Flip-Flop Jet Nozzle

Hermann Viets*
Wright State University, Dayton, Ohio

A nozzle development program was undertaken to produce a time-dependent flow at the nozzle exit. The oscillatory character of the flow was achieved without the use of moving parts by incorporating a fluidic feedback loop into the nozzle design. The nozzle thrust efficiencies approached 90% and the half-width spreading rates attained exceeded that of the slot nozzle by a factor of more than three.

Introduction

RECENT experiments and analyses related to thrust augmenting ejectors[1,2] have pointed out the importance of the mixing rate between the primary (jet) and secondary (entrained) flows. The thrust augmentation of the ejector device has been shown to be directly proportional to the degree of mixing attained at the ejector exit. Thus the primary jet nozzles used for ejector application must have the ability to mix very rapidly without accepting a large penalty in nozzle efficiency.

In addition to ejector mechanics, the rapid mixing of primary and secondary flows finds many diverse applications. These include such seemingly unrelated subjects as the fuel injectors in ramjets and the production of foam for sophisticated fire fighting equipment.

For ejector application, a very effective method of primary air injection is achieved by the hypermixing[1-5] nozzles produced at the Aerospace Research Laboratories. These nozzles incline the exiting flow at an angle to the entrained flow. The angle is alternately positive and negative in sections across the span of the nozzle. The hypermixing nozzles have been shown to increase significantly the mixing rate between the primary and secondary streams.

Other investigations have pursued a different phenomenon to achieve more rapid mixing of a primary jet with its surroundings. This is the deliberate introduction of an unsteady component to the jet flow. Crow and Champagne[6] mounted a loudspeaker upstream of the nozzle exit and in this way caused a time-dependent variation in the exit velocity of the jet. Although their interest was mainly in the acoustic character of the flow, they found that at certain forcing frequencies the centerline decay of the jet was substantially enhanced.

The introduction of an unsteady velocity component designed explicitly to increase the rate has been studied by several experimenters. Binder and Faire-Marinet[7] employed a spinning butterfly valve, driven by a variable-speed motor and mounted upstream of the nozzle, to produce the velocity pulsations at the nozzle exit. The unsteady component causes an increase in the jet spreading rate. Thus the experiment is certainly a success in the sense of increasing the mixing rate, but the method of producing the velocity fluctuations leaves room for improvement. The spinning butterfly valve is likely to produce large energy losses and is therefore unlikely to be applied to a system where these losses are of great importance.

In an experiment designed to improve the performance of the boundary-layer control slots, Williams, Ambrosiani, and Palmer[8] investigated the effect of an unsteady flow component on boundary-layer attachment. As in the case of the freejet experiment discussed above, the conclusion was reached that the fluctuating nozzle flow did, in fact, lead to increased mixing and entrainment. In this case, the mass flow could be reduced by more than half without affecting performance, merely by pulsing the jet rather than maintaining a steady flow. However, the fluctuating velocity was produced by a sliding valve plate, which is opened and closed by an eccentric cam, which is in turn driven by a variable-speed electric motor. Thus, even if the losses are not greatly increased, the additional complexity of the valving must be taken into consideration.

Further basic work in unsteady jet flows was performed by Curtet and Girad[9] in their flow visualization study of an unsteady jet. The fluctuations are produced by the use of an oscillating piston, and therefore the mechanism is not likely to be of direct applicability to an engineering system. However, the photographs are excellent and clearly show the character of the flow.

Thus, at the outset of the present investigation two facts were relatively clear:

1) Inclining the nozzle exit flow at a moderate angle to the streamwise direction can cause a substantial increase in the jet mixing rate, especially if the angle is alternately positive and negative.

2) Introducing an unsteady component into the jet flow can likewise cause an increase in the mixing rate. However, the unsteadiness must be produced without a large efficiency loss or a great increase in complexity. In addition, the method should be self contained and not require an external driver.

In view of these points, a new nozzle which incorporates some of the advantages of the hypermxing nozzles as well as the advantages of an unsteady primary flow was produced at the Aerospace Research Laboratories. In addition, the driving mechanism is self-contained, requires no moving parts, and has a moderate cost in terms of nozzle thrust efficiency.

Concept and Preliminary Experiments

In principle, the unsteady nozzle development described here is based on the simple fluid amplifier in general and the fluidic oscillator in particular. The operation of the fluid amplifier is dependent upon the fact that a jet exiting into a space between two sufficiently near walls is bistable (i.e., may attach to either wall). In addition, a rather small pressure gradient across the jet at its exit may cause the jet to detach from one wall and attach to the opposite one.[10] A simple bistable fluidic element, showing the effect of the more important parameters, has been examined by Warren.[11]

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*Associate Professor. Associate Fellow AIAA.

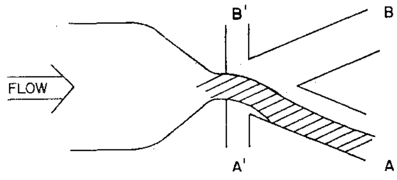

Fig. 1 Schematic of a simple fluidic element.

A fluidic amplifier with the two control ports connected to each other was investigated by Spyropoulos.[12] In this way, it was possible to cause the jet to oscillate from one channel to the other. The basic principle of operation is as follows. Consider the jet to be attached to wall A in Fig. 1. Then, due to the large amount of entrainment into the jet, the pressure at the control port A' is relatively low while the pressure at the control port B′ is relatively high. Since the ports are attached to each other, a compression wave travels from port B′ to port A′, tending to raise the pressure there and push the jet off the wall. Simultaneously, an expansion wave originates at port A′ and travels to port B′, tending to lower the pressure there and pull the jet onto wall B. Thus, if the element is well designed, the jet will separate from wall A and attach to wall B, at which time the process begins anew.

At this point the question arises: Can this oscillation phenomenon be applied at the exit of a primary nozzle? If so, it offers a combination of the hypermixing nozzle concept of inclining the flow to the streamwise direction and the concept of an unsteady flow component introduced to accelerate the mixing process.

Three basic necessary changes from the device tested by Spyropoulos[12] present themselves immediately: 1) To avoid large losses, the proposed nozzle exit must be far shorter than the conventional fluidic elements. 2) The splitter plate (Fig. 1) must be removed entirely. This is due to the fact that the splitter plate is exposed to the high-velocity stream at the nozzle exit and would cause substantial losses. 3) The nozzle exterior must be aerodynamically smooth to avoid large losses when exposed to the entrained flow.

To test the oscillation potential of a short element without a splitter, a variable geometry nozzle was constructed of Plexiglas, and a wide range of geometrical changes could be combined. These included the variation of the power jet exit size, the size of the control ports, the angle of the diffuser, the length of the device, and the location of the splitter, if any.

The observations made during the initial experimental runs were simply to see if the oscillation occurred and, if so, the sensitivity of that oscillation to other perturbations such as pressure variations or blockage at the exit. The basic result of the experiments was clearly that the nozzle could be made to oscillate in spite of its short length and the absence of the splitter. Further, more detailed tests utilizing new nozzles were then pursued and are described in the following sections.

A concurrent research program is being pursued by Platzer,[13] utilizing an alternate fluidic feedback method. In that case, a percentage of the jet flow is actually scooped off at the nozzle exit and directed back on the jet to cause the oscillation. A discussion of this type of fluidic oscillator is also found in Ref. 10.

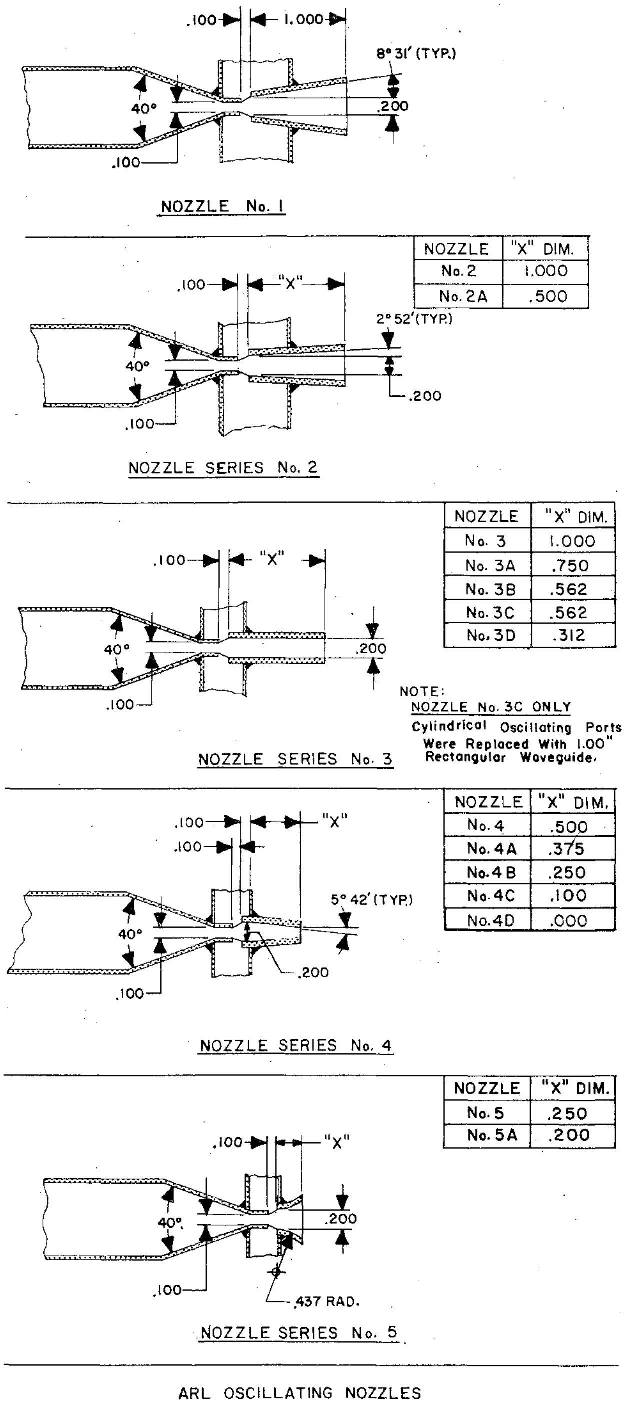

Fig. 2 Details of small-scale test nozzles.

Small-Scale Nozzle Tests

Based upon the insight gained from the tests of the adjustable Plexiglas nozzle model, a series of brass nozzles was constructed. The objective of this portion of the program was to do a limited parametric study of the effect of the geometry on the nozzle thrust efficiency as well as the basic ability of the nozzle to oscillate. The designs for the nozzles employed in this portion of the investigation are shown in Fig. 2. For each of the nozzles the depth is 1 in., yielding an aspect ratio at the throat of 10. The aspect ratio at the nozzle throat was found to be a parameter critical to the operation of the nozzle. If the aspect ratio is too low, the end wall effects dominate the flow in the nozzle, and the oscillation is destroyed. In the case of a very large aspect ratio, various parts of the oscillating flow are out of phase with each other. This results in a cancellation of the compression waves from one part of the nozzle by the expansion waves from another part. In this way, no coherent wave pattern is set up in the connecting tube between the two control ports, and the oscillation is destroyed.

Thrust Efficiency

As in any physical process, a price must be paid in terms of efficiency in order to cause the jet to oscillate from side to side. A nozzle thrust efficiency is defined as the measured thrust divided by the isentropic thrust of the mass flow through the nozzle. Thus $\eta = T/\dot{m}V_i$ where η is the nozzle

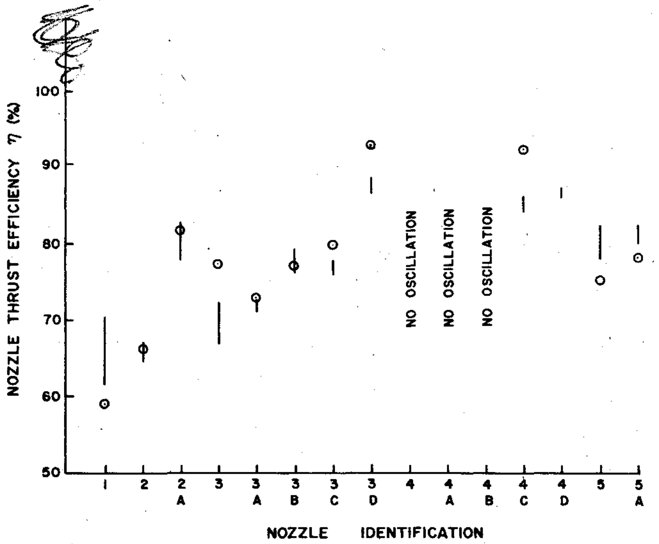

Fig. 3 Nozzle thrust efficiencies for small-scale nozzle tests.

thrust efficiency, T is the measured thrust, $\dot{m}$ is the rate of mass flow, and V_i is the isentopic velocity which would be obtained at the nozzle exit if the flow were expanded from the stagnation plenum pressure to the ambient pressure with no losses.

The details of the thrust efficiency measurements as well as further background to the present paper, may be found in Ref. 14.

The measured thrust efficiencies of the nozzle configurations depicted in Fig. 2 are shown in Fig. 3. The nozzle identification refers to the nozzle series as well as the particular x dimension, as noted in Fig. 2. The encircled data points are those taken at a plenum stagnation pressure of 1 psig, the lowest plenum reading taken. Since the pressure is relatively low, the errors involved are relatively high, and these points should be considered suspect. The remaining data are taken in the pressure range between 2 and 15 psig. It may be seen from the figure that the most efficient nozzle tested is 3D, followed closely by nozzle 4D. Both of these nozzles have parallel wall diffusers. That is, the diffusion process if very abrupt (as in all the nozzle designs) and is then followed by a parallel wall section.

Contraction sections on the nozzle apparently destroy the oscillation, as indicated by nozzle series 4. No oscillation occurs while a substantial contraction section exists on the nozzle. However, when the nozzle is cut back toward the 0.10-in. parallel wall segment so that the contraction is essentially gone, the jet not only oscillates but also operates relatively efficiently. When the nozzle is cut back even farther, the efficiency increases slightly. With respect to the contraction, a probable explanation is that to maintain a sufficient pressure difference across the jet and thereby control the flows, the static pressure in the control ports must be less than the ambient value. With the presence of the contraction section at the nozzle exit, keeping the pressure below ambient is not possible, and the oscillations do not occur.

In terms of nozzle thrust efficiency, the effect of decreasing the total nozzle length is to *increase* the efficiency. This may be seen in series two and three and, to a lesser extent, series four and five. In series three, in particular, the increase in efficiency with decreasing nozzle length is rather dramatic.

Nozzle thrust efficiency is not the complete answer, since nozzles with high thrust efficiencies generally possess relatively poor mixing qualities. Thus, there must be a tradeoff between the two basic parameters, nozzle thrust efficiency and the mixing rate, which will be discussed below.

Mixing Rate

The method chosen here to indicate the mixing rate between the jet and the outside fluid (whether that fluid be in motion or not) is the streamwise increase in the half-width dimension. The definition of the half-width at any streamwise position is the distance between the jet centerline and that point on the velocity profile where the local velocity is equal to the mean between the centerline value and the coflowing stream value. In the present set of experiments, there is no coflowing stream; so the half width defines the point where the velocity is half the jet centerline velocity at that streamwise position. In addition, the velocities referred to here are the time average velocities, obtained by employing a constant-temperature hotwire anenometer. The primary jet was mounted between two parallel plates to prevent entrainment at the sides of the nozzle and thereby attempt to preserve a degree of two dimensionality.

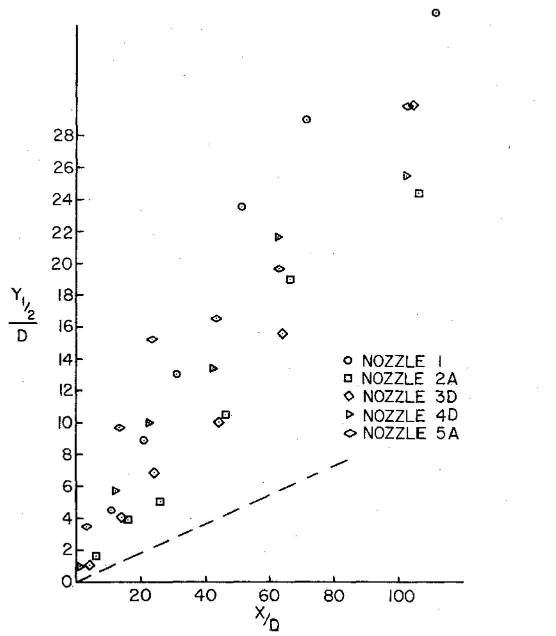

Fig. 4 Half width growths for small-scale test nozzles. Dashed line represents growth of slot nozzle.

The half-width dimension defined above is presented in Fig. 4 as a function of the distance downstream. Both the half-width and the streamwise coordinate are nondimensionalized with respect to the nozzle throat. The various nozzles tested are the last members of each nozzle series, and therefore each is the most efficient nozzle in its series, as shown in Fig. 3. The dashed line in Fig. 4 indicates the half-width growth of a two-dimensional slot nozzle. Compared with the slot nozzle, the oscillating nozzle exhibits a dramatic increase in the rate of half-width growth.

By comparison of the half-width growth data (Fig. 4) with the thrust efficiency (Fig. 3), some general observations can be made. As might be expected, the spreading rate decreases as the nozzle thrust efficiency rises. This is most clearly illustrated by a comparison of nozzle 1 with nozzle 2A. The two nozzles are of similar geometry, differing only in diffusion angle and length. In terms of nozzle thrust efficiency, nozzle 2A is clearly superior, while in terms of jet mixing, nozzle 1 is the better. Thus, the penalty in thrust efficiency must be accepted in order to accelerate the mixing of the jet. It may be pointed out that the result shown in Fig. 4 is conservative, since the streamwise distance x is measured from the nozzle throat and not the exit.

Flow Variation With Time

The time-dependent character of the flow may be seen in oscilloscope traces taken near the exit of nozzle 3D and shown in Fig. 5. The magnitude of the velocity is plotted as a function of time at the nozzle centerline (b) and at the two half-width positions (a, c). The flow at the half-width position may be seen to have almost a square wave shape; so the jet is either

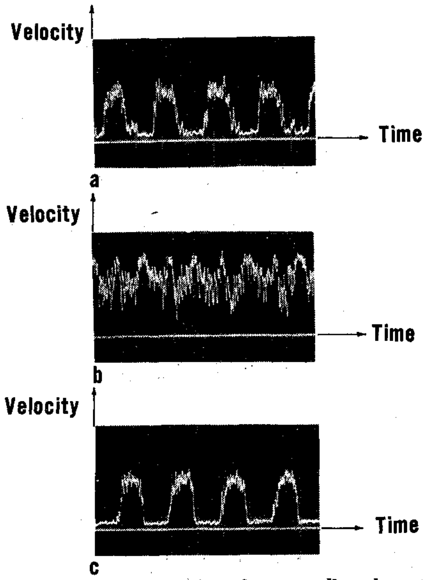

Fig. 5 Time dependent velocities from small-scale test nozzles.

"on" or "off" at any particular time. It is interesting to note, however, that even in the "off" configuration the velocity at the half-width position is not zero. This indicates that the oscillating jet has set up a steady motion in the entrained flow in addition to the time-dependent fluctuations. Thus, the jet cannot be treated as quasi-steady. That is, the entrainment pattern is not instantaneously the same as a steady jet in the same orientation. This induced steady motion is what leads to the increased entrainment and mixing rates which distinguish the unsteady jet.

Large-Scale Nozzle Tests

Single Element Nozzle

A scaled-up version of nozzle 3D was constructed with a throat dimension of 0.3 in., width = 4 in., and a separation of the parallel wall section of 0.55 in. The nozzle proved that the fluidically controlled nozzle could be scaled to match previous ejector tests and that the feedback loop could be incorporated into the nozzle design to present an aerodynamically smooth exterior.[14] Further results with this nozzle will be indicated.

Schlieren Photographs

To indicate visually the enhanced spreading rate of the oscillating jet and also to show that the jet is indeed flapping from side to side rather than existing as a smeared jet across the entire exit plane, a Schlieren experiment was set up with the large-scale single element nozzle as the prime example.

To increase the contrast in the Schlieren photographs, helium was added to the jet flow. The results may be seen in Fig. 6, where the jet exit is shown on the left and the flow is from left to right. The extreme positions of the jet oscillation may clearly be seen, and concur with the results shown by the oscilloscope traces in Fig. 5 because, even in the extreme positions, there is still flow at the center of the nozzle. Therefore, at the half-width position the flow has an on-off character while at the jet centerline the velocity fluctuates but the jet is always present.

Effect of Stagnation Pressure on Frequency

The large-scale single-element nozzle was run at various stagnation pressures. The results are shown in Fig. 7, and indicate that the frequency increases with stagnation pressure. The reason for this increase is probably the fact that, as the stagnation pressure increases, the velocity within the nozzle increases. This results in a more rapid production of the pressure waves in the feedback loop and hence in an increased frequency.

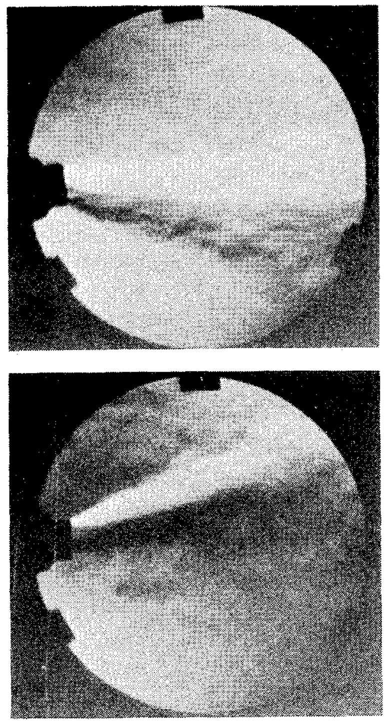

Fig. 6 Schlieren photographs of oscillating jet flowfield.

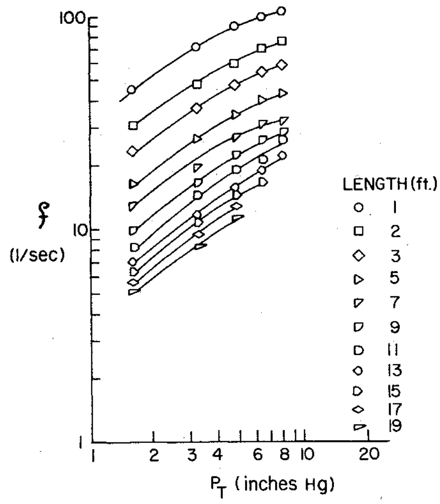

Fig. 7 Effect of stagnation pressure on oscillation frequency.

Effect of Feedback Length on Frequency

At first glance it is evident that the oscillation frequency must be inversely proportional to the length of the feedback loop from one control port to the other. This is due to the fact that the pressure waves which pass through these tubes move at the speed of sound. Thus, if the actual time required for the pressure waves to cause the jet to flip is ignored, the frequency is simply inversely proportional to the time required for the waves to pass through the tube or, equivalently, the length of the tube. For such a situation, the data will fall on the -1 slope line indicated in Fig. 8, where the frequency is plotted as a function of feedback tube length.

The experimental results shown in the figure confirm the expectation that for long tube lengths the frequency does, indeed, vary inversely with feedback length. Thus, in this regime, the switching time required for the jet actually to flip from one wall to another is negligible in comparison with the time required for the waves to pass through the feedback tube.

For shorter lengths (and correspondingly higher frequencies), the data diverge from the -1 slope. In particular, the frequency is not as high as would be predicted by extension of the inverse proportionality. This is due to the fact that, as the

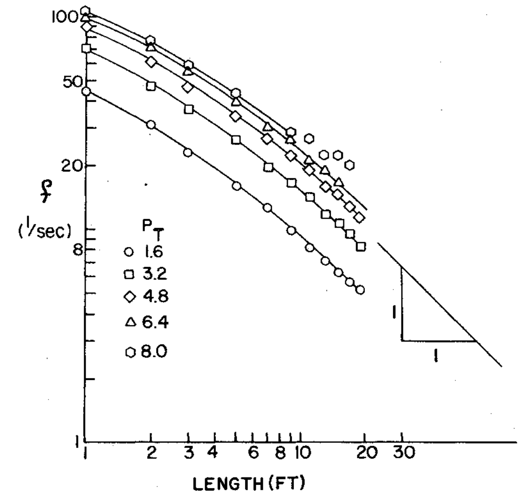

Fig. 8 Effect of feedback length on oscillation frequency.

tube lengths become shorter, the time required for the actual flipping of the jet from one wall to the other becomes a significant fraction of time required for the waves to travel through the feedback tube. The switching character of the jet is similar to that exhibited in the oscillating fluidic amplifier case, which has been discussed in more detail by Spyropoulos.[12]

Multicomponent Large-Scale Nozzle

A nine-element nozzle, each of whose elements has approximately the same geometry as the single-element nozzle has been constructed and successfully operated. The performance of this nozzle is currently being investigated, both as a freejet and as the primary nozzle in a low area ratio ejector test. The feedback tubes pass around the back of the nozzle to the corresponding control port on the other side. Thus, each nozzle element oscillates independently and has no specific phase relationship with the nozzles on either side of it.

The possibility of interconnecting the various elements of the nozzle in order to achieve some desired phase relationships between neighboring nozzles was explored briefly. However, in spite of the various configurations attempted, oscillation of the flow was not achieved.

Conclusions

The data previously presented indicate that the oscillating jet nozzle is a viable alternative to the successful hypermixing designs to shorten further and improve the performance of thrust augmenting ejector devices. In addition, the oscillating nozzles may be of use as fuel injectors on ramjet configurations and numerous other devices of practical significance. Further effort is required to demonstrate the actual performance of oscillating nozzles under applied conditions.

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