CHARACTERISTICS OF HIGH-VELOCITY JETS

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INTRODUCTION

The investigation herein described is currently being carried on by the staff of the Iowa Institute of Hydraulic Research for the David Taylor Model Basin and the U. S. Coast Guard. It owes its origin to a young Coast Guard officer, Lt. F. E. Munley, who discovered that a vaned barrel placed just ahead of the nozzle on a 3-inch fire monitor caused a 30 percent increase in the range of the jet. This information when relayed to the Washington office led immediately to an intensive search of the literature on nozzles and ultimately to a contract with the Institute for the design of an improved fire monitor.

Aside from a recent investigation by Blair [1] on the discharge coefficients of small nozzles one inch and less in diameter and on the trajectories under relatively low pressures, little of a fundamental nature has been done since the classic investigation of Freeman [2] in 1888. Freeman determined the discharge coefficients of a great number of conventional nozzles of various sizes and proportions and measured the trajectories of the fire streams at several inclinations and pressures. He found that the discharge coefficients of the nozzles having cylindrical tips lay between 0.96 and 0.98. Lower coefficients, due mainly to contraction of the jet, were found for ring nozzles of various types. There is no question but that the high discharge coefficients found by Freeman as well as the all-around thoroughness of his work effectively discouraged any subsequent research in this area. Two keen observations recorded in his paper, however, when viewed in the light of present-day knowledge, are of great significance. The first was that if the shoulder of the nozzle was of smaller diameter than the
play pipe immediately ahead of it the jet had poor characteristics and reduced range. The second was that if the hose leading to the nozzle was not laid straight the range of the jet was decreased.

There were thus indications that even though little could be done to increase the discharge of a nozzle at a given pressure there were possibilities of increasing the range of the jet by attention to conditions immediately upstream from the nozzle. From the standpoint of the fire fighter, it is the amount of water which can be concentrated on the target rather than the amount which can be forced through the nozzle that is important.

Fig. 1—Disintegration of a Turbulent Jet. View Taken 25 Feet from Nozzle. Jet is Approximately 1 Foot Wide and Moving at a Speed of 125 Feet per Second.

Role of Turbulence

The fundamental research of recent years on turbulence has disclosed the presence of innumerable eddies and vortices moving along in the flow with a general translatory motion. Observation of the velocity at a point therefore reveals velocity components in transverse directions as well as variations in the longitudinal direction as the eddies pass the point. So long as the flow is confined, particles of water moving outward from the centerline are turned back by the boundaries and the average longitudinal components must equal the mean velocity of flow.

Once the flow emerges into the air, however, small masses of fluid having transverse velocity components are free to move laterally and separate from the jet without interference from the boundary. Likewise, variation of velocity in the forward direction can result in loss of contact between water particles, since no vacuum is produced by their separation. It is at once apparent that a free
jet containing any degree of turbulence is destined to break apart and disintegrate at a rate dependent upon the amount of turbulence in the flow as it leaves the nozzle. Indeed, this type of disintegration would occur even though the jet were discharged into a vacuum.

In air, however, the eddies which whirl out of the main stream are immediately retarded and disintegrated by the resistance of the air. Furthermore, voids caused by separation of water particles are immediately filled with air. Fig. 1, a high-speed photograph of a turbulent jet taken about twenty-five feet from the nozzle, clearly shows the great amount of separation which has occurred in a fraction of a second. The jet at this point is about one foot wide and, though appearing solid to the naked eye, is in reality a procession of individual masses of water separated by air.

One of the characteristics of a jet which surprised the writers was its ability to set in motion large quantities of air, an action particularly typical of poor jets. It was apparent that such a jet might not only fail to bring water to the target in adequate amounts but might actually aid the fire by pumping in significant quantities of oxygen.

Fig. 2—Eddies Breaking Out of 1½-inch Jet Near Nozzle.

Fig. 2, a high-speed picture of a 1½-inch jet leaving a nozzle, shows unmistakable evidence of eddies turning out of the main jet shortly after their escape from the nozzle boundaries. The velocity of the water in these pictures (Figs. 1 and 2) is approximately 125 feet per second and the time of exposure 1/20,000 second.

Turbulence of sufficient intensity to cause disintegration of the jet may have three recognizable sources. Of greatest importance
is the internal turbulence caused by the monitor. Figs. 3 and 4 show the 3-inch and 6-inch Coast Guard monitors in present-day use. A horizontal swivel joint with an interior rod to resist the upward thrust and the symmetrical "ram's horns" to balance the horizontal thrusts and provide freedom of movement in the vertical plane account for the general shape of the unit. The relatively small and tortuous passages create severe secondary currents and favor the formation of numerous eddies as the water encounters the many changes of direction in its route. The smaller monitor is obviously more likely to create intense internal turbulence than the larger.
A second source of turbulence lies in the form of the nozzle itself. There is curvature in most of the flow lines as the flow starts to converge at the base of the nozzle. Eddy formation in such zones is characteristic. Nozzles having cylindrical tips offer another source of turbulence due to the likelihood of separation at the change in boundary direction at the junction with the cylinder. Eddies formed by boundary shape would probably be found near the surface of the jet and would account for much of the frosty appearance of the stream as it issues from the nozzle.

Fig. 5—Experimental Monitor.

The third source of turbulence is in the surface of the nozzle walls. A long, tapered nozzle will develop a fine-scale turbulence in the boundary layer which also causes a somewhat frosty appearance of the jet, though not of the same whiteness as that caused by separation.

An experimental monitor designed to minimize turbulence due to the causes described above is shown in Fig. 5. Large passages to reduce the velocity through the monitor, vaned mitre bends to reduce secondary currents and eddy formation, and a short nozzle having an easy transition from the barrel and no reversal of curvature at the top appeared to offer the best possibility of reducing
the amount of turbulence in the jet and, at the same time, of meeting the practical requirements of maneuverability demanded of these units. Interest centered entirely on the hydraulic characteristics of the experimental monitor; the joints and flanges seen in the picture served merely to facilitate alteration or substitution of particular elements of the monitor.

**Experimental Equipment**

In order to make quantitative measurements upon which a comparison of monitor performance could be based, it was necessary to assemble or develop a considerable amount of equipment. A set of eight Chrysler-Hale pumps of the type used in the Coast Guard fire boats was installed at the south end of the laboratory. One of the river flumes under the laboratory was bulkheaded and used as a test chamber, the bottom of the flume serving as the sump into which the jet fell; this space was 120 feet long, 10 feet wide, and 18 feet high and made it possible to eliminate the variable effect of natural wind currents as well as to operate during the winter months (see Fig. 6). A discharge pipe and a suction pipe, each 12 inches in diameter, led from the pumps to the test chamber. The first supplied a monitor stand as well as a 10-foot length of 12-inch pipe used in testing nozzles. The opposite end of the discharge line supplied two monitor stands on the river side of the laboratory.

A sampler mounted on a travelling carriage was constructed for use in measuring the concentration of discharge at some distance from the nozzle (Fig. 7). Nine 3/4-inch tubes mounted in a slender vertical boom

![Fig. 7—Jet Striking Sampler Mounted on Travelling Carriage.](image-url)
at one-foot intervals were connected by rubber tubing to a distributing panel inside a cabin hung from the carriage (Fig. 8). The panel could be moved horizontally in such a manner as to deliver the water caught by the tubes to graduated flasks or to divert it to waste troughs. The boom containing the nine sampling tubes could be moved 5 feet horizontally and 1 foot vertically by controls inside the cabin.

![Figure 8](image)

**Fig. 8—Distributing Panel and Graduated Flasks.**

Other equipment, including two Emery Bourdon gages, calipers, a pitot tube, an inclinometer, and a special camera were purchased or constructed as needed. The Bourdon gages, specially made for the project, had a range of 250 pounds per square inch and when compared with a 40-foot mercury column were found to be accurate within 0.5 percent.

**Test Procedures**

Relative jet characteristics were determined in three ways, the first being a velocity traverse by pitot tube. A conventional plot of velocity versus radius of jet indicated the effect of nozzle boundaries. Since the registration of a pitot tube on the edge of a high-velocity jet is subject to some uncertainties, the traverses were not used to determine discharge but were valuable for indicating the
depth of boundary influence. Direct gravimetric calibration of the nozzles was made using the main laboratory scales.

Observation of the concentration at some 500 points in a vertical plane 90 feet from the nozzle tip provided data for a contour plot such as that shown by the worksheet of Fig. 9. Because of the common use of gallons per minute as a flow unit by fire fighters, the plots were based on gallons per minute per square foot of jet area and could be integrated to yield the total flow reaching the

**Fig. 9—Typical Plot of Jet Concentrations 90 Feet from Nozzle.**
section. For purposes of comparison, the jet diameter in all cases was made 1½ inches and tests were run at 100 pounds per square inch total (pitot) pressure.

The third test procedure consisted simply of taking outdoor photographs of the jets at times when little or no wind was blow-

![Fig. 10—Jet from 3-inch Coast Guard Monitor.](image)

ing. A fixed-focus camera mounted at a certain point across the river from the monitors and using the laboratory building as a background provided good comparative evidence on the actual range and dispersion of the jets. Fig. 10 is a typical photograph, showing the 3-inch Coast Guard monitor discharging at 100-pound-per-square-inch base pressure.

**Test Series**

The testing program was divided into two series. The first dealt with nozzle form only. A 10-foot length of 12-inch pipe with a perforated plate at its entrance, a honeycomb near the middle, and a conical reducer at the downstream end preceded a 6-inch barrel 2 feet in length on which the nozzles were mounted. Approach conditions were therefore identical for all nozzles, and turbulence in the approaching flow was thought to be at a minimum. Nozzles varying in form from a plane orifice to a conventional 7° cone with
a cylindrical tip as shown in Fig. 11 were tested for concentration at 90 feet by the sampling procedure previously described.

The second series of tests was run on the 3-inch and 6-inch Coast Guard monitors and on the experimental monitor with the 45° nozzle. Likewise, outdoor photographs were made of the monitors at base pressures of 100 and 150 pounds per square inch. Fig. 12 shows the marked difference in the concentration of the jet from the same nozzle when mounted on the 3-inch monitor and on the 12-inch pipe.

Tentative Results

Because of the rapid acceleration of the flow in the nozzles, an almost uniform velocity was indicated by the pitot traverses re-
Fig. 12—Difference in Jet Concentration Caused by Approach Conditions.

Reduction of velocity at the surface is evident in the latter case, though it will be observed that the difference is confined to a thin layer approximately 0.06 inch thick. The pitot-tube size is indicated in the figure. Indicated velocities are plotted opposite the position of the centerline of the pitot tube. Since pitot pressures are recorded as soon as the edge of the tube enters the jet, this gives apparent velocities outside of the jet boundary. The assump-

Fig. 13—Velocity Distribution in 1½-inch Jets.
Fig. 14—Concentration in Jets from Nozzles of Various Forms.
Fig. 15—Concentration in Jets from Monitors.
tion that the pitot pressure correctly indicated the velocity at the jet side of the square-ended pitot tube permitted integration of the pitot results to obtain close agreement with discharges obtained by timing and weighing.

It was observed during the tests that jets having reduced velocity at the edge caused by separation have a frosty appearance while those with the uniform distribution characteristic of the short nozzles without cylindrical tips were smooth and nearly transparent. It is thus apparent that nozzle form influences the surface texture of the jet and accounts for much of the spray which falls off as the water leaves the nozzle.

Jet concentration was determined from the contour plots by integrating the flow and plotting as ordinates the cumulative discharge between contours expressed as a percentage of the nozzle discharge, and as abscissas the cumulative area of the contours from the center outward as shown in Figs. 14 and 15. The failure of the curves to rise to 100% of the discharge from the nozzle is attributed mainly to the fact that some of the water fell as spray between the nozzle and the sampler and to some extent to the fact that no attempt was made to measure the fine spray at the edges of the jet.

The comparison of the concentration of jets from different forms of nozzle (Fig. 14) indicated that the long nozzle with a cylindrical tip has a relatively low concentration in the center of the jet (at small areas) but ultimately puts a high percentage of the nozzle discharge into a large area such as 10 square feet. The short nozzles without cylindrical tips show the opposite tendency, yielding high concentration near the center of the jet but failing to get as much of the water to the target area, ultimately, as does the more conventional form. It was supposed that the high concentration at the center of the jet would indicate the ability of the jet to travel greater distances. However, this supposition could only be verified by the outdoor tests.

A comparison of concentration in 1½-inch jets from the 3-inch and 6-inch Coast Guard and the experimental monitor with a short 45° nozzle is shown in Fig. 15. The superiority of the experimental monitor is indicated by the higher concentrations throughout the entire range of jet area, although the 6-inch Coast Guard monitor is not greatly excelled.

Pictures taken outdoors with the three monitors throwing 1½-
inch jets are compared in Figs. 16 and 17, which were taken at base pressures of 100 and 150 pounds per square inch, respectively. From top to bottom are shown the 3-inch Coast Guard monitor, the 6-inch Coast Guard monitor, and the experimental monitor with 45°, 30°, and 7° nozzles. The latter had a cylindrical tip with a
large-radius rounding between the conical and cylindrical sections, the length of the rounding being 2 tip diameters. The marked superiority of the lower photographs is evidence that a considerable amount of turbulence is eliminated by the design of the experimental monitor, the best jet travelling nearly twice as far as that from the 3-inch monitor.

Fig. 17—Photographic Comparison of Monitors at 20° Inclination, 150 psi Pressure.
The presence of slugs of water and dropping spray fairly close to the monitor suggests that further improvements in design may be possible both in the monitor and in the nozzles, and at the time of writing new nozzle forms are being prepared. There is some indication that the best nozzle form may have curved boundaries which would make machining difficult. Possibly nozzles formed with a suitable plastic could overcome this practical difficulty and have the added advantage of smooth interior surfaces.

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References
