A Plating Method for the Construction of High-Precision Nozzles*

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Abstract

A research program to study the effects of density ratio and exit Mach number on the development of a compressible, axisymmetric jet has been undertaken, using different gases to change the density of the jet. However, each gas and Mach number combination requires a unique nozzle contour, and the manufacture of the planned number of nozzles by traditional methods would have been prohibitively expensive. A plating technique to inexpensively manufacture high precision nozzles was developed, and a prototype nozzle constructed. Data are presented which shows the flow quality to be as good as or better than the nozzles used by previous experimenters.

1 Introduction

Recent interest in compressible mixing has greatly enhanced our understanding of the two dimensional shear layer, since that is usually the geometry of choice for experimenters. Equivalent experimental studies of ideally expanded, parallel flow, axisymmetric supersonic jets are not abundant, and data on the effects of different density ratios are virtually unattainable. In view of the axisymmetric geometry's importantance in combustion, plume recognition, etc., this is somewhat suprising.

The experiments that have been performed have concentrated on the noise produced by the jets, both in jets dominated by shock cells and in ideally expanded jets. The development of the jet itself has generally been a peripheral topic. Recently, there has been an upsurge in interest in the mixing of jets, and there is a need to understand how mixing in jets is affected by compressibility and density ratio, as has been done for plane shear layers [1].

A parametric study over a range of density ratios and Mach numbers was planned, as shown in Table 1. Since each gas and Mach number combination has a unique contour, this requires a large number of nozzles. A review of the existing literature showed that one of the most common experimental difficulties was in obtaining good flow from the nozzle: that is, a nozzle free from internal shocks with thin boundary layers and parallel flow at the exit. Furthermore, estimates to produce such nozzles averaged about $2000 per nozzle.

Throughout this paper, the nomenclature used to describe the jet will be as shown in Figure 1, which is fairly standard throughout the jet literature. There is an initial 'potential core' region, an 'intermediate,'region, where the potential core has disappeared but the profile shape is still changing, and a 'developed' region, where the jet profiles are similar at each station. In addition, for a supersonic jet, a transition from supersonic to subsonic flow occurs within the developed region.

In order to provide an easily duplicated, well defined boundary condition at the exit, an end

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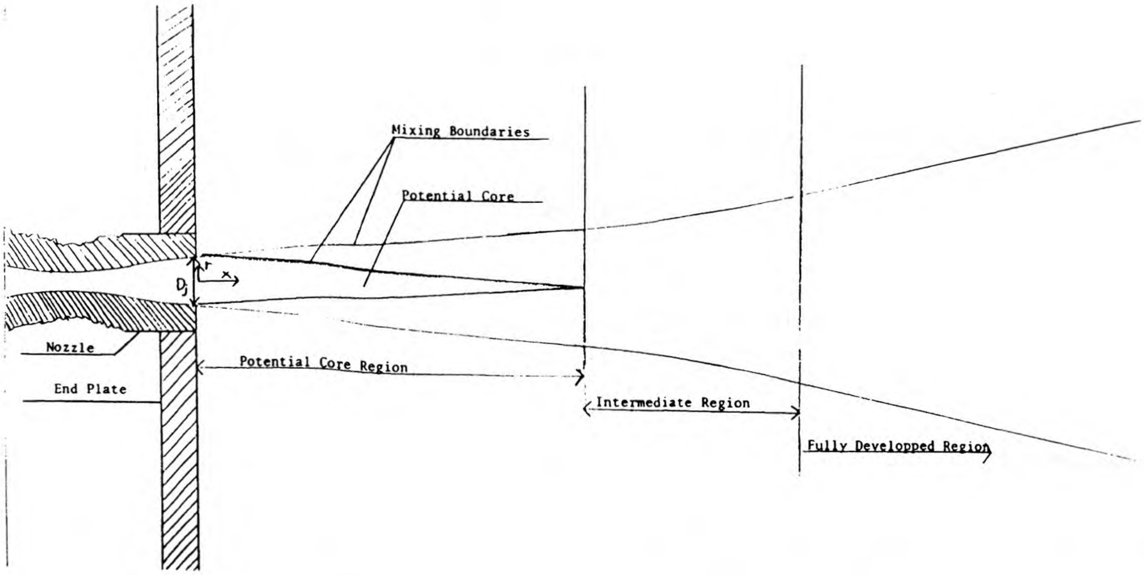


Figure 1: Jet Nomenclature

Gas	M Exit	Dia.[1]	Re [2]
Ar	< 1.0	.500	$< 4.5x10^5$
He	< 1.0	.500	$< 1.1x10^5$
N_2	< 1.0	.500	$< 4.2x10^5$
SF_6	< 1.0	.500	$< 8.2x10^5$
Ar	1.4142	.500	$8.2x10^5$
He	1.4142	.500	$1.9x10^5$
N_2	1.4142	.500	$6.2x10^5$
Ar	2.0	.500	$2.1x10^6$
He	2.0	.500	$6.5x10^5$
N_2	2.0	.500	$1.4x10^6$
N_2	2.0	.125	$3.5x10^5$
SF_6	2.0	.125	$5.0x10^5$
Ar	3.0	.500	$5.0x10^6$
He	3.0	.500	$1.6x10^6$
N_2	3.0	.500	$3.4x10^6$

[1] Inviscid Exit Diameter
[2] Re based on Inviscid Exit Diameter

Table 1: Nozzle Parameters

plate was used, as shown in Figure 1. This avoids the need to specify trailing edge thickness and angle, as is required for co-flowing jets and 2-d shear layers. It also eliminates the wake of such a geometry and its associated interation with the jet.

Perhaps the first researcher to study the development of the mixing region in axisymmetric supersonic jets was N.H.Johannsen [2, 3]. He studied a Mach 1.4 air jet exhausting into still air. Initially, he used a nozzle designed with the Foelsch method. He found that the flow was greatly affected by a strong shock wave emanating from inside the nozzle, originating just downstream of the throat. Suprisingly, he found that the subsonic approach played a large role in the strength of the shock. Tests with the Foelsch nozzle showed an abnormally short potential core and fast axial velocity decay along the centerline, accompanied by the breakup of the jet into large structures.

Subsequent tests using a nozzle designed with the Clippinger method were more satisfactory. Although weak waves could be seen, there was no large shock, and the jet decay was gradual. The only anomaly in the data was a static pressure variation along the axis of the jet that could not be explained, and was attributed to probe difficulties.

Simultaneously, research into compressible jet mixing was started at Princeton [4, 5, 6]. Warren [5] designed and built three nozzles, for M=1.0, M=1.5, and M=2.6, again using a Foelsch design, with the throat consisting of a bump on the M=1.0 contour. The M=1.5 nozzle was unusable in the experiments due to extremely strong shocks, and internal shocks can be seen emanating from within the M = 2.6 nozzle. Large variations in both pitot and static pressures were present at the exit plane of the M=1.0 and M=2.6 nozzles. As had Johannesen, Warren found large static pressure variations on the axis in the potential core.

Other experimenters who tried to manufacture ideally expanded, parallel flow nozzles [7, 8, 9, 10, 11, 12] found that their flow had an axial cell structure present downstream. It should be pointed out that the cell structure can be caused either by a weak shock pattern or an axisymmetric instability as predicted by Tam [13] for an infinitesimal pressure mismatch. The wavelength of the instability is shorter than that of Mach wave cells.

In order to conduct the desired experiments, the nozzles used needed to produce a flow with uniform exit conditions and without shocks at the desired Mach number. The remainder of this paper will be devoted to discussing the design and manufacture of, and initial results from, a prototype nozzle for M=2.00 Nitrogen.

2 Nozzle Design

Most of the nozzles of previous experimenters have been of the Foelsch type. This type is based on a radial source flow, with a conical section followed by a cancellation region designed using the method of characteristics. The advantage of the Foelsch method, particularly when it was first introduced, is that the calculation can readily be done by hand, with the nozzle profile in the cancellation region consisting of a simple polynomial. However, the transition from the conical section to the cancellation region inherently involves a discontinuity in the curvature of the nozzle wall, which results in a converging series of compression waves being launched from that point. While this generally does not cause any problems in a 2-d flow, where Foelsch type nozzles have been used successfully, in an axisymmetric flow the geometry focusses any disturbance onto the axis, and often results in a Mach-disk being formed inside the nozzle just downstream of the throat.

In the present work, the supersonic portion of the nozzles was designed using the code developed by Sivels [14]. This code also uses the method of characteristics to calculate the contours, but unlike the Foelsch nozzle, does not involve any discontinuity of curvature. It allows the user to specify either a Mach number or velocity distribution from the throat to the exit, and includes a boundary layer correction. A computer is required to generate the contour, but that is not a serious drawback in this day and age. It was found that the convergence of the code depended strongly on the specified ratio between the throat radius (Rt) and the axial throat radius of curvature (Rc), and after some trial and error a radius of Rc/Rt = 20/Me was used. A 4th order Mach number distribution was used from the throat to the exit in the prototype nozzle.

With a supersonic contour in hand, the next task was to design the subsonic approach section. A common choice has been to match the curvature of the throat, and specify an inflection point in the nozzle contour [15, 16], which results in a 7th order polynomial for the subsonic section. Pope, however, suggests that the appropriate contour is one that results in a continuous Mach number distribution at the throat, rather than one that simply matches curvature at the throat [17]. The two approaches will be nearly equivalent for the 2-d case, but Pope's approach will result in a slower contraction near the throat for the axisymmetric case, due to the square root relation between the diameter and the cross sectional area. Johannesen had found that the exit properties of a nozzle did, in fact, depend on the subsonic inlet design [2]. He found that the exit flow quality improved as the inlet became less curved, and the sonic line straighter. Therefore, Pope's approach was used to design the subsonic section of the nozzles described herein.

As a 4th order Mach number distribution had been used for the supersonic section, it was decided to make the Mach number distribution of the subsonic section match to 4th order at the throat. The Mach number and the first 4 derivatives were specified at the throat; a Mach number dependent on the contraction ratio and the first four derivatives equal to 0 were specified as the condition at the start of the contraction. This requires a tenth order polynomial, in Mach number, for the subsonic section. The Mach number calculated from the polynomial for a given axial location was used to calculate the local area ratio and diameter. A linear boundary layer growth was then added so that the thickness at the throat was matched with that calculated by the supersonic code.

In addition to the supersonic nozzles, three nozzles were designed for M=1.0 flow using the same method, but with the derivatives zero at the exit as well as the entrance. Even though the constraints result in a unique Mach number distribution, three nozzles are needed because the area ratio at a given Mach number depends on γ. No boundary layer correction was added to the sonic nozzles.

3 Nozzle Construction

The manufacture of a nozzle by direct machining so that it matches the desired contour has been very difficult, even for the M=1.0 case. Machining must be done from a larger towards a smaller internal diameter. This requires a long, thin tool bit which tends to flex and chatter, decreasing the accuracy and leaving tool marks, respectively. In a Laval nozzle of any appreciable Mach number, the situation is worse, since it requires that the part be removed from the lathe, turned around, and the machining completed from the other side. Machine shops are only willing to guarantee accuracies of about .001" for such an operation. Although that may seem to be a small mismatch, the throat area is extremely sensitive, and a .001" step can have large adverse affects on the flow quality at the exit. Any machining marks left in the supersonic portion of the nozzle will create patterns of waves in the nozzle, which is again undesirable.

One experimenter describes the use of grinding paste in an attempt to obtain a smoother final contour [9]. However, only one out of three of their nozzles was deemed usable, and even that one exhibited large flow asymmetries. Due to the difficulty of directly machining such nozzles, machine shops quoted about $2000 per nozzle with a .001" tolerance and a 30 microinch surface finish. Clearly, a new method was needed to make the large number of nozzles required for the desired experiments affordable.

The driver of the cost in machining a small, relatively deep internal shape like a Laval Nozzle is that a special tool bit smaller in diameter than the throat but longer in length than the either the contraction or the supersonic portion must be made. Such a bit is inherently flexible because of its relative thinness, and it causes problems both with the tolerance and surface finish. Any method that hopes to do significantly better with respect to cost or accuracy must either have most of the machining performed on an external contour or use a technique that doesn't rely on a tool bit. The possibilities that were explored were plug nozzles, edm, broaching, casting, and plating.

Plug nozzles would allow all complex machining to be done on an external contour, as well as allowing for changes to flow conditions in a manner similar to swapping nozzle blocks. The drawbacks to a plug nozzle are that there is no existing code to compute a contour, and that this geometry introduces a wake into the middle of the flow. Electron Discharge Machining (EDM) was the only direct-machining approach considered. EDM can give a very accurate contour, but cannot give a good surface finish. In addition, one still must deal with alignment problems at the throat. Broaching a nozzle, where a plug is made out of tool steel and then pressed hydraulically into aluminum to make the part, is extremely accurate, and lends itself to mass-production of nozzles. However, the nozzle must be split longitudinally and made in two halves to avoid alignment problems at the throat, and it is the most expensive method if only a single nozzle of any contour is going to be built.

The two most attractive methods are casting and plating. Both allow a male mold to be made with external machining only, a part formed around it, and then the mold eliminated. Casting has the advantage that it is very fast. Once a part is cast, it can be used almost immediately. Plating a nozzle, as described in detail in the next section, has the advantages that it has a better surface finish, since the inner surface of the nozzle is a molecular match for the outer surface of the part, and that it is cheaper, since the plating process simply requires residence time in the plating tank, with none of the complex equipment that casting requires. The primary drawback to plating is that it takes about four weeks to make a part.

It was decided to make a prototype nozzle using the plating method, both to confirm that a .250" thickness (the desired nozzle wall) was achievable using plating, and to test the computed contours for the desired flow properties. The prototype nozzle, a Mach = 2.0 Nitrogen nozzle was manufactured as follows: Using a CNC lathe, a nozzle mandrel was machined out of 2024 Aluminum so that the external surface matched the computed contour, and then hand polished to achieve a mirror finish. The mandrel was placed in a nickel plating tank and left for 2 weeks, the amount of time it took to build up the thickness to a .250" minimum. At the end of that time, it was removed from the tank and a flange machined on the external nickel surface to allow the nozzle to be mounted in the facility. The nozzle was then placed in a saturated NaOH solution to dissolve out the mandrel. This process took another two weeks. When it was finished, the nozzle was used in preliminary tests to confirm the flow properties, both by direct observation and by comparing the results with prior similar experiments.

3.1 Details of the Plating Process

The nozzles were constructed using an electroform nickel process, which deposits a pure nickel coating on an aluminum substrate. An equivalent process, using copper instead of nickel, was also considered. Nickel is extremely hard and resistant to corrosion, while pure copper is prone to corrosion and fairly soft. Both are difficult to machine; the nickel is difficult due to its extreme hardness, while the copper is so soft that it is gummy and doesn't cut well. Nickel offered a better solution to the present problem, but if heat transfer is important, copper would be a better choice.

The thickness of the nickel is limited only by the amount of time that the mandrel sits in the plating tank. However, as the thickness builds up the rate of plating decreases, and there quickly comes a point of diminishing returns. For the prototype nozzle, since it was not known how many flaws, voids, and dislocations there would be in the nickel, and because the stagnation pressure would exceed 1000 p.s.i. for some cases, a factor of safety of 50 was used in determining the required thickness. No flaws were evident in the prototype nozzle, and a thinner one could be built without danger. The inner surface is a match on a molecular level for the outer surface of the mandrel, so that if the mandrel has a mirror finish, the finished nozzle will as well. Any shape can be plated, with the caveat that sharp internal corners will not be smoothly plated and should be avoided.

In contrast to the inner surface, the outer surface is rough and uneven, since the plating rate varies with the local curvature. A means must be provided for holding the plated mandrel in a lathe so that any necessary machining can be performed on the nozzle. In the present case, an external fitting was manufactured that could be held in a lathe collet, was centered on the nozzle mandrel with a dowel pin, and had an offset screw to both secure it to the mandrel and to transmit the driving torque. Using this fitting, a flange was turned on the contraction end of the nozzle to mate it to the settling chamber, and a straight section was turned on the exit end, to allow the end-plate to be attached.

Once the external machining is done, the mandrel may be dissolved out. This is accomplished by placing the nozzle in a saturated solution of NaOH. It is important that a strong base be used, since that dissolves the aluminum via the following reaction :

$$2Al(s) + 2OH^{-}(aq) + 6H_2O(l) \rightarrow$$

$$2[Al(OH)_4]^{-}(aq) + 3H_2(g)$$

If a strong acid, instead of a strong base, is used, the corresponding reaction produces aluminum oxide solid, which is what gives anodized aluminum its hardness and corrosion resistance. If an acid is used to dissolve the aluminum, a surface coating of the oxide will quickly build up and stop any further reactions. The $Al(OH)_4^-$, on the other hand, dissolves, which leaves fresh aluminum on the surface to be attacked. The nickel is not attacked by the NaOH because the aluminum acts in a similar fashion to the zincs used on boats.

When this was tried on the prototype nozzle, the initial rate at which the aluminum was dissolving was extremely slow. The solution next to the aluminum was being depleted of hydroxyl, and the reaction was slowing. The solution was to drill a through hole on the mandrel, using a diameter smaller than the throat, and to place the nozzle vertically in the solution. The hole acted as a chimney, with the bouyancy of the hydrogen providing the motive power, and the rest of the dissolving went reasonably quickly. The aluminum dissolves at the rate of .050" per day, and in this case it took about 2 weeks to completely remove it.

During this process, a black substance was also being formed and deposited on the nickel. After some thought, it was realized that the substance was copper oxide, with the the copper coming from the alloy used in the mandrel (2024). Although the copper oxide was eliminated with a quick acid bath, it can be avoided altogether by using 5052, which is void of copper, or 6061, which has only a trace amount. 6061-T6 Alloy was used in the non-prototype nozzles, since 5052 is available only in billet form.

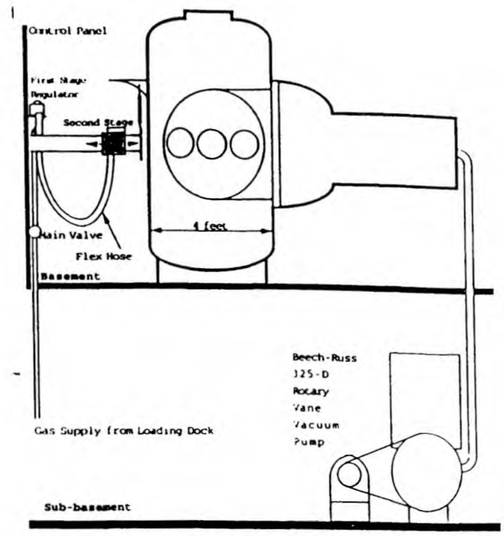


Figure 2: Supersonic Jet Facility Layout

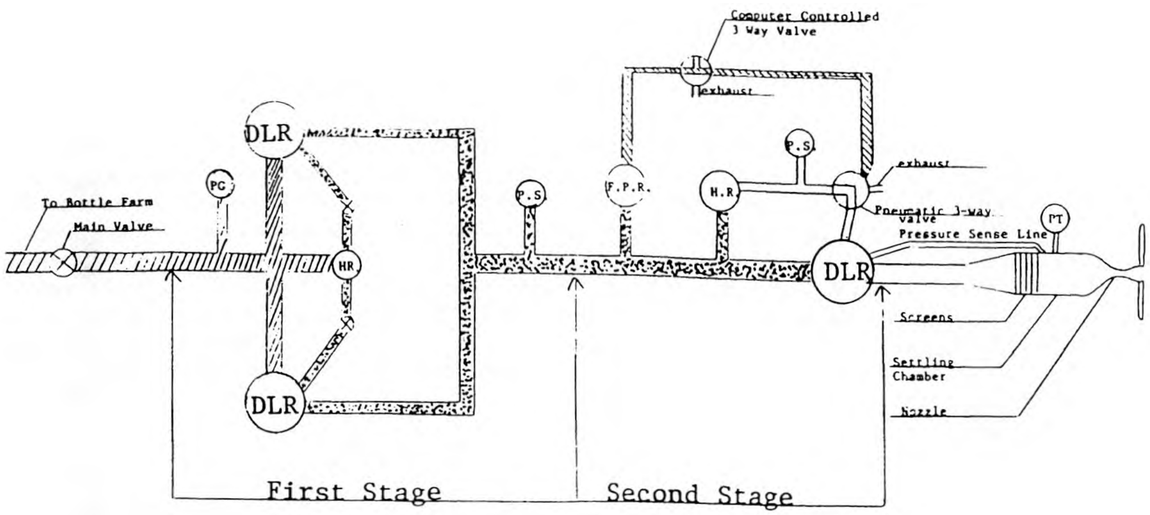
4 Facility Description

4.1 Tank and Gas Supply

The experiments were conducted in an arc jet facility that had lain dormant for many years. The hardware associated with the arc was removed, and equipment for a gas supply was installed. The facility is shown in Figures 2 and 3. The vacuum pump can be used to evacuate the chamber so that different gases can be used as the ambient fluid, and to allow the jet Reynolds number to be varied. It was not used in the present experiments, which were conducted in air at 1 atm. A schematic of the flow control is shown in Figure 4; the flow is turned on and off via computer.

4.2 Instrumentation

The instrumentation for the flow consists of a total pressure probe and a spark shadowgraph optical system. The probe is carried on a 3-axis traverse with a positioning accuracy of .0001", which is controlled by the same computer that turns the flow on and off. The data



Notes: [1] P.G. = Pressure Gauge
[2] P.S. = Pressure Sensor (only one can be read at a time)
[3] P.T. = Pressure Transducer (Kulite Gauge always read by the computer)
[4] D.L.R. = Dome Loaded Regulator
[5] H.R. = Hand Regulator
[6] F.P.R. = Fixed Pressure Regulator (P out = 200 psi)

Figure 4: Flow Regulation System

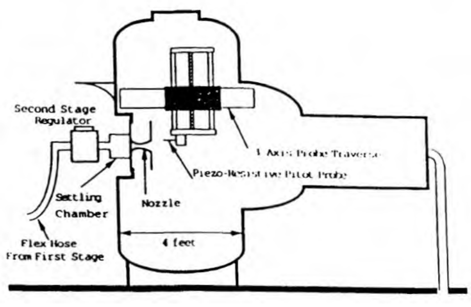


Figure 3: Facility Interior

is acquired on a second computer, triggered by the first, using an ISC-16 computerscope.

A typical run takes about 6 seconds, with data being collected during the central 4 seconds. The data collected on the prototype nozzle consisted of settling chamber, tank ambient, and total pressures, as well as an intermediate stage pressure from the gas supply.

Pressure probes were used because they are one of the simplest ways to obtain data in a flow, particularly one that is supersonic. In addition to mean flow data, it was decided to attempt to obtain some frequency data from the pressure probes, in order to enhance our understanding of the mixing and transition processes taking place; hot wires, the common method of obtaining frequency data, have not been very successful in supersonic flows at atmospheric pressure. The pressure sensors are of the piezo-resistive type, and were all manufactured by Kulite. Their frequency response is about 500 KHz. The total pressure sensor is installed as close as possible to the opening in a conically tipped probe. The cone angle of the tip is 10 degrees, in order to minimize flow interference, and the tip of the cone is changeable. Tips with hole diameters from .010" to .055" are available to allow a tradeoff between spatial resolution and frequency response. The data presented herein were taken with the .013" diameter opening, and, following the analysis of Bergh and Tijdeman [18], the frequency response for this tip is estimated to be 1KHz. The data was taken at 2 KHz, with a 2nd order anti-aliasing filter used at 1KHz. The spark shadowgraph system consists of a Nanolamp, capable of producing either a 10 or 20 ns 150mj pulse, mirrors, and a 4x5 film holder. One of the advantages of exhausting into quiescent fluid is that there are no boundary layers on the windows, so that picture quality can be very high. The 150 mj output of the Nanolamp was found to be adequate for single exposure photographs using 800-1600 ASA T-Max Film.

As the distance between the jet and the image plane is increased, the sensitivity increases, but the spatial resolution decreases. The distance from the jet to the film plane for the best compromise between spatial resolution and contrast required that the film be placed inside the tank. A pneumatically operated system was designed and installed which allows for 6 pictures to be taken before the tank needs to be opened to change film.

A typical run consisted of turning on the amplifiers and probe power about 12 hours prior to the test, to allow everything to reach an equilibrium temperature. The gas inlet line was opened and the two stage pressure regulation system set with the desired pressures, typically 500 psi out of the first stage and 130 psi out of the second. (An approx 15 psi difference exists between the pressure set in the dome and the outlet pressure, due to the helper spring on the regulator poppet valve) The probe was moved to a position 1/2" away from the position where data would start being collected. The data acquisition computer was set up, and the system then waited for an operator trigger. When triggered, the first computer turned on the gas and accelerated the probe, since it takes 1 sec to establish the flow and achieve the desired probe speed. After that time, it triggered the data acquisition system. After the data was collected, which typically took 4 sec and 2" of probe movement, the first computer triggered the spark lamp, shut the gas off, stopped the probe, and moved it to the next traversing point.

5 Results

This section describes the results obtained from tests on the prototype nozzle during the past year. They were gathered primarily for the purpose of proving the nozzle design and construction methodology. More complete data and results will be gathered with the other nozzles and presented in the future.

A single spark shadowgraph of the flow from the nozzle is shown in Figure 5, and a 50 spark average over 1 sec is shown in Figure 6. Both show that the flow is parallel at the exit, with minimal compression waves originating from the exit where the shear layer starts to grow. Acoustic waves can be seen in the outer flow in Figure 5, and have a cut-off angle as predicted by Tam [19].

A very weak wave can be seen emanating from within the nozzle at the top of each photograph. This is due to a nick less than .001" deep accidentally put into the nozzle during the polishing process. Although it does not appear to affect the flow, it underscores the care needed to design a truly shock-free nozzle. Other than that wave, however, there are none of the extraneous waves that other experimenters have had to contend with.

Raw data from a typical traverse at 4 diameters, in the middle of the potential core, are shown in Figure 7. The uniformity of the flow in the potential core and symmetry of the jet are evident. The advantages inherent in a two-stage regulation system are also visible. Even though the output of the first stage fluctuated slightly, since the gas was running out, the stagnation pressure remains constant within the resolution of the probe, once it reaches steady state.

Mach 2.00 Nitrogen into Quiescent Air

Pstatic =1 Atm., Red = 1.4 Million

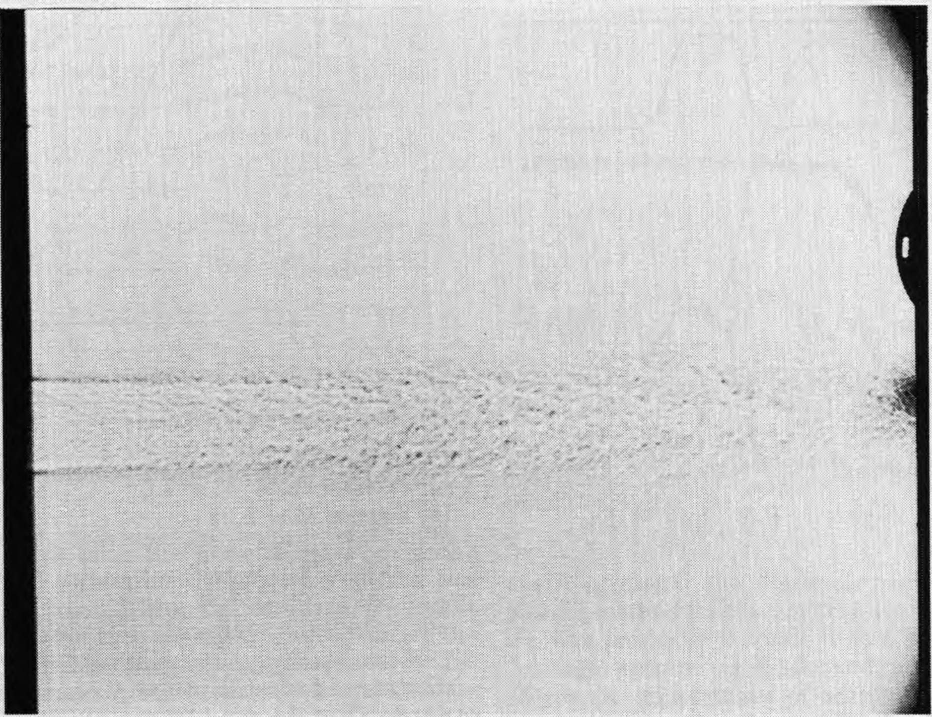


Figure 5: **20 ns Single Spark**

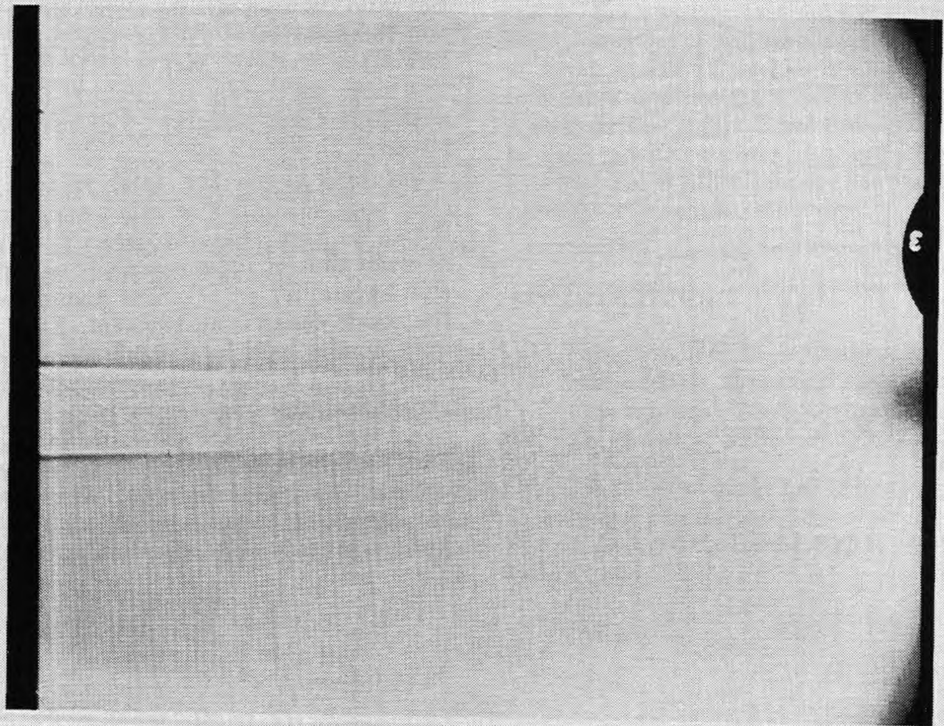


Figure 6: **50 Spark Average Exposure**

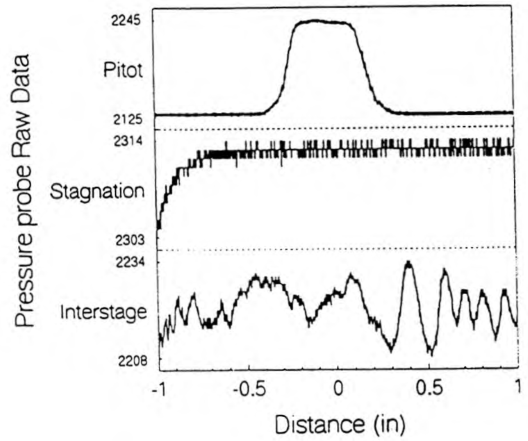
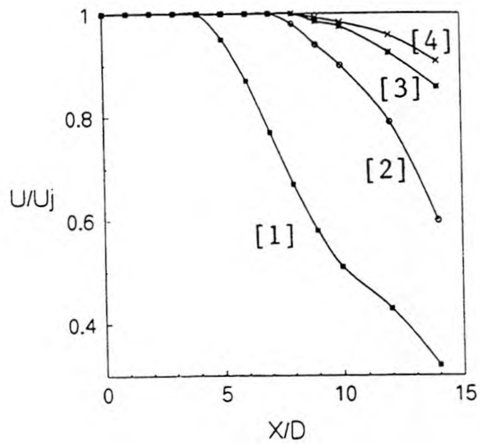


Figure 7: Raw Data: 4 dia



[1] Johannesen Jet 1; M = 1.4
[2] Johannesen Jet 6; M = 1.4
[3] Present Work; M = 2.0
[4] Eggers; M = 2.22

Figure 9: Centerline Velocity Decay

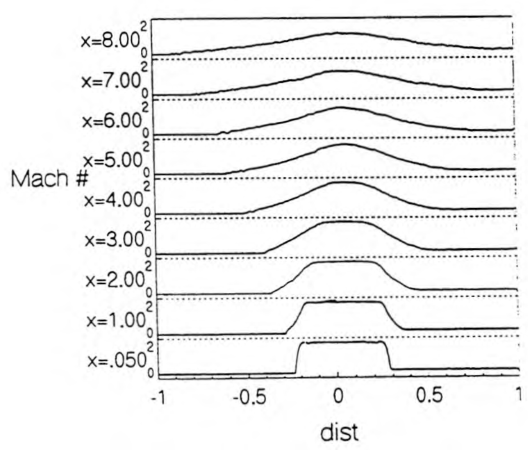


Figure 8: Mach Number Profiles: 0-16 dia

Mean Mach number profiles from 0 to 16 diameters downstream are presented in Figure 8. They clearly show the symmetry of the jet, the decay of the potential core, and the development of the far-field profile. Based on the ratio between the measured exit pressure and the pressure in the settling chamber, the exit Mach number (Me) is 2.01. The transition from supersonic to subsonic flow on the centerline takes place at 23 diameters downstream.

Figure 9 shows the axial velocity decay, compared with that of other experimenters. It can be seen that the velocity decay falls between that of Johannesen's M = 1.4 jet [2] and Eggers' 2.2 jet [7]. The marked effect of the nozzle design is also evident. Even though both nozzles used by Johannesen were nominally M = 1.4, their decay characteristics are very different.

Pseudo-rms profiles are shown in Figure 10. They were obtained by averaging the raw data, using a Gaussian weighting, over 100 neighboring points, which is roughly equivalent to

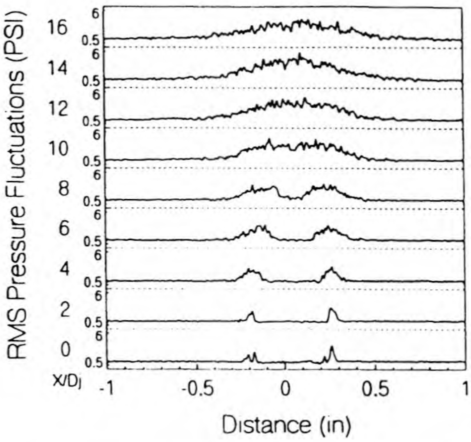


Figure 10: 'RMS' Profiles: 0-16 dia

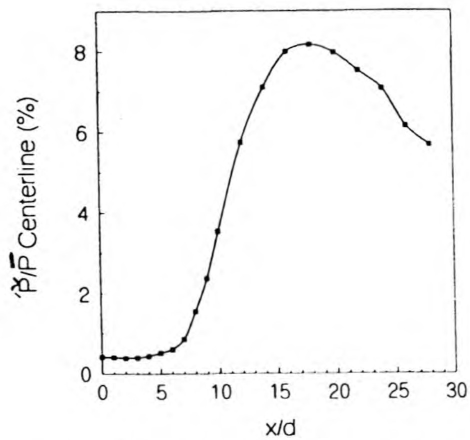


Figure 11: Centerline RMS Pressure Fluctuations: 0-28 dia

the time it takes the probe to move one probe opening diameter. This averaged data was then subtracted from the raw data, the result rectified and then averaged again to obtain the result. It also shows the development of the shear layers until they merge at about 8 diameters downstream, and the gradual change to the fully developed profile.

Runs without the probe moving were used to generate figure 11, which shows the centerline rms pressure fluctuations, normalized by the mean local total pressure, as a function of downstream distance. The results are visually similar to the velocity fluctuation obtained by previous experimenters [9, 20], although the values are, of course, different. The pressure fluctuations are very small until the end of the potential core, and then they increase rapidly. After a peak which occurs at about 2 potential core lengths, the level decays.

6 Conclusion

The prototype nozzle described above was developed to prove the feasibility of producing a large number of high quality, inexpensive nozzles in order to conduct an experimental, parametric study of supersonic jet mixing. Careful design of both the supersonic and subsonic nozzle contours, and the implementation of a plating method for the construction of the nozzle, has produced a nozzle with a flow that is free from extraneous shocks and pressure variations. A complete set of nozzles for a parametric study of the effects of Mach number and density ratio on the mixing of an axially symmetric supersonic free jet has been manufactured. Each nozzle cost approximately $300, nearly an order of magnitude less than the cost of direct machining, while maintaining closer tolerances and having a better surface finish. Although this method has only been applied to axisymmetric nozzles, it could also be used for elliptical or other shapes that would be impossible to machine internally.

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