NOZZLE PERFORMANCE IN ROTARY APPLICATIONS

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D. Wright, J. Wolgamott, G. Zink
StoneAge, Inc.
Durango, Colorado, U.S.A.

ABSTRACT

Waterblast cleaning is widely used due to improved productivity, effectiveness and environmental friendliness. The development of new waterjet tools and more capable pumping equipment has contributed to this acceptance. A critical aspect of all these tools is the jet quality produced. The flow path through these tools is often very disruptive, which results in turbulent upstream conditions and poor jet quality. The type of nozzle used can mean using an expensive pump to its fullest advantage, or throwing away up to 50% of its power.

This paper studies the performance of common, commercially available nozzle types under both poor and good upstream conditions. Variations in flow, pressure, standoff distance, traverse velocity and jet angle were compared. Flow conditioning methods such as vanes, screens and feeder tubes were evaluated for relative performance. The range of study included flow rates of 7.5 to 150 lpm (2 to 40 gpm), pressures from 35 to 105 MPa (5000 to 15000 psi) and standoff distances from 3.8 to 185 cm (1.5 to 73 in.), corresponding to 50 to 1000 nozzle diameters.

A mixture of cement and sand was used as a target material. The volume removed was measured to determine jet effectiveness. Resulting jet performance was quantified and compared to real life cleaning tasks.

1. INTRODUCTION

The performance of a waterjet cleaning tool is dependent on applying the necessary power to the surface for proper cleaning. Once the jet exits the nozzle, it begins to lose power as it travels through the surrounding air. The better the jet quality (the tighter the jet) the more power it will deliver to the target surface. Jet quality is influenced primarily by the upstream flow path conditions and the particular nozzle design.

Jet power deteriorates over distance after it leaves the nozzle. When this distance is expressed in terms of nozzle diameters, the deterioration is uniform for all sizes of a nozzle style. For this reason, standoff distances are best expressed in terms of nozzle diameters. This method of expressing performance was first suggested by Leach and Walker (1966). For example, if the standoff distance to the surface to be cleaned is 750 mm (30 in.), the distance in terms of nozzle diameters for a .75 mm (.030 in.) diameter nozzle would be 1000 nozzle diameters; while for a 1.8 mm (.073 in.) diameter nozzle this distance would be 410 nozzle diameters. If both jets had the same pressure at the nozzle, the jet from the larger nozzle would reach the surface with more remaining power than the smaller nozzle jet.

Material to be removed from a surface has a minimum threshold pressure, below which it will not be affected. Therefore, it must be attacked with a certain minimum amount of power for effective cleaning. If this pressure is known, along with the standoff distance and the rate of deterioration of the jet through the air, minimum operating conditions of pressure and flow can be estimated. This paper addresses the rate of deterioration of various nozzle types and the effect on this rate with different upstream conditions. Standoff distance, nozzle size, pressure, surface speed, and jet angle were tested over a typical range of operating values.

2. TEST PROCEDURE

Test samples measuring 30 cm square by 14 cm thick (12 in. square by 5.5 in thick) of a cement/sand aggregate were prepared from a single mixed batch. An apparatus consisting of an air powered gearbox, high pressure water swivel, and nozzle head was used to rotate the jet resulting in specific surface speeds across the sample. The carriage with the nozzle head attached advanced 5 mm (.2 in.) with each revolution of the head. This was accomplished with a tooth belt drive from the rotating shaft to a threaded shaft. This equipment is shown in Figure 1. The sample was masked with a steel plate to expose a fixed surface area of the sample measuring 7.6 by 10 cm (3 by 4 in.) A typical test sample is shown in Figure 2. After the tests had been run, the volume removed was measured using the struck sand method. This entailed pouring sand into the blasted out void, scraping off level with the top, and then collecting and measuring the resultant volume of sand. A total of 260 tests were conducted over a period of 3 months.

3. STUDIES

3.1 Nozzle Type Performance

Nine types of nozzles were tested with both poor and good upstream conditions at various flow rates and pressures. The cross sections and nozzle types are described in Figure 3. These nozzles are commonly used in waterblasting operations. Each nozzle was tested at standoff distances of 50, 200 and 500 times the nozzle diameter. Surface speed across the samples for all tests was .6 m/sec (2 ft/sec). Section 3.3 provides a description of the upstream conditions used.

The results of nozzle performance with good upstream conditions are shown in Figure 4. With good upstream conditions, nozzle I and nozzle B had the best performance. Nozzle I uses the carbide insert as nozzle B, combined with a transition section to blend the nozzle entrance. The internal geometry of these nozzles, in terms of inlet taper and length, is the closest to the optimum found by Shavlovsky (1972) and Savanick and Frank (1976). Their studies showed an optimum inlet angle between 10 and 14 degrees, and a straight section of nozzle 3 to 4 times the orifice diameter.

The results of nozzle performance with poor upstream conditions are shown in Figure 5. Under poor upstream conditions, nozzle A had the best performance. This is due to the vane type flow conditioner, described in Section 3.4. The use of this type flow conditioner would improve the performance of any nozzle type when operating under poor upstream conditions.

The type of nozzle used can mean using an expensive pump to its fullest advantage, or throwing away up to 50% of its power. This study measured performance in terms of volume of material removed; some nozzles are optimized for other purposes, such as fan jets, which are optimized for surface cleaning. It was observed during these tests that different nozzle types had different impact patterns, which would result in different cleaning paths. For example, nozzle F cut a very narrow path, and left ribs of material between passes. Nozzle C cut a wider path than the other nozzles, which would be useful in surface cleaning where complete coverage is required.

3.2 Effect of Flow and Pressure

A single nozzle type was tested at a variety of conditions to measure performance over a range of standoff distances. Nozzle type A was tested with both poor and good upstream conditions, at standoff distances of 50, 200, 500 and 1000 times the nozzle diameter, at pressures of 35, 70 and 105 MPa (5000, 10000 and 15000 psi), and at flow rates of 19, 57 and 150 lpm (5, 15 and 40 gpm) at each of the pressures. Surface speeds across the samples for all tests were .6 m/sec (2 ft/sec).

Figure 6 shows the relationship of performance to standoff distance for the three different flow rates. A nozzle with good upstream conditions will decay by 35 percent between 50 and 500 nozzle diameter standoffs, while a nozzle with poor upstream conditions will decay by 60 percent over the same range. Figure 7 shows the relationship of performance to standoff in nozzle diameters for the three different pressures. A similar rate of decay occurs with pressure as did with flow. From this analysis, expressing performance versus standoff distance in terms of nozzle diameters appears reasonable within this range of flows and pressures.

3.3 Effect of Upstream Conditions

Two types of nozzle heads were used; one typical of poor upstream conditions found in common waterjet tools, the other to represent good upstream conditions. These two heads are shown in Figure 8. A feeder tube was used to produce good upstream conditions. Ideal feeder tubes are straight and axially symmetric with a smooth bore leading to the nozzle. The good upstream condition used for these tests was based on findings by Shavlovsky (1972), where the length of the feeder tube should not be less than 40 to 50 times the inside diameter. For this study, the length of feeder tube used was 61 cm (24 in.) with an inside diameter of 1.2 cm (.46 in.), resulting in a ratio of length to inside diameter of 52 times.

Figure 9 shows the results obtained with poor upstream conditions using nozzle type B, relative to the results obtained by Leach and Walker (1966) when testing the Shavlovsky nozzle design. Leach and Walker measured the performance of a nozzle by measuring the stagnation pressure of the jet on a surface relative to the pressure at the nozzle, whereas this study measured nozzle performance in terms of volume of material removed. The results appear very similar.

Figure 10 compares nozzle type B, poor upstream conditions, with the same nozzle, good upstream conditions tested at a flow rate of 19 lpm (5 gpm). This shows that good upstream conditions can double the performance found with poor upstream conditions. Overall, all nozzle types showed an average improvement of 45% over poor upstream conditions.

The importance of good upstream conditions increases as flow rates increase. This can be seen in Figure 11, comparing poor and good upstream conditions at flow rates of 19, 57 and 151 lpm (5, 15 and 40 gpm). At 19 lpm (5 gpm), the ratio of poor upstream performance divided by the good upstream performance was .76, while at 151 lpm (40 gpm), this ratio dropped to .46. At the highest flow rate, the inside diameter of the feeder tube used for good upstream conditions was only 3.5 times the nozzle diameter used for this condition. Shavlovsky (1972) found that increasing the inside diameter of the feeder tube up to ten times the nozzle diameter gave the optimum performance.

3.4 Effect of Flow Conditioning

Limitations of access to pipes, ducts or vessels often require that nozzle head designs with poor upstream conditions be used. In these cases, more compact methods of flow conditioning become important. Four different methods of flow conditioning were evaluated at 70 MPa (10000 psi), 57 lpm (15 gpm) at standoff distances of 200, 500 and 1000 nozzle diameters. Figure 12 shows the four types evaluated. The cone and screen type flow conditioners showed no performance improvement at the conditions tested. However, other field results at flow rates above 300 lpm (80 gpm) have shown screens to be beneficial.

The effect of the vane type flow conditioner to improve poor upstream conditions is shown in Figure 13, relative to results obtained with no flow conditioning, and results with good upstream conditions. The vane flow conditioner provided an improvement of 40 percent over a nozzle without one, but was still 25 percent less effective than the nozzle with good upstream conditions.

Further study was conducted on the effect of length feeder tubes when used for flow conditioning. The use of feeder tubes has limitations; the length of feeder tube is often limited by the size of the access to the vessel or pipe to be cleaned. Using feeder tubes, or nozzle arms, as they are commonly called, serves the purpose of reducing the standoff distance to the surface, as well as conditioning the flow.

Figure 14 shows the performance of feeder tubes with increasing ratio of length to inside diameter. Lengths of 5, 10, 25 and 60 cm (2, 4, 10 and 24 in.) with an inside diameter of 1.2 cm (.46 in.) were compared in these tests. Nozzle A, with the vane type flow conditioner, was used in these tests, conducted at 70 MPa (10000 psi), 57 lpm (15 gpm). The ratio of the inside diameter of the feeder tube to the nozzle diameter was 6.5. The shortest section improved jet performance by 22 percent overall. Improvement was seen out to the maximum lengths tested, with increasing effect as standoff distance was increased.

3.5 Effect of Surface Speed

Tests were conducted to study the effect of jet surface speed. Surface speeds of 1.5, 3, 6 and 12 m/sec (5, 10, 20 and 40 ft/sec) at standoff distances of 200, 500 and 750 nozzle diameters were tried. Multiple passes were made at the faster speeds to achieve a constant energy application. A single pass was made at 1.5 m/sec (5 ft/sec), two passes at 3 m/sec (10 ft/sec), four passes at 6 m/sec (20 ft/sec), and eight passes at 12 m/sec (40 ft/sec).

The testing of surface speed effect was done using poor upstream conditions, at 70 MPa (10000 psi), 57 lpm (15 gpm) with nozzle A. The results are shown in Figure 15. The maximum performance was achieved with eight passes at 12 m/sec (40 ft/sec) at a 200 nozzle diameter standoff. At a standoff of 500 nozzle diameters the optimum effect occurred with four passes at 6 m/sec (20 ft/sec). At a standoff of 750 nozzle diameters, the optimum effect occurred with a single pass at 1.5 m/sec (5 ft/sec).

In a single pass, slower speed results in a deeper cut. There are cases where a single slow pass can result in penetration to a boundary layer, such as a hard, brittle material in a steel vessel, which results in larger pieces being spalled off at the boundary layer. This method of material removal might be more efficient than slowly eroding the material in shallow fast passes.

3.6 Effect of Nozzle Angle

Tests were conducted to determine jet performance relative to exit angles from the head. The sample surface remained parallel to the axis of rotation, so the angle of impingement was the same as the exit angle. Figure 16 illustrates the angles tested.

Performance of the angled jets relative to 90% was affected by the direction of progression of successive passes of the angled jets. Plowing describes the progression in the same direction as the jet; dragging is progression opposite to the jet angle, as shown in Figure 16. When the jet was plowing, the performance with the 45% and 135% angle was 12 percent better than that achieved with the 90% jet. However, if the angled jet traveled in the dragging direction, the performance of the 45% and 135% angle was 27 percent less than that of the 90% jet. Figure 17 shows the effect of jet angle and direction of travel on jet performance. Overall, with nozzle A, the jet exiting at 45% exhibited 10 percent better quality than the jet exiting at 135%.

The improved performance resulting from the plowing direction of travel was dependent on the cumulative effect of successive passes; the path spacing used for these tests was close to matching the jet path width. Single, independent passes at 45% were not as effective as the 90% angle of attack.

4.0 CONCLUSIONS

4.1 Nozzle Selection

The results of the tests performed on various nozzles showed a difference in performance of up to 50 percent between nozzle types. The optimum performance with good upstream conditions was obtained by the nozzle type with a geometry that has been proven in tests by others to be the best. When poor upstream conditions exist, nozzles with vane type flow conditioners should be used when possible.

4.2 Upstream Conditions

Poor upstream conditions reduce jet performance by 25 to 55 percent compared to performance with good upstream conditions. The deterioration increases with increasing flow rate. Poor upstream conditions can be improved through the use of flow conditioning. The vane type flow conditioner is inserted behind a nozzle, and will improve performance by up to 40 percent.

Feeder tubes or nozzle arms are useful for reducing standoff distance; they also act as flow conditioners. A length of 4 times the inside diameter of the feeder tube improved performance by 22 percent. Feeder tubes with lengths up to 50 times their inside diameter have greater effect at large standoff distances.

4.3 Surface Speed

The effect of surface speed was dependent on standoff distance. At a 200 nozzle diameter standoff, the optimum was found to occur at or above 12m/sec (40 ft/sec) when multiple passes were made. At a standoff distance of 750 nozzle diameters, the optimum occurred with a single pass at 1.5 m/sec (5 ft/sec).

4.4 Jet Angle

The jet angle exiting the head between 45% and 135% affected jet quality by up to 10 percent. However, performance differences of between 12 and 25 percent were seen depending on direction of travel over the surface relative to the jet angle.

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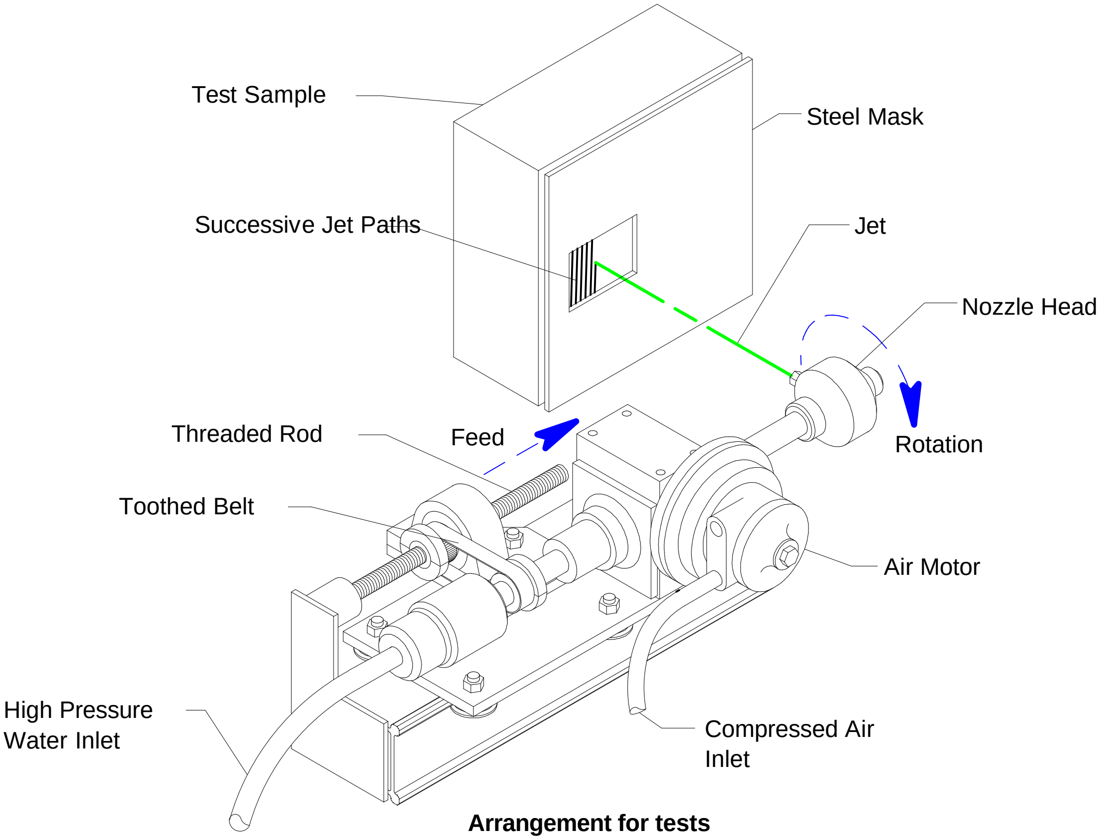
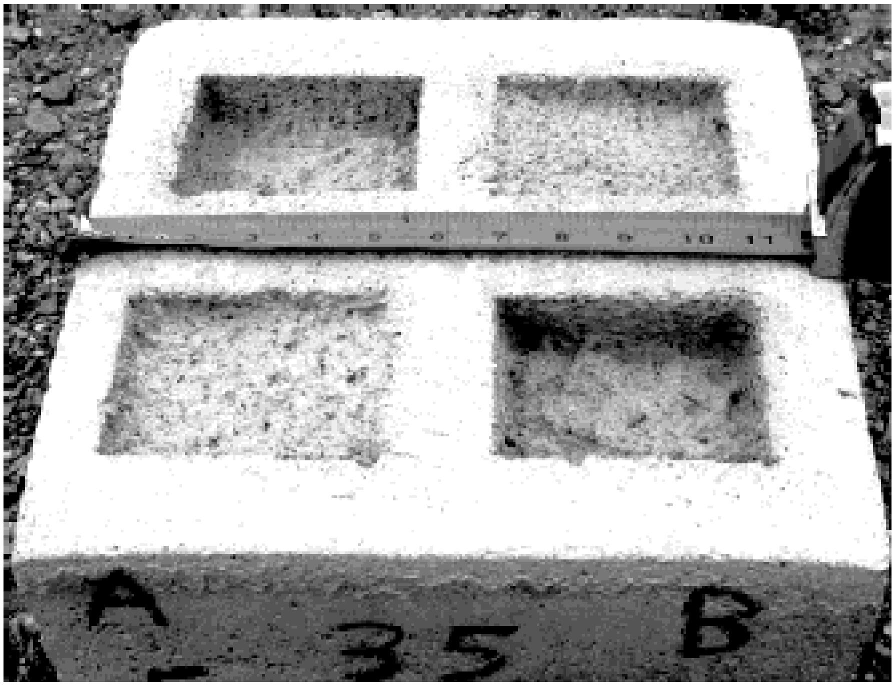
Savanick, G.A., and Frank, J.N., "Force Exerted by Water Jet Impact at Long Standoff Distances," *Third International Symposium on Jet Cutting Technology,* pp. B5-59-B5-68, BHRA Fluid Engineering, Cranfield, UK, 1976.

Shavlovsky, D.S., "Hydrodynamics of High Pressure Fine Continuous Jets," *First International Symposium on Jet Cutting Technology,* pp. A6-81-A6-92, BHRA Fluid Engineering, Cranfield, UK, 1972.

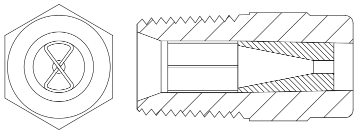


Arrangement for tests

Figure 1

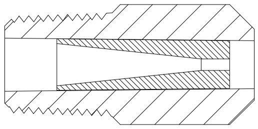


Test Sample
Figure 2



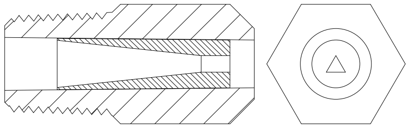
Carbide, round orifice with
vane flow conditioner

Nozzle A



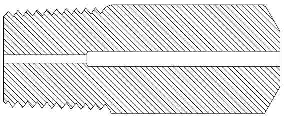
Carbide, round orifice

Nozzle B



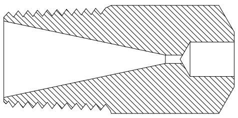
Carbide, triangle orifice

Nozzle C



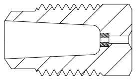
Steel, round orifice

Nozzle D



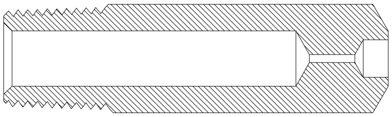
Steel, round orifice

Nozzle E



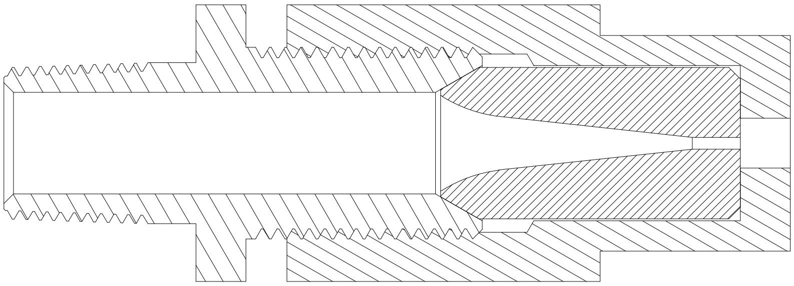
Sapphire, round orifice

Nozzle F



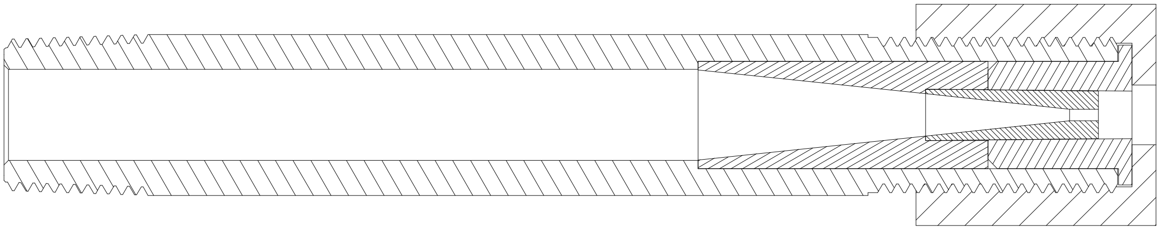
Steel, round orifice

Nozzle G



Carbide, round orifice

Nozzle H

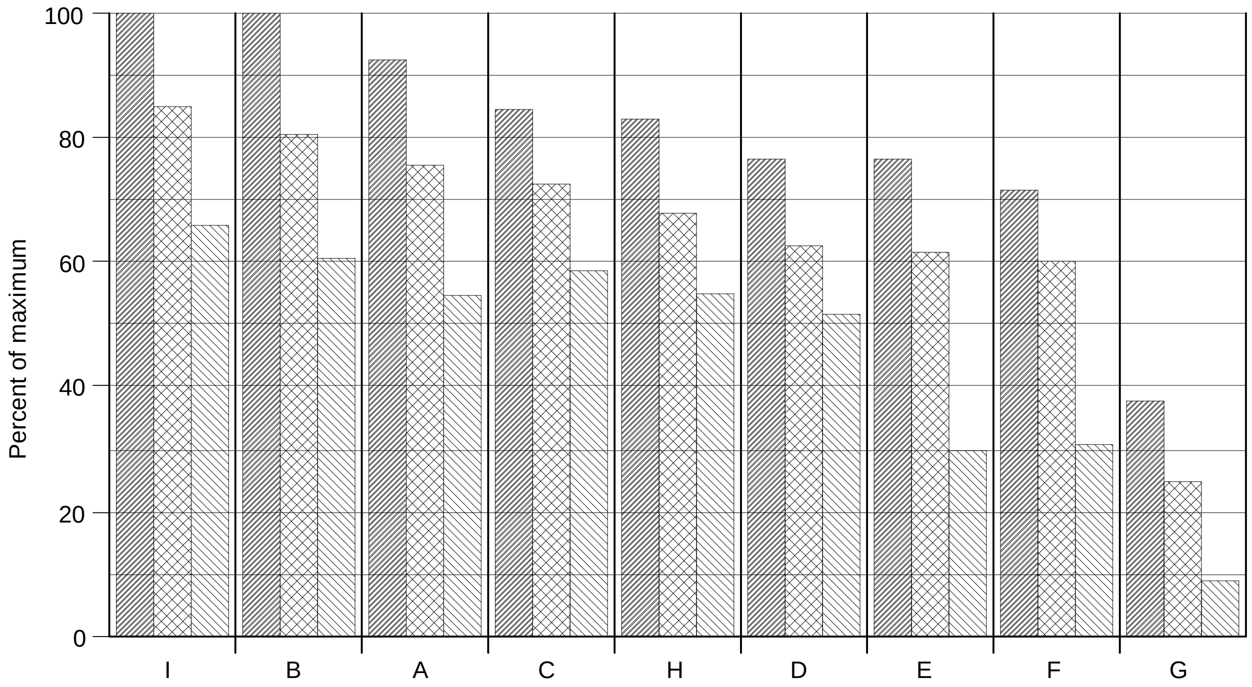


Carbide, round orifice

Nozzle I

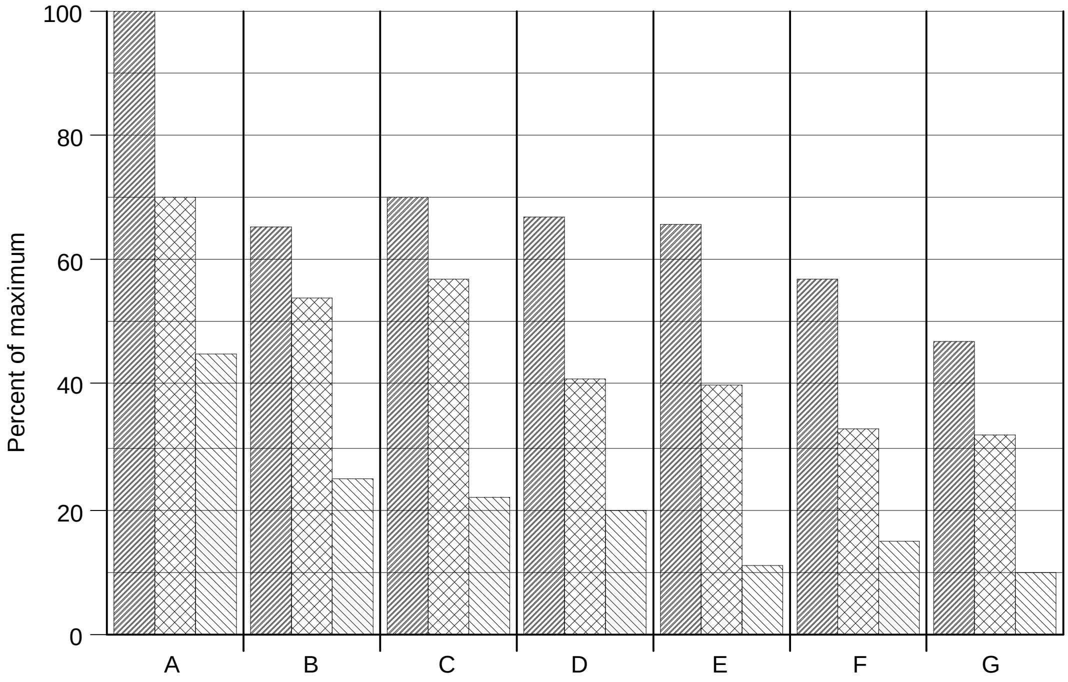
Nozzle types used for testing, shown full scale

Figure 3



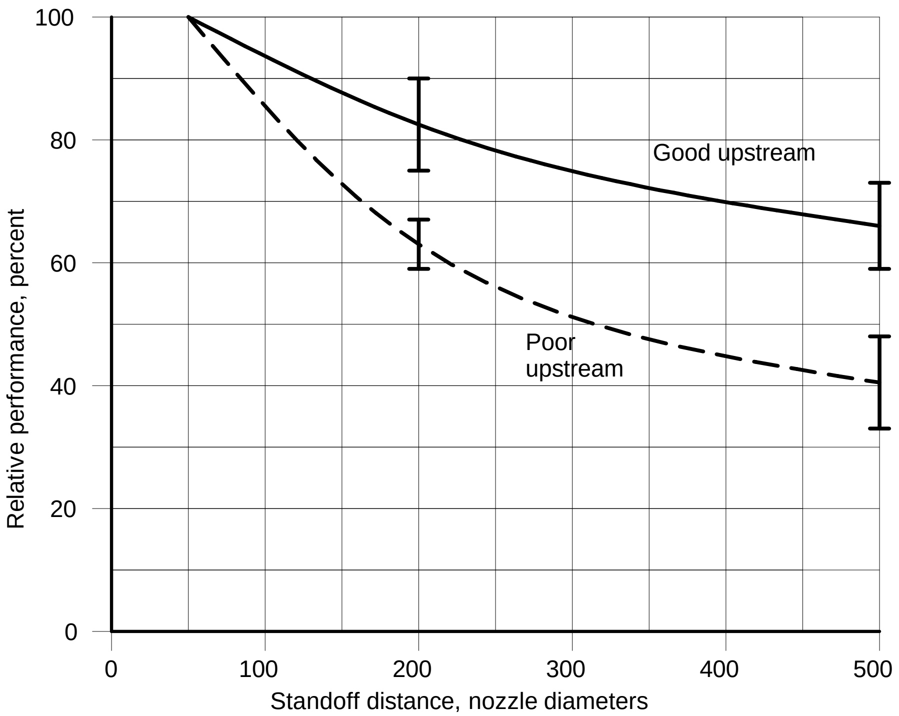
Performance of nozzle types with good upstream conditions at standoffs of 50, 200 and 500 nozzle diameters

Figure 4



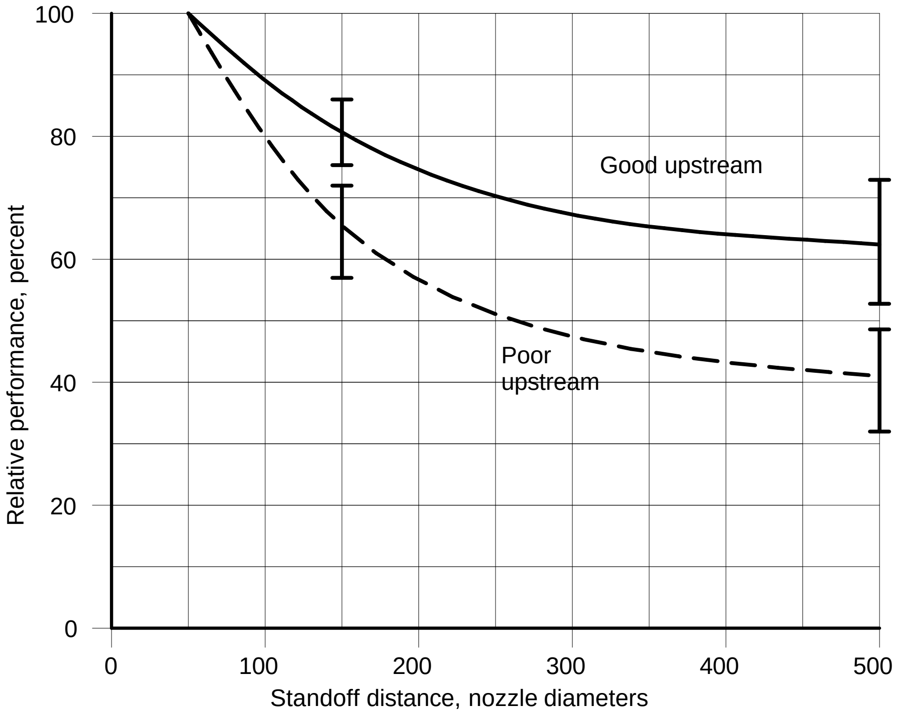
Performance of nozzle types with poor upstream conditions at standoffs of 50, 200 and 500 nozzle diameters

Figure 5



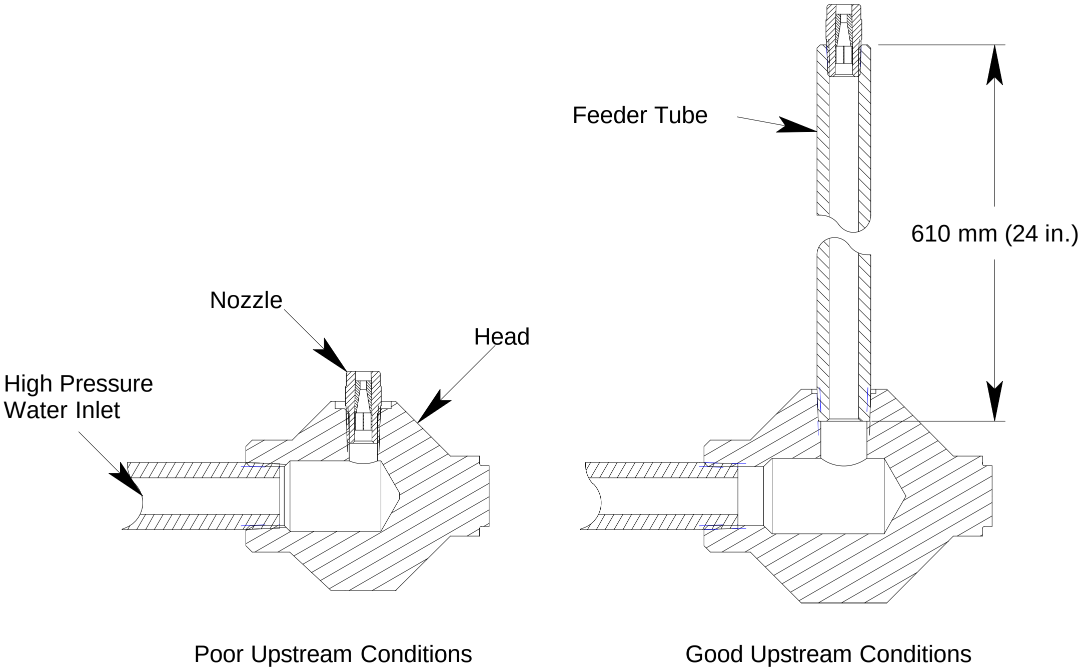
Performance with good and poor upstream conditions, tested with flow rates of 19, 57 and 151 lpm (5, 15 and 40 gpm)

Figure 6



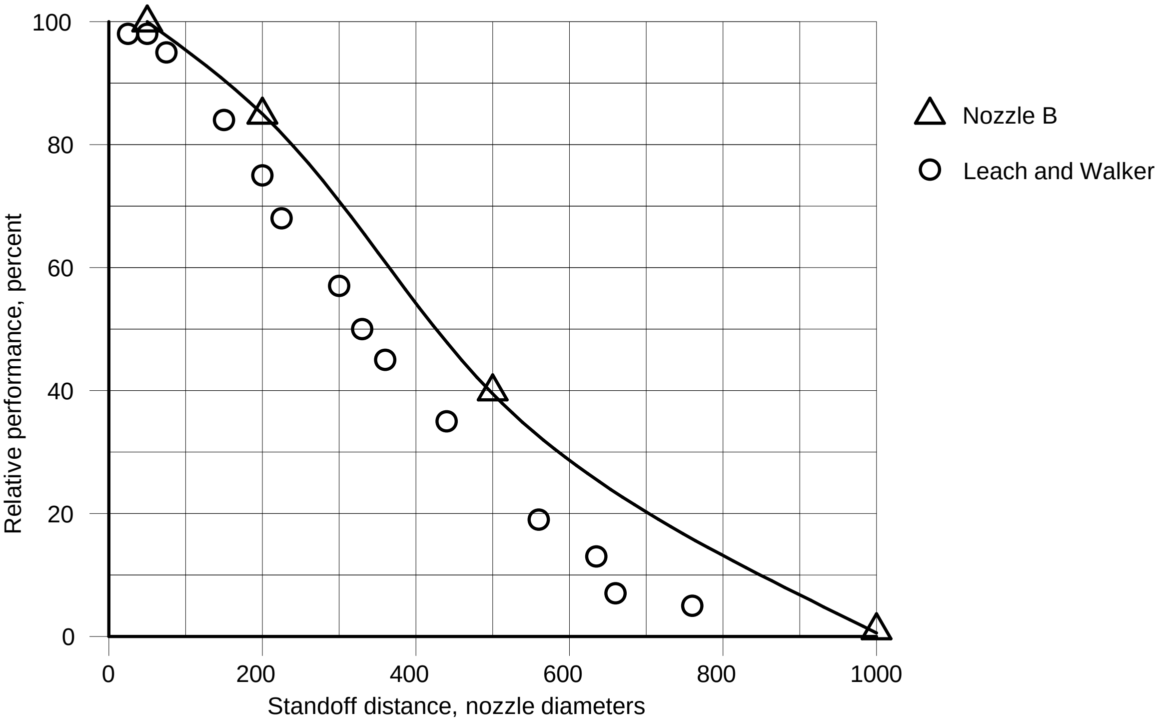
Performance with good and poor upstream conditions, tested with pressures of 35, 70 and 105 MPa (5, 10 and 15 ksi)

Figure 7



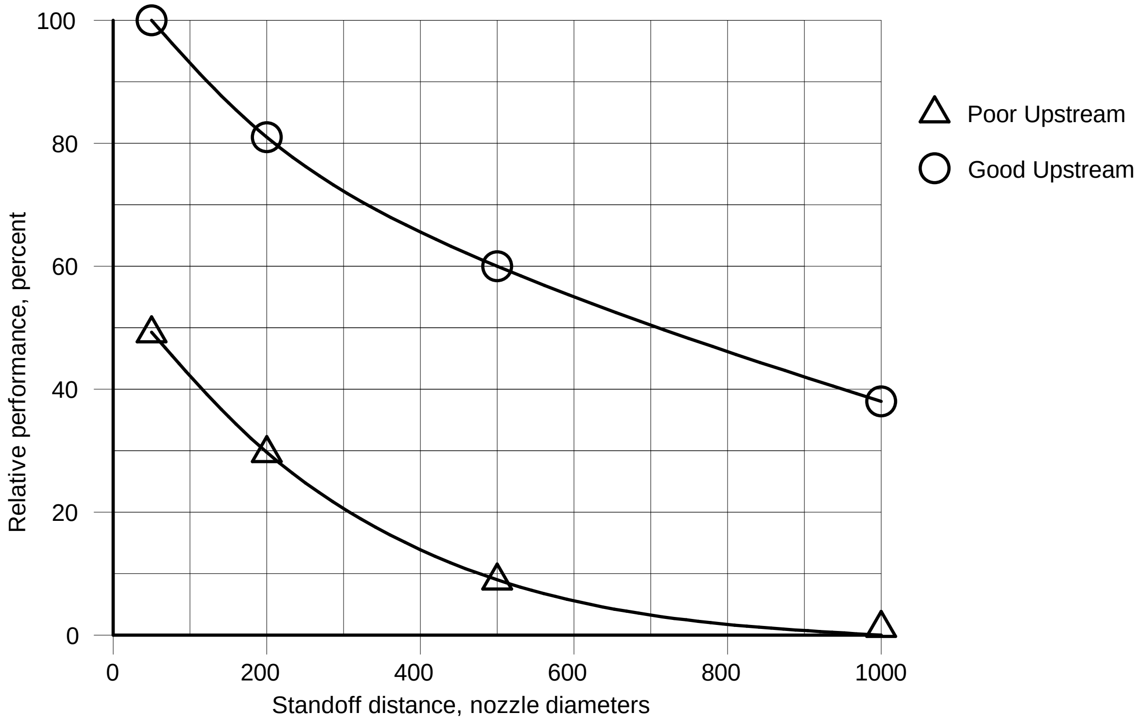
Nozzle heads used for tests

Figure 8



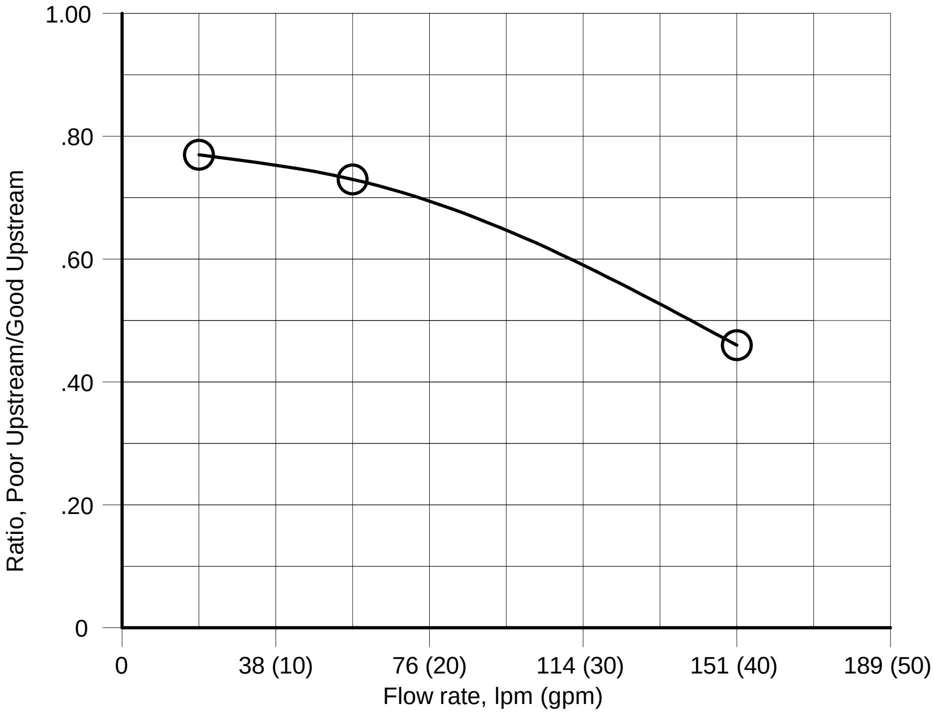
Performance of Nozzle B with poor upstream conditions compared to results obtained by Leach and Walker (1966)

Figure 9



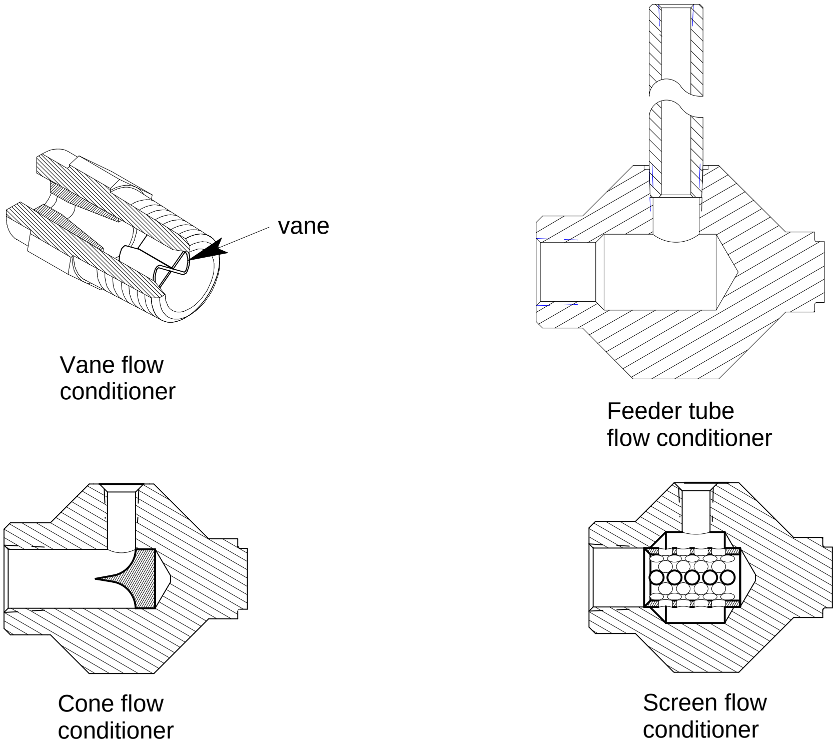
Performance of Nozzle B with poor upstream conditions compared to results with good upstream conditions

Figure 10



Performance of Nozzle A with increasing flow rate as a ratio of poor versus good upstream

Figure 11



Vane flow conditioner

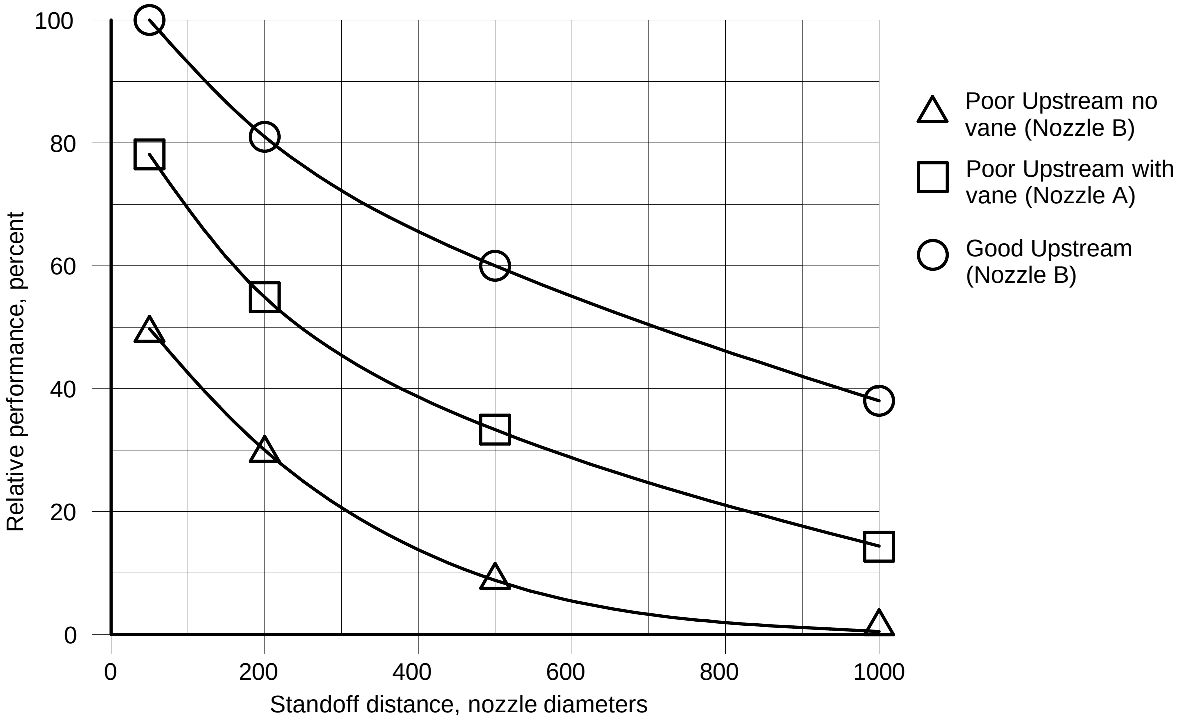
Feeder tube flow conditioner

Cone flow conditioner

Screen flow conditioner

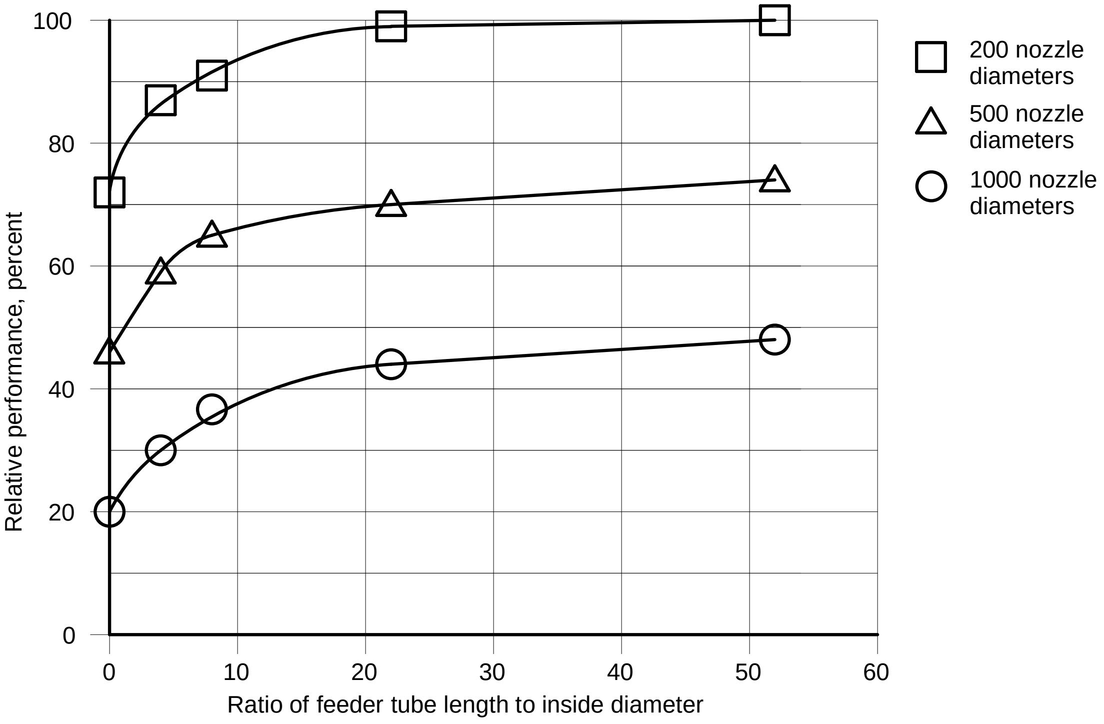
Four types of flow conditioning methods tested

Figure 12



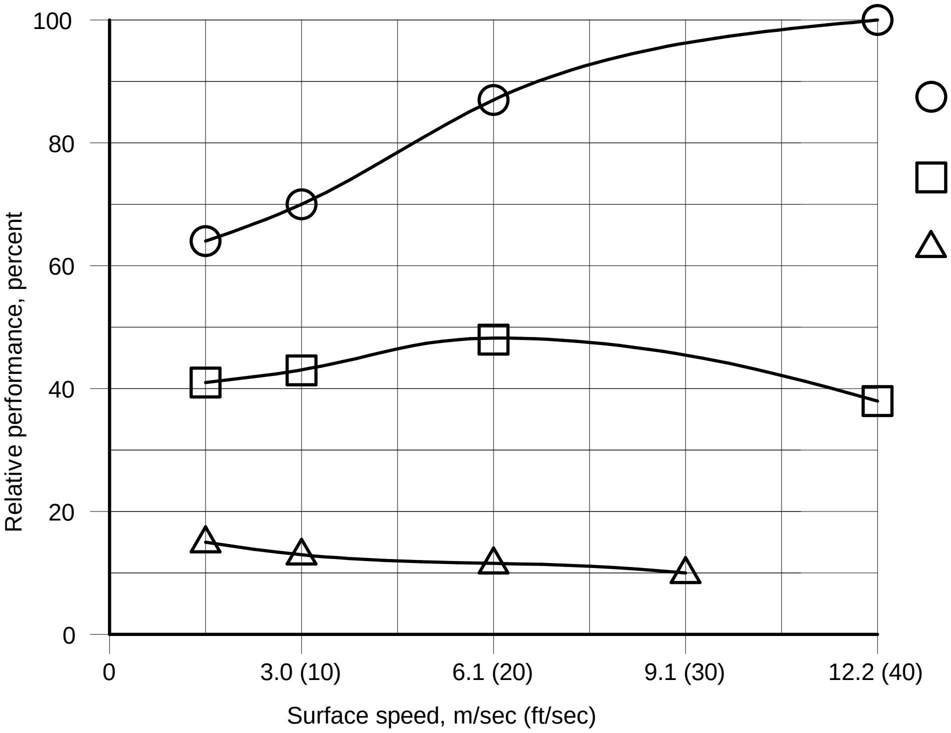
Relative performance of vane flow conditioner

Figure 13



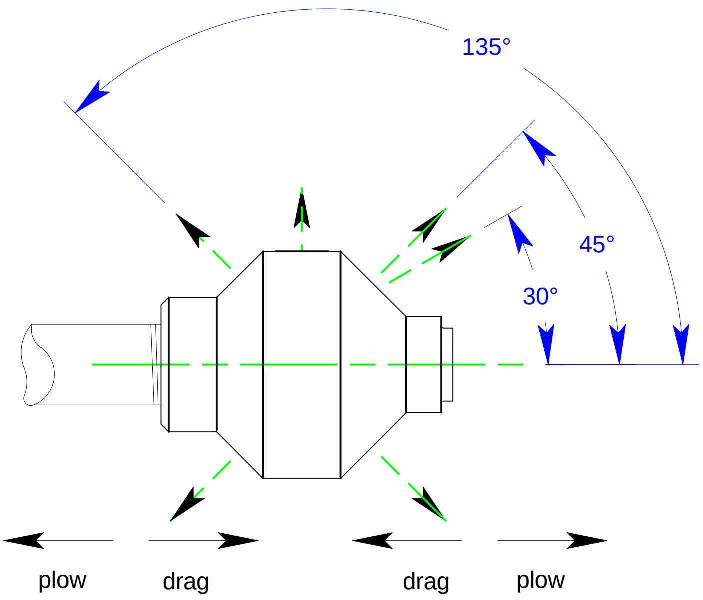
Performance of Nozzle A with increasing length of feeder tube at three standoff distances

Figure 14



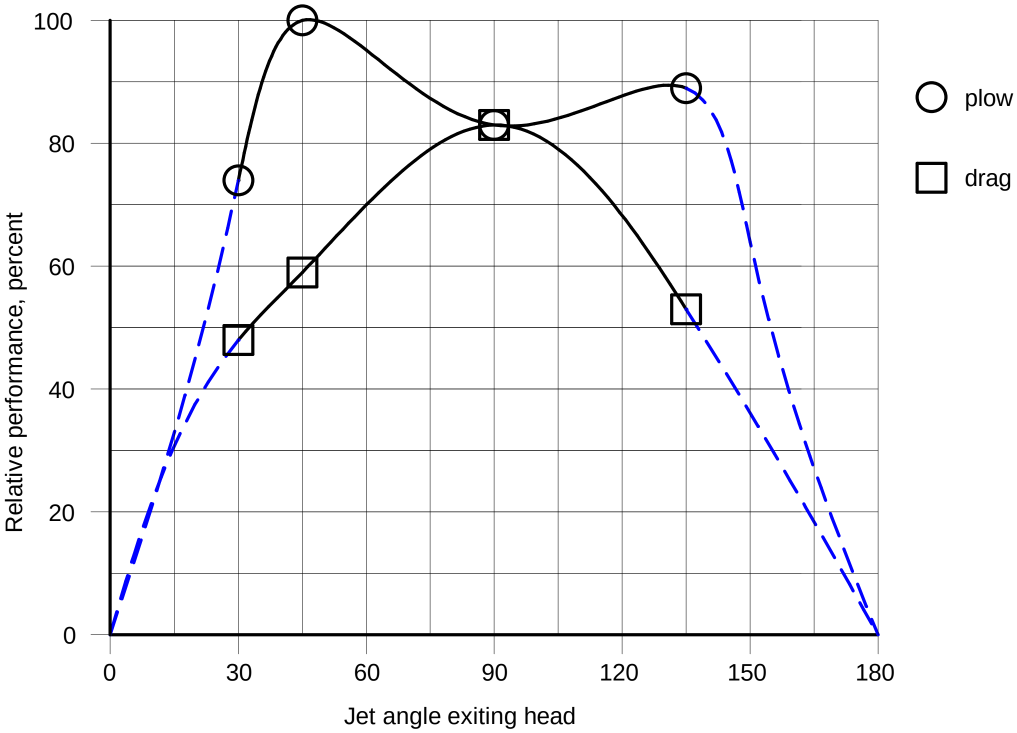
Performance versus surface speed at three standoffs

Figure 15



Nozzle exit angles tested

Figure 16



Performance versus jet angle and direction of traverse

Figure 17