ARTICLE NO. 79-0634R

J80-116

20007

Effect of Density on Noise Radiation from Subsonic Inverted Velocity Profile Jets

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In this study, experiments were performed to investigate the influence of jet density in the generation of noise from inverted velocity profile subsonic jets. Such jets consist of low-speed gas flow in the center and a higher-speed annular flow. A combination of helium, nitrogen, and argon gases at various flow velocities were expanded through center and through annular convergent nozzles to obtain the desired density effects. Shadowgraphs of the jet flow were obtained, and mean velocity profiles and radiated noise were measured. The results clearly show that a difference in density between the inner and outer flows is an important factor in the development of the jet flow and in the production of jet noise.

Nomenclature

A = area
d = center nozzle exit diameter
D = annular nozzle exit diameter
r = transverse coordinate
V = mean velocity in X direction
V_j = mean annular flow nozzle exit velocity
V_0 = mean center flow nozzle exit velocity
X = streamwise coordinate
ρ_0 = density of center flow
θ_I = angle to the intake (see insert in Fig. 2)

Introduction

THERE have been numerous investigations in the past to determine the influence of gas temperature on the production of jet noise.[1-4] The present study was motivated by the fact that large differences in gas temperatures and consequently in density exist in the noise-producing mixing layers of present day jet-engine exhaust streams. Changes in the temperature of a jet relative to the surrounding fluid[5] have been shown to modify the quadrupole sources. Also, additional noise sources have been identified related to noise from hot jets, for example, the presence of entropy fluctuations which are caused by the temperature fluctuations.[6] Then, other sources of noise from heated jets have been identified,[7] such as those that result from the presence of velocity fluctuations in a mean transverse density gradient of dipole and monopole origin. A consequence of the presence of all these noise sources caused by changes in the temperature is that noise radiated from hot jets has not yet been satisfactorily explained. Thus, there is still a controversy on the dependence of temperature on noise. For example, in Refs. 1 and 4 the radiated noise has been shown to be influenced by the jet temperature; whereas, in Ref. 3 it is reported that there is no dependence on temperature. As an attempt to resolve this controversy of noise from heated jets, the effect of density alone on modification of noise sources was undertaken. The density difference of the noise producing hot jets was simulated by gases of different molecular weights.

However, the influence of the density of the jet on radiated noise has been studied for a limited range of nozzle flow conditions.[8] The results clearly indicated that the pressure of the radiated noise signal varied directly with the jet density. No detailed measurement of the jet flow was made. This study also does not report how the density affects the directivity pattern of the radiated jet noise.

It is known that large changes of density ratio that occur across the noise-producing mixing layer of a jet engine can significantly modify the mixing and the growth of the jet.[9] This modification in the turbulent mixing region is accompanied by a significant change in the entrainment of a different density fluid.[10] Very little is known of the changes in jet development which occur due to density differences between the two streams and the relationship to the production of jet noise. This paper addresses itself to this important consideration.

In the variable stream control engines (VSCE), which employ inverted velocity profiles,[11,12] there is some control over the jet stream temperature, and, therefore, the density of the streams.[13] As a consequence of the promising potential of the inverted profile jet proposed for use in an advanced supersonic transport,[13] it was decided to simulate such a jet to investigate the influence of density ratio in the production of jet noise. It is anticipated that the present findings will be of fundamental importance in determining the role of jet density in the production of noise from hot jets. These results will also assist in optimizing the shape of the inverted velocity profile for maximum noise reduction.

Experimental Apparatus and Instrumentation

The experimental setup employed to investigate the effect of density on jet noise consisted basically of a coaxial nozzle arrangement shown in Fig. 1. The exit diameters of the center and the annular nozzles were $d=1.27$ cm and $D=2.03$ cm, respectively. Hence, the area ratio $A_{annular}/A_{center}$ was 1.56. Argon, helium, and nitrogen gases were passed through the two nozzles, both separately and simultaneously. Combinations of the flow of these gases through the center and the annular nozzles provided the desired density effects on mixing that simulated the combination of hot and cold jets which emerge from coannular nozzle jet engines. In carrying out these experiments, a particular gas at a fixed annular-flow velocity V_j was established while the low-speed center-flow velocity V_0 was varied. The exit velocity V_0 was computed from the mass flow rate passed through the center nozzle.

Presented as Paper 79-0634 at the AIAA 5th Aeroacoustics Conference, Seattle, Wash., March 12-14, 1979; submitted April 12, 1979; revision received Nov. 6, 1979.

Index category: Jets, Wakes, and Viscid-Inviscid Flow Interactions.

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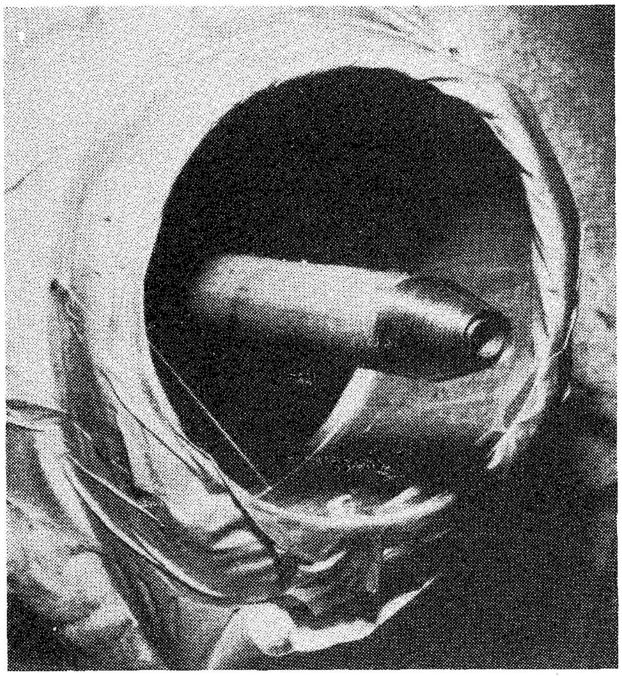

Fig. 1 Coaxial nozzle test apparatus.

This flow rate was measured by use of carefully calibrated rotameters. The mean velocity profile at various downstream locations was evaluated experimentally across the entire radius of the jet from measurements obtained by traversing a pitot tube across the jet.

This experimental setup was located in an anechoic chamber where the far-field noise measurements were made. The radiated noise was measured by using microphones which had a diameter of 1.27 cm. The microphone data were recorded on a tape recorder and played back through an all-digital spectrum analyzer to obtain the spectrum of the jet-noise signal. A narrow 100-Hz bandwidth was used for the spectrum analysis of the pressure signal. Instant spark shadowgraphs of the jet flow were taken using an electronic stroboscope with a flash duration of less than 0.3 μs. The density gradients needed for taking spark shadowgraphs were provided automatically flowing different gases through the center nozzle with nitrogen gas flowing through the annulus.

Results of Jet Noise Measurements

In the present investigation it was observed that the annular jet without any flow through the center nozzle was as noisy as an equivalent area circular jet with the same exit velocity. These findings were consistent with those of Williams et al.[14] They also reported, however, that when the central space of the annular jet was ventilated to the atmosphere, a 2 to 3 dB noise reduction was observed in comparison to an equivalent velocity circular jet. These findings, as discussed below, were observed in the present study as well.

Typical results indicating the influence of center flow on the noise emitted by a fixed subsonic annular flow of angles with respect to the intake of $\theta_I = 60$, 90, and 140 deg are shown in Fig. 2. The radiated noise at various angles was normalized to an arc of radius 100D. Throughout these tests the annular flow nitrogen gas was kept constant so that V_J was always 295 m/s. The influence of flowing argon, helium, and nitrogen gases through the center nozzle was studied over a range of center velocities V_0, from 0 to 300 m/s. As pointed out previously, there was a sharp decrease in the radiated noise at all angles as a small quantity of flow was introduced through the center nozzle and gradually increased. A reduction in noise of as much as 6 dB was obtained. This occurred at center velocities between about 50 and 100 m/s. At larger

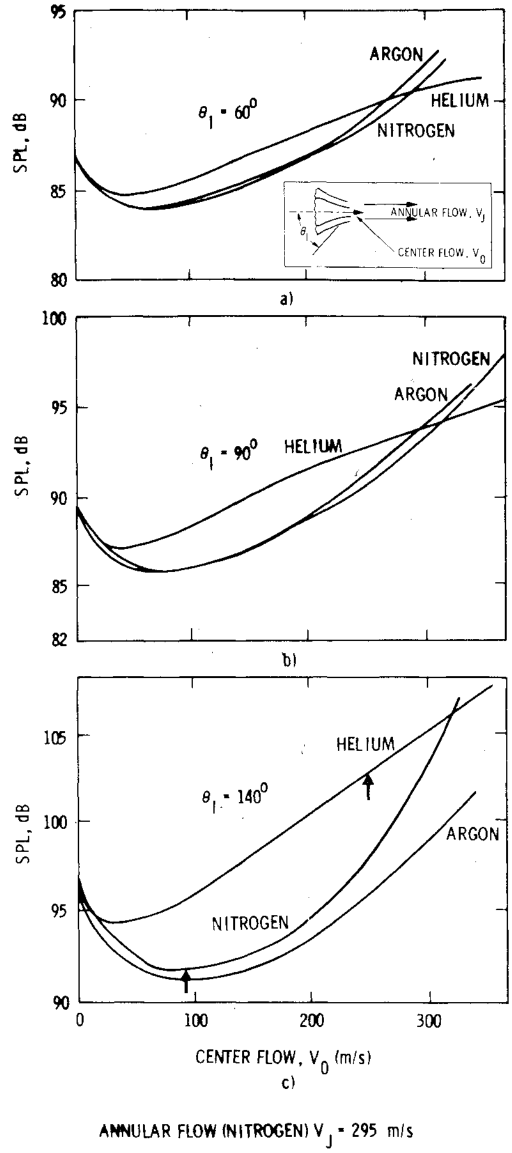

Fig. 2 Influence of density of the center flow on noise radiated from an inverted profile jet with nitrogen gas in the annulus.

center velocities the noise reduction became less. This resulted primarily because a high-velocity center flow, $V_0 > 120$ m/s, contributed directly to the overall noise generated by the coaxial nozzle flow system. It is also quite evident from the results shown in Fig. 2 that the density of the center flow greatly influences the radiated noise and also its directivity.

Results of jet noise measurements in Fig. 2 at a given center velocity V_0 further indicate that for a gas of higher density (e.g., nitrogen) in the center results in less noise production than when a lighter gas discharges from the center nozzle. It is important to note that such a comparison at a given value of V_0 is not a comparison at a given thrust. The comparison that can be made here is based on an arbitrary choice of a reference flow condition taken to be at the minimum noise condition with nitrogen flow in the center. This reference condition together with the equivalent thrust for helium flow in the center have been marked by arrows in Fig. 2. For nitrogen gas flowing in the center, the velocity V_0 is 91 m/s. To achieve the same thrust with helium gas through the center nozzle the value of V_0 is 242 m/s. As indicated in Fig. 2, an excess noise of the order of 10.5 dB would be generated with the helium gas. This is at an angle of $\theta_I = 140$ deg. Similar calculations were performed for the results presented in Fig. 4 which are discussed later in this section, with $V_0 = 60$ m/s as the reference condition. In this case a center velocity of

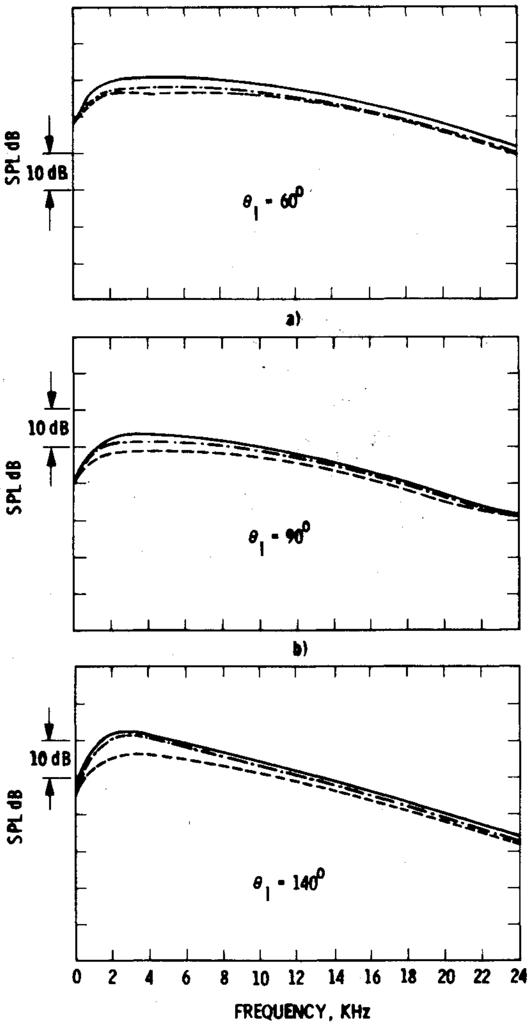

Fig. 3 Effect of density of the center flow on the spectrum of the radiated noise with nitrogen flow in the annulus.

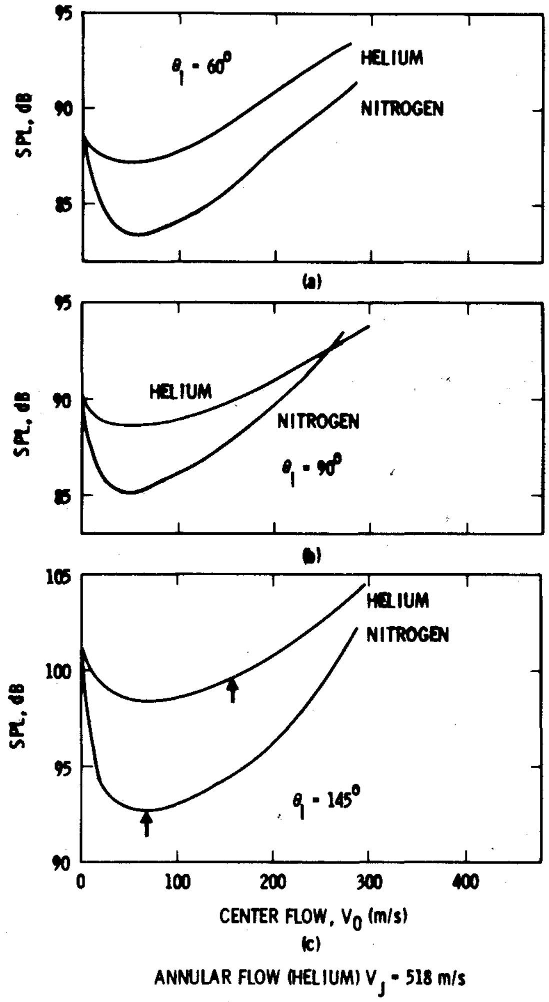

Fig. 4 Influence of the density of the center flow on noise radiated from an inverted profile jet with helium gas in the annulus.

$V_0 = 159$ m/s was required. Thus, an excess noise of about 7 dB was generated by flowing helium gas instead of nitrogen through the center nozzle. Note that this is not the only means of comparison of noise for a given thrust that an engine designer has at his disposal.

The spectrum showing the influence of the center flow density on radiated noise at $\theta_I = 60$, 90, and 140 deg for $V_J = 295$ m/s and $V_0 = 84$ m/s is indicated in Fig. 3. It is interesting to note that the influence of the density of the center jet on the reduction of jet noise is more pronounced in the rearward quadrant close to the jet axis, e.g., at $\theta_I = 140$ deg, than in the forward quadrant, $\theta_I = 60$ deg. At $\theta_I = 60$ deg there was noise reduction with helium and nitrogen gas flow in the center over the entire frequency range. At $\theta_I = 140$ deg, however, helium gas flow in the center did not change the noise spectrum as compared to no flow in the center. On the contrary, with nitrogen gas flowing through the center significant reduction of the relatively low-frequency component of jet noise was observed at $\theta_I = 140$ deg. These results indicate that a low-density gas flow (simulating a high-temperature stream) in the center does not greatly alter the mean velocity profile of the jet flow many diameters downstream where most of the low-frequency noise is generated. It would be expected, however, that the mean velocity profile downstream would be affected with high-density flow in the center. This is discussed in more detail in the next section.

The results in Fig. 4 and 5 represent the influence of the center flow density on the noise radiated from the jet with helium gas flow through the annulus. Comparisons are made with both helium and nitrogen gases flowing through the center. This arrangement simulates more closely the density distribution of an inverted velocity jet where high-temperature flow discharges from an annulus, e.g., the VSCE discussed previously. The strong dependence of density of the center flow in modifying the radiated jet noise and the directivity pattern is evident with the low-density gas flow in the annulus just as it is with the higher-density annular gas flow (Figs. 2 and 3). The minimum noise for a fixed annular flow V_J occurred at a center flow velocity around 60 m/s. Nitrogen gas in the center produced as much as 5-7 dB less noise than the lower-density helium gas at the same velocity V_0. The spectra of the radiated noise again show that in the forward quadrant, i.e., 40 deg $< \theta_I \leq 90$ deg, the introduction of inner flow influences both the low and the high-frequency contents of the radiated noise; whereas, close to the rearward quadrant, i.e., deg $\leq \theta_I < 150$ deg, there was more noise reduction in the low-frequency range. From the results of Figs. 4 and 5, it is apparent that the modification of the jet flow region which generates relatively low-frequency noise is the one that is largely altered by the higher-density nitrogen gas flow in the center. With low-density gas flow in the annulus, there is less potential for noise reduction where the center flow also consists of a low-density gas flow. Hence,

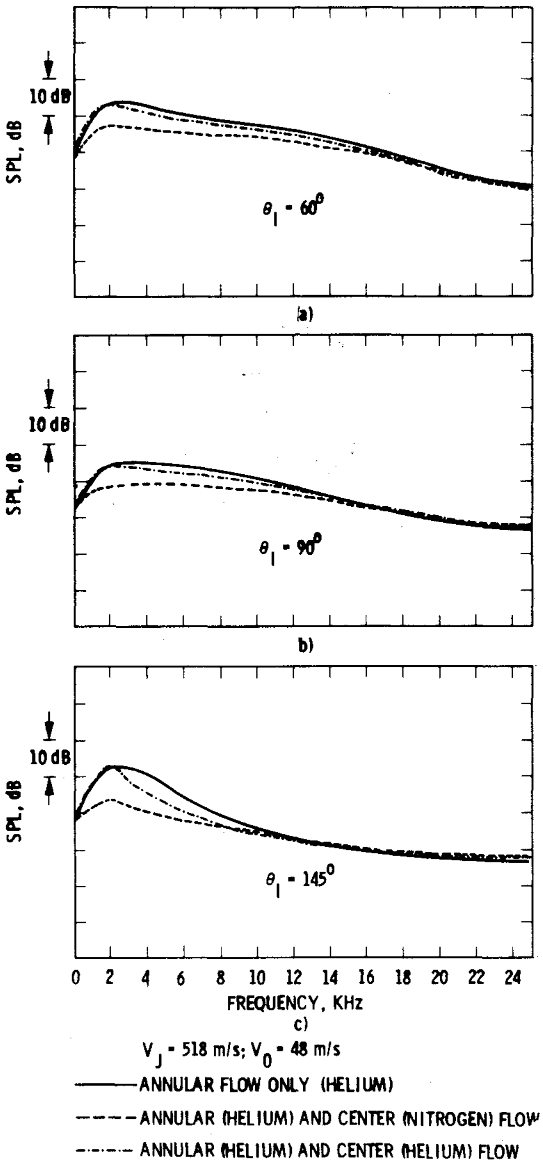

Fig. 5 Effect of the density of the center flow on the spectrum of the radiated noise with helium flow in the annulus.

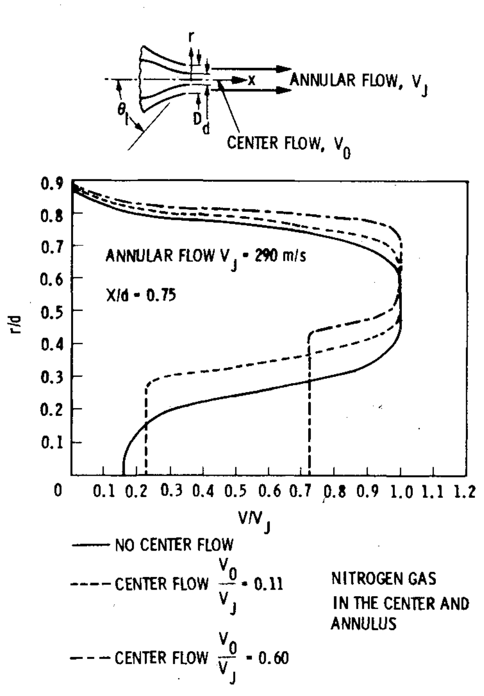

Fig. 6 Effect of center flow on mean velocity profiles at $X/d = 0.75$.

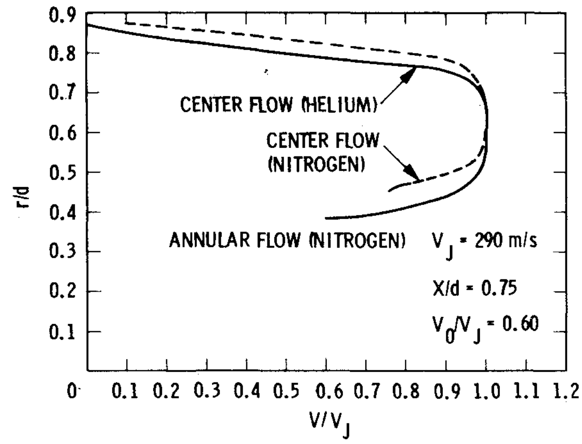

Fig. 7 Influence of center flow density on mean velocity profile for an inverted flow.

both the velocity and the density distribution are important factors in optimizing the noise reduction potential of inverted velocity profile jets.

Mean Velocity Profiles

To acquire further understanding of the mechanisms by which the density of the center flow influences the noise radiation from inverted velocity profile jets, mean velocity profiles by traversing a pitot tube were obtained at selected axial locations along the jets. These measurements showed that without any center flow, subatmospheric pressure existed in the central region of the jet in the vicinity of the nozzle exit. This condition had also been observed previously.[15] The subatmospheric pressure caused the streamlines of the annular flow to curve radially inward. In the present study, this subatmospheric region was observed at axial distances as far as $X/d = 0.5$ from the nozzle exit. Because of this rapid closure of the inner mixing layer of the annular jet (without center flow), the annular jet "filled up" the center region and became almost a circular jet at an axial distance of approximately 3.0 center jet diameters ($X/d = 3.0$). This is probably the main reason that noise radiated from annular jets is very nearly the same as that radiated from equivalent nozzle-area circular jets.

At $X/d = 0.75$ annular mean velocity profiles with no center flow and with center flow velocity ratios $V_0/V_J = 0.11$ and 0.60 are shown in Fig. 6. The annular flow velocity at the nozzle exit was kept constant for all of these tests at $V_J = 290$ m/s. Nitrogen gas was passed through both the center and the annular nozzles. A few distinct changes in the development of the annular jet occur with the introduction of center flow. First, because of the absence of subatmospheric pressure near the nozzle exit, the jet flow was not drawn radially inward and consequently, the mean annular velocity profile was displaced radially outward. This outward radial displacement is accompanied by a reduction in the width of the annular portion of the jet. It is important to note that even at X/d as low as 0.75, where d is the diameter of the inner jet, the center flow modifies the annular flow. Thus, as one would expect, the radial displacement of the annular jet is a function of the center flow velocity V_0, as indicated in Fig. 6. Note also in this figure that the annular flow had rapidly accelerated the flow that discharged through the center nozzle.

The influence of the density of the inner flow on the annular flow at $V_0/V_J = 0.60$ and $X/d = 0.75$ is indicated in Fig. 7. As a reminder, the annular flow in this case was nitrogen with $V_J = 290$ m/s. With helium gas flow in the center the

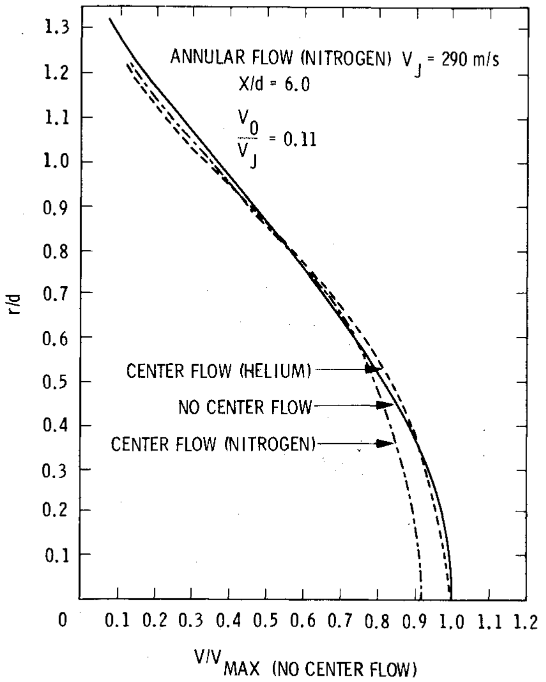

Fig. 8 Effect of the density in the center flow on the development of the mean velocity profile.

annular flow was larger in radial extent and in addition, the radial outward displacement of the annular flow was not as great as with nitrogen flow in the center. Velocity profiles obtained further downstream at $X/d = 6.0$ are shown in Fig. 8. It is apparent that with helium flow in the center the mean velocity profile was nearly the same as with no flow through the center, however, the velocity profile differs; in fact, the maximum velocity was lower than for the other two cases.

All of these results are consistent with the noise data shown in Figs. 2-5. For example, at low center flow velocities $V_0 < 100$ m/s most of the noise is produced by shearing action along the center and inner "surfaces" of the annular flow. Near the nozzle exit, which is where the relatively higher-frequency noise is generated, there is not much difference in the noise levels at the high frequencies, as is indicated in Figs. 3 and 5. Even though there is a displacement of the annular flow between helium and nitrogen center flow conditions as indicated in Fig. 7, not much difference in the slopes of the velocity profiles was observed. This similarity in velocity profiles was also observed farther downstream, as shown in Fig. 8. Hence, it would be expected that the conditions with helium flow in the center would be more nearly like those with no flow discharging through the center nozzle and that the difference in radiated noise would not be excessive. This is consistent with the data of Figs. 2-5. For the conditions with nitrogen flow in both the center and in the annulus the velocity profile, e.g., in Fig. 8 shows that not only the velocity gradients but also the mean jet velocities are less than for the other cases; hence, the noise would be expected to be lower, particularly the relatively low frequency jet noise, and this result is consistent with the noise data shown in Figs. 3 and 4.

Flow Visualization

An even better understanding of the role that the density of center flow plays in noise radiated from inverted profile jets can be obtained from spark shadowgraphs of the jet flowfield. Typical results are shown in Figs. 9 and 10 for $V_J = 295$ m/s and two values of $V_0 = 30$ and 231 m/s, respectively. These shadowgraphs show the dramatic changes that occur in the inner mixing layer of the annular flow as the density of the center flow varied. In both figures the annular flow is nitrogen. The low density helium gas in Fig. 9 did not seem to penetrate radially outward into the annular region as much as the nitrogen gas flow did for the same velocity V_0. It is evident in Fig. 9 that the helium flow converges radially inward and, consequently, accelerates toward the center as it flows downstream. This reduces the effective shear with respect to the annular flow. Consequently, the mixing of the two streams is reduced and becomes less effective in altering the dissipation of the noise producing annular flow. This may be the reason that in Figs. 9 and 10 the helium gas seems to remain unmixed and identifiable in large "chunks" as far as 10-12 diameters from the nozzle. The flowfields observed in Figs. 9 and 10 with the higher-density nitrogen gas flow in the center differ significantly. These density effects on the development of the annular flow are such that the annular

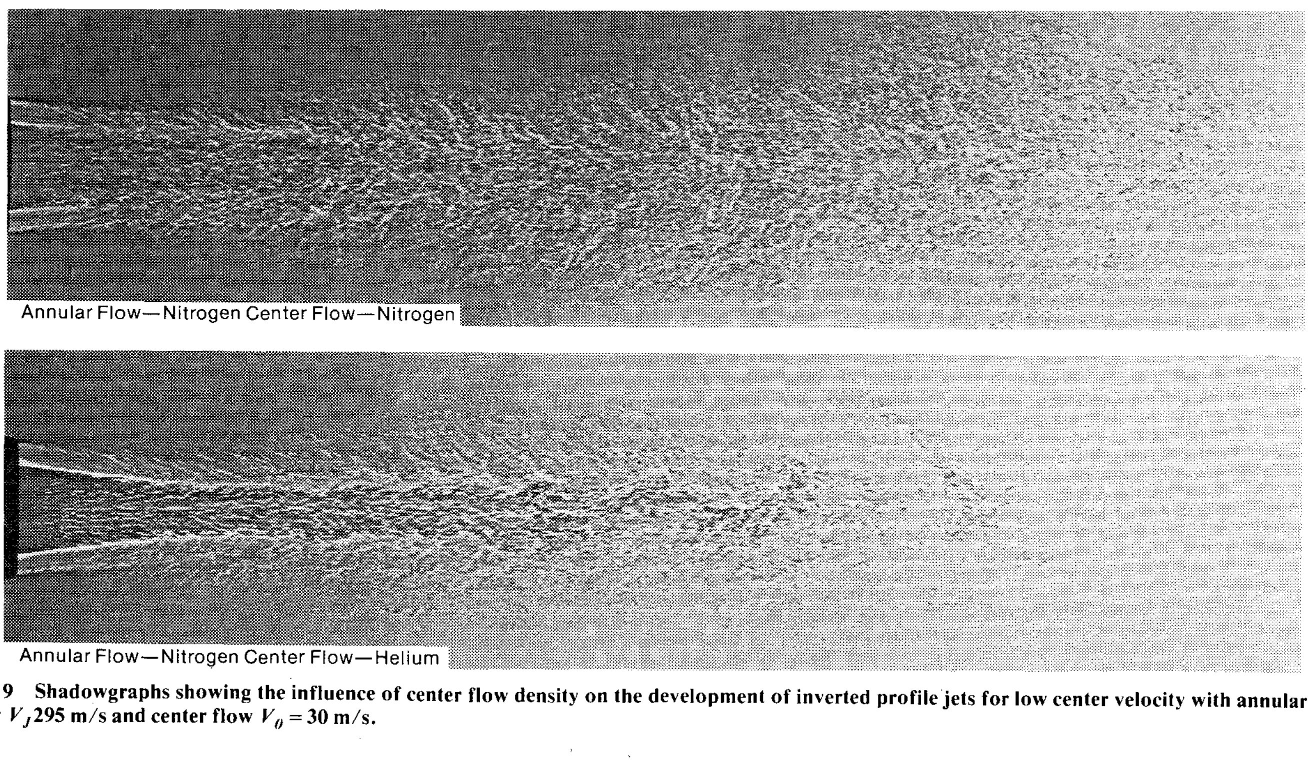

Fig. 9 Shadowgraphs showing the influence of center flow density on the development of inverted profile jets for low center velocity with annular flow V_J295 m/s and center flow $V_0 = 30$ m/s.

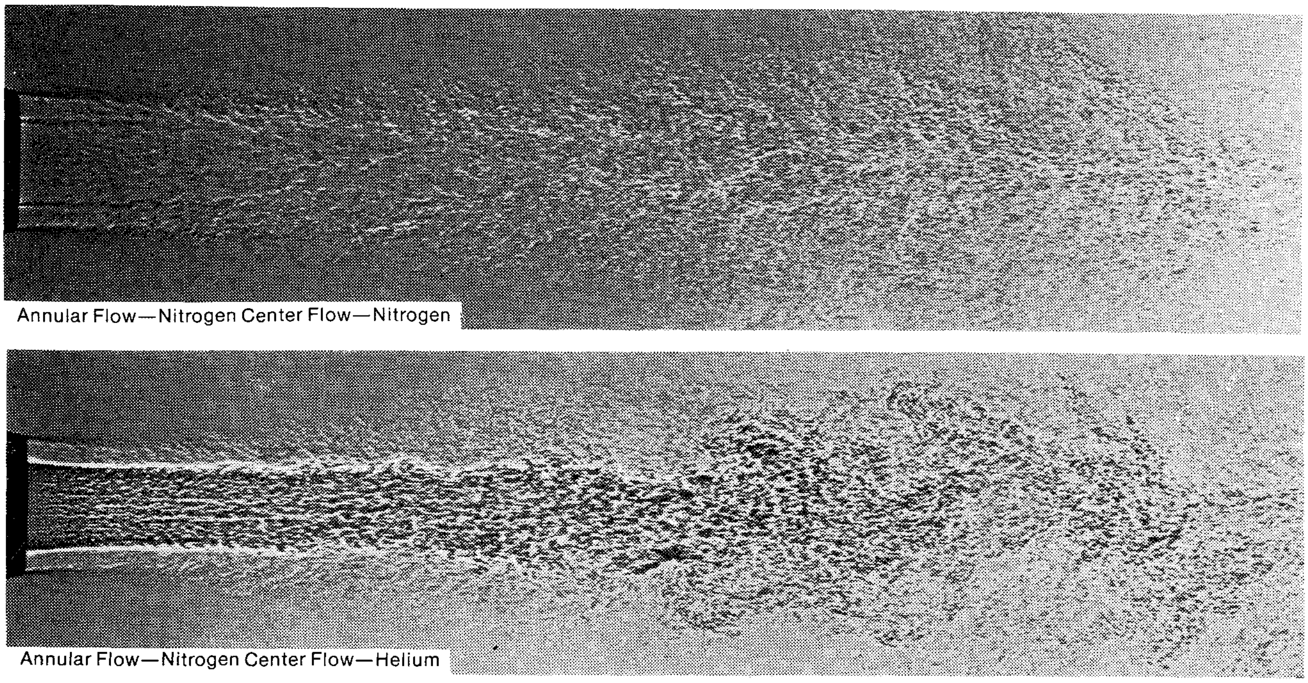

Fig. 10 Shadowgraphs showing the influence of center flow density on the development of inverted profile jets for high center velocity with annular flow $V_J = 295$ m/s and center flow $V_0 = 231$ m/s.

flow is slowed down faster when the higher density gas is in the center. These shadowgraphs show what happens along the jet in a pictorial sense and provide an explanation for the mean velocity profiles as, for example, shown in Fig. 8.

Discussions and Conclusions

The present experimental investigation clearly demonstrates the importance of jet density in the production of jet noise for inverted velocity profile jets. In the flow system investigated, both the density ρ_0 and the velocity V_0 of the center flow play a key role in the development of the high-speed annular flow and, consequently, the radiated noise. For a given annular flow, the degree to which the center flow is capable of radially displacing the annular mean profile (Figs. 6-8) will depend upon the momentum $\rho_0 V_0^2$ of the center flow. Furthermore, the entrainment of the low-density center flow by high-speed annular flow is much greater than with high-density center flow.[10] Therefore, the extent to which the center flow influences the growth of the annular flow will be a function of the center nozzle mass flow rate $\rho_0 V_0$. The density of the center flow plays such an important role in the production of noise radiated from high-speed annular flows because the momentum, mass flow rate and entrainment of the center flow by the annular flow is directly related to the density of the center flow ρ_0 (for a fixed velocity V_0). It is anticipated that these findings will be of use for design engineers seeking methods to optimize the radiated noise from the inverted velocity profile jets of variable stream control engines.

The main conclusions of this investigation are:

1) The density of the center flow is very germane to the production of noise by the annular flow of an inverted velocity profile jet. A more dense gas flow in the center tends to produce less noise than a less dense flow.

2) The minimum far-field noise for a given annular flow was observed to occur with a center flow velocity in the range of 50-100 m/s. This minimum noise was dependent on the density of the fluid passed through the center nozzle.

3) The directivity pattern of the radiated noise signal depended strongly on the density of the center flow.

Acknowledgment

This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract NAS 7-100, sponsored by NASA. The authors express deep gratitude to M. Noel and T. Bui for their dedicated assistance in carrying out this research. In addition, the assistance of F. H. Slover, W. Bixler, and J.J. Godley in assembling and conducting these experiments is greatly appreciated.

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