A new, substantially nondissipative process of energy separation in two-phase flows has been investigated. Mixtures of air with water, kerosene, and an aqueous solution of diethylene glycol were studied at initial pressures of 3-20 bar. It was found that ice was formed in an air-water mixture issuing from a supersonic nozzle, and for a mixture of air with a nonfreezing diethylene-glycol solution the liquid obtained after nonequilibrium separation had a negative temperature. The possibility of effective freezing out of moisture on an uncooled solid surface exposed to a current of moist air from a supersonic nozzle was demonstrated.

One of the basic properties of two-phase flows is that mechanical and thermal energy may be transferred between the phases over the whole flow field. This internal energy transfer leads to the appearance of temperature differences between the phases. Most investigations in this field relate to suspensions of solid particles in gases [1, 2]. Using optical methods, temperature differences between the solid particles and the gas were recorded experimentally in [1] for the flow of suspensions in a nozzle. However, the practical separation of phases with different temperatures at the nozzle outlet was not considered in these works.

Below, experimental results are presented on energy separation in two-phase gas-liquid media moving in tubes at high velocity; it is found that after complete deceleration and separation of the two phases, they have different temperatures and, in particular, there has been substantial cooling of the liquid phase.

From the enthalpy equation for an adiabatic flow of ideal gas $T = T_o - w^2/2C_p$, where $T$ and $T_o$ are the static and total absolute temperatures, $w$ is the velocity, and $C_p$ is the isobaric specific heat, it follows that increase in flow velocity is accompanied by a reduction in the static temperature in the flow. Significant cooling of the gas in the flow occurs predominantly at supersonic velocities, but there is less pronounced cooling even at subsonic velocities.

If liquid particles of initial temperature $T^o$ are introduced into a cooled (for example, by adiabatic expansion in a Laval nozzle) gas flow, transfer of thermal and mechanical energy between the particles and the gas results either in cooling of the particles and heating of the gas or else the reverse, depending on the relation between $T$ and $T^o$. If $T^o < T$, the particles will be heated and the gas cooled until $T^o = T$; if acceleration of the gas continues, so that $T^o$ becomes greater than $T$, inversion occurs, and heating of the gas begins again. In the presence of mass-transfer processes associated with evaporation, condensation, and freezing, the phenomenon is considerably more complex, but it remains essentially the same as long as the flow continues to be two-phase. If sufficiently rapid deceleration of the two-phase flow and separation of the component phases are now carried out, it may be observed that the total temperatures of the two phases are not the same. Since, in principle, passing a gas flow through a supersonic nozzle leads to a very high degree of expansion, and hence a very low temperature, it is possible by this means to obtain a very low temperature of the liquid after separation. Depending on the relation between the initial param-
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Fig. 1

eters of the two phases, it is possible to obtain not only strong cooling of the particles, but also, where required, very strong heating of the gaseous phase by using a hot liquid. A high total temperature of a gas may be obtained, for example, by the combined expansion in a supersonic nozzle of a strongly heated, initially liquid metal and an inert gas. Note that it is impossible to introduce liquid particles directly into a supersonic gas flow, since in this case shock waves are formed in the flow, reducing the flow velocity and increasing the static temperature in the region of the particles. Therefore the two-phase flow must be formed at a sufficiently small subcritical velocity, well before admission to the throat of the nozzle.

The experimental apparatus is shown in Fig. 1. Compressed air from compressor 1 passes through heat exchanger 2 and six apertures 3 (diameter, 6 mm) and is fed at right angles into a liquid jet; the liquid jet is driven by a pump 5 along the axis of the nozzle through 10 apertures 4 (diameter, 0.8 mm; length, 4 mm). In the mixer 6, at low velocity, a two-phase coarsely disperse mixture, homogeneous in temperature and pressure, is formed and then proceeds to the supersonic nozzle 7, where additional dispersion and cooling of the liquid occurs through internal heat transfer with the gas. Following the nozzle there is a removable stainless steel deflector 8; deflectors with various angles of inclination ($\alpha = 20$, 30, and 40°) of the polished plane surface can be fitted. By means of the deflector, the two-phase mixture is directed into a heat-insulated grid separator 9 through a connecting tube 10. The separated liquid is collected in reservoir 11, and the air is released to the atmosphere. There are five KhK thermocouples 12 fitted flush (in 2-mm-diameter recesses) in the plane surface of the deflector. The conical expansion section of the nozzle is of length 150 mm, the throat and the outlet section being of diameter 10 and 25 mm, respectively. The tapering section of the nozzle is of length 20 mm. The cylindrical mixer 6 is of diameter 25 mm and length 113 mm. The distance from the apertures 3 to the tapering section of the nozzle is 60 mm.

Operation of the apparatus was possible both with direct release of treated air and liquid into the atmosphere and also with discharge of the mixture under a counterpressure. The liquid could be preheated as required, by means of water vapor. The air flow rate was measured by a standard diaphragm and the liquid flow rate, volumetrically. The air and liquid temperatures at the mixer inlet and also the temperature of the liquid film on the deflector and inside the separator were measured by KhK thermocouples connected to an EPP-09M3 automatic electronic potentiometer. The thermocouple readings were recorded on a diagram throughout the experiment. The pressures were determined by a standard hairspring manometer.

It was established in preliminary experiments that a steady spray of liquid is obtained for a pressure difference at the aperture of more than 0.3 bar. In the experiments this difference was in the range 0.5-1 bar, depending on the particular liquid. For a smaller pressure difference, a self-oscillating process was observed, with the emission from the nozzle alternately of two-phase mixture and of pure air, with a frequency of 1-2 Hz.

One feature of the investigated nozzle is that, whereas the pressure difference calculated for the nozzle (neglecting the effect of the liquid phase) is $p_0:/p_2 = 68$, where $p_0$ and $p_2$ are the pressures at the inlet and at a section of the nozzle, values found experimentally lie in the range 3-20. Therefore, the expansion section of the nozzle behaves simultaneously as a supersonic nozzle and a subsonic diffuser with an initial pressure discontinuity. Depending on the conditions of operation, the accelerating supersonic section accounted for between $1/4$ and $1/2$ of the length of the expansion section of the nozzle, while the remaining $3/4$ to $1/2$ of the length was responsible for deceleration of the two-phase