INVESTIGATION OF HIGH-PRESSURE PULSED JETS BY MEANS OF ROENTGENOGRAPHY

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Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 5, pp. 160–162, 1965

Reference [1] contains photographs of pulsed jets produced by IV-4 and IV-5 water cannons, obtained with the aid of spark photography. These photographs provide some information on the acceleration process and the subsequent disintegration of the jets. As was shown, however, a jet with a velocity of the order of 1 km/sec is enveloped by a haze of water droplets due to the interaction of the jet with the air. This haze makes it difficult to study the structure of the jet. Attempts to make light penetrate the haze or to separate the latter from the main jet proved unsuccessful. Success was finally achieved with the air of pulsed roentgenography.

A schematic diagram of the apparatus employed is given in Fig. 1. This apparatus had to satisfy the following requirements: reliable operation in conditions of high humidity, x-rays soft enough to obtain photographs of thin water jets with a contrast sufficient for printing, and reliable starting at any moment after ejection of the jet from the nozzle.

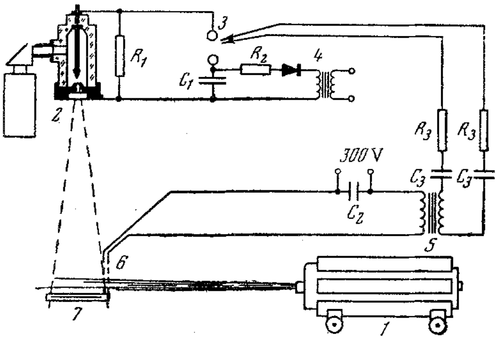

Fig. 1

The apparatus operates as follows: when the water cannon (1) is ready to be fired, the capacitors C_1 and C_2 are charged. After firing, the jet closes the contacts (6), which consist of thin aluminum foil, and this leads to a discharge of capacitor C_2 through the primary winding of the transformer (5); then the igniting-voltage pulse is applied to the gap (3), a discharge occurs in the x-ray tube (2), the radiation from which impinges on a film holder with an amplifying screen (7). The capacitors C_3 and the resistor R_3 prevent the high voltage from reaching the igniting circuit. This method of synchronization with the closure of the contacts resulted in a delay of the main discharge during which the jet penetrated 8 to 12 cm beyond the contacts after closure. This factor was taken into account in preparing the experiments.

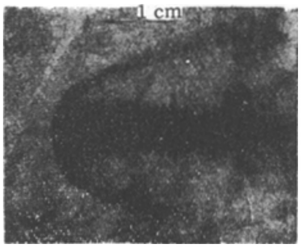

Fig. 2

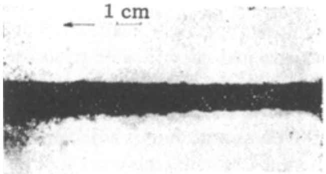

Fig. 3

The apparatus used a continuously pumped fine-focus flash-discharge x-ray tube of the type described in [2]. A tube of this type has an emission time of the order of 10^{-6} sec, which is sufficient to provide sharp photographs at jet velocities on the order of 1 km/sec. The housing of the tube was made of plastic. The tube used a sharp-pointed tungsten anode and a cylindrical steel cathode with cuspidal edge. The position of the anode was preadjusted for maximum illumination of the film and directivity of radiation. The window in the tube was made of celluloid to ensure minimum retardation of the soft radiation component. The vacuum in the tube was on the order of 10^{-4} to 10^{-5} mm Hg. The operating voltage (80–100 kV) was selected in preliminary tests to satisfy the requirements of a sufficiently large degree of contrast and intensity of illumination of the x-ray film. The intensity of x-rays passing through a medium is known to equal $I(x) = I_0 e^{-\mu x}$.

The coefficient μ increases with increasing density of the retarding medium and with decreasing voltage in the x-ray tube. To achieve good contrast it is necessary, therefore, to decrease the voltage in the x-ray tube and, thus, to increase the wavelength of the x-rays. On the other hand, a decrease in voltage leads to a reduction in radiation intensity and, hence, to a weaker illumination of the film.

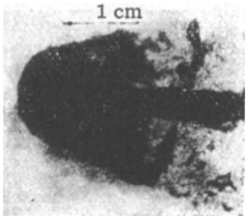

Fig. 4

Attempts to increase the contrast of the photographs by adding soluble salts (e. g., iron sulfate) to the water proved unsuccessful. The use of salts of heavier metals did not improve the situation because the reduced metal was deposited on the internal components of the cannon, thereby impairing its operation. A series of experiments was next performed with plasticine, with which the high-pressure cylinder of the water cannon was first filled. The degree of contrast achieved in the x-ray photographs was the most satisfactory in these tests. The distance from the window in the x-ray tube to the film holder was roughly 1.2 m; this made it possible, with the aid of two combined film holders, to obtain satisfactory photographs of ~40 cm long portions of the jet.

Fig. 2 shows an x-ray photograph of a jet from the IV-4 water cannon after traveling ~15 cm (the arrows on the figure indicate the direction of the jet). The blurring of the jet as a result of interaction with the air is clearly seen on the photograph. A thin sheet separates

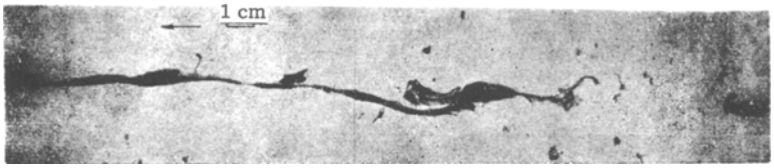

Fig. 5

from the head of the jet and impairs visualization of the basic structure of the jet by conventional photographic techniques. The shape of the jet head, as shown on the x-ray photograph, correlates well with the theory of cumulative jets of the type obtained by Lavrent'ev [3]. Figure 3 shows the portion of the jet adjacent to the head after traveling ~1.5 m. At this distance, the process of acceleration of the jet by a series of compression waves produced by the action of the piston on the water in the cylinder of the cannon has been completed. It can be seen that the cross section of the jet decreases slightly downstream from the head. Small disturbances and flow separations can be seen along the contour of the jet. The actual process of acceleration of the jet is as follows:

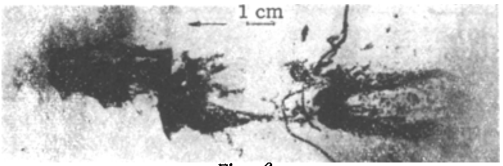

Fig. 6

After the piston impacts against the water in the cylinder, the water is ejected from the nozzle at a velocity corresponding to the pressure behind the first compression wave reflected from the forward end face of the high-pressure cylinder. The second zone of the jet corresponding to the next compression wave has a higher velocity than the first and breaks up the latter in passing through it, and so forth. This acceleration process repeats itself until a maximum velocity is established at the heat of the jet. Fig. 4 shows a plasticine jet after traveling ~60 cm from the nozzle exit section. It can be seen that the next high-velocity region is approaching the head (characteristic bulge behind jet head). From the x-ray photos, as well as from pictures obtained by spark photography [1], one may conclude that for the IV-5 water cannon the acceleration process is completed when the head of the jet has traveled 1.5 to 2 m. This distance roughly coincides with that obtained in parallel tests, in which jets from the IV-5 cannon were studied from the imprints resulting from impingement of the jet upon an obstacle. In these tests the greatest spreading of the jet and minimum density of the imprints were observed at distances of up to 1.5 m between the nozzle and the obstacle. The jet acceleration time apparently corresponds to the time for maximum pressure to build up in the jet. Estimates obtained from pressure oscillograms [4] indicate that this time is equal to 1 to 1.5 μsec.

When acceleration is complete, the jet propagates as a single entity, the jet velocity gradually decreasing downstream from the head as a result of the continuous deceleration of the piston. This causes the jet to elongate, narrow, and finally to break up into separate regions. This effect is shown in Fig. 5, which shows a jet after it has traveled in excess of 3 m. A discontinuity in the jet can be seen at a distance of roughly 130 cm from the head. As for the head itself, it also becomes unstable after the leading high-speed portion of the jet has been eroded by the air. The head begins to disintegrate into several separate regions, as can be seen from Fig. 6.

The effect of nozzle profile on jet stability was also investigated. It was found that jets ejected from cylindrical or convergent nozzles break up faster than those from slightly divergent nozzles. This is apparently associated with the fact that in convergent and cylindrical nozzles the static pressure in the jet substantially exceeds atmospheric pressure and the jet expands after leaving the nozzle, which facilitates its disintegration. A slightly divergent nozzle relieves the static pressure in the jet to a value close to atmospheric.

It should be noted that cumulative erosion of the jet is to be observed only at sufficiently high jet velocities (on the order of 500 m/sec), which corresponds to high ejection energies. This pattern does not hold at low velocities at which the disintegration of the jet proceeds at a faster rate. The destructive power of the jet is greatest at approximately the distance from the nozzle at which the acceleration process terminates. At this distance the impact against an obstacle is the hardest. At greater distances from the nozzle the effectiveness of the jet starts to decrease. This is associated with the fact that the leading high-velocity portion of the jet is eroded by the air, and the rest disintegrates and loses stability.

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30 April 1965 Novosibirsk