 \approx$ const (with an accuracy of 5%), the quantity measured Δp_2 is roughly proportional to the amount of liquid helium flowing into the adpater slit.

Figure 4 shows the distribution of the flow of the liquid phase G over a cross section perpendicular to the direction of the incident gas flow for u_∞ = 77 m/sec, u_4 = 45 m/sec, $p_\infty = 1.4\cdot 10^5$ Pa, T_∞ = 145 K. The crosses are the average values of the mass flow of liquid nitrogen which were obtained from the measurements of Δp_2 at different distances y; the dashed line, bounding the hatched area, marks the boundaries of the jet in the z direction. The total flow rate of nitrogen through the nozzle was equal to 60 g/sec, and the measured flow rate in the section (hatched) was equal to 25 g/sec. The region of atomization is lens shaped; at one apex of the lens the coordinate y is equal to the coordinate at which the jet breaks up (determined from the photograph) and the second apex coincides with the visual front (along the flow) boundary of the spray cone.

The upper limit of the sizes of the drops formed can be estimated from the front boundary of the spray cone by comparing the observed trajectories with the computed trajectories. The latter trajectories are determined by integrating the equations of motion of a drop in the flow taking into account the transfer of heat and mass between the drop and the flow. The dependence of the Nusselt number on Re and the Prandtl number Pr is assumed to be of the form [4] $Nu = 2 + 0.393\ Re^{0.55} Pr^{0.36}$.

The integration was performed numerically on a computer. The parameters of the flow were assumed to be constants. This assumption can be justified only for the extreme (front) trajectory and less precisely for trajectories on the outer surface of the spray cone. For drops located in the interior regions of the spray cone the change in the velocity of the flow and the temperature of the gas due to the evaporation of liquid nitrogen must be taken into account. The maximum drop sizes d, estimated in this manner, satisfy the empirical relation $d/D = (3.7 \pm 0.4)\ We^{-1/2}$ in the range of Weber numbers $We = \rho_\infty u_\infty^2 D/\sigma = 2.5\cdot 10^3\text{-}1.2\cdot 10^4$ (D is the nozzle diameter and σ is the surface tension).

The experiments yielded the following interesting result: If the flow of liquid is additionally made turbulent in the forechamber of the nozzle (by inserting a 1 mm in diameter wire into it perpendicular to the axis), then a dip appears in the measured distributions at the center of the spray cone. This probably caused by the fact that turbulence, which results in breakup of primarily the most turbulent volumes of the liquid, plays a significant role in the breakup of the jet.

LITERATURE CITED

1. V. S. Valeev, A. V. Kudryavtsev, and G. M. Kuznetsov, "Experimental investigation of atomization of a liquid injected with a jet nozzle perpendicular to the direction of air flow," Izv. Vyssh. Uchebn. Zaved., Aviats. Tekhn., No. 3 (1984).
2. Yu. A. Agureev, Yu. V. Burov, A. S. Bushmin, and S. I. Tarasov, "Automated data acquisition and processing system for an apparatus with cryogenic temperatures," Inzh.-Fiz. Zh., 54, No. 5 (1988).
3. V. A. Borodin, Yu. F. Dityatin, and L. A. Klyachko, Atomization of Liquids [in Russian], Mashinostroenie, Moscow (1967).
4. S. S. Kutateladze and B. M. Borishanskii, Handbook of Heat Transfer [in Russian], Gosenergoizdat, Moscow (1959).

FORMULATION OF PROBLEMS WITH MOVING PHASE-TRANSITION BOUNDARIES IN HYDROTHERMAL STRATA

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The study of heat and mass transfer processes in hydrothermal strata is of unquestionable interest for the design of systems for extracting geothermal energy, an alternative energy resource, as well as for a better understanding of the dynamics of thermal processes in the lithosphere. Hydrothermal systems are natural strata saturated with hot water, steam, or a water–steam mixture. A change in the external conditions (e.g., a change in the heat flux of the Earth or drilling of a well into the formation) results in filtration flow of water (steam), accompanied by water–steam phase transitions and a change in the temperature, pressure, and phase composition of the formation. The mathematical description is constructed on the basis of the laws of conservation of mass and energy and Darcy's law for two-phase nonisothermal filtration. The model is closed by using the phase diagram for water. The known models of heat and mass transfer in hydrothermal strata [1-4] have been formulated in terms of pressure and enthalpy. The water saturation in the case of a steam–water mixture is calculated from the water and steam densities and the enthalpies of the water, steam, and steam–water mixture. The use of enthalpy as the sought function presumes that the system of conservation equations is closed with the p–h diagram of water. In fact, this model, a realization of the well-known enthalpy approach to the description of phase transitions [5], does not explicitly contain a moving phase boundary, i.e., a surface of a strong discontinuity of the water saturation function. The approach described above, however, has some shortcomings. The boundary conditions must be given in terms of the enthalpy, which is difficult to do in the case of boundary conditions of the first and third kinds. Moreover, the temperature field, which must be known for an understanding of the processes in the formation, remains undetermined.

In this paper a mathematical model of heat and mass transfer processes with phase transitions in hydrothermal strata, is formulated in terms of the temperature, pressure, and saturation and admits the existence of moving phase-transition surfaces, which are strong discontinuities of saturation function. The solution is constructed within the framework of the generalized solution of the Stefan problem [6], in many ways resembling analogous solutions of problems of the freezing and thawing of soils [7, 8] and the decomposition of gaseous hydrates in natural strata [9].

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