NASA Technical Memorandum 83503

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(NASA-TM-83503) ON SOME FLOW CHARACTERISTICS OF CONVENTIONAL AND EXCITED JETS (NASA) 22 p HC A02/MF A01 CSCL 20A

N84-13922

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G3/71 42604

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Prepared for the
Twenty-second Aerospace Sciences Meeting
sponsored by the American Institute of
Aeronautics and Astronautics
Reno, Nevada, January 9-12, 1984

ON SOME FLOW CHARACTERISTICS OF CONVENTIONAL AND EXCITED JETS

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E-1843

Abstract

Improved correlations of jet centerline velocity and static temperature decay data for convergent circular nozzles are developed. From these empirical correlations, a relationship was devised by which the static temperature decay for a nonisothermal jet plume can be determine from cold-flow jet centerline velocity decay data for prediction. This relationship is shown to apply as well to jet plumes for various nozzle shapes. It is assumed, by analogy, that this relationship also applies to acoustically excited jet plumes. Jet plume spreading with and without excitation is discussed. Finally, the radial velocity and temperature profiles for conventional and enhanced mixing jet flows are shown and their implication for excited flows is discussed.

Introduction

Serious consideration of means to alter or control fluid flow by sound had its beginnings in the 1930-50 period when the research was oriented to the control of flames during combustion. After 1950, the research in flow control, i.e., shear layer effects, began to be accelerated and the method of the flow alteration was primarily accomplished by sound. Since the 1970's the motivation in the field of flow control has been, in large part, the result of research directed at jet noise generation mechanisms and reduction in which the objective has been to gain an expanded and improved understanding of the flow characteristics (velocity, turbulence, and temperature) in the jet field. As part of this work, means of rapidly mixing out the jet in the surrounding air has been studied for a variety of practical applications. Initially, the common procedure was to utilize mixer-type nozzles to reduce the jet centerline velocity. However, jet noise research also showed that enhanced jet mixing can also be achieved by flow excitation using acoustic or mechanical means.

The effect of flow excitation on a jet plume is shown schematically in Fig. 1. With excitation the jet potential core length is decreased while the plume spread is increased compared with a non-excited jet.

It should be noted that turbofan/turbojet engine jets operate in an acoustically excited environment that can cause their jet aerodynamic characteristics to be significantly different from an unexcited or model jet[1]. Furthermore, it has been shown that the jet mixing enchancement by mechanical means is analogous to that by an acoustic source[2]. Very briefly and with gross simplification, the phenomena may be expressed as the following: A wave generated by a mechanical or acoustic source interacts with the existing instability waves in the shear layer of a steady-state flowing jet producing effects on the spreading rate of the jet plume, jet velocity and temperature profiles, and its turbulence characteristics. The effect on the jet plume characteristics depends on the frequency and strength or magnitude of the waves produced by the excitation source.

This paper considers the mixing enhancement of the jet plume velocity and static temperature characteristics by some acoustic excitation and mechanical perturbation devices. Enhancement of jet mixing by means of flow excitation can be achieved by any of the following devices:

1. Acoustic drivers or loud speakers
2. Whistler nozzle
3. Elliptical focusing radiator
4. Oscillating vane

A general description of some of these flow excitation devices will be summarized briefly later in the paper.

Initially, the present paper considers the mean-flow characteristics associated with convergent circular nozzle jet exhaust flows under static conditions. An improved correlation of the centerline velocity decay, based on previous work on cold-flow jet decay experiments is presented. The method is then extended to heated jets. The range of conditions considered includes subsonic and low supersonic jet flows. A centerline jet static temperature decay correlation for convergent circular jets is then presented. From these correlations, it is then possible to obtain the centerline jet static temperature decay from cold-flow velocity decay data. The centerline velocity/static temperature decay correlation based on convergent circular nozzle data is shown to apply to several nonsymmetric jets and external mixer nozzles.

The paper then summarizes and discusses the results from various experimenters on the effect of excitation on jet plume characteristics. Centerline velocity decay curves for a number of excitation methods are included. These methods are not optimized. Further work directed at understanding the mechanism involved in flow excitation is needed before optimization is achieved. The variation of centerline static temperature decay is shown for non-excited data. In addition, the centerline temperature decay for an excited jet with a composite velocity decay characteristic (measured velocity decay independent of the plume decay enhancement means) is illustrated and discussed. A discussion of the effect of excitation on the jet spread and mean radial velocity profiles follows this portion of the paper. Finally, flight effects on the centerline velocity and temperature decay and jet spread are discussed briefly for both excited and unexcited jets.

Representative Jet Excitation Methods

In order to excite the jet flow structure, researchers have used many different devices. A brief description of some of the devices follows.

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Acoustic excitation. - The acoustic source section used for the jet excitation experiments of Ref. 3 is centered around a 10-cm diameter duct and utilizes four electro-acoustic 100 watt Altec drivers (Fig. 2(a)). Each driver is enclosed in a pressure vessel to equalize the pressure across the driver diaphragm. To protect the diaphrams during high temperature tests, tubes connecting the drivers to the source section have provisions to provide cooling air. The source section is located in the constant 10-cm diameter pipe section, six meters upstream of the nozzle exit plane. The most critical feature of the source section is the requirement to generate modes in isolation. To achieve this, the input signal for each driver is passed through individual power amplifiers with provision for input (amplitude and phase) control in order to ensure generation of the plane-wave (azimuthal) mode, (0,0) mode, or helical (1,0) mode. Maximum excitation of the jet plume was obtained with the (0,0) mode; consequently only these data are included herein.

Whistler nozzle. - The Whistler nozzle[4,5] is a passive device consisting of a constant-diameter tail pipe, attached to the downstream and of a jet nozzle, and a constant-diameter collar which can slide over the pipe (Fig. 2(b)). Depending on the step height (i.e., the difference between the inside radii of the pipe nozzle and the collar), the jet speed, and the pipe length L_p, as the collar is gradually pulled out (i.e., moved downstream), the jet produces a loud pure-tone sound; this is the first stage. With increasing collar length (i.e., the streamwise projection of the collar beyond the pipe exit), the frequency of the tone decreases monotonically and the sound strength increases, reaches a peak and then decreases until it disappears. With further increase of the collar length, the sound quite abruptly reappears at a slightly lower frequency; this is the second stage. The sound is the result of resonance of the pipe nozzle as an open-open organ pipe in either the full-wave mode or the half-wave mode. Note that "mode" refers to half-wave or full-wave organ-pipe resonance of the pipe nozzle while "stage," as explained above, denotes the same as that in any edge-tone system. According to Ref. 5, the pipe length, L_p, has the greatest effect on the aerodynamic characteristics of the jet plume for a Whistler nozzle.

Elliptical focusing radiator. - A sketch of the experimental arrangement is shown in Fig. 2(c)[6]. The generator (1), which is driven by compressed air from a compressor, is situated at one focus (f_1) of the elliptical focusing radiator (2), which is truncated in the plane of the second focus (f_2). An air nozzle is placed at the latter, through which air is forced under a pressure. The spent air is completely exhausted from the focusing radiator through special ports (the generator operated in the air backwash regime) and does not affect the jet plume.

In addition to the preceding excitation devices, jet exhaust mixing can be enhanced by other devices such as: (1) Rotating turbulence generation disk[7], (2) inserting an oscillating vane or ribbon[8], (3) by swirling the exhaust flow upstream of the nozzle exit plane[9], and (4) spark generation and fluid generation (see Ref. 5).

Centerline Jet Velocity Decay

Without Flow Excitation

In Ref. 10, the cold-flow jet plume decay along the nozzle centerline was correlated in terms of M/M_j as a function of an axial distance parameter given by $X/(D_e\sqrt{1+M_j})$. In the present work the velocity decay term is changed, for convenience, from M/M_j to U/U_j. In addition, a static temperature ratio parameter, $(t_j/t_o)^{0.25}$ is included in the axial distance parameter to account for static temperature variations in the jet as well as with heat addition (heated jets). The exponent for this static temperature ratio is similar to that suggested in Refs. 11 and 12; differing only slightly in the magnitude of the exponent because of a difference in the formulation of the axial distance parameter used in these references.

Cold-flow. - In Fig. 3 is shown the convergent circular nozzle jet centerline velocity decay for jet Mach numbers from 0.28 to 1.37 (data from Ref. 13). It is apparent that the axial distance parameter used including the static temperature ratio parameter correlates the data extremely well about the curve drawn through the data. It should be noted that the temperature term contributes a variation of only about 8-percent in the abscissa; consequently, the most significant conclusion to be drawn from this data correlation is that the $\sqrt{1+M_j}$ term, which contributes a variation of 35-percent inthe data shown, correlates the centerline velocity decay over a wide range of jet Mach numbers (see also Ref. 10).

Additional cold-flow jet centerline velocity decay data for convergent circular nozzles, together with that from Fig. 3, are shown in Fig. 4. In general, the data are well correlated by the parameters shown. The curve shown in Fig. 4 is given by the following relationship:

$$\frac{U}{U_j} = \left[1 + \left(\frac{X}{6D_e\sqrt{1+M_j}}\right)^8 \left(\frac{t_j}{t_o}\right)^2\right]^{-0.125} \qquad (1)$$

and is seen to fit the data well. The data presented starting in Figs. 4 and 5 from Refs. 15 and 16 represent supercritical non-isentropic data. The form of these data presented here is different than presented in Refs. 15 and 16 where it is in the form of dynamic pressure. The dynamic pressures were transformed to the dimensionless velocity U/U_j using isentropic relationships. These relationships introduced effects of compressibility into the results, but those are believed minimized by the low supercritical conditions at which the data were obtained.

Heated flow. - The jet centerline velocity decay data for convergent circular nozzles with heated flow is shown in Fig. 5 using the same parameters as those for the cold-flow data of Fig. 4. The curve shown in the figure is that previously shown in Fig. 4 and given by Eq. (1). Again, the data are well correlated by the parameters shown in the figure and by the correlation equation.

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With Flow Excitation

As discussed earlier, jet flow excitation can be achieved by the use of several techniques involving flow phenomena (Whistler nozzle), mechanical means (oscillating devices), and acoustic.

In the next several figures, the excited jet centerline velocity decay data for convergent circular nozzles are shown. All of the data sources included data without excitation as reference values. However, not all of the reference values fell on the velocity decay correlation curves of Figs. 4 or 5. Such data were arbitrarily normalized to coincide with the velocity decay correlation curve (Eq. (1)) and the excited data were adjusted similarly by the same factor (i.e., a 10-percent adjustment in the $X/(D_e \sqrt{1 + M_j})$ $(t_j/t_o)^{0.25}$ parameter for the unexcited jet data resulted in the same adjustment for the excited jet data). Data so adjusted are identified as "normalized" in the figures. In all figures, the centerline velocity decay curve for unexcited flow (Eq. (1)) is shown for comparison.

Acoustic-tone excitation. - Centerline jet velocity decay data obtained with a tone-excited jet[3] are shown in Fig. 6. The data shown are for jet Mach numbers of 0.58 and 0.78, an acoustic excitation source at the nozzle exit of 141 dB, and a constant Strouhal excitation number, St_e of 0.5. Reductions in the local velocity ratio were obtained in the jet core flow region (especially for $M_j = 0.58$) and in the mixed flow region. For the conditions of the experiment, the effectiveness of acoustic excitation on the velocity decay decreased with increasing jet Mach number. Also, a decrease in the acoustic-tone level decreased the change in the velocity decay from the unexcited values.

Elliptical focusing radiator. - The elliptical focusing radiator used for the jet excitation experiments in Ref. 6 is also an acoustic device. Acoustic levels of 170 dB were obtained with this device. The centerline jet velocity decay with and without excitation is shown in Fig. 7. For the data shown, only the higher jet Mach number data were normalized (factor of 1.1). For these data, a more rapid decay was obtained with the higher jet Mach number than that with the lower one, contrary to the trend noted for the previous figure. However, this effect may be due to a change in excitation Strouhal number between the data in Fig. 7. Reference 6 indicates that the maximum velocity decay produced by excitation occurred at an excitation Strouhal number, St_e, of 0.25 while a minimum occurred at a St_e of 0.5. The jet core flow region was significantly shortened with the excitation level of 170 dB and large velocity decay values were measured downstream of the shortened core as shown in Fig. 7. The jet core flow region was significantly shortened with the excitation level of 170 dB and large velocity decay values were measured downstream of the shortened core as shown in Fig. 7.

Whistler nozzle. - The centerline jet velocity decay of a Whistler nozzle depends greatly on the geometry of the nozzle[5] for both unexcited and excited mode of operation. As in the case of the elliptical focusing radiator flow excitation technique, the measured centerline jet velocity decay data for unexcited flow were normalized to the curve given by Eq. (1), with the excited flow data adjusted by the corresponding normalization factor. It is presumed that this data normalization is the result of flow losses in the Whistler nozzle which cause a more rapid velocity decay than that obtained with a conventional conical nozzle.

The maximum normalized centerline velocity decay at $M_j = 0.11$ obtained in the experiments reported in Ref. 5 is shown in Fig. 8. (Similar unpublished results, made available by Professor Hussain to the author, were obtained at a M_j value of 0.37). The normalization factor for the data in Fig. 8 was 1.11; i.e., the axial distance parameter was adjusted by this factor. It is apparent that the velocity decay was significantly more rapid with excitation than without. In fact, almost the entire jet core flow velocity ratio was reduced by up to 25-percent. These U/U_j reductions are the same order of magnitude as those obtained with the elliptical focusing radiator.

Centerline Jet Temperature Decay

Without Flow Excitation

The jet centerline static temperature decay $(t - t_o)/(t_j - t_o)$, for convergent circular nozzles is shown in Fig. 9 as a function of the same axial distance parameter used in the correlation of the velocity decay data. Also shown is a curve faired through the data and given by:

$$\frac{t - t_o}{t_j - t_o} = \left[1 + \left(\frac{X}{5D_e \sqrt{1 + M_j}}\right)^8 \left(\frac{t_j}{t_o}\right)^2\right]^{-0.125} \qquad (2)$$

The right hand side of Eq. (2) is similar to Eq. (1) except that the constant is 5 instead of 6. This means that the static temperature core length at the jet centerline is less than that for the velocity. The data shown are correlated well by Eq. (2) over the wide range of flow and temperature conditions included in the figure.

It should be noted that Eq. (2) does not apply to isothermal jets; i.e., t/t_o must be greater than 1.0.

With Flow Excitation

At this time the jet centerline static temperature decay data for heated excited jets are not available[a]. However, a method for estimating this decay, based on the assumption of similarity between unexcited and excited jet flow characteristics, will be discussed later.

Plume Velocity/Temperature Relation

Without Flow Excitation

From the correlation equations for U/U_j and $(t - t_o)/(t_j - t_o)$ as functions of the axial distance parameter (Eqs. (1) and (2)), the relation of U/U_j to $(t - t_o)/(t_j - t_o)$ can be established.

[a]See appendix for recently obtained (unpublished) limited excited jet static temperature decay data.

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Convergent circular nozzles. - This relationship is shown in Fig. 10 for convergent circular nozzles. The curve for convergent circular nozzles is given by the following:

$$\frac{t - t_o}{t_j - t_o} = \left[1 + 4.3\left\{\left(\frac{U_j}{U}\right)^8 - 1\right\}\right]^{-0.125} \qquad (3)$$

The convergent circular nozzle data scatter about this curve, shown by the shaded region in the figure, and is the same as that shown by the data in Figs. 5 and 9. A similar relationship, with respect to data trends, is given in Ref. 16 in which the temperature ratio is plotted as a function of dynamic pressure ratio.

Nonsymmetric nozzles. - In Fig. 11, nonsymmetrical nozzle centerline velocity/temperature plume data are shown in terms of the same parameters as in Fig. 10, together with the convergent circular nozzle curve (Eq. (3)). In general, good agreement is observed between the different nozzle shapes. The deviation of the nonsymmetric nozzle data from the curve (Eq. (3)) is of the same order of magnitude as the deviation of the convergent circular nozzle velocity decay data (taken from the same reference) from the correlation curve shown in Fig. 5. Thus, the data deviation from the curve appears to be related to the particular experiment rather than a shortfall of the correlation procedure. The TF-34 engine data show some deviation from the model scale data; however, this is believed due to a severe exit flow separation problem for the engine nozzle configuration.

Enhanced Jet Mixing with Heated Flow

The static temperature/velocity relationship for an excited heated jet is currently not available. However, in Ref. 7, one case of heated ("warm") flow is presented for which a rotating turbulence generator disk was used to pulsate the flow on and off thus enhancing jet mixing. The term enhanced jet mixing is used here when discussing the data from Ref. 7. Unfortunately, the absolute jet temperature level is not stated in the reference. In order to assess the effect of mixing enhancement on the static temperature/velocity relationship for this device, a t_j/t_o value of 1.05 was assumed. The resultant static temperature/velocity variation is shown in Fig. 12, together with the correlation curve given by Eq. (3) and the data without mixing enhancement. It is apparent that both sets of data are in good agreement with the correlation curve. It should be noted that larger values of t_j/t_o than 1.05 would not significantly change the results because both $(t - t_o)/(t_j - t_o)$ and U/U_j are functions of $(t_j/t_o)^{0.25}$.

Excited Jet Flow

As stated in the preceding section, the jet static temperature decay data for excited, heated conditions is not presently available[b]. However, it does not appear unreasonable that by simple analogy the static temperature/velocity decay relationship existing for unexcited jets (Eq. (3)) also applies to excited jets. Thus, the response of the jet plume static temperature decay to acoustic excitation should be analogous to the response of the velocity decay to acoustic excitation. With this premise, use of Eq. (3) with cold-flow acoustically excited jet centerline velocity decay data should yield the excited jet centerline static temperature decay for heated jets.

In order to illustrate this procedure, an envelope curve of the cold-flow excited jet velocity decay data was constructed. This curve was based on the measured data shown by the velocity decay curves in Fig. 13(a). The data used for these curves include M_j values from 0.08 to 0.9. The resultant composite velocity decay curve is shown in Fig. 13(b). From the relationship given in Fig. 13(b), and Eq. (3), the centerline static temperature decay curves for the excited jet plume, can be determined. This static temperature decay curve together with the composite velocity decay curve from Fig. 13(b) represent the effect of excitation and are shown in Fig. 14. The static temperature and velocity decay curves for the unexcited jet (represented by Eqs. (1) and (2), respectively) are also shown in this figure. As in the case of the velocity decay, the rate of static temperature decay with axial distance is significantly enhanced by the assumed effect of excitation.

The preceding example illustrates the significant changes in jet plume characteristics that appear to be achievable with acoustic excitation. While the example is concerned with a convergent circular nozzle, similar benefits can be expected with nonsymmetric nozzle plumes.

In terms of a practical application, as for example a STOL aircraft, jet excitation could reduce significantly the aerodynamic forces on the flap system. In addition, the flap skin and structural temperatures would be greatly reduced by the use of jet excitation. The reduction in both aerodynamic forces and metal temperatures would result in a lower structural weight for the flap as well as reducing vibrational fatigue that can cause cracking of flap skin.

Jet Spreading Rate

Unexcited Jet Flow

The variation of the jet spread at a constant value of $U/U_j = 0.5$ is shown in Fig. 15 as a function of axial distance ratio, X/D, for both the velocity and temperature[7]. In general, the spread rate for both velocity and temperature increases with X/D. The temperature spreading rate for these data is about 12-percent greater than the velocity spreading rate.

Enhanced Mixing Jet Flow

The variation of jet velocity and temperature spread at a constant value of $U/U_j = 0.5$ using a rotating disk device[7] for enhanced mixing of the flow is shown in Fig. 16 as a function of axial distance ratio, X/D. Also shown in the figure are the conventional unexcited jet flow curves from Fig. 15. It is apparent that with enhanced jet

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[b]As previously cited, see appendix for recently obtained (unpublished) limited excited jet static temperature decay data.

mixing, the velocity and temperature spreading parameters, $r_{0.5v}/R$ and $r_{0.5t}/R$, respectively, have larger values than those with conventional flow at the same X/D locations. The enhanced flow $r_{0.5v}/R$ curve is higher by an average of about 30-percent than the conventional flow curve over the range of X/D values shown. Similarly, the enhanced flow $r_{0.5t}/R$ curve is higher by an average of about 40-percent than the conventional flow curve.

Excited Jet Flow

In Ref. 3, limited data for cold-flow acoustically excited jets are shown in terms of the jet half-width velocity spreading parameter, b/R. These data are shown in Fig. 17. In general, the spreading of the velocity field in a radial direction diverges similarly to that shown in Fig. 16 for the enhanced jet mixing rotating disk device. On the basis of overall similarity of the flow velocity spreading characteristics it is reasonable to assume that the static temperature spreading characteristics of a heated excited jet plume would behave in a like manner to that of the rotating disk enhanced jet mixing plume shown in Fig. 16.

Radial Velocity/Temperature Profiles

Unexcited Jet Flow

In the literature, radial velocity profiles of the jet plume are generally divided into regions as those in the shear layer surrounding the core flow and those downstream of the core.

In the core region, the radial velocity ratio, U/U_c, is generally shown to vary with an η_v^* parameter defined as $(r - r_{0.5v}/X)$ (Refs. 21 and 22); however, at the end of the core and downstream U/U_c is represented simply as a function of $r/r_{0.5v}$. A typical variation of U/U_c as a function of η^* for data taken from Refs. 7 and 22, is shown in Fig. 18. It is apparent that the data are well represented by this relationship for both cold and heated flows. Furthermore, although this parametric representation was developed only for core flow, the data shown also includes some radial velocity measurements downstream of the core region (X/D = 8) which are correlated equally well.

The radial temperature profiles of a jet plume are simiarly treated in the literature; i.e., $(t - t_0)/(t_c - t_0)$ as a function of $\eta_t^* = (r - r_{0.5t})/X$ for the core region[22] and $(t - t_0)/(t_c - t_0)$ as a function of $r/r_{0.5t}$ downstream of the core.

Excited Jet Flow

Radial velocity profiles for excited jet plumes are currently not available. However, in general, acoustic excitation tends to increase the jet mixing; i.e., shortens the core and increases the jet velocity and temperature spread as discussed previously. This is analogous to the effects of mechanical mixing devices on the plume velocity/temperature characteristics. It is not inappropriate then to assume that the radial velocity and temperature characteristics of a jet plume subjected to the actions of a rotating disk[7] are analogous of the effects of acoustic excitation on the plume characteristics.

Based on this assumption, the data of Ref. 7 can serve to illustrate the possible effect of enhanced plume mixing associated with acoustic excitation.

In Fig. 19, the radial velocity profiles obtained with a rotating disk device[7] are shown for X/D = 4 to 12. Also shown is a correlation curve for conventional jet plumes from Ref. 23 given by

$$\frac{U}{U_c} = \left[1 - \left(\frac{r}{2.27 r_{0.5v}}\right)^{1.5}\right]^{2.0} \tag{4}$$

It is evident that the enhanced jet mixing flow profile data are represented by the same correlation curve as the conventional flow radial velocity profiles. Similarly, the radial temperature profiles in terms of $(t - t_0)/(t_c - t_0)$ as a function of $r/r_{0.5t}$ are shown in Fig. 20 for both conventional and enhanced jet mixing flow[7]. Also shown in the figure is a curve given by:

$$\frac{t - t_0}{t_c - t_0} = \left[1 - \left(\frac{r}{2.27 r_{0.5t}}\right)^{1.5}\right]^{2.0} \tag{5}$$

The preceding equation is similar to that for the radial velocity profile (Eq. (4)) differing only in that $r_{0.5t}$ is used in place of $r_{0.5v}$. It is apparent from Fig. 20 that, as in the case of the radial velocity profiles, there are no significant differences between the conventional and enhanced mixed flow radial temperature profiles in terms of the parameters shown in the figure. Also Eq. (5) appears to be a good representation of the data. On the basis of the preceding radial velocity and temperature profile characteristics (Figs. 19 and 20), it appears reasonable to assume that excited jet flows follow similar trends and can be represented by Eqs. (4) and (5); however, experimental verification for this assumption is needed.

Flight Effects

The flight effect on a conventional jet plume is to extend the core length and decrease the local rate of plume spreading. This causes a reduction in the centerline velocity decay, which is associated with a similar trend in the static temperature decay.

The effect of flight on an excited jet plume is similar to that observed with an unexcited jet. In Ref. 3, the effect of flight speed on an acoustically excited model-scale jet for limited conditions is documented. The data of Ref. 3 are grossly correlated in terms of a simple acoustic level parameter and a flight speed parameter in Ref. 24.

Concluding Remarks

Significantly more fundamental and applied research needs to be conducted to understand local velocity decay characteristics associated with acoustically excited jets. This research must include:

Fundamental Research

a. Studies of the large-scale turbulence structures in shear layers.
b. Mechanisms associated with the acoustic control of shear layers.
c. Effects of shear layer modification on turbulence levels.
d. Shock interaction effects with conventional and excited shear layers.
e. Flight effects on the conventional and excited large-scale structures in shear layers.
f. Development of computational fluid mechanics codes for excited flows.

Applied Research

a. Plume radial and axial velocity and temperature measurements for both subsonic and supersonic heated jets for various shaped nozzles.
b. Establish the effect of scaling on the excited plume characteristics.
c. Evaluate the importance of shock/shear layer interaction in excited heated jet plumes.
d. Determine the effect of altitude on excited heated jet plumes.
e. Performance/benefit trade-off studies.

Conclusions

The following conclusions may be drawn from the present study on the jet plume characteristics with and without flow excitation.

1. Improved methods for correlating the jet centerline velocity and static temperature decay for convergent circular nozzles were developed.
2. On the basis of the preceding improved methods, a technique has been established from which the static temperature decay can be estimated for various nozzle shapes, from cold-flow jet velocity decay data for predictions. The technique is believed to be applicable to acoustically excited jets.
3. The effect of excitation on jet centerline velocity decay is essentially independent of the excitation method. Furthermore, as shown in the literature, the rate of jet centerline velocity decay is increased with an increase in the acoustic excitation level.
4. Similarity of the jet radial flow field is maintained for conventional (unexcited) and enhanced mixed plumes downstream of the jet core.

Symbols

b	half width of local jet
D	diameter of nozzle
h	step height (Whistler nozzle)
L_p	Whistler nozzle pipe length
M	Mach number
r	jet plume radius
R	nozzle radius
St_e	Strouhal excitation number
t	static temperature
U	jet velocity
X	jet axial centerline distance
η^*	radial profile parameter, $\eta^* = \frac{r - r_{0.5}}{X}$.

Subscripts:

0.5	jet plume at $U = 0.5U_c$
c	local centerline
j	jet exit
o	ambient
t	temperature
v	velocity

Appendix - Excited Jet Centerline Static Temperature Deday

Over a period of several years, the Lewis Research Center has been supporting contractual research with the Lockheed-Georgia Corporation on the effect of acoustic excitation on jet noise and on the jet plume velocity and temperature decay. Recent jet centerline static temperature decay data with and without acoustic excitation obtained under NASA contract NAS3-23708 are shown in Fig. A-1 as a function of velocity decay. Also shown is a curve based on Eq. (3), herein, that relates the velocity and static temperature decay. It is apparent that the unexcited and excited decay data follow similar relationships and are represented quite well by Eq. (3).

From these limited results and those shown in Fig. 12 in the text, Eq. (3) appears to correlate the jet centerline velocity and static temperature decay for both mechanically turbulated jet plume and one in which mixing is enhanced by acoustic means.

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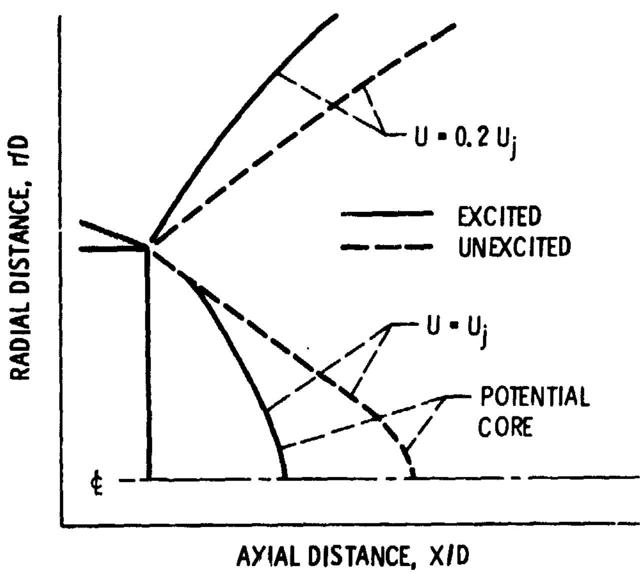
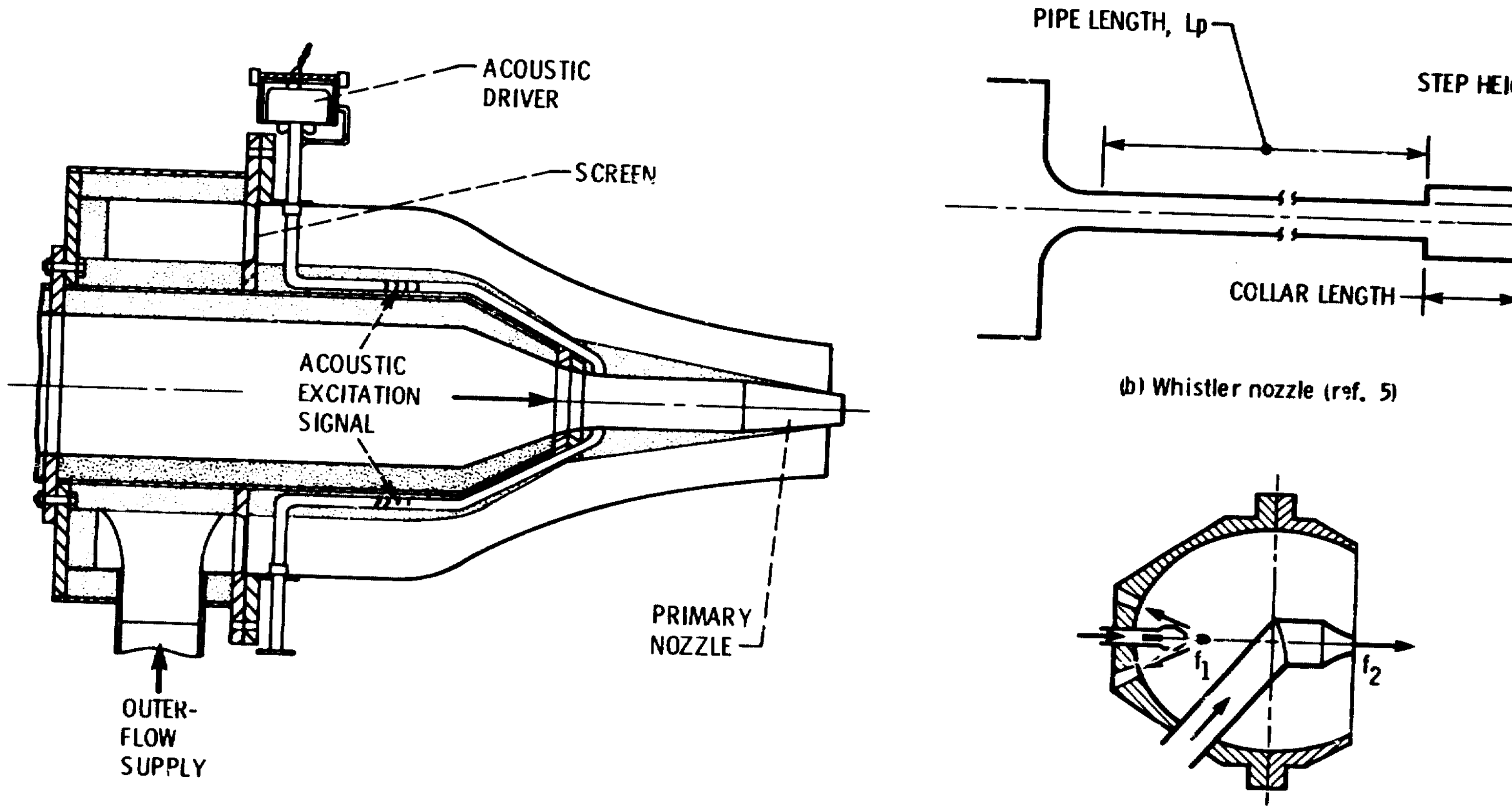


Figure 1. - Schematic sketch of acoustic excitation effects on jet velocity decay.



(a) Acoustic drivers (ref. 3)

(b) Whistler nozzle (ref. 5)

(c) Elliptical focusing radiator (ref. 6)

Figure 2. - Representative Jet Excitation Methods.

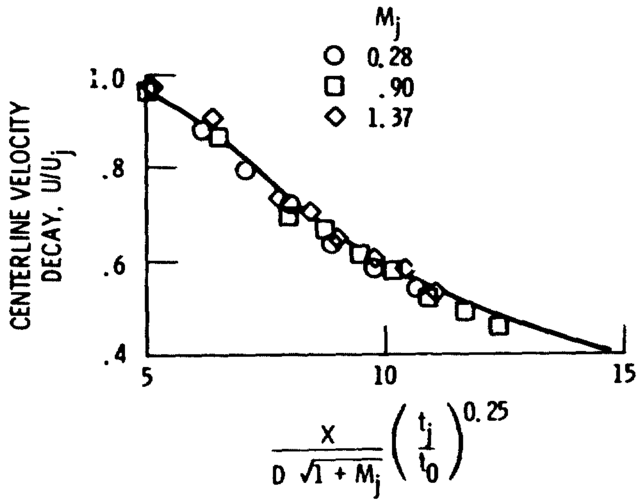


Figure 3. - Correlation of jet centerline velocity decay for several jet mach numbers. Ref. 13 data; convergent circular nozzle; unexcited cold flow.

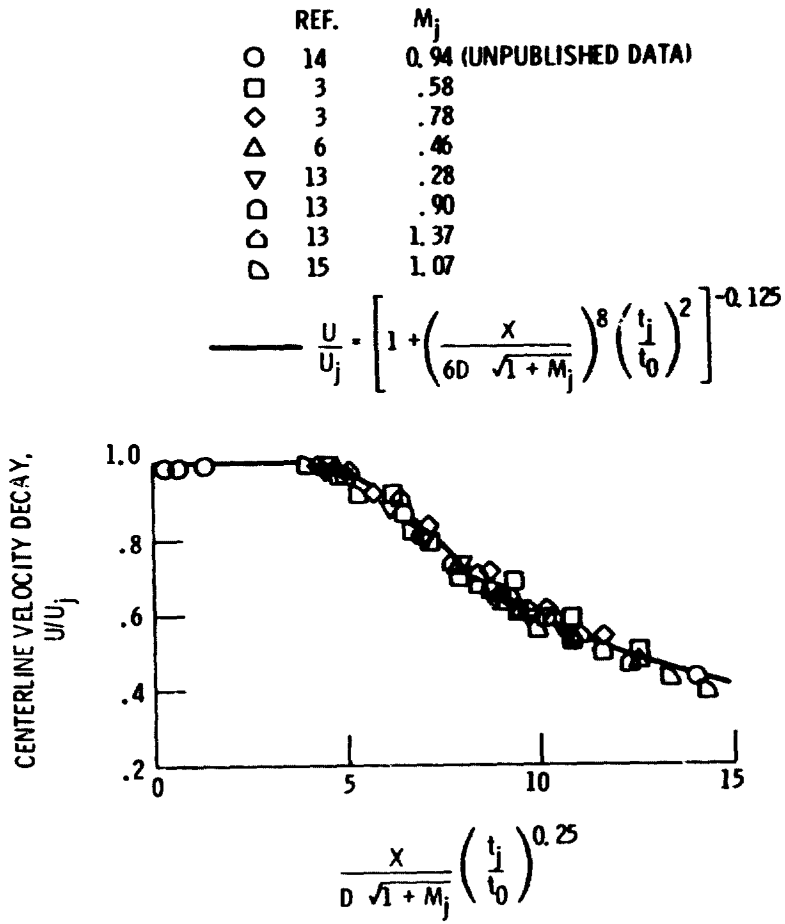


Figure 4. - Unexcited jet centerline velocity decay for convergent circular nozzles with cold flow: $\frac{t_j}{t_0} \leq 1.0$.

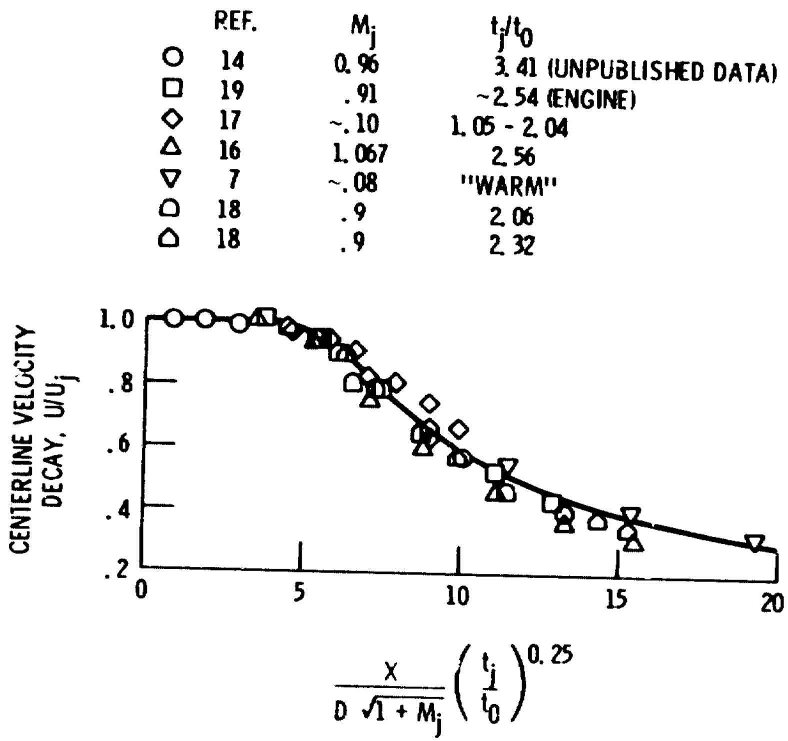


Figure 5. - Unexcited jet centerline velocity decay for convergent circular nozzles with heated flow. $\frac{t}{t_0} \geq 1.0$

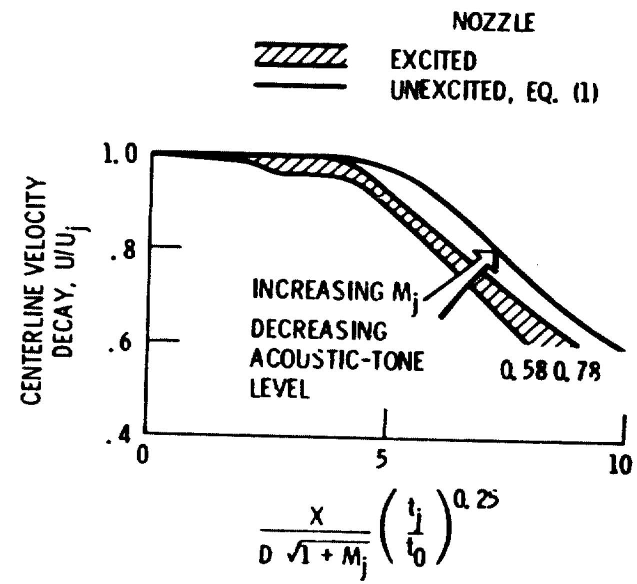


Figure 6. - Comparison of acoustically excited jet centerline velocity decay with unexcited decay characteristics. Cold flow; ref. 3; excitation level, 141 dB; convergent circu'ar nozzle.

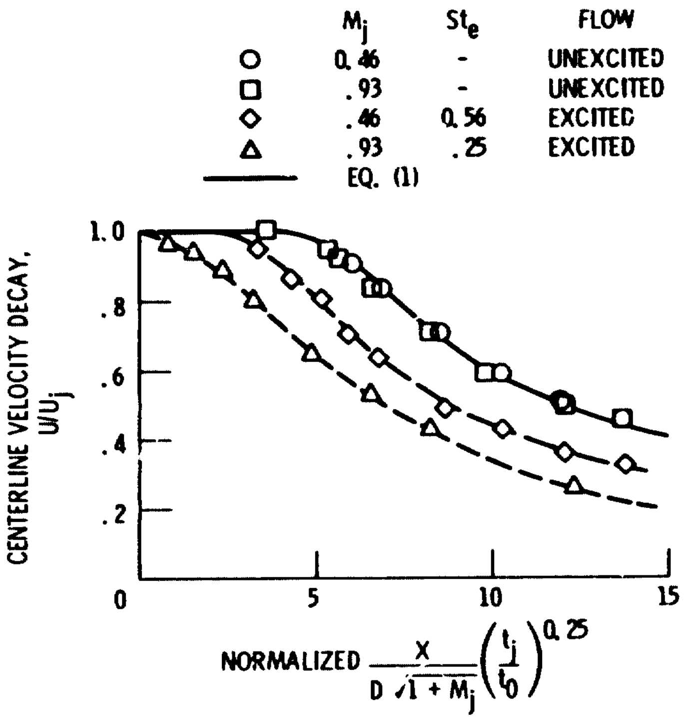


Figure 7. - Normalized jet centerline velocity decay for convergent circular nozzle with and without elliptical focusing radiator excitation. Excitation level, 170 dB; ref. 6.

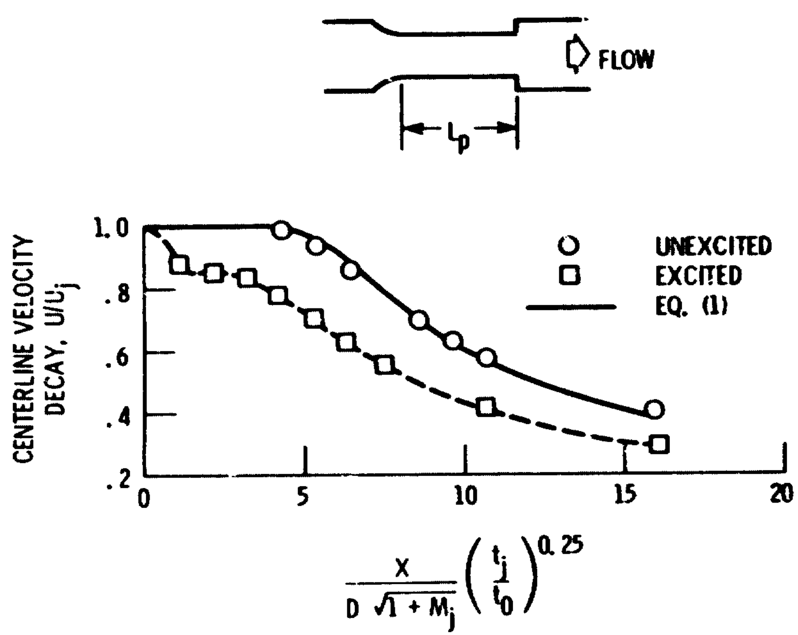


Figure 8. - Representative whistler nozzle cold-flow jet centerline velocity decay. L_p, 15.24 cm; M_j, 0.11; reference 5.

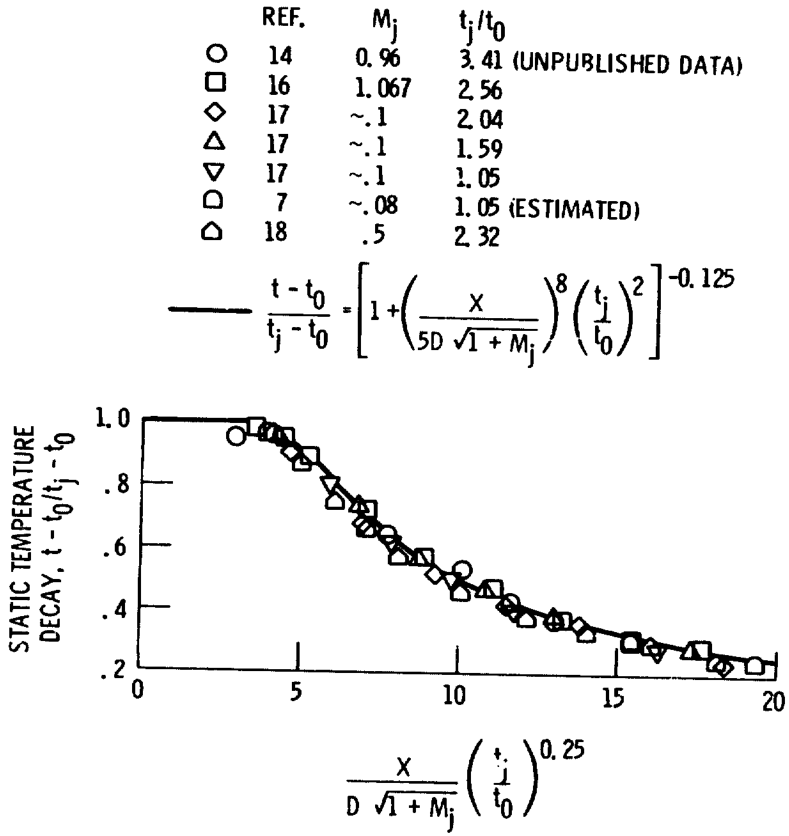


Figure 9. - Jet centerline temperature decay for convergent circular nozzles. Unexcited flow; $t_j/t_0 \geq 1.0$.

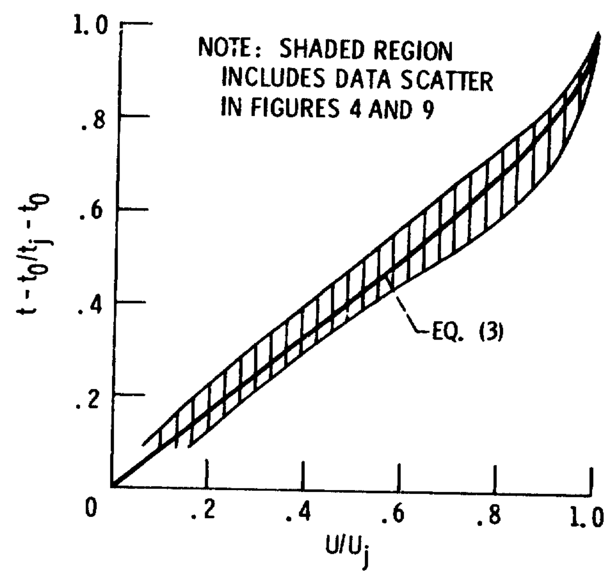


Figure 10. - Variation of static temperature ratio with velocity ratio on jet centerline. $t \geq t_0$; convergent circular nozzles; unexcited flow.

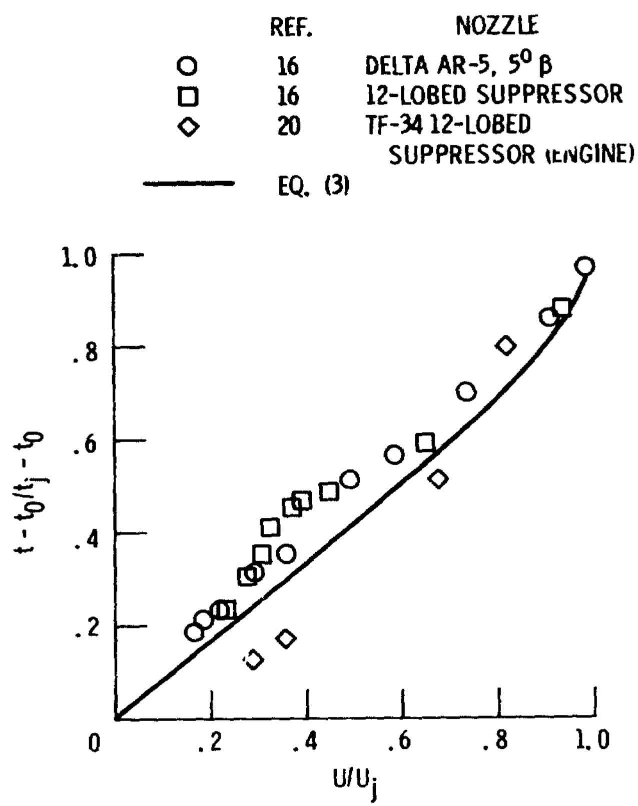


Figure 11. - Variation of unexcited static temperature ratio with velocity ratio on jet centerline. Non-symmetric nozzles. $t \geq t_0$.

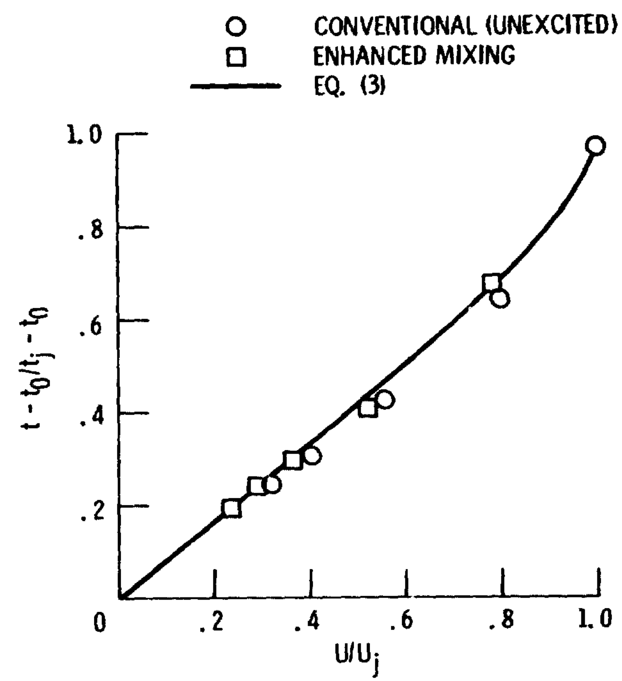


Figure 12. - Centerline static temperature relationship to jet velocity with and without disk turbulator rotation. Reference 7.

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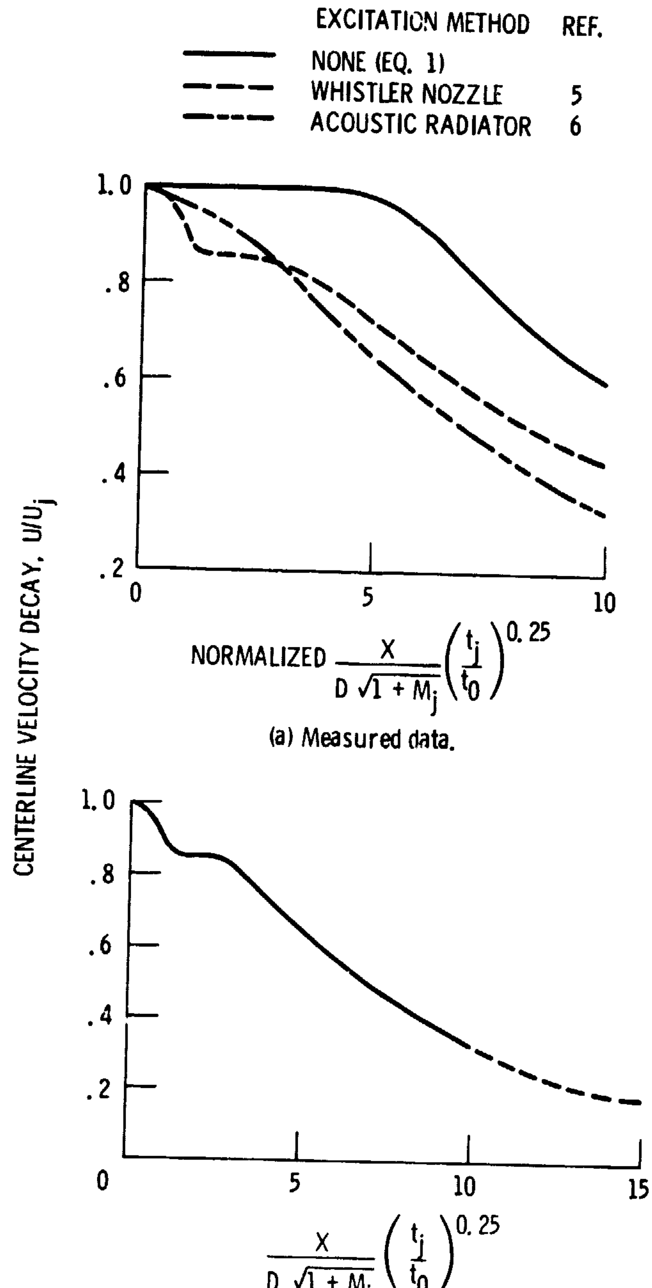

(a) Measured data.

(b) Composite velocity curve of measured data shown in figure 13(a).

Figure 13. - Cold-flow jet centerline velocity decay measured with various excitation methods.

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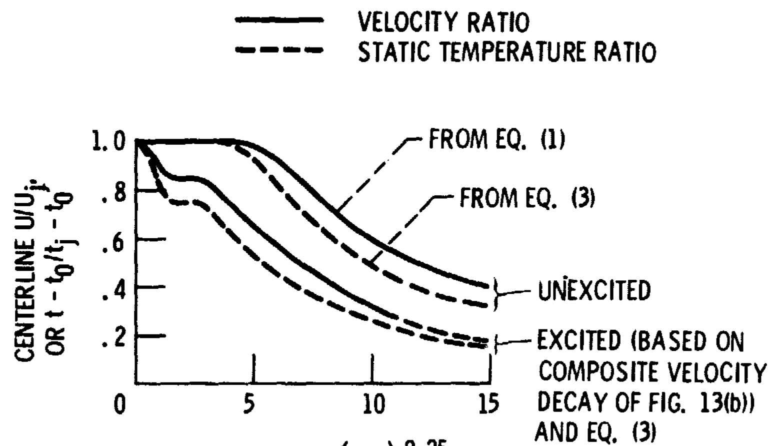

$$\frac{X}{D\sqrt{1+M_j}}\left(\frac{t_j}{t_0}\right)^{0.25}$$

Figure 14. - Calculated jet centerline velocity and static temperature decay with and without flow excitation. Convergent circular nozzle.

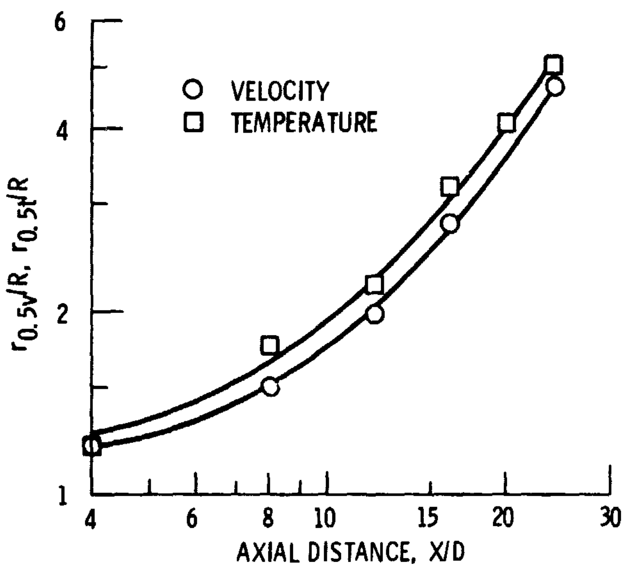

Figure 15. - Variation of jet spread at which U/U_c and $t - t_0/t_c - t_0$ equal 0.5 without excitation as a function of X/D. Reference 7 data.

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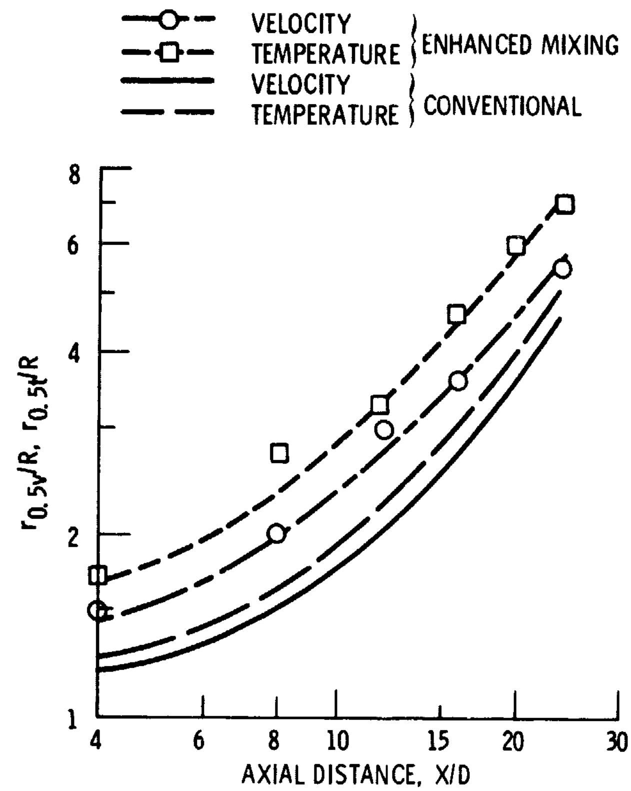

Figure 16. - Comparison of radial distance for U/U_c and $t - t_0/t_c - t_0 = 0.5$ as a function of X/D with and without enhanced mixing. Reference 7 data.

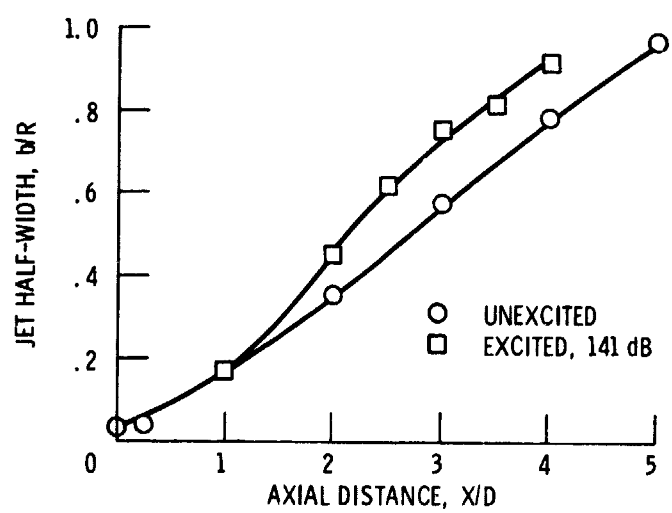

Figure 17. - Variation of jet shear layer spread for unexcited and excited cold-flow jets. Reference 3.

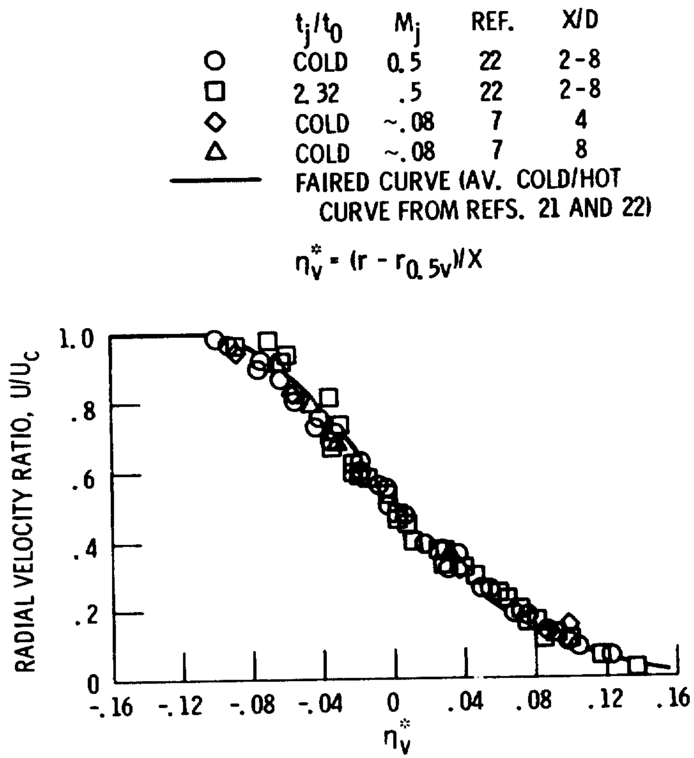

Figure 18. - Unexcited radial velocity profile as a function of η_v^*-parameter. Convergent circular nozzle.

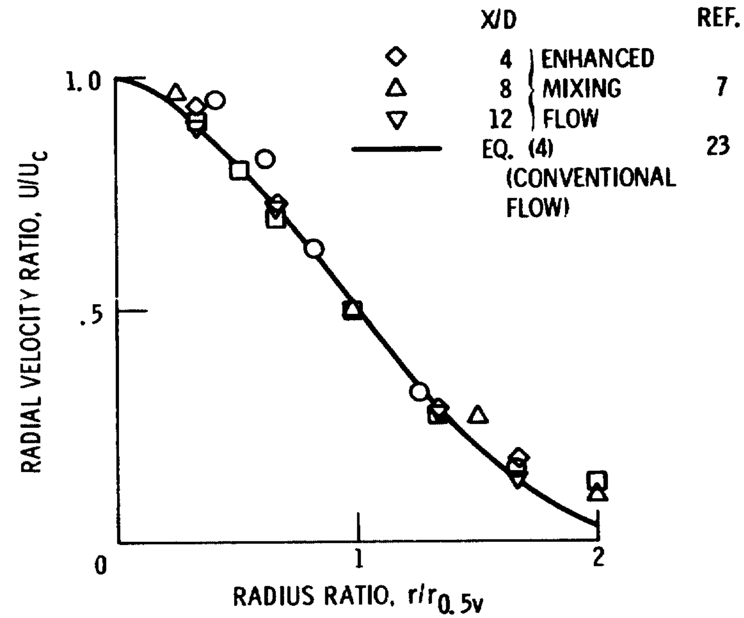

Figure 19. - Comparison of radial velocity profiles downstream of core for conventional and enhanced mixing jet flow. Convergent circular nozzle.

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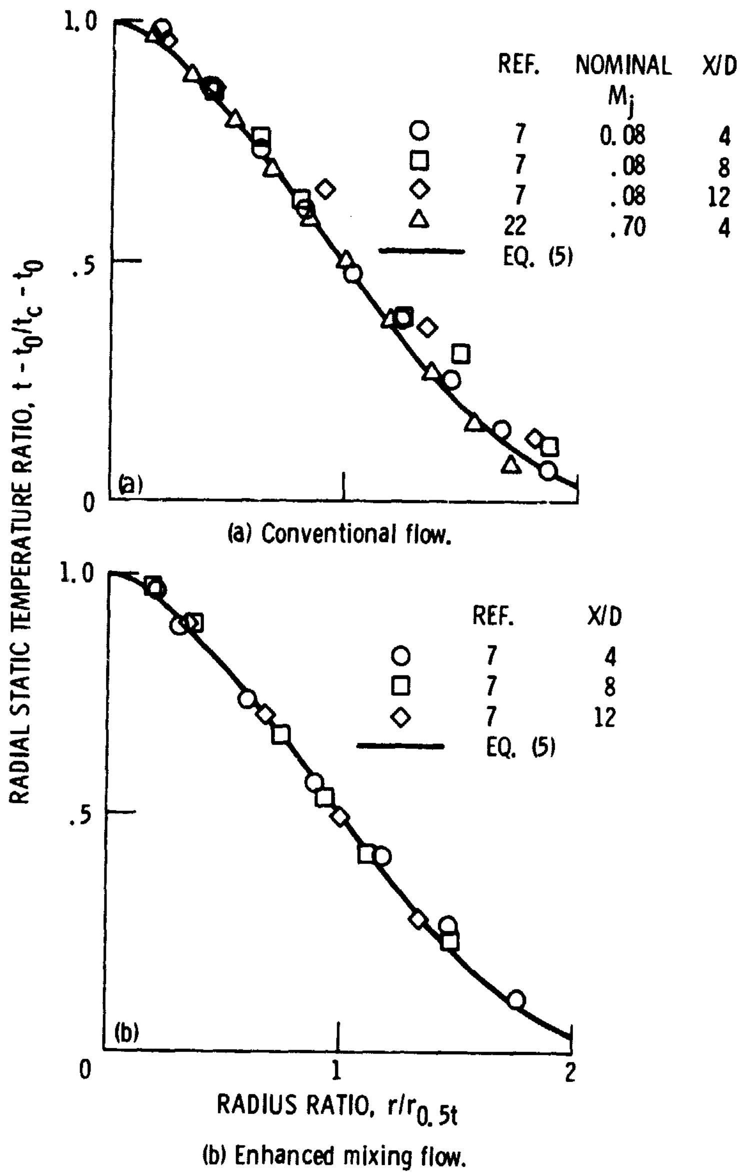

Figure 20. - Radial static temperature profiles. Convergent circular nozzle.

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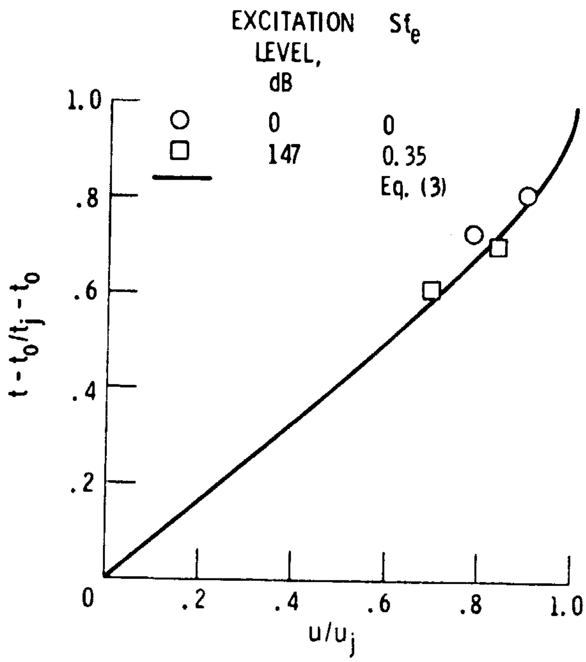

Figure A-1. - Static temperature relationship to jet velocity with and without acoustic excitation. Unpublished data; M_j, 0.8; t_j, 489.