OUTFLOW FROM A LAVAL NOZZLE WITH CONDENSATION OF THE VAPOR PHASE ON A CONCOMITANT JET OF COLD LIQUID

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It is known that when two-phase media (vapor and drops) flow out of a Laval nozzle into free space its mouth (exit section) at a certain value of back pressure p_* is blocked, i.e., the pressure p_- at the mouth remains constant with further reduction of p. This outflow regime corresponds to the most efficient operation of the nozzle [1]. The value of p_- depends on the inlet pressure p_0 and the mass vapor content x_0. Injection of cold liquid beyond the nozzle leads to additional effects, which can appreciably affect the outflow regime. The aim of the present work was to investigate experimentally and theoretically the outflow from a nozzle with condensation of the vapor phase on a concomitant jet of cold liquid beyond its mouth.

The experiments were conducted on a steam–water test rig. The outflow is shown schematically in Fig. 1. The Laval nozzle 1 with central body 2 was similar in design to that described in [1]. The central body was a thermally insulated liquid nozzle. The mounts of the nozzles lay in plane 3. Beyond the nozzle mouths a cylindrical control section 4 was mounted. The mass flow vapor content at the inlet varied in the range x_0 = 0.15-0.3, the pressure was maintained at $2 \cdot 10^5$ N/m^2, and the temperature of the cold liquid was 15-17°C.

The results of the experiments are shown in Fig. 2. As Fig. 2 shows, the presence of the concomitant jet of cold liquid leads to an increase in pressure p_m at the nozzle mouth (curve 2) in comparison with choking operation in the case of outflow into free space (curve 1). This increase is greater, the smaller x_0. Figure 3 also shows the variation of pressure along the nozzle and control section. The nozzle mouth corresponds to the zero on the x axis. The ratio of the flow of cold water to the flow of mixture through the Laval nozzle is characterized by the coefficient u. In the given regimes the diameter of the liquid nozzle was 4.0 mm, the flow of mixture was 0.160 kg/sec, and x_0 = 0.147. The pressure discontinuity is clearly seen (although it is small), indicating off-design operation of the nozzle. It is of interest to note that an increase in temperature of the condensing liquid reduces p_m/p_-, while an increase in its amount without alteration of the exit diameter of the liquid nozzle does not affect the value of this ratio. In the absence of condensation the pressure distributions along the nozzle in the case of outflow into a cylindrical section and free space are the same.

An increase in pressure at the point of delivery of cold liquid into the supersonic part of the nozzle was reported in [2] and was attributed by the authors to breakup at the injected jets and to the consequent increase in resistance of the section, which can only be overcome by a greater pressure drop, created, according to [2], in the shock waves. In the considered case there was no appreciable breakup of the jet in the cylindrical channel beyond the nozzle, but the pressure increase was still present. We propose the following explanation of this flow picture.

When the flow passes out of the nozzle into the cylindrical control section there is an abrupt change in the boundary conditions. If the flow of vapor through the side surface of the central body in the nozzle is zero (the wall impermeability condition), then for condensation on the liquid jet in the mixing chamber we require that $I(r = r_0) = I_0$ (see Fig. 1), where I_0 is the amount of vapor condensing on unit surface in unit time. The latter leads to the appearance in the vapor of a radial velocity component v_r, which causes rotation of the velocity vector at the nozzle mouth through an angle θ. In a supersonic flow such rotation with fairly large θ is effected in the shock waves.

We will estimate the role of condensation on the jet in the pressure increase. We assume that the jet radius r_0 is constant and equal to the radius of the central body at the nozzle mouth, i.e., at the entrance to the cylindrical section the cross section of the channel is constant. We will assume that there is no condensation in the volume, and the rate of condensation I_0 on the jet is constant. In these conditions the problem of flow through the cylindrical section reduces to the problem of flow between coaxial cylinders of radius r_0 and R with suction occurring on the inner surface (see Fig. 1).

We assign the velocity distribution in the form

$$\rho v_r = f(r)/r,\ \rho v_z = \rho_- v_- - z f'(r)/r, \qquad (1)$$
$$v_- = v_{z-},\ \rho = \varphi \rho^\circ_\varepsilon$$

which identically satisfies the equation of continuity of the vapor phase

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r) + \frac{\partial}{\partial z}(\rho v_z) = 0,$$

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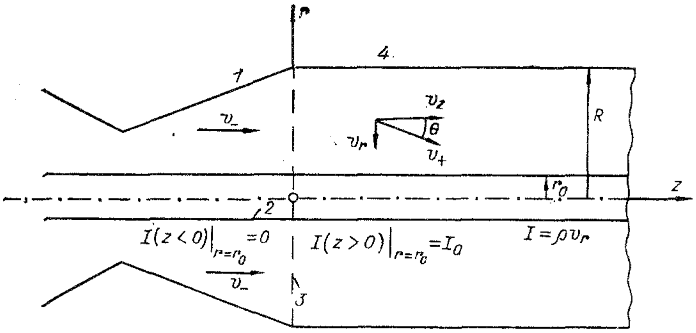

Fig. 1

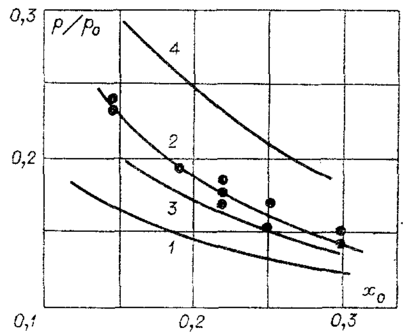

Fig. 2

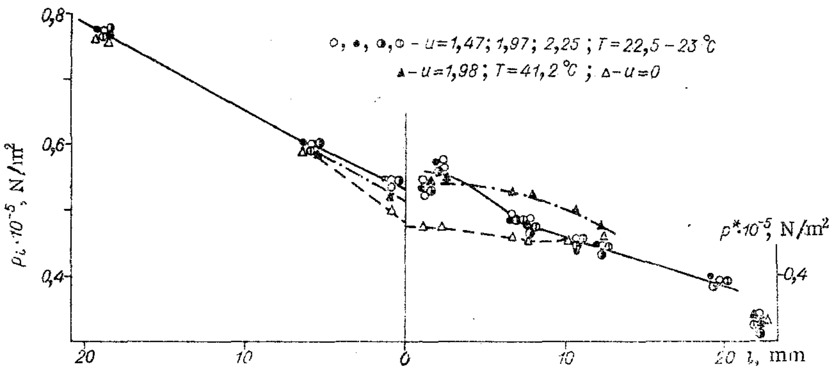

Fig. 3

where φ is the volume vapor content; ρ^0 is the true vapor density; v_r and v_z are, respectively, the radial and longitudinal components of the velocity vector; the – sign refers to the values of the quantities before the shock wave, which is presumably formed at the nozzle mouth. Following [4], we write

$$f(r) = C_1 r^2 + C_2, \tag{2}$$

where C_1 and C_2 are constants, determined from the boundary conditions

$$I(r_0) = -I_0, \quad I(R) = 0.$$

According to Fig. 1,

$$\operatorname{tg}\theta = \frac{v_r}{v_z} = \frac{\rho v_r}{\rho v_z} = \frac{I}{\rho v_z},$$

from which, using (1), (2), we obtain

$$\operatorname{tg}\theta = \frac{I_0}{\rho_- v_-}\,\frac{r_0}{R^2 - r_0^2}\left(r - \frac{R^2}{r}\right). \tag{3}$$

The conditions on a discontinuity surface in an inviscid two-phase medium [5] can be put in the form

$$\begin{gathered}\operatorname{tg}\frac{(\gamma-\theta)}{\operatorname{tg}\gamma}=\frac{v_{n+}}{v_{n-}}=\frac{b-\sqrt{b^2-4ac}}{2av_{n-}},\\ b=v_{n-}+\frac{p_-}{\rho^0_- v_{n-}},\quad c=\frac{\varphi_-}{\varphi_+}\left(T_-+\frac{v^2_{n-}}{2c_p}\right)R,\quad a=1-\frac{\varphi_-}{\varphi_+}\frac{R}{2c_p},\\ p_+=p_-+\rho^0_- v_{n-}(v_{n-}-v_{n+}),\quad v_{n-}=v_-\sin\gamma,\end{gathered} \tag{4}$$

where γ is the angle between the direction of v and the compression wave, R is the gas constant, T is the temperature, p is the pressure, c_p is the heat capacity of the vapor; the + sign refers to values of the quantities behind the shock wave. According to [5], when $(1-\varphi)\rho^0_-/(\varphi\rho^0_1)\ll 1$, which is the case in the investigated regimes (ρ^0_1 is the density of the liquid), we can neglect the effect of the liquid phase on the gas flow parameters after the shock wave, i.e., we can assume that $\varphi_-=\varphi_+$.

The system of equations (4) connects the angle of rotation θ of the flow with the angle γ. Of the two possible values of γ we chose for the calculations the one which corresponded to a weak shock wave. The flow parameters before the shock wave were known from experiments on outflow into free space without condensation [1]. The value of I_0 was determined from the formula [6]

$$I_0=\sqrt{\frac{2m}{\pi k}}\left(\frac{p_-}{\sqrt{T_-}}-\frac{p_s(T_0)}{\sqrt{T_0}}\right), \tag{5}$$

where m is the mass of the vapor molecule, k is the Boltzmann constant, T_0 is the temperature of the injected liquid, p_s is the saturation pressure [the condensation coefficient in (5) was taken as 1].

On the basis of (3), (5) we can expect a reduction of tan θ with increase in T_0, other conditions being equal, and, consequently, a reduction in the degree of pressure increase after the shock wave, as we found in the experiments (see Fig. 3).

The calculations were made for the case when r_0 = 2 mm and T_0 = 288°K. The results are given in Fig. 2, which shows the curves corresponding to the values of p_+ for r = 6.65 mm (curve 3) and r = 3 mm (curve 4). We note that curve 3 corresponds to the angle θ averaged over the cross section ($\langle\theta\rangle$), and given by $\operatorname{tg}\langle\theta\rangle=\frac{2}{R^2-r_0^2}\int_{r_0}^{R}\operatorname{tg}\theta r\,dr$. The increase in p_+ with reduction of the flow vapor content at the inlet x_0 is due both to an increase in I_0 and to a reduction of $\rho_- v_-$.

Thus, condensation of vapor on a liquid jet after the nozzle mouth can in certain conditions significantly affect the outflow process.

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