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INVESTIGATION OF TWO-PHASE LAVAL NOZZLES

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A two-phase supersonic nozzle is an essential element of any liquid-metal MHD-generator scheme. At the present time there is no strict theory for such a nozzle, and existing methods for approximation calculations are based on many simplifications the validity of which are not at all clear. On the other hand, experimental investigations of two-phase nozzles are extremely limited and, in addition, contain information (Refs. 1 - 4) pertaining to a particular case. The accumulation of experimental data on two-phase nozzles, at the present stage, is an important problem. Below we have presented an account of some results of the experimental investigation of two-phase nozzles completed in 1967 and early 1968 in a Heat Exchange Laboratory.

A METHOD FOR DETERMINING SLIP

Data on slip in a two-phase nozzle end is of great value both to the development of a method for calculations and for determining the efficiency of the nozzle operation. Presented below is a method for determining the true phase velocities based on experimental measurements of velocity and the parameters of the mixture at a nozzle cross-section (Ref.5). Although the method is simple, we were not aware of it, otherwise it would have been used earlier. A model for the discharge and the assumed designations are presented in Fig.1.

We applied the following assumptions:

a) The process of discharge is adiabatic.
b) In sections 1 and 2, the phases are in thermodynamic equilibrium.
c) The physical properties of the vapor and liquids do not depend on the curvature of the division (partition).
d) The mixture completely fills the end of the nozzle cross-section.

In this case, the process of discharge may be expressed by the following system of equations:

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$$G\overline{W}_A = G_2'' \overline{W}_2'' + G_2' \overline{W}' \quad (1)$$

$$G = G'' + G' \quad (2)$$

$$G'' = \overline{W}_1 \cdot \gamma_1'' \cdot F_1'' = \overline{W}_2'' \cdot \gamma_2'' \cdot F_2'' \quad (3)$$

$$G_1' = \overline{W}_1' \cdot \gamma_1' \cdot F_1' = \overline{W}_2' \cdot \gamma_2' \cdot F_2' \quad (4)$$

$$Gi_1 + \frac{A}{2g} G_1'' (\overline{W}_1'')^2 + \frac{A}{2g} G_1' (\overline{W}_1')^2 = Gi_2 + \frac{A}{2g} G_2'' (\overline{W}_2'')^2 + \frac{A}{2g} G_2' (\overline{W}_2')^2 \quad (5)$$

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(Here, $A = \frac{1}{427}$ *kcal/kg-m* and $g = 981$ *m/sec*^{2}, i_1 *and* i_2 - the corresponding enthalpy of the mixture in sections 1 and 2.)

and the supplementary equations:

$$F = F' + F'' \tag{6}$$

$$Gi = G''i'' + G'i' \tag{7}$$

(Here, i' and i'' correspond to the enthalpy of liquid and vapor)

We introduce, at this point, the supplementary designation

$$x = \frac{G''}{G'} \tag{8}$$

x is the dryness of the vapor and, consequently,

$$\frac{G'}{G} = (1 - x) \tag{9}$$

$$\phi = \frac{F''}{F} \tag{10}$$

ϕ is a part of the section filled with vapor or, otherwise, the true volume of vapor content (Volumetric dryness).

From Eqs. (10) and (6)

$$\frac{F'}{F} = 1 - \phi \qquad (11)^*$$

From the system of equations (Eqs. 1 - 11), it is possible to determine the effective velocity of the medium at the nozzle end. On the other hand, it may be computed by a draft or active force of the stream.

In the case of the measurement of the draft (i.e., the reactive force of the stream), the nozzle is considered (Fig. 2). The force necessary for restraining the nozzle to a null position is equal to the developed draft of the nozzle corresponding to the established regime (conditions).

In this case, the reactive forces on the nozzle R is proportional to the average velocity of discharge of the mixture $\overline{W}_*$ and the difference in pressure on the nozzle end P_2 and behind the nozzle (the surrounding medium) P_0.

$$R = \frac{G}{g} \cdot \overline{W}_* + (P_2 - P_0) \cdot S \tag{12}$$

where S is the cross-section of the nozzle end (m^2).

If, at the discharge of the mixture $P_2 = P_0$, then the relation of Eq. (12) takes

$$R = \frac{G}{g} \overline{W}_* \tag{13}$$

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* Transl. Note: This equation was not numbered in the original text.

For the measurement of the active forces, the nozzle was rigidly secured (Fig. 3), and the steam discharging from the nozzle was directed to the rigid suspension, and the deflected stream was directed by the perpendicular axis of the nozzle.

In this case, the force R, necessary for retaining the suspension in a null position, is proportional to the change in momentum

$$R = \frac{G}{g} (\overline{W}_* \pm \overline{W}y \cdot \cos \alpha) \tag{14}$$

$\overline{W}y$ is the average velocity of the stream deflected by the angle α. If α = 90 deg, then Eq. (14) converts to Eq. (13).

In both variants, the measurement of the force R makes it possible to compute the average for the cross-section of the velocity of discharge of the mixture on the nozzle end corresponding to the total phase momentum.

By makeing use of Eqs. (12) - (14), it is possible to obtain a system from the two equations:

$$\frac{R \cdot F_2 \cdot g}{G_2} = \frac{x_2^2}{\phi_2 \gamma_2''} + \frac{(1 - x_2)^2}{(1 - \phi_2) \cdot \gamma_2'} \tag{15}$$

and

$$i_2 + \frac{AG^2}{2gF_1^2} \left[\frac{x_1^3}{\phi_1^2 (\gamma_1'')^2} + \frac{(1 - x_1)^3}{(1 - \phi_1)^2 (\gamma_1')^2}\right] = i_2 + \frac{AG^2}{2gF_2^2} \left[\frac{x_2^3}{\phi_2^2 (\gamma_2'')^2} + \frac{(1 - x_2)^3}{(1-\phi_2)^2 (\gamma_2')^2}\right] \tag{16}$$

Since it is usual for the nozzle $W_1' \ll W_2'$ and $W_1'' \ll W_2''$, then disregarding the kinetic energy of the stream in section 1-1 (Eq. 16) is written as:

$$i_1 - i_2 = \frac{AG^2}{2gF_2^2} \left[\frac{x_2^3}{\phi_2^2 (\gamma_2'')^2} + \frac{(1-x_2)^3}{(1-\phi_2)^2 (\gamma_2')^2}\right] \tag{16a}$$

and considering Eq. (7), in the same way

$$r_2 = i_2'' - i_2' \tag{17}$$

$$\frac{2gF_2^2}{AG^2} (i_1 - i_2' - r_2 x_2) = \frac{x_2^3}{\phi_2^2 (\gamma_2'')^2} + \frac{(1-x_2)^3}{(1-\phi_2)^2 (\gamma_2')^2} \tag{18}$$

The system of Eqs. (15) and (18) is solved relative to x_2 and ϕ_2 if R, x_1 and the pressure in sections 1-1 and 2-2 are known; then, from Eqs. (3) and (4) the discharge velocity phase in the nozzle end is known (determined).

In the case where x= const along the nozzle axis, i.e., when $x_1 = x_2 = x$ the acceleration (dispersion) by gas of the liquid and solid particles) for the determination of ϕ for the measured draft and discharge of the phase is sufficient for one Eq. (15).

EXPERIMENTAL SETUP

The investigation was conducted in air-water (Refs. 6 and 7) and steam-water flow (Ref. 8).

In the air-water installation, the discharge of air and water, the reactive forces (according to the scheme in Fig. 2), the pressure along the nozzle axis, and the temperature of the flow were measured. The parameters were varied: $P_1 = 1.5 \div 4.0$ atm, $P_0 = 1$ atm, $x = 0.02 \div 0.3$. The accuracy of the measurement of the reaction of the stream was ±1.0% (when the draft is ≈0.5 kg) and ±0.6% (when the draft is 2 - 2.5 kg). The characteristics of the investigated nozzle are presented below.

Nozzle Designation	Nozzle length,mm	Diam of throat,mm	Diam of end,mm
L183A1.62	183.5	10.23	13.01
L123A1.65	123.0	10.23	13.10
L123A1.405	123.0	10.23	12.13
L61.8A1.203	61.8	10.23	11.24
30A1.172	30.5	12.73	13.80

Here, $A \equiv \frac{D^2}{d^2}$

In the steam-water unit, the overall discharge of the steam-water mixture, the active forces, the generated steam (Fig.3), the pressure along the nozzle axis, and also the pressure and temperature at the inlet and outlet of the nozzle were measured.

The parameters varied within:

$P_1 = 1\text{-}10$ atm, $x_1 = 0\text{-}0$ and 11, $G = 0.1$ to 0.2 kg/sec when $P = const = 1$ atm. The accuracy of the measurement of the active forces correspond to the accuracy of the measurement of the reactive forces in the first unit. The characters of the investigated nozzle are presented:

Nozzle Designation	Nozzle length,mm	Diam of throat,mm	Diam of end,mm
L130A7.46	130	5.5	15
L130A6.5	130	5.5	14
L50A3.0	50	12	20.5
L65A1	65	17.5	17.5

SLIP

Typical dependencies of slip on dryness are presented in Figs. 4 and 5 (water-air) and Fig. 6 and 7 (steam-water).

In the literature, there are various dterminations for slip (Refs. 1,3, and 4). With a goal of releiving the perception in Fig. 5, a relation is presented for the slip coefficient computed by two different methods. The qualitative character of the relation can be seen, is retained. Figures 8 and 9 illustrate the character of the relation of slip to the initial pressure at a constant dryness (in the absence of mass exchange) for a nozzle of differing geometric dimensions. Figure 10 illustrates the character of change of the static pressure on the nozzle axis.

Analysis of the data on slip makes it possible to make the following conclusions:

a) The relation of slip to dryness has an extreme character.
b) The mass exchange essentially influences the absolute value of the slip on the character of its relation on the parameters of discharge and nozzle geometery.
c) Slip also depends on nozzle geometry (the length and degree of expansion). For the given parameters of discharge of the nozzle axis, there is a definite excess which does not decrease, and the slip increases.

NOZZLE EFFICIENCY

An important characteristic of the nozzle is its efficiency. Depending on a scheme for a liquid-metal MHD unit, the plant may have values for different efficiencies; for a scheme having an injector-condenser:

$$\eta_1 = \frac{x_2(\overline{W}_2'')^2 + (1-x_2)(\overline{W}_2')^2}{\overline{W}_0^2} \qquad (19)$$

for a scheme having a separator:

$$\eta_2 = \frac{(\overline{W}_2')^2(1-x_2)}{\overline{W}_0^2} \qquad (20)$$

Here, $\overline{W}_0$ is the isentropic velocity of the mixture on the nozzle end.

Some of the data on efficiency, obtained as a result of the experiments, are presented in Figs. 11 and 12 (water-air) and in Fig. 13 (steam-water).

Analysis of the data on the efficiency makes it possible to arrive at the following conclusions:

a) Mass exchange has an influence on the absolute value for nozzle efficiency and the character of it depends on the discharge parameters and nozzle geometry.

b) The true efficiency of the nozzle depends, by complex methods, on slip and on the absolute value which is noticeably below the value usually assumed for the calculated scheme.

STRUCTURE OF THE TWO-PHASE FLOW IN THE NOZZLE

Visual observations were made and photographs were obtained of the stream of the water-air mixture in a flat transparent nozzle. When $x = 0.1$, the mixture is homogenous and uniformly fills all sections of the nozzle. When $x = 0.1$, the air is chiefly concentrated in the walls of the nozzle, and the liquid - in the center of the end. Inequality increases with an increase in the dryness of the mixture. Consequently, when $x = 0.1$, the actual value of dryness in the nucleus of the stream is less than calculated for the discharge characteristics and, therefore, the loss in friction decreases. In this condition, along the nozzle axis, the liquid is driven off more effectively. When $x = 0.1$, the picture substantially changes - the losses are less when the nozzle is shorter.

An analogous picture is seen in a steam-water mixture, but at significantly less degree of dryness at the nozzle inlet.

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FIGURES

1. Assumed designations.
2. Scheme of the setup for measuring nozzle draft along the reactive force.
3. Scheme of the setup for measuring nozzle draft along the active force.

4. The dependence of slip on dryness and the initial pressure of the water-air mixture. Nozzle L183A1.62.
5. The dependence of slip on dryness and the initial pressure of the water-water mixture. Nozzle L123A1.405.
6. The relation of discharge phase velocity on the dryness of a steam-water mixture. Nozzle L130A7.46.
7. The relation of slip to the dryness of a steam-water mixture for nozzles L130A7.64, L130A6.5, and L50A3.0.
8. The relation of slip on the initial pressure for the two different nozzles. The mixture is water-air.
9. The relation of slip on the initial pressure for nozzle L123A1.405. The mixture is water-air.
10. Change of static pressure along the nozzle axis of L123A1.405. The mixture is water-air. $P - P_0$ in the graduated scale for the manometer is 100 gradations = 2.5 atm.
11. The dependence of η_1 on the dryness of the water-air mixture for various Laval nozzles.
12. The dependence of η_2 on the dryness of the water-air mixture for various Laval nozzles.
13. The dependence of η_1 on the dryness of a steam-water mixture at the inlet of nozzle L130A7.46.