EXCESS PRESSURE IN A PULSED LIQUID JET

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In 1954-1956 Dunne and Cassen [1] made a theoretical and experimental study of the behavior of liquid jets and came to the conclusion that the jet consists of discrete segments moving at different velocities. At the junction between the "fast" and "slow" jets it is possible to observe a liquid disk moving at a velocity equal to the arithmetic mean of the velocities of the liquid on either side of the interface. Such a disk was also observed in [2] in connection with the supersonic water jet created by a piston compressor, when the pressure ahead of the nozzle is a periodic function of time associated with the forward and reverse motion of the piston. V. P. Borodin* established a correspondence between the motion of the discrete portions of the jet at different velocities and the pressure waves that develop in a shock chamber ahead of the nozzle of a pulsed water cannon. As a result of the interaction of the parts of the pulsed jet accelerated to different velocities water is ejected laterally at various angles to the jet axis. Below it is shown that a discrete pulsed jet is characterized by excess pressure.

1. If the flow of the individual sections of the jet is stationary on a time interval corresponding to the motion of the pressure wave from the nozzle to the piston rod of a water cannon and back, Bernoulli's equation applies on each section. At the interface between adjacent sections the equation

$$p_i + {}^1\!/_2\,\rho_i u_i^2 = p_{i+1} + {}^1\!/_2\,\rho_{i+1} u_{i+1}^2 \tag{1.1}$$

is satisfied.

Here p_i and p_{i+1}, ρ_i and ρ_{i+1}, u_i and u_{i+1} are the pressure, density, and velocity of the jet components on either side of the interface reckoning from the nozzle.

Owing to the deceleration of the fast portion of the jet on crossing the line of velocity discontinuity the pressure should change continuously. The excess pressure Δp is determined from Eq. (1.1) and for a water jet (it may be assumed that $\rho_i = \rho_{i+1} = \rho$) is equal to

$$\rho_i = \rho_{i+1} = \rho) \quad \Delta p = {}^1\!/_2\,\rho\,(u_{i+1}^2 - u_i^2) \tag{1.2}$$

This pressure front moves into the head of the jet at a velocity ${}^1\!/_2(u_{i+1} + u_i)$, and as a result of the relief of pressure behind the front a halo-like liquid disk is formed. The diameter and length of the halo are the greater, the greater the difference in the velocities of neighboring discrete portions of the jet and the greater their length. As the velocities are equalized along the length of the jet, the excess pressure decreases, disappearing as the section with the maximum velocity reaches the head of the jet.

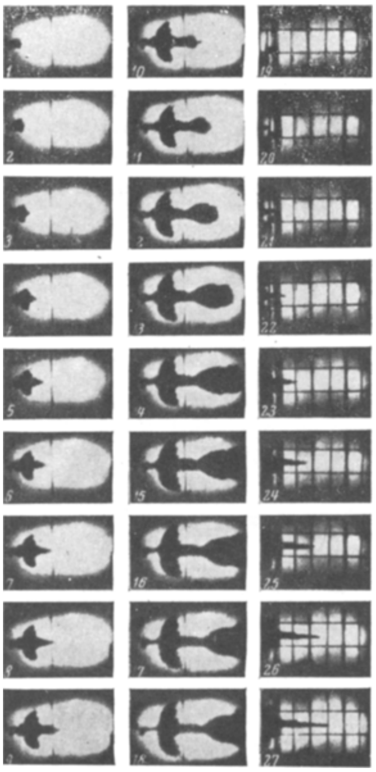

Fig. 1

Figure 1 shows a series of frames of the pulsed jet of a IV-5 water cannon taken with a SKS-1M high-speed motion-picture camera at a maximum pressure of 690 MN/m^2 in the barrel of the

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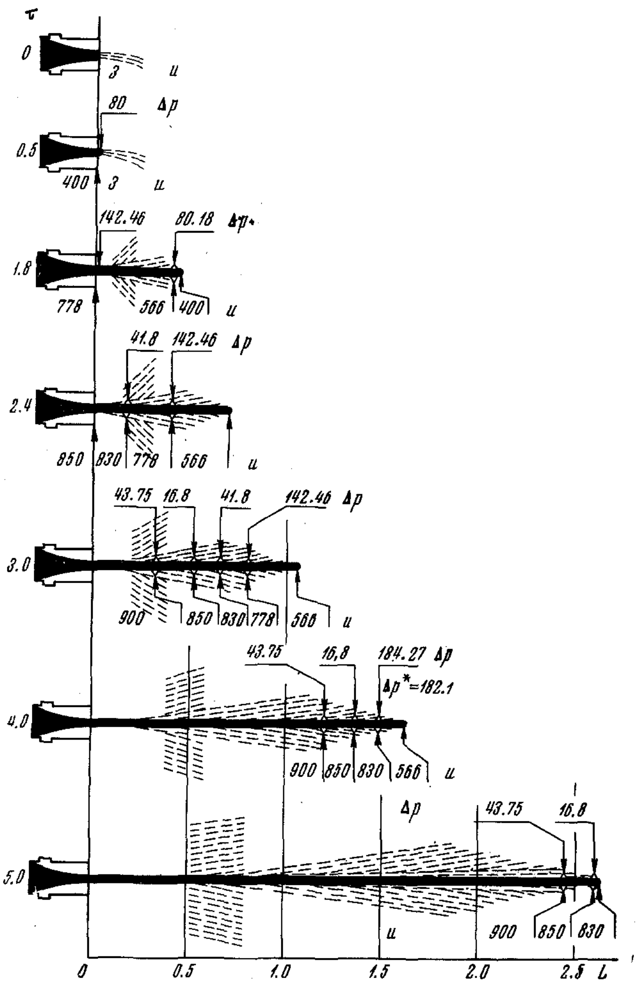

Fig. 2

water cannon. The first zone (without a grid) covers the interval from 0 to 2.1 m, the second zone (with a grid) covers the interval from 2.0 to 4.3 m reckoning from the nozzle. In the first zone (film speed 3500 frames/sec) it is easy to distinguish the bulging resulting from the interaction of the discrete portions ot the jet moving at different velocities. As the fast sections reach the head of the jet, immediately behind the excess pressure front the bulges are converted into well-developed haloes, which absorb the entire jet. When the fast section reaches the head, the excess pressure in the jet disappears and the haloes begin to lag behind. In the frames corresponding to the second zone (film speed 4700 frames/sec) it is possible to distinguish a small swelling of the jet caused by the passage of the fastest section at a velocity little different from that of the preceding section of the jet.

At the moment at which the sections with maximum velocity reached the head of the jet, the process of pressure development in the barrel of the water cannon ends and its value begins to decrease, the nozzle velocity of the jet decreases, a negative pressure drop is created in the jet, and it should break up. Breakup has been experimentally observed by V. P. Borodin in the course of an x-ray study of pulsed jets.

Figure 2 shows a theoretical picture of the acceleration of a pulsed jet as the pressure in the water cannon barrel, recorded by strain gauges, rises to 433 MN/m^2. In this case the water may be regarded as a barotropic ideal liquid and viscosity forces and thermal conductivity may be neglected, since the Reynolds number $Re = 10^6 - 4 \cdot 10^6$ and the Peclet number $Pe = 5 \cdot 10^6 - 30 \cdot 10^6$. Here and in what follows the following notation has been employed: τ, jet flow time from entry of piston rod into water-cannon barrel, msec; μ, velocity of discrete sections of the jet, m/sec; Δp, excess pressure developed at interface, MN/m^2; Δp^*, hydrodynamic impact pressure jump, MN/m^2; L, distance from nozzle, m.

Calculations show that the excess pressure in the jet may have a considerable value (in the example presented $\Delta p = 16.8 - 184.27$ MN/m^2).

Table 1

Nozzle profile	d, mm	p, MN/m^2	u, cm/sec	u^*, cm/sec
Slightly convergent, cone angle $\alpha = 10'$	11.42	667	1101	1300
Conical $\alpha = 13°$ with expansion at the end $\beta = 50'$	11.1	690	1118	1250
Exponential	11.35	604	1051	1091
Slightly divergent $\beta = 18'$	11.2	447	911	940
Conical $\alpha = 8°$ with expansion at the end $\beta = 2°$	11.67	422	886	963
Exponential	13.15	319	776	1063
Catenoidal	13.18	346	808	946
Catenoidal	13.18	454	919	966
Slightly divergent $\beta = 12'$	15.03	212	639	681
Slightly divergent $\beta = 12'$	15.03	319	776	810

2. As the fast sections of the jet reach the head, the slow sections disappear, for the most part being dispersed in the haloes. After the disappearance of the adjacent (i + 1)-th section the fast (i + 2)-th section begins to interact with a new slow i-th section. At the initial moment of impact of the (i + 2)-th and i-th sections a shock wave, at whose front the pressure increases sharply, develops.

The pressure jump may be determined from the impact equation for compliant rods of the same cross section [3]

$$\Delta p^* = \rho_i c_i u_c \frac{\rho_{i+2} c_{i+2}}{\rho_i c_i + \rho_{i+2} c_{i+2}} \quad (2.1)$$

$$u_c = {}^1/_2 (u_{i+2} + u_{i+1}) - u_i \ , \quad (2.2)$$

Here $\rho_i \approx \rho_{i+2} \approx 1000\ kg/m^2$ is the density of water; $c_i \approx c_{i+2} \approx 1530$ m/sec is the speed of sound in water; and u_c is the impact velocity of the sections at the initial instant, m/sec.

In the jet of the MPI-2 water cannon shown in Fig. 2 a pressure jump $\Delta p^* = 182.1\ MN/m^2$ occurs 4 msec after the jet begins to flow, when the section with velocity $u_{i+2} = 830$ m/sec begins to interact with the section at velocity $u_i = 566$ m/sec.

The resulting shock waves travel to the head of the jet, as a result of which it acquires a velocity greater than the value obtained from the condition of stationary flow of a compressible fluid. Experiments reveal the presence of this velocity increase, despite the fact that as a result of impact and air friction losses the velocity of the head of the jet should be less than the value calculated (without allowance for losses).

Table 1 gives the maximum calculated values u (stationary) and the maximum recorded values u* of the head velocities of the pulsed jets of IV-5 and MPI-2 water cannons as a function of the nozzle diameter d and the maximum pressure in the barrel p. These results confirm the conclusion relating to the acceleration of the jet by the resulting shcok waves.

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