Nozzles for forming smooth jets: a literature review

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Publication details:
Report No. UNSW Water Research Laboratory Report No. 188
0858240203 (ISBN)

Publication Date:
1996

DOI:
https://doi.org/10.4225/53/5785d7b102665

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Research Report No. 188
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https://doi.org/10.4225/53/5785c73a5a6ca

BIBLIOGRAPHIC DATA SHEET

Report No. 188	Report Date: December 1996	ISBN: 0/85824/020/3

Title

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Sponsoring Organisation

Supplementary Notes

This report was published under the direction of the Director of the Water Research Laboratory.

Abstract

A review has been undertaken of literature on formation of coherent water jets. Jet breakdown mechanisms and methods for controlling this are specifically covered. Aspects of nozzle design are discussed and recommendations for a nozzle design are made.

Distribution Statement

For general distribution

Descriptors

Water jets; Free jets; Nozzles; Coherent jets.

Identifiers

Number of Pages: 18	Price: On Application.

CONTENTS

LIST OF FIGURES

1. INTRODUCTION

This literature review summarises literature on forming smooth stable jets.

The following computerised databases were searched:

- University of New South Wales Water Reference Library
- University of New South Wales Physical Sciences Library
- Current Contents Database
- FLUIDEX (fluids) (1973 – December 1995)
- Compendex (engineering) (1970 – March 1996)
- World Wide Web

Between them, these databases list publications from virtually every significant journal and conference in the areas of fluids and engineering.

Keywords used in the most productive searches were:

jet(s) and free and water; nozzle and design

excluded words were (publications containing these keywords were ignored):

chemical, rocket, magnetic, supersonic, submerged, gas

The literature search revealed that much of the relevant literature was in proceedings of conferences on Jet Cutting. For this reason, all available proceedings from this series of conferences were individually checked for useful articles. Two prominent journals in fluid mechanics were also checked separately for useful articles, these being *the Journal of Fluid Mechanics* and the *Annual Review of Fluid Mechanics*.

This review consists of Section 2 which is background reading. Sections 3 and 4 summarise the material found on producing stable jets and make some recommendations.

2. BACKGROUND

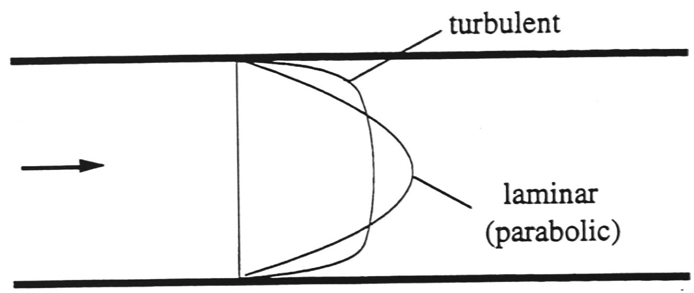

Figure 1. Schematic of velocity profiles in a pipe

The degree of non-uniformity of the velocity profile is indicated by the kinetic energy coefficient α:

$$\alpha = \int_0^A u^3 \, dA \bigg/ A\left(\int_0^A u \, dA\right)^3 \qquad (1)$$

where u is the velocity and A is the cross sectional area of the pipe. A uniform profile would have $\alpha = 1$. In practice, for flow in a pipe, $\alpha = 2$ for a laminar flow and α is between 1.1 and 1.2 for a turbulent flow.

3. JET BREAKDOWN

Some jets have rough surfaces with noticeable air entrainment and a milky appearance while others have an appearance similar to a glass rod (see the figure below). It is this latter case that will form the most coherent jet which will travel the maximum distance.

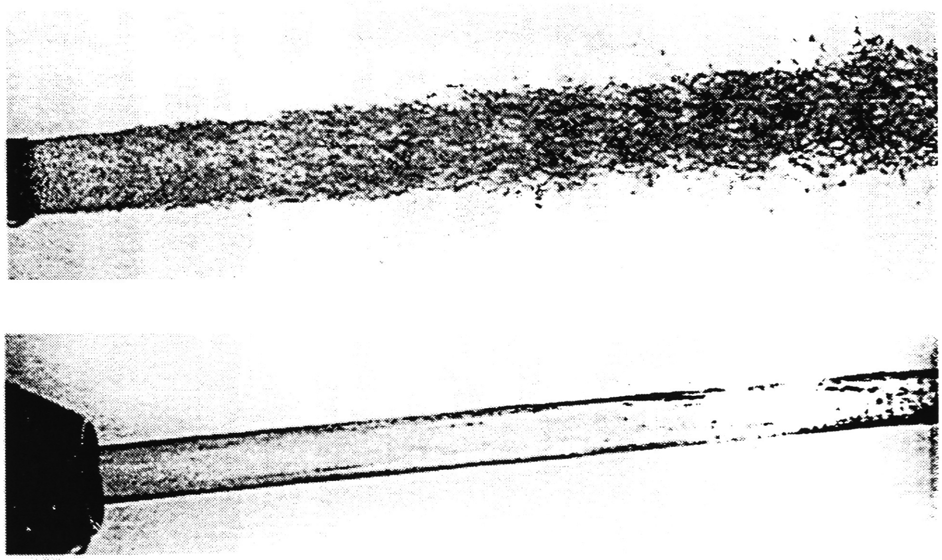

Figure 2. Jets with similar flow rates and diameters showing quite different behaviour. From plates 2 and 5 of Thorne and Theobald (1978).

There are several different modes by which a free jet (*ie* a jet of fluid in air) can break up. Researchers usually distinguish three main regions (van Sande and Smith, 1976) which depend upon Reynolds number or jet velocity. The behaviour of the jet break up length L_B is shown in the following schematic which is known as a stability curve.

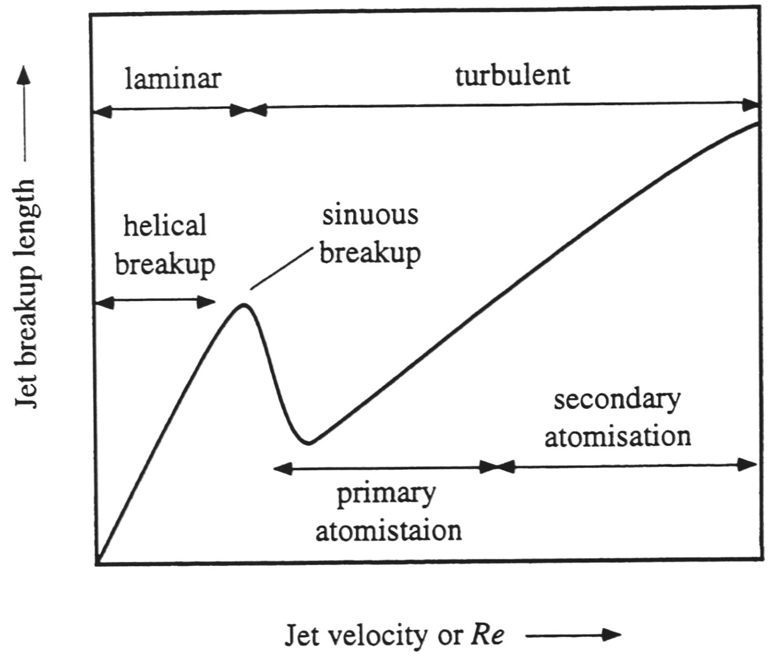

Figure 3. Schematic of change of jet break up length L_B with jet velocity

At low velocities (*ie* low Reynolds numbers) the jet is laminar and breakup is due to a helical instability (Hoyt and Taylor, 1977) with the breakup often being referred to as varicose (McCarthy and Molloy, 1974). As the jet velocity increases beyond a certain critical value (which will be different for each nozzle design) the jet becomes unstable due to turbulence developing or amplifying. It is in this region that atomisation occurs. The third region shown in the above diagram is a region in which the presence of the air surrounding the jet (through form drag) starts to affect the jet behaviour and is frequently referred to as secondary atomisation. The possible range of jet behaviour is reasonably well shown in the diagrams below.

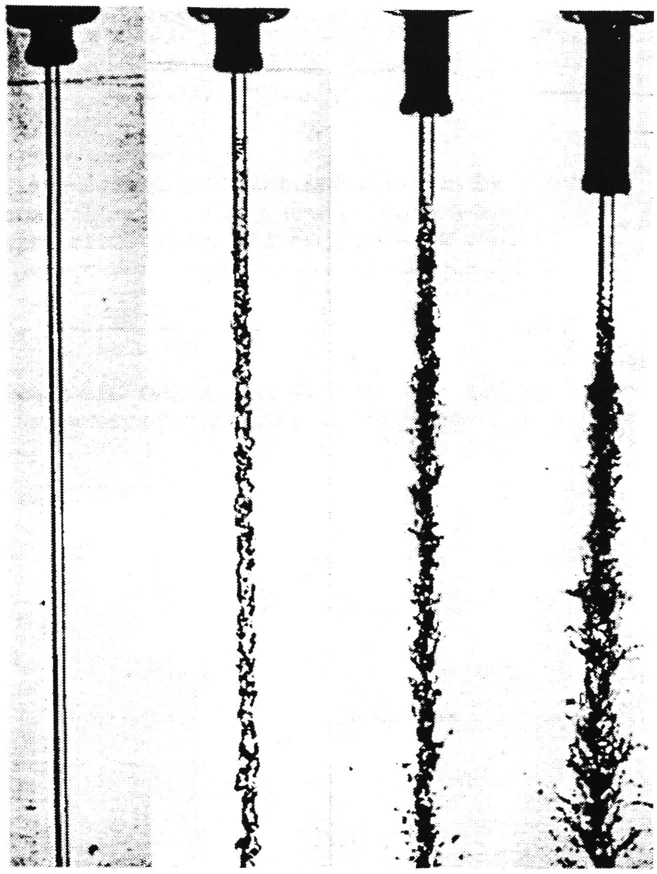

Figure 4. Jet behaviour, from left to right: stable jet which later broke down as a varicose jet with helical instability; sinuous breakup with transverse waves; turbulent breakup with atomisation; and turbulent breakup with secondary atomisation.

Figure 5. A jet displaying a helical instability - from plate 4 of Hoyt and Taylor (1977).

3.1 Influence of Jet Velocity Profile on Stability

The influence of jet velocity profile on stability has been discussed by McCarthy and Molloy (1974). They point out that a jet passing through a relatively frictionless medium will tend towards uniform flow. McCarthy and Molloy (1974) referred to this as a (velocity) profile relaxation effect. If the jet is not initially uniform (*ie* $\alpha > 1$), then shear stresses must be transferred laterally through the fluid to achieve uniform flow. It is presumably these shear stresses which can have a destabilising effect on the flow. The highest values of α that are normally obtained in an axisymetric flow (*ie* a pipe or nozzle) are those of the laminar flow case. McCarthy and Molloy (1974) point out that a laminar jet with $\alpha = 1$ should be the most stable.

3.2 Other Effects on Jet Breakup

3.2.1 Air in Feed Water

Thorne and Theobald (1978) show a rather spectacular photograph of jet break up which is reproduced below. It is hypothesised that the water entering the nozzle contained an air bubble. Upon entering the final low pressure section of the nozzle and exiting the nozzle, it is likely that rapid expansion of the air bubble caused a major disruption to the jet.

Figure 6. Disruption of a jet by an air bubble in the feed water - from plate 9 of Thorne and Theobald (1978)

3.2.2 Heating

Hoyt and Taylor (1985) showed that, unlike flat plate theory, heating of the nozzle appears to destabilise the jet. They attributed this to the heat being confined to the boundary layer – resulting in a significant temperature rise in the boundary layer. One possible effect of such a temperature rise could be to raise the vapour pressure, which, in turn, would increase the likelihood of cavitation.

3.2.3 *Polymers*

Long chain polymers are known to dampen turbulent fluctuations in water. Studies on this include Berner and Scrivener (1980), Berman (1978), and Hoyt et al. (1982). For most practical problems, the expense of the polymers limits their usefulness.

3.2.4 *Ribbed Surfaces*

Early work on ribbed surfaces involved the use of compliant surfaces (*eg* Ash et al., 1977 and Riley et al., 1988). A wide variety of conflicting results were obtained and it is unclear whether these - surfaces are effective at reducing drag. More recently, ribbed surfaces (actually microgrooves aligned with the flow) have shown to be effective in reducing turbulent levels. The grooves will only reduce turbulence over a particular speed range. Outside of this range turbulent levels can be increased. As yet there has been little practical use of microgrooves (one notable exception to this being a yacht in the 1987 America's Cup).

3.2.5 *Suction*

The pressure gradient on a surface can be altered by suction. This is usually achieved through fine holes in the solid surface. The ability of large amounts of suction to induce 'relaminarisation' has been clearly demonstrated by Narashima and Screenivasan (1979).

3.2.6 *Air Movement*

An air flow opposing the jet motion can destabilise the jet, while an air flow in the direction of the jet can enhance stability (Hoyt and Taylor, 1977). A sketch of Hoyt and Taylors apparatus is shown below.

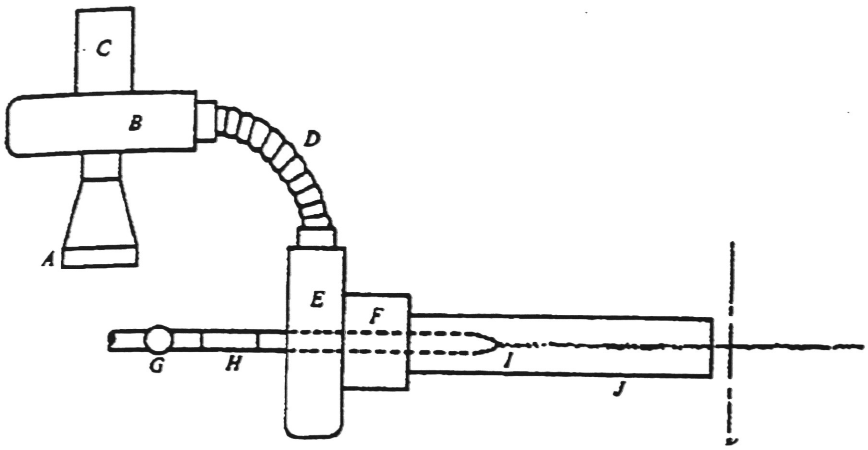

Figure 7. The apparatus used by Hoyt and Taylor (1977) (Figure 1 of Hoyt and Taylor, 1977). Air from an air blower (B) is fed to a chamber (E-F) which directs the air flow tangentially to the water jet.

4. NOZZLE DESIGN

For a fluid of given properties, McCarthy and Molloy (1974) list the following as the main design factors for a nozzle:

- the contraction ratio $b = d/D$
- the nozzle aspect ratio $R = L/d$
- the contraction angle α
- streamlining of the nozzle interior
- smoothness of the nozzle interior

These geometrical parameters are shown on the following diagram.

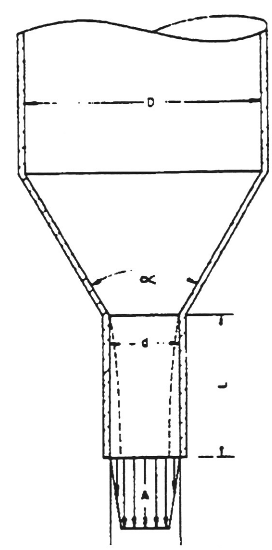

Figure 8. Geometrical parameters of an arbitrary nozzle design - from Figure 7 of McCarthy and Molloy (1974).

4.1 The Contraction Ratio β and Angle α

Small values of b mean that the flow is being significantly contracted (note that b is rarely less than sixteen - Hoyt and Taylor, 1985). This results in the flow being accelerated and the pressure reducing. The rate at which the flow contracts is governed by the contraction angle α. The net result of a contraction is:

- a positive pressure gradient (or accelerating flow)
- the flow tends to become more uniform
- the boundary layer reduces in thickness (as does the viscous sublayer)
- the head loss in the nozzle increases

Examining each of these in turn:

4.1.1 Positive Pressure Gradient

A positive pressure gradient reduces the likelihood of separation and the turbulence subsequently introduced by that separation.

4.1.2 Uniform Flow

As discussed above, a uniform flow is conducive to a stable jet. In fact, a sufficiently high degree of contraction can reduce turbulent fluctuations and result in 'relaminarisation'. This occurs because the shear stress essentially reduces to zero apart from immediately adjacent to the wall. The lack of shear stress deprives the turbulence of a production mechanism causing the turbulence to decay or 'relaminarise' (Smits and Wood, 1985). Further discussions can be found in Hussain and Ramjee (1975), So and Mellor (1973) and Gillis and Johnston (1983).

4.1.3 Viscous Sublayer Thickness

The thickness of the viscous sublayer is important as an hydraulically smooth nozzle surface is critical if the jet is to be stable (McCarthy and Molloy, 1974; Barker and Selberg, 1978; Shavlosky, 1972).

4.1.4 Head Loss

The higher the head loss, the higher the head or pressure required just upstream of the nozzle to drive the fluid through the nozzle at the required flow rate. This high pressure results in an adverse pressure gradient just upstream of the nozzle which, in turn, increases the likelihood of separation. This is demonstrated in the following figures which show: examples of pressure gradient (along the axes of several nozzles); and possible resulting separation zones.

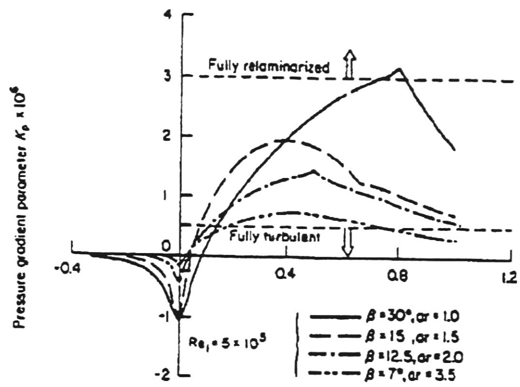

Figure 9 Normalised pressure gradient K_p versus distance along the nozzle axis for four different nozzle designs (Figure 4 of Davies and Jackson, 1985). Note that an adverse pressure gradient is negative in sign

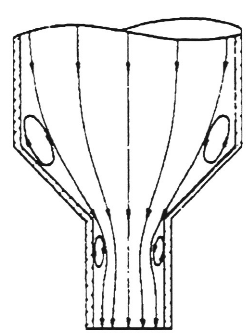

Figure 10. Possible separation zones in a nozzle due to an adverse pressure gradient.

If the contraction is made long (*ie* α made smaller) then separation effects will be minimised at the entrance to the nozzle. However, boundary layer effects will increase (*ie* more turbulence will be generated at the boundary) (McCarthy and Molloy, 1974).

4.2 Smoothness and Streamlining

Rounding of sharp angles will help minimise separation. This means that all joins should be flush and all surfaces tangential to one another. The exact degree of rounding is largely a matter of trial and error. Although, if it looks good to the eye then it probably is (McCarthy and Molloy, 1974).

All of the jet literature stresses the importance of nozzle smoothness. For high speed jets (around 30 ms^{-1} and upwards) it can be difficult to machine and finish nozzles to smoothness sufficient to ensure hydraulically smooth flow (Barker and Selberg, 1978). However, for lower speed jets this should be far less of a problem.

4.3 Nozzle Aspect Ratio

The larger the nozzle aspect ratio, the longer the length over which the boundary layer can grow after the contracting region. This growth results in jet instability (through increased turbulence and velocity profile relaxation) and is the reason why early designs of fire hose nozzles (which had high nozzle aspect ratios) performed poorly (McCarthy and Molloy, 1974).

Modern designs of nozzles for producing stable jets typically have a nozzle aspect ratio of zero. This is taken to the extreme by having the nozzle exit consist of a sharp edged orifice (Hoyt and Taylor, 1985; Theobald, 1981).

4.4 Recommendations for Nozzle Design

Shavlosky (1972) claimed that the following were essential if a jet were to be stable:

- the feeders upstream of the nozzle and the nozzle must be smooth and have axial symmetry
- stabilisers must be used to suppress turbulence upstream of the nozzle
- the nozzle must have a shape that minimises turbulence and does not cause cavitation. Cavitation is most likely to be a problem at the nozzle exit where flows are at their fastest and pressures their lowest (Lohn and Brent, 1976). Note that cavitation occurs when the pressure in the fluid falls below the vapour pressure of the fluid.

Lohn and Brent (1976) were more specific with their design criteria and suggested that the nozzle should be designed so that:

- the thickness of the boundary layer is minimised at the nozzle exit
- separation is avoided or minimised within the nozzle

Hoyt and Taylor (1985) recommended that:

- the upstream flow must be treated in order to reduce large scale or non-axisymetric motions to a minimum.
- a substantial contraction region be used - with no particular geometry providing an advantage
- a rapid final convergence in the nozzle
- a minimal nozzle aspect ratio (ie a sharp edged orifice)

A sketch of Hoyt and Taylor's (1985) nozzle design is shown below. This nozzle proved very successful in producing stable jets when compared to previous designs.

The recommendations of Davies and Jackson (1985) are similar to those of Hoyt and Taylor (1985) except that Davies and Jackson suggest that the initial part of the contraction should be gradual.

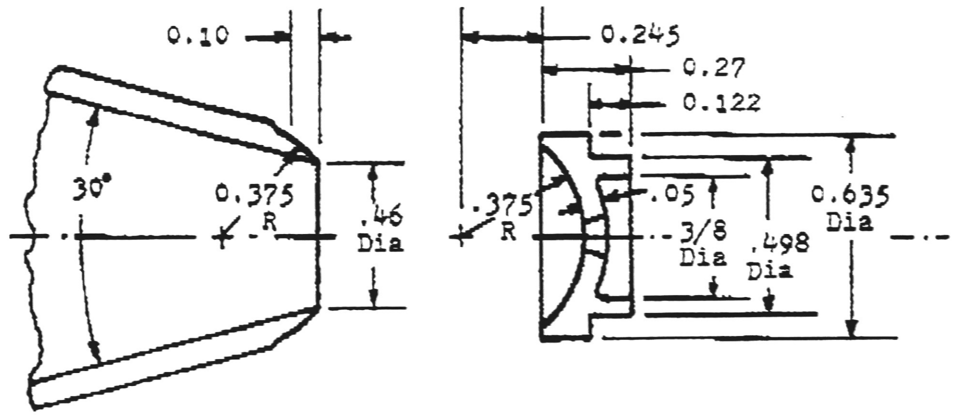

Figure 11. Schematic of the nozzle used by Hoyt and Taylor (1985) (Figure 10 of Hoyt and Taylor, 1985).

4.5 Analytical Design Methods

There is only a limited amount of literature which provide algorithms for designing nozzles to produce stable jets. The most promising research in this area is that of Davies and Jackson (1985) who assumed that a potential flow analysis could be used to determine the flow apart from immediately adjacent to the walls. The potential flow analysis allows velocities to be determined at all points in the nozzle. Use of Bernoulli's equation then allows pressures to be determined. A pressure gradient parameter K_p was found to be useful in determining if cavitation is likely to occur for a particular nozzle (the higher the minimum value of K_p the less the likelihood of cavitation). K_p is given by:

$$K_p = \frac{\nu}{U^2}\frac{dU}{dx} \tag{2}$$

Davies and Jackson (1985) showed, as expected, that the sublayer thickness decreased towards the nozzle exit. This means that a smoother finish is required at the nozzle exit than elsewhere.

4.6 Upstream Turbulence Control

Many articles point out the importance of upstream turbulence control. Hoyt and Taylor (1985) used flow straighteners consisting of stainless steel honeycombs which were inserted about 45 cm upstream of the nozzle. Splitter plates were used by Lohn and Brent (1978) to control flow being turned through 90° upstream of the nozzle. It should be recognised that the splitter plates themselves will have a wake (Baines and Peterson, 1951).

An alternate method of reducing large scale turbulence is by using mesh screens where the mesh spacing is smaller than the scale of the motions which need to be removed (Groth and Johansson, 1988). The damping ability of a screen improves as the mesh size is decreased (unfortunately, the head loss will also increase). Groth and Johansson (1988) demonstrated that turbulent intensity could be reduced by over an order of magnitude by using several screens of different sizes in series.

4.7 Other Factors

Some practical factors which need to be considered are:

- Although some nozzles perform well in tests, they can be sensitive to both upstream turbulence and non-uniform velocity distributions at the inlet to the nozzle (Theobald, 1981).

- There will be an optimum pressure for any given nozzle to produce a stable jet. Increasing the pressure will result in an unstable jet (Theobald, 1981).

4.8 Conclusions

A conceptual design which incorporates the key recommendations from above is shown below.

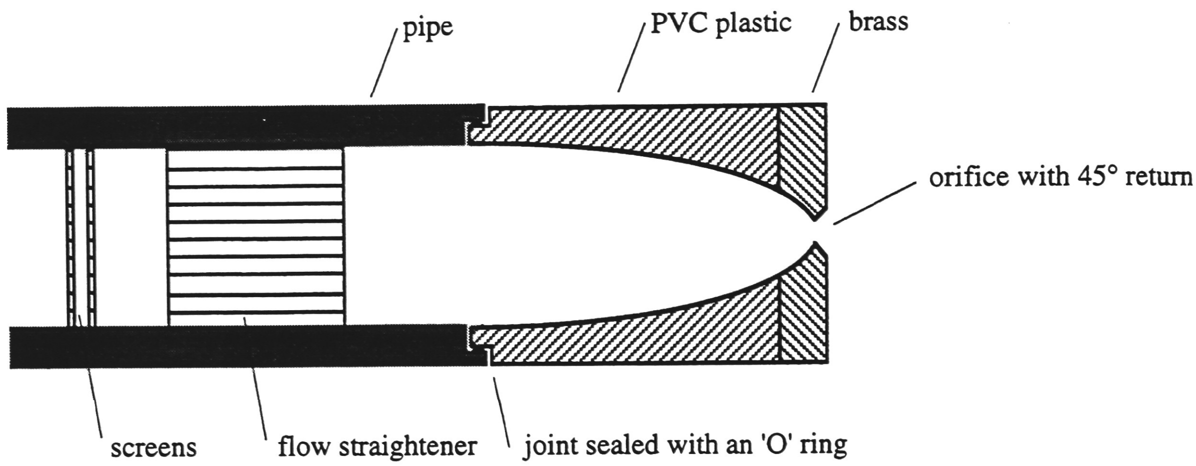

Figure 12. Conceptual nozzle design for producing coherent jets.

More complicated nozzle designs could make use of suction, polymers, microgrooves and surrounding air jets. However, it is believed that it is unnecessary to have such a sophisticated nozzle design for most purposes. A prototype of the nozzle shown above can be can be made from PVC using a standard lathe followed by polishing. The nozzle cap, however, would need to be made of brass or similar to ensure that the orifice could retain a sharp edge. A flow straightener could be used upstream of the nozzle with provision made to allow grids to be inserted upstream of this.

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