

Using Eqs. (3) and (6), together with Eq. (5), it is possible to calculate the probability of any values of specific heat and density, given the degree of filling and volume. This is of particular importance in situations which involve very small samples, for example, in carrying out experiments in microcalorimeters or in the differential thermal analysis of materials.

NOTATION

P_{igr} , fraction by weight; P_i , fraction by volume; γ_i , density; c_i , specific heat of i -th component; P , mean degree of filling (by volume); C_n^m , number of combinations of m elements from a set of n .

LITERATURE CITED

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ENERGY SEPARATION IN TWO-PHASE FLOWS

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A new, essentially nondissipative effect of energy separation in steady two-phase flows is discussed.

The separation of gas molecules by energies in gravitational and centrifugal force fields (the Rank effect) is very widely known. Recently, several thermodynamically more favorable methods of energy separation in gaseous media have been discovered, for example, by means of pulsing gas columns and in cryptosteady motion. Common to these effects is a redistribution of internal mechanical energy and the accompanying thermal energy among the individual particles of initially homogeneous continuous media under the effect of an external mechanical perturbation.

The present work gives theoretical and experimental results regarding a new, fundamentally different energy-separation effect, which takes place in a two-phase, initially homogeneous medium moving at high velocities; after deceleration and separation of the two phases, their temperatures are found to be significantly different.

§ 1. Essentially, the physical basis of the effect is as follows. In an adiabatic flow of ideal gas, the relation between the absolute deceleration temperature T_0 and the static temperature T is given by the specific-heat equation in the form

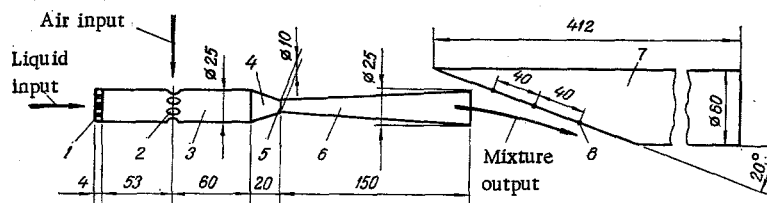


Fig. 1. Experimental nozzle-separator system: 1) atomizer (10 holes, diameter 0.8 mm); 2) air inlet (6 holes, diameter 6 mm); 3) mixer; 4) tapering section of nozzle; 5) neck; 6) broadening section of nozzle; 7) separator; 8) thermocouples (aligned along principal axes of ellipse: one at the center, two on the minor and two on the major axes, respectively, 15 and 40 mm from the center).

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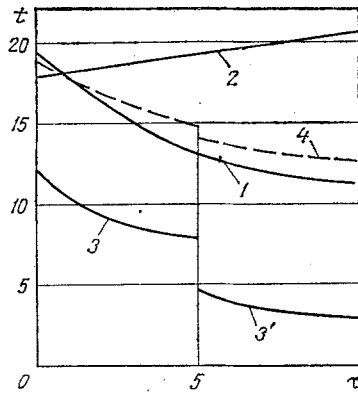


Fig. 2

Fig. 2. Change over time (τ , min) in the temperature (t , °C) of air (1) and kerosene (2) at the inlet to the mixture and of the separated liquid film (3, 3'): 3) air pressure 6 bar; 3') 8 bar; 4) calculated temperature of mixture; room temperature + 23°C.

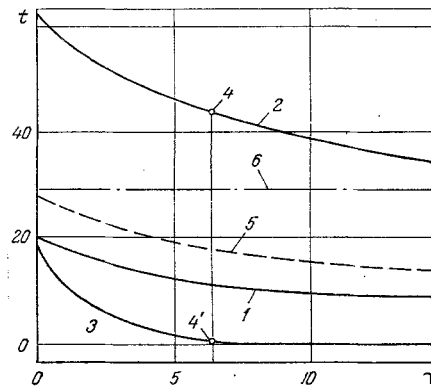


Fig. 3

Fig. 3. Change over time in temperature (t , °C) of air (1) and water (2) at the mixer inlet and of the separated liquid film (3); 4, 4') appearance of ice; 5) calculated temperature of mixture; 6) room temperature; air pressure 7 bar.

$$\frac{T}{T_0} = 1 - \frac{w^2}{2C_p T_0} \quad (1)$$

Equation (1) may also be written in the form

$$\frac{T}{T_0} = 1 - \frac{\kappa - 1}{\kappa + 1} \mu^2 \quad (2)$$

From Eqs. (1) and (2) it follows that the temperature in the flow falls as the rate of flow increases. Significant cooling of the gas occurs predominantly at supersonic velocities ($\mu > 1$) and, on reaching a limiting velocity $\mu \rightarrow \sqrt{(\kappa + 1)/(\kappa - 1)}$, the temperature $T \rightarrow 0$. For subsonic flow ($\mu < 1$), the cooling of the gas is less pronounced, although it does occur. Imagine a flow of gas cooled, for example, by adiabatic expansion in a Laval nozzle, and suppose that liquid or solid particles of initial temperature T_r are now introduced. The presence of internal degrees of freedom in the two-phase medium and, in particular, the possibility of a transfer of thermal and mechanical energy between the particles and the gas mean that, depending on the relative values of T and T_r , there will be either cooling of the liquid and heating of the gas, or else the opposite effect. If $T_r < T$, the particles are heated and the gas is cooled, until their temperatures are equalized ($T_r = T$); if there is further acceleration of the gas, i. e., if $T_r > T$, inversion occurs and the gas begins to be heated. Note that, in addition to these effects, there is also transfer of mechanical energy as a result of the dispersion and breaking down of the particles. In the presence of mass-transfer processes caused by evaporation and condensation, the phenomenon is even more complex, but in essence it remains the same as long as the flow continues to be two-phase. If the deceleration of the two-phase flow and its separation into the component phases are now carried out sufficiently rapidly, it may be observed that the temperatures of the two phases are not the same. In supersonic nozzles in particular, a very high degree of expansion is achieved, and hence also considerable cooling of the gas and particles. Depending on the initial phase parameters, not only are the particles cooled but, of necessity, the gaseous phase will be very strongly heated if the particles and the gas were heated initially. In the general case, the deceleration temperature of the gas after separation is found to be higher than, equal to, or less than the initial temperature, while the temperature of the particles is close to the lowest temperature of the gas (the gas temperature at the end of expansion). Note that the particles must be introduced into the flow at sufficiently small subsonic velocities right up to the nozzle inlet, since the introduction of particles into a supersonic flow leads to the formation of shock waves, reducing the flow velocity and increasing the temperature in the region of the particles. In addition, the time of contact of the particles and the gas in the flow should considerably exceed the duration of the deceleration of the two-phase mixture and its separation into the component phases. The absence of symmetry with respect to time in the internal heat transfer between the phases in the joint flow and the separation of the two-phase

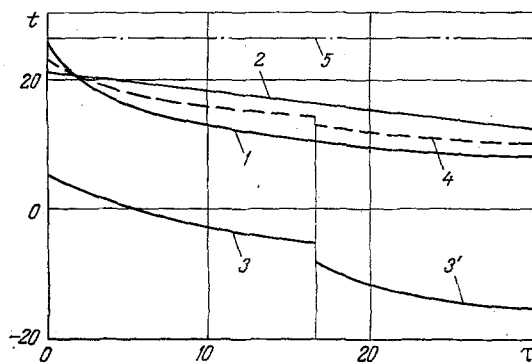


Fig. 4. Change over time in temperature of air (1) and aqueous diethylene glycol solution (2) at the mixer inlet and of separated liquid film (3, 3'); 3) air pressure 7 bar; 3') 11 bar; 4) calculated temperature of mixture; 5) room temperature.

mixture into its components lead to the appearance of a considerable temperature difference and are the bases for the creation of new, essentially nondissipative methods of cooling and heating.

§ 2. The investigated nozzle-separator system is shown in Fig. 1. Compressed air is pumped to the mixer at right angles to the jet, resulting in the formation of a two-phase mixture that is homogeneous in temperature and pressure at low velocities, some distance before the inlet to the supersonic Laval nozzle. Loss of air pressure in the mixer does not exceed 0.5-0.8 bar, while a stable spray of liquid is obtained for a pressure drop of more than 0.3 bar in the atomizer. The polished stainless-steel separator plane is provided with five 2-mm-diameter holes to accommodate thermocouples. Experiments can be carried out both with closed circulation of the liquid for expansion of the mixture under atmospheric pressure, and with open circulation of the liquid for expansion of the mixture with a counterpressure. The system provides for the liquid to be heated by water vapor. The air flow is measured by a standard diaphragm and the liquid flow is measured volumetrically. The air and liquid temperatures at the inlet to the mixer and also that of the separated film are recorded by thermocouples connected to an automatic electronic ÉPP-09M3 potentiometer with thermocouple readings every 5 sec and continuous recording on a diagram. The pressures of the air and liquid are determined by a standard hairspring manometer.

The calculated pressure drop for the investigated nozzle (neglecting the effect of the nongaseous phase) was $p_0/p = 68$ (where p_0 and p are the pressures at the inlet and midsection of the nozzle), and in experiments this value did not exceed 11, as a result of which the nozzle was operated with pressure discontinuities and with internal breakaway of the boundary layer. Particles passing successively through zones before and after the discontinuity are, respectively, cooled and heated. Estimating the time-averaged temperature of the particles at the outlet from this nozzle by the formula

$$\bar{T} = \frac{1}{\tau} \int_{(\tau)} T d\tau,$$

where τ is the time, gives $\bar{T}/T_0 = 0.945$; for $T_0 = 290^\circ\text{K}$, this means a calculated reduction in the particle temperature of approximately 16°C (close to that obtained experimentally).

Energy distribution in two-phase flows was examined experimentally on mixtures of air with kerosene, water, and an aqueous solution of diethylene glycol. The pressures of air and liquid at the mixer inlet differed only by the pressure loss of the liquid in the atomizer and were in the region of 6-11 bar.

Experimental data for the air-kerosene mixture are shown in Fig. 2. The temperature drop of the kerosene film is caused by the change in air pressure at the inlet from 6 to 8 bar. The ratio $n = m_r/m_0$ of the mass flow of kerosene m_r to that of air m_0 was $n = 0.15$ for $p_0 = 6$ bar and $n = 0.1$ for $p_0 = 8$ bar. For comparison, Fig. 2 also shows the temperature of the mixture calculated from the thermal balance for an isobaric mixture

$$\left(n + \frac{C_p}{c_r} \right) t_m = n t_r + \frac{C_p}{c_r} t_0,$$

where c_r is the specific heat of the liquid; t_0 and t_r are the temperatures of air and liquid at the mixer inlet; and t_m is the temperature of the mixture. The actual temperature of the kerosene film is 8–10°C less than the calculated temperature of the mixture and 5–8°C less than the air temperature.

In Fig. 3, analogous curves are shown for the water–air mixture (pressure 7 bar, $n = 0.1$). The distinctive feature of the experiment with water is that, at a certain temperature of the water at the mixer inlet, snow and ice were formed at the separator, in amounts that increased steadily as the water temperature at the inlet was reduced. The formation of a crust of ice at the separator was preceded by the appearance at the nozzle outlet of fine hail. In these experiments, the water was preheated to 90°C. It is interesting to note that for a pressure of 7 bar and a water temperature at the mixer inlet of 85–65°C intensive vaporization was observed at the nozzle outlet. At temperatures below 65°C, vaporization ceased. The temperature of the water film was 12–17°C lower than the calculated mixture temperature.

Experiments with diethylene glycol solution were carried out at air pressures of 7 bar ($n = 0.34$) and 11 bar ($n = 0.222$) (Fig. 4; curves 3 and 4 show the difference between the experimental and calculated temperatures). It was possible to achieve negative temperatures of the nonfreezing separated liquid film down to –15°C, amounting to 17–24°C less than the calculated temperature of the mixture.

The experimental results shown in Figs. 2–4 were obtained for expansion of the liquid and air mixture under atmospheric pressure. Experiments carried out with a counterpressure gave basically the same results, although when the counterpressure was changed by a factor of 2–4 in experiments with air–kerosene and water–air mixtures the temperature of the separated liquid film was 1–2°C higher.

Analysis of the experimental data showed that the achieved level of cooling of the liquid cannot be explained as the result of mixing air with the liquid nor by the presence of a Joule–Thomson effect, which is only 1–2°C in the investigated range of pressures (to 11 bar) and temperatures (0–20°C) in air. The considerable cooling of the liquid observed is associated with energy separation in the two-phase flow. The significant result of this work is the experimental proof of the possibility of separating liquid and gaseous phases in nonsteady temperature conditions.

§ 3. From the foregoing it follows that the energy separation achieved in a two-phase flow should depend on parameters characterizing the convective heat exchange in the flow, the heat conduction of the nongaseous phase, the degree of dispersion of the particles, the ratio of the mass flow rate of the particles and the gas, and the change in their temperature. Such parameters might be

$$n = \frac{m_r}{m_0}; \theta = \frac{\omega^2}{C_p \Delta T}; Pe = \frac{wdc_r \rho_r}{\lambda_r}; We = \frac{\sigma_r}{d \rho_r \omega^2},$$

where d is the mean particle size; ρ_r , λ_r , and σ_r are the density, heat conduction, and surface tension of the homogeneous phase; ΔT is the excess temperature. Multiplying these parameters together, we obtain a parameter characterizing the energy separation achieved in a two-phase flow

$$E = n \frac{\sigma_r c_r \omega}{\lambda_r C_p \Delta T}.$$

Numerical values of this parameter found experimentally were 1.78 for kerosene, 1.875 for water, and 2.02 for an aqueous solution of diethylene glycol. On average, for an estimate of the excess temperature in similar conditions, we have $E = 2$.

Energy separation in two-phase flows may have many applications in various cold and hot cycles, and also in a whole series of technological processes.

NOTATION

T , absolute temperature; \bar{T} , time-averaged absolute temperature; ΔT , excess temperature; t , temperature; p , absolute pressure; c , specific heat; C_p , isobaric specific heat; C_V , specific heat at constant volume; ρ , density; λ , heat conductivity; σ , surface tension; R , universal gas constant; τ , time; d , mean dimension of particle; $\kappa = C_p/C_V$, adiabatic constant; $a_0 = \sqrt{2\kappa RT_0/(\kappa + 1)}$, critical velocity of sound; w , flow velocity; $\mu = w/a_0$, velocity coefficient; m , mass flow rate; $n = m_r/m_0$, relative mass flow rate of particles; $Pe = wdc_r/\lambda$, Péclet number; $We = \sigma/d\rho w^2$, Weber number; $\theta = w^2/C_p \Delta T$, dimensionless temperature parameter. Indices: 0, deceleration of gaseous phase; r , particles; m , mixture.