EXPERIMENTAL STUDY OF INTERNAL CAVITATING FLOWS

A. F. Babitskii

UDC 532.528

The parameters of a cavitating liquid are determined on the basis of measurements of the initial flow parameters and forces acting on the nozzle. The volume concentrations of a cavitating flow are also measured by a conductometric method simultaneously with a determination of their values from measurements of the forces acting on the nozzle.

The solution of a number of engineering problems requires knowledge of the structure and quantitative characteristics of a flow both outside and in the interior of a chamber. The methods used to investigate cavitating flows [1-5] are based primarily on the hydrodynamics of a single-phase incompressible fluid. In addition to visual observations, the volumetric fluid flow rate and pressure along the flow have been measured in this connection.

We have obtained the characteristics of one-dimensional cavitating flows by measuring and calculating the forces acting on a moving nozzle in which there is a cavitating flow. A diagram of the experimental arrangement is given in Fig. 1. The tests were performed on two transparent nozzles ($l = 0.300$ m, $d_2 = d_4 = 0.150$ m, $d_3 = 0.100$ m and $d_3 = 0.112$ m) and on one opaque ($l = 1.50$, $d_2 = d_4 = 0.170$ m, $d_3 = 0.140$ m). The method of investigation is to determine the characteristics of the cavitating flow at the nozzle exit from measurements of the forces acting on the nozzle and the flow parameters at the nozzle entry. A movable sealed coupling is formed between the nozzle and the pipeline by means of packing glands. Since the flow diameter is large ($d = 0.150$ m), the ratio of the friction force in the glands to the force acting on the nozzle as measured with a strain gauge does not exceed 5 to 10%. The rate of flow of water into the nozzle is determined from the pressure difference in the convergent section ($d_1 = 0.400$ m) between cross section 1-1 and 2-2. The pressure in the pipe sections and the working section (cross sections 1, 2, 3, 4) is measured with standard laboratory manometers.

In the experiments we used tap water at 5 to 23°C. Temperature measurements in the flow and inside the chamber by differential thermocouples show that the temperature inside the chamber is 1 or 2°C lower, on the average, than in the freestream flow.

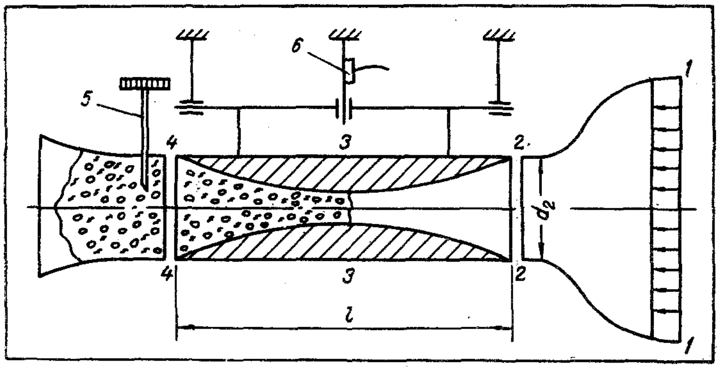

Fig. 1. Experimental arrangement. 1-4) Labeled cross sections; 5) probe for measurement of the volume concentration of mixture components [6]; 6) suspension system with strain gauge.

Institute of Fluid Mechanics, Academy of Sciences of the Ukrainian SSR. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 26, No. 2, pp. 309-313, February, 1974. Original article submitted July 31, 1973.

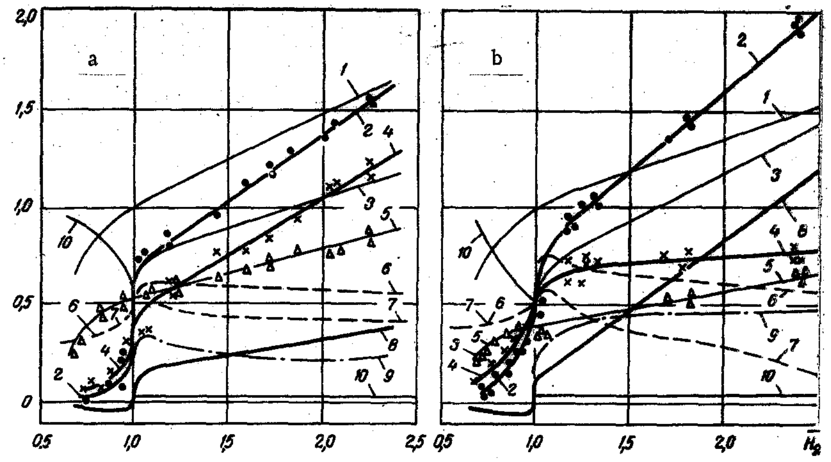

Fig. 2. Experimental and analytical data for nozzles (l = 0.3 m, $d_2 = d_4$ = 0.150 m). a) d_2/d_3 = 1.33; b) 1.5. 1) Water velocity $\bar{v}_3$ in narrowest section of nozzle (cross section 3-3); 2) pressure induced reaction component $\bar{R}_p$; 3) velocity $\bar{v}_4$ of mixture at nozzle exit (cross section 4-4); 4) reaction $\bar{R}$ acting on nozzle; 5) entry velocity $\bar{v}_2$ of water into nozzle (cross section 2-2); 6) head loss factor ζ_h; 7) energy loss factor ζ_e; 8) reaction component $\bar{R}_m$ due to change of momentum; 9) volume concentration c_g of gas (vapor and air) at nozzle exit; 10) ratio $\bar{p}_4$ of nozzle exit pressure to nozzle entry pressure.

The equation for the reaction force acting on the nozzle is written as follows in the one-dimensional approximation:

$$R = m(v_4 - v_2) + S_4p_4 - S_2p_2 = R_m + R_p. \tag{1}$$

The mass flow through the nozzle is

$$m = S_2v_2\rho_L = S_3v_3\rho_L = S_4v_4(c_L\rho_L + c_g\rho_g), \tag{2}$$

where

$$c_L + c_g = 1. \tag{3}$$

Equation (2) is constrained by the condition that the liquid medium and vapor formed (air) move across cross section 4-4 at the same velocities.

With regard for Eq. (2) the reaction force component induced by the change of momentum of the mass moving through the nozzle is

$$R_m = m(v_4 - v_2) = \rho_L v_2^2 S_2 \left(\frac{v_4}{v_3} - 1\right). \tag{4}$$

Accordingly, the second component of the reaction force is

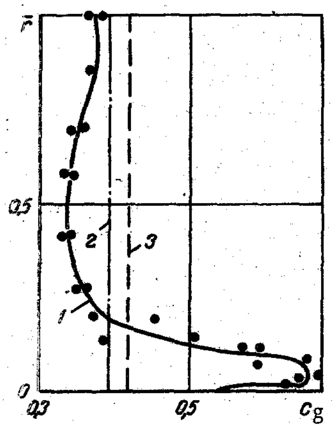

Fig. 3. Volume concentration c_g of vapor and air at nozzle exit (l = 1.50 m, $d_2 = d_4$ = 0.17 m, d_2/d_3 = 1.2 for $\bar{H}_2$ = 1.24); $\bar{r} = r/r_4$ is the dimensionless nozzle radius at cross section 4-4. 1) From conductometric measurements [6]; 2) from measurements of forces on nozzle; 3) average value for curve 1.

$$R_p = S_2(p_4 - p_2) \quad \text{for} \quad S_2 = S_4. \tag{5}$$

In the experiment we measured the pressure-induced component of the reaction force according to Eq. (5) and the total force R, from which it is then possible to determine R_m and so the velocity and density of the fluid emerging from the nozzle:

$$\frac{c_L \rho_L + c_g \rho_g}{\rho_L} = \frac{\rho_L S_2^2 v_2^2}{(R - R_p) S_4 + \rho_L S_2^2 v_2^2}. \tag{6}$$

At the same time, the volume concentration of air (vapor) in the cavitating flow is

$$c_g = \frac{(R - R_p) \rho_L S_4}{(\rho_L - \rho_g)[(R - R_p) S_4 + \rho_L S^2 v_2^2]}. \tag{7}$$

Inasmuch as the pressure of the cavitating liquid is usually small, the density of the gaseous components can be neglected in most cases.

The experimental and analytical data on one-dimensional cavitating flows are given in Figs. 2a and 2b in the dimensionless form

$$\bar{R} = \frac{R}{S_2 H_c}; \quad \bar{R}_m = \frac{R_m}{S_2 H_c}; \quad \bar{R}_p = \frac{R_p}{S_2 H_c}; \quad \bar{p}_4 = \frac{p_4}{p_2};$$

$$\bar{v}_2 = \frac{v_2}{v_c}; \quad \bar{v}_3 = \frac{v_3}{v_c}; \quad \bar{v}_4 = \frac{v_4}{v_c};$$

$$\zeta_h = 1 - \frac{H_4}{H_2}; \quad \zeta_e = 1 - \frac{H_4 S_4 v_4}{H_2 S_2 v_2};$$

$$\bar{H}_2 = \frac{H_2}{H_c}; \quad H_2 = p_2 + \frac{1}{2}\rho_L v_2^2; \quad H_L = p_L + \frac{1}{2}\rho_L v_c^2;$$

$$H_4 = p_4 + \frac{1}{2}(c_L \rho_L + c_g \rho_g) v_4^2.$$

The pressure and velocity at the inception of cavitation in cross section 3-3 are identical for both transparent nozzles ($d_2/d_3 = 1.50$ and $d_2/d_3 = 1.33$): $p_c = 0.2$ N/m; $v_c = 24$ m/sec.

The head loss factor ζ_h and energy loss factor ζ_e are best represented as follows in the given case:

$$\zeta_h = 1 - \frac{\varkappa_4 + \bar{v}_2 \bar{v}_4}{(1 - \varkappa_c)\bar{H}_2} = 1 - \frac{\varkappa_4[1 - c_g(1 - \bar{\rho}_g)] + \bar{v}_2^2}{(1 - \varkappa_c)[1 - c_g(1 - \bar{\rho}_g)]\bar{H}_2}, \tag{8}$$

$$\zeta_e = 1 - (1 - \zeta_h)\frac{S_4 v_4}{S_2 v_2} = 1 - \frac{\varkappa_4[1 - c_g(1 - \bar{\rho}_g)] + \bar{v}_2^2}{(1 - \varkappa_c)[1 - c_g(1 - \bar{\rho}_g)]^2 \bar{H}_2}. \tag{9}$$

Here

$$\varkappa_4 = \frac{2p_4}{\rho_L v_c^2}; \quad \varkappa_c = \frac{2p_c}{\rho_L v_c^2}; \quad \bar{\rho}_g = \frac{\rho_g}{\rho_L}.$$

The results of conductometric measurements [6] of the volume concentrations at points of cross section 4-4 and a simultaneous determination of the volume concentrations by measurement of the forces acting on the nozzle are presented in Fig. 3.

The following conclusions are based on these experimental investigations of internal cavitating flows. The flow parameters suffer a discontinuity (jump) at the inception of cavitation.

The pressure in the expanding part of the nozzle, as observed in the experiments of Hochschild [2], is not restored. However, the almost complete loss of potential energy inside the chamber at the exit from the nozzle is largely offset by growth of the flow kinetic energy ($v_4/v_2 > 1$; $R_m > 0$). The total losses of potential and kinetic energy (see Figs. 2a and 2b, curve 7) range from 50 to 15%, depending on the constriction of the nozzle (d_4/d_2) and the cavitation flow regime ($\bar{H}_2$). With an increase in the degree of expansion of the duct the lost head increases as well, while the energy losses decrease; this behavior is explained by the compressibility (expansibility) of the vapor—air—water mixture.

It is evident from a comparison of the flow velocities (curves 1, 3, and 5 in Figs. 2a and 2b) that the exit velocity of the vapor—air—water mixture is greater than the water entry velocity to the nozzle, but less than the flow velocity at the narrowest cross section, for all cavitation flow regimes.

The conductometric measurements of the volume concentrations of the mixture components at points of the flow cross section show that the chamber has a wall layer 8 to 10 mm thick, inside which the vapor and air are 70 to 80% by volume. The flow core is denser and the vapor-air in it less by volume: 30 to 60%, depending on the nozzle constriction (d_4/d_2) and the cavitation flow regime ($\overline{H}_2$).

A comparison of the volume concentration measurements by the two different independent methods exhibits reasonably good agreement.

NOTATION

p is the pressure;
v is the velocity;
ρ_L is the density of the liquid;
ρ_g is the density of the gas (vapor);
c_L is the volume concentration of liquid;
c_g is the volume concentration of gas (vapor);
S is the flow cross-sectional area.
The numerical subscripts indicate the labeled cross sections of the working length, as illustrated in Fig. 1.

LITERATURE CITED

1. G. S. Nazarov, Inzh.-Fiz. Zh., 14, No. 3 (1968).
2. L. Prandtl, Fundamentals of Hydro- and Aeromechanics, McGraw-Hill, New York—London (1934).
3. K. K. Shal'nev, Izv. Akad. Nauk SSSR, Otd. Tekh. Nauk, No. 8 (1956).
4. R. Kobayshi, Trans. ASME, D89, No. 3 (1957).
5. W. H. Li and J. P. Walsh, Proc. Am. Soc. Civil Engrs. (J. Engng. Mech.), 90, No. 6 (1964).
6. A. F. Babitskii and A. M. Kravchenko, in: Fluid Mechanics [in Russian], No. 20, Naukova Dumka, Kiev (1972).