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NITROGEN CONDENSATION IN A HYPERSONIC NOZZLE

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We will investigate the numerical calculations and the experimental study of homogeneous nitrogen condensation in a hypersonic nozzle at $M \gtrsim 20$.

Saturation conditions are often achieved when gases expand in the nozzles of hypersonic aerodynamic equipment [1-4]. If this occurs at a sufficiently low pressure (for nitrogen and air, less than $4 \cdot 10^{-3}$ bar) and the impurity content of the gas is low, then significant supercooling of the flow occurs [1-3]. It then becomes important to determine the range of braking parameters at which gas flow in the nozzle occurs without the condensation process having a significant effect. Theoretical prediction of conditions for the onset of condensation presents a number of difficulties in principle, so that, as a rule, it is necessary to commence from experimental results. As has been shown in [3-7], in interpreting the experimental results obtained, fairly good results may be obtained by classical homogeneous-condensation theory, if we specially select the coefficients in the expressions which extrapolate the dependences of the condensed-phase parameters to the temperature range below the triple point. In the present study numerical calculations will be performed on the basis of classical theory to generalize experimental data on nitrogen condensation in a hypersonic nozzle [8]. The results of the study show that when the dependence of condensed-phase surface tension coefficient on droplet radius is considered, classical homogeneous-condensation theory can be used to predict conditions for the commencement of condensation in apparatus with high value breaking parameters.

Experimental data on nitrogen condensation in a hypersonic tube were obtained for the following conical nozzle parameters: critical-section diameter 1 mm, half-aperture angle 9°, output-section diameter 220 mm. The braking pressure was measured behind the direct shock wave in the working portion of the device while the temperature was decreased in the gas forechamber as the pressure therein was maintained constant. As the braking temperature T_0 was decreased, the braking pressure behind the shock wave P_0' first remained constant at its isentropic level, after which, at some braking temperature T_{0c} it began to decrease and then behaved irregularly with further decrease in T_0. As careful measurements [1, 2] reveal, the static pressure in the working section P begins to increase with reduction in T_0, with deviation from the isentropic value of P commencing at approximately the same temperature T_{0c}. In comparing the numerical calculation results to experimental data it is assumed that deviation of P and P_0' from their isentropic values occur at one and the same braking temperature T_{0c}. Nonsteady-state processes in the experiments may be neglected, since the characteristic time for change in T_0 comprised $\sim$10 sec, while the characteristic time for flow establishment in the nozzle was $\sim 10^{-3}$ sec.

The value of T_{0c} was measured for three values of braking pressure P_0. For variant No. 1 $P_0 = 106.75$ bar, $T_{0c} = 1143$°K, $M = 22.8$; No. 2, $P_0 = 71.92$, $T_{0c} = 943$°K, $M = 22.2$; No. 3, $P_0 = 51.66$, $T_{0c} = 900$°K, $M = 21.8$. M is the Mach number in the working section of the device in the absence of condensation, which can be calculated from the measured ratio P_0'/P_0 and expressions for isentropic nitrogen flow. The gas pressure in the forechamber was monitored by an 0.16 accuracy class manometer, and remained constant within 0.81 bar. The braking temperature T_0 was measured by a PP-1 thermocouple 0.1 mm in diameter with systemic error no greater than 1%. The braking pressure at the compression discontinuity was measured by a

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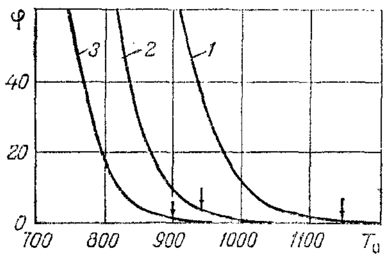

Fig. 1

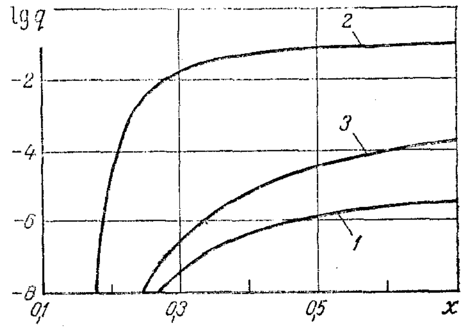

Fig. 2

Fig. 1. Function $\varphi = (P/P_0)/(P/P_0)_{is} - 1$ (%) vs braking temperature T_0 (°K) for various forechamber pressures: 1) P_0 = 106.57 bar; 2) 71.92; 3) 51.66; arrows are experimental values of T_{0c}.

Fig. 2. Change in mass concentration of condensate q along axial nozzle coordinate x at various values of parameter δ in the Tolman equation: 1) δ = 0; 2) 1; 3) 0.3; δ, Å; x, m.

DMI-1 sensor connected to a 170-mm-long tube with probe located in the working section. The probe had a planar face with outside diameter of 3 mm and inside diameter of 2 mm. The response time of the system consisting of the pressure sensor and tube was 30 msec, which corresponds to an error in T_{0c} determination of not more than 1%. Specially purified nitrogen was used (O_2 and H_2O concentration less than 10 particles per 10^6 particles of N_2, no trace of CO_2), so that the effect of impurities may be neglected and condensation treated as homogeneous [9].

Theoretical analysis of the experimental results was performed in the following manner. For a given value of braking pressure at various braking temperatures the Runge—Kutta method was used to solve a system of ordinary differential equations describing the flow of nitrogen in the nozzle with condensation. The change in braking temperature upon transition from one variant to the other was 250°K. On the basis of the calculation results the dependence of the quantity

$$\varphi = (P/P_0)/(P/P_0)_{is} - 1 \quad (1)$$

on braking temperature was determined. In Eq. (1) P is the static gas pressure in the working section.

Figure 1 shows curves of the function $\varphi(T_0)$ obtained in the calculations for various values of braking pressure. From these curves one can easily find the braking temperature at which condensation begins to effect the gasdynamic parameters. Performing calculations with classical homogeneous-condensation theory, by varying the free parameters one can achieve agreement of this braking temperature with the value T_{0c} obtained from the experimental dependence $P_0'(T_0)$. If calculations with parameters chosen in this manner give satisfactory agreement with other experiments, this theory can then be used to predict condensation for the given device over a range of forechamber conditions. It is just such a method which the majority of studies on theoretical interpretation of experimental data on gas condensation use [4, 6, 7].

The calculations of the present study are based on a system of equations for gas flow with condensation which may be found, for example, in [10]. The calculations were performed in the quasi-one-dimensional approximation; the effect of viscosity was estimated by introducing an effective nozzle aperture angle corresponding to that determined experimentally from the ratio of P_0'/P_0 to the Mach number at the nozzle exit. This approximation is satisfactory for determining conditions for commencement of condensation, since from the experimental results of [6, 11] we can expect that flow inhomogeneity does not have a significant effect on the results of the present calculation. This is confirmed by further comparison of calculated and experimental data on the beginning of condensation.

Data on the thermophysical properties of gaseous and condensed nitrogen and its saturation line were taken from [4]. For example, extrapolation formulas for the surface tension coefficient and density of condensed nitrogen at temperatures below the triple point are written in the form

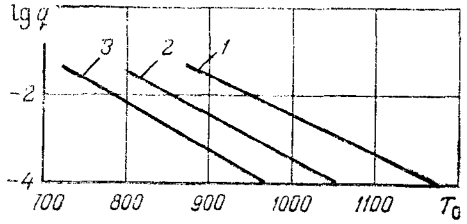

Fig. 3. Mass concentration of condensate q at nozzle output vs braking temperature T_0 (°K) for various forechamber pressures: 1) P_0 = 106.57 bar; 2) 71.92; 3) 51.66.

$$\sigma = 0{,}0258 - 0{,}00022T, \tag{2}$$

$$\rho_2 = 1177 - 4{,}76T, \tag{3}$$

where σ is expressed in N·m, and ρ_2 in kg/m^3. However, the calculations performed reveal that using only the extrapolation expressions of [4], one cannot obtain good agreement between calculation and experiment. At the nozzle output one obtains a condensate mass concentration on the order of 10^{-5}, which cannot markedly affect flow parameters.

The theoretical description of condensation will be more precise and agree better with experimental results if we consider the dependence of surface tension coefficient of the condensed nitrogen phase on droplet size r. To do this we use Tolman's equation [12]

$$\sigma(r,\ T) = \sigma(T)/(1 + 2\delta/r), \tag{4}$$

where the function $\sigma(T)$ is assumed specified by Eq. (2); δ is a parameter having the dimensions of length.

Figure 2 shows results of a calculation of condensate concentration change along the nozzle axis. The curves show that consideration of the dependence of surface tension coefficient on droplet size is important for such calculations. The mean temperature of the condensed phase T_2, upon which the mean condensate droplet growth rate depends, can be calculated by using an expression for the pressure of the gas in equilibrium with droplets of mean radius $\bar{r}$ [13]:

$$P = P_\infty \exp\left[(2\sigma(\bar{r})/\bar{r} + d\sigma(\bar{r})/dr)/\rho_2 RT\right], \tag{5}$$

where P_∞ is the saturation pressure at temperature T_2 above a plane surface of the condensed phase. The parameter δ is chosen by considering the dependences of the quantity φ, obtained for various δ values determined by Eq. (1) on braking temperature, as described above. For experimental point No. 1 the value δ = 0.3 Å was obtained. Figure 1 shows the results of calculating functions $\varphi(T_0)$ for various experimental points at δ = 0.3 Å.

It follows from Fig. 3 that the function $q(T_0)$ obtained by the calculations for the nozzle output section is exponential, and marked deviation of the gasdynamic parameters from their isentropic values begins at a mass concentration of condensate approximately equal to $5 \cdot 10^{-4}$. For these curves we may propose an approximate interpolation expression

$$\lg q = 2{,}8847 + 0{,}03273P_0 - 0{,}008812T_0. \tag{6}$$

Commencing from this expression and the fact that condensation begins to have a marked effect on the flow at $q = 5 \cdot 10^{-4}$, we obtain the relationship

$$T_{0k} = 702 + 3{,}714P_0. \tag{7}$$

This expression will predict the value of T_{0c} for the experimental points indicated above to within 4%.

NOTATION

P_0', braking pressure behind direct shock wave; P, pressure; T, temperature; M, Mach number; ρ, density; φ , deviation of static pressure at nozzle output from static value; σ, surface tension of condensed phase; r, condensate droplet radius; $\bar{r}$, mean condensate droplet radius; δ, parameter in the Tolman equation; R, gas constant; q, mass condensate concentration. Subscripts: 0, braking parameters; is, isentropic flow values; 2, condensed-phase parameters.

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