Effects of Nozzle Exit Boundary-Layer Conditions on Excitability of Heated Free Jets

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This paper reports an experimental study on the effects of nozzle exit boundary-layer conditions on the excitability of heated free jets. The results were obtained at a Mach number of 0.8 and total temperatures of 300 and 670 K. External acoustic excitation was used to excite the jet. The excitation frequencies ranged up to 6 kHz, and the excitation levels were up to 150 dB. A level of 147 dB was used for most of the test points. Nozzle exit boundary-layer characteristics were controlled by boundary layer tripping upstream of the nozzle exit plane. It has been shown that the free jet mixing rate strongly depends on the boundary-layer characteristics at the nozzle exit. Furthere, it appears that jets with a thin laminar nozzle exit boundary layer are more selective about the otimum excitation frequency than those with a thick turbulent nozzle exit boundary layer. Finally, for the jet of Mach number 0.8, it appears that free jet mixing and development may be controlled by flow excitation as well as by nozzle exit boundary-layer modifications.

Nomenclature

D	= nozzle exit diameter
f	= frequency
$H_{\delta\theta}$	= displacement/momentum shape factor
$H_{\epsilon\theta}$	= energy/momentum shape factor
L	= acoustic level
M	= Mach number
p	= pressure
R	= nozzle exit radius
Re	= Reynolds number (based on D)
St	= Strouhal number, fD/U
T	= temperature
U,u	= velocity
X	= axial distance
y	= radial distance
δ	= displacement thickness
ϵ	= energy thickness
θ	= momentum thickness

Subscripts

A	= ambient
e	= excitation
ex	= excited
J	= jet
P	= probe
T	= total
un	= unexcited
θ	= momentum thickness

Introduction

JET excitation is a promising way to control and promote mixing of adjacent streams of fluids. The mixing enhancement of unheated jets by acoustic excitation[1-4] and turbulence suppression by controlled excitation[5,6] are well documented in the open literature. Fewer studies, however, have been devoted to the mixing enhancement of heated jets.[7,8] Studies carried out by the Lockheed-Georgia Company[8,9] indicated that, at certain jet operating conditions, the mixing of heated jets is less controllable by acoustic excitation than that of unheated ones. This was observed mainly for jet operating conditions where the nozzle exit boundary-layer characteristics of the heated jets significantly differed from those of unheated jets at the same jet exit Mach number.

Several studies[6,10,11] pointed out that the nozzle exit boundary-layer conditions significantly affect the development of mixing layers in a free jet. For low-speed unheated jets, it was concluded in Ref. 6 that "For laminar initial boundary layer, external acoustic excitation can lead to a decrease in the spreading velocity of the mixing layer..." and for the same jet operating and acoustic excitation conditions "...the influence of the acoustics disappeared when the boundary layer became turbulent."

Thus, a detailed experimental study was carried out to understand the effects of nozzle exit boundary-layer characteristics on the excitability of heated free jets.

Method of Approach

The main objective of this study was to determine the effects of nozzle exit boundary-layer characteristics on the excitability of heated free jets. To achieve this goal, experiments were carried out on acoustically excited, heated free jets with artificially modified nozzle exit boundary layers.

The experiments were conducted at two different jet operating conditions consisting of a jet exit Mach number of 0.8 and jet total temperatures of 300 and 670 K. The jet was excited using external acoustic excitation in a frequency range of 550–6000 Hz. The corresponding excitation Strouhal number range was different for each of the jet operating conditions according to the particular jet exit velocity. The range common to both jet operating conditions covered Strouhal numbers of 0.2–0.8. The jet was excited mostly at a constant excitation level of 147 dB measured at the center of the nozzle exit for no-flow conditions.

Test Facility and Instrumentation

Jet Facility

The experiments were conducted in Lockheed-Georgia's Jet Flow Facility shown in Fig. 1. This consists of a 256 mm diam plenum, followed by an initital contraction to 102 mm and a 690 mm long supply duct. The stainless steel converging test

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nozzle is mounted to the supply duct. The nozzle exit diameter is 50.8 mm and its length is 178 mm. The plenum-to-nozzle area contraction ratio is 25. The flow in this facility is supplied by compressed air and may be heated by a through-flow propane burner up to 1000 K at pressure ratios up to 4.

External Excitation Source

The partially assembled external excitation source section, mounted on the supply duct of the jet facility, is shown in Fig. 1. The external excitation source consists of eight 100 W Altec drivers, each mounted to a 35 mm diam connecting tube. At the nozzle end, the connecting tubes are bent toward the jet centerline and terminated in the proximity of the jet shear layer. The centers of the tube exits are located at a distance of 0.125 D_J downstream from the nozzle exit plane on a diameter of 80 mm. The connecting tubes are supported by adjustable spokes attached to the nozzle supply duct.

A constant, sufficiently high level of excitation was desired throughout the required Strouhal number range. Driver limitations, however, forced the compromise to a nominal level of 147 dB, measured at the center of the nozzle exit, which was attainable over all but the upper end of the frequency range. The excitation levels quoted throughout this paper are those measured at the nozzle axis at the focus at $X/D_J = 0.125$ of the driver tubes with *no nozzle flow.* The centerline level was measured using a microphone on the nozzle axis, and the amplifier setting was recorded for that level. This amplifier setting then was used to produce that same excitation level for both no-flow and flow cases.

The excitation levels were measured by a 6.4 mm diam Bruel and Kjaer microphone. The measurement uncertainty was ± 1 dB.

Instrumentation

The plenum total pressure, probe total pressure, plenum total temperature, and ambient temperature were continuously monitored during the experiments. In addition, the ambient pressure was read before each test set.

United sensor probes were used for the total pressure measurements: probe PAC-12-KL for the plenum total pressure, probe BR-020-12-C-11-120 for the boundary-layer total pressure, and miniature Kiel probe KAC-12 for the flowfield total pressure. Validyne pressure transducers P305D rated ± 220 and ± 86 kPa were used with these probes.

Pressure transducer outputs were digitized in steps of 100 μV. This represents steps of 4.4 Pa for the pressure transducer with a range of 220 kPa and 1.7 Pa for a transducer in the 86 kPa range. The voltage/pressure conversion was based on the best cubic-parabola fit through the calibration test points. The maximum standard deviation of the calibration test points from this fit was less than 110 Pa (range 220 kPa).

The plenum total temperature and ambient temperature were measured by Omega thermocouple probes CAIN-18U-12. All thermocouple readings were converted to the Kelvin scale using the multi-input process monitor Digi-Link (model LK-S) from Kaye Instruments.

The temperature conversion accuracy of the Digi-Link processor was ± 2.4 K at 700 K and ± 1.5 K at 300 K.

Boundary-Layer Modification

A number of parameters may characterize the nozzle exit boundary-layer conditions. The important parameters are boundary-layer displacement/momentum shape factor $H_{\delta\theta}$ and boundary-layer momentum thickness θ. The main objective of the boundary-layer modification was to keep these two parameters constant and, therefore, independent of the jet operating conditions.

To achive this goal, it was decided to trip the boundary layer inside the test nozzle. The main effort was devoted to nozzle exit boundary-layer modification of high-speed, highly heated jets ($M_J = 0.8$, $T_T = 670$ K). Several tripping rings of different ring diameter and wire diameter were employed. The most satisfactory results were achieved for a ring of 1.63 mm diameter wire placed 67 mm upstream of the nozzle exit plane.

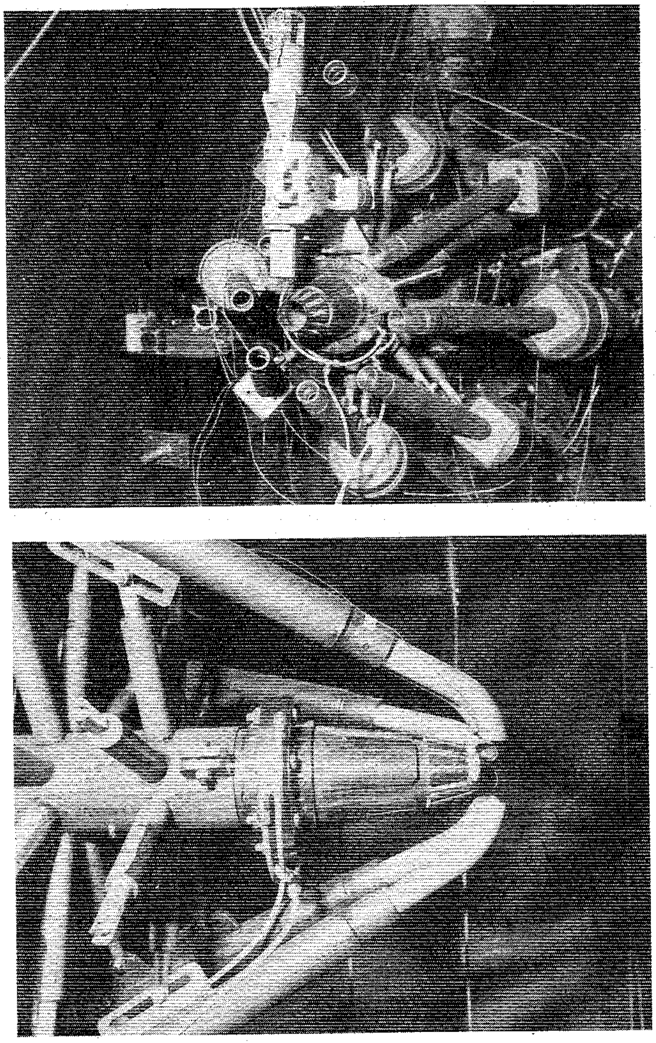

Fig. 1 Test facility.

Experimental Results

Unexcited, Untripped Jets

Nozzle exit boundary-layer profiles for both unheated and heated jets are shown in Fig. 2. From these profiles, nozzle exit boundary-layer characteristics were computed. The boundary-layer thickness was defined as the distance from the nozzle inner wall to the point where the total pressure profile gradient dropped to 0.5% of the total head per momentum thickness. The shape factor for the unheated untripped jet was 2.095; for the heated untripped jet, it was 2.557. A summary of untripped nozzle exit boundary-layer characteristics is given in Table 1. From this, it is obvious that significant changes take place in the nozzle exit boundary layer as the jet temperature increases. The nozzle exit boundary layer tends to relaminarize as the flow temperature rises. Radial profiles of flow Mach number measured at $X/D_J = 9$ are shown in Fig. 3. These measurements indicate a high degree of symmetry of the velocity radial profiles (circle symbols of the left-hand branch are replotted as triangular symbols in the right-hand half of the plots).

Excited, Untripped Jets

The jet response to excitation Strouhal number was determined by measurement of flow Mach numbers at the jet centerline at nine nozzle exit diameters downstream of the nozzle exit plane. The excitation Strouhal number effects are shown

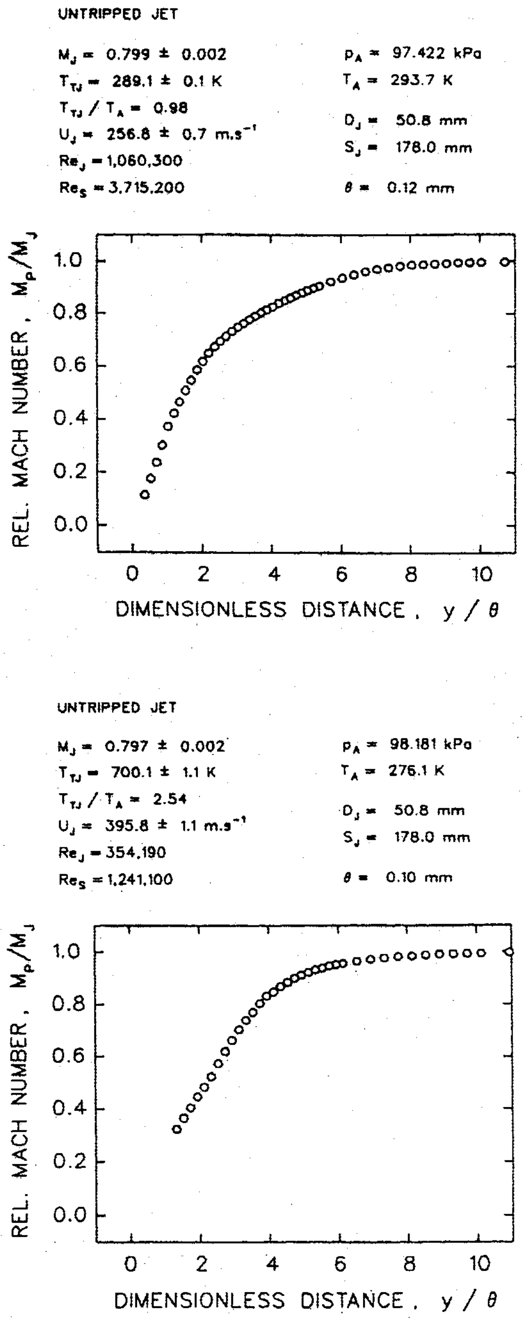

Fig. 2 Nozzle exit boundary-layer profiles of unheated and heated untripped jets.

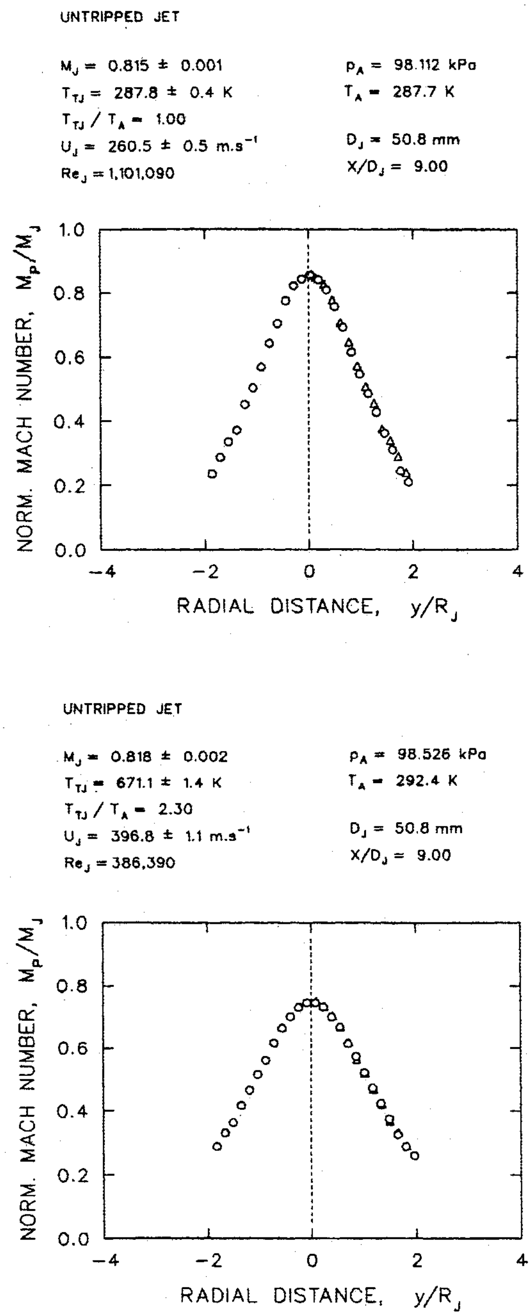

Fig. 3 Radial profiles at $X/D_J = 9$ of unheated and heated untripped jets.

in Fig. 4. Here, the flow Mach number of the excited jet is compared with the Mach number at the same point in the jet flowfield but in the absence of acoustic excitation (peak values from Fig. 3). As seen in Fig. 4, the unheated jet is affected at practically all examined Strouhal numbers. The heated jet, however, shows significantly weaker response to the applied acoustic excitation. Furthermore, the jet response is limited to certain frequencies.

Unexcited, Tripped Jets

To isolate the effects of flow heating on jet excitability, the nozzle exit boundary-layer dependence on jet operating conditions must be eliminated. In essence, the heated and unheated jets must have idential nozzle exit boundary-layer conditions. To avoid the problem of transition from a turbulent to a laminar boundary layer due to heating of the flow, a tripping device was employed. Nozzle exit boundary-layer profiles for heated and unheated tripped jets are shown in Fig. 5. The profiles closely resemble each other. The tripped boundary-layer

Table 1 Untripped nozzle exit boundary-layer characteristics

M_J	0.80	0.80
T_T, K	289	700
$H_{\delta\theta}$	2.095	2.557
$H_{\delta\epsilon}$	1.654	1.593
δ, mm	0.26	0.25
θ, mm	0.12	0.10
ϵ, mm	0.21	0.15
Re_θ	2605	676
$Re_J \times 10^6$	1.060	0.354

shape factors $H_{\delta\theta}$ were 1.816 for the unheated tripped jet and 1.796 for the heated tripped jet. The identity of shape factors also indicates close similarity of the two nozzle exit boundary-layer profiles. A summary of tripped nozzle exit boundary-layer characteristics is given in Table 2. As seen from the

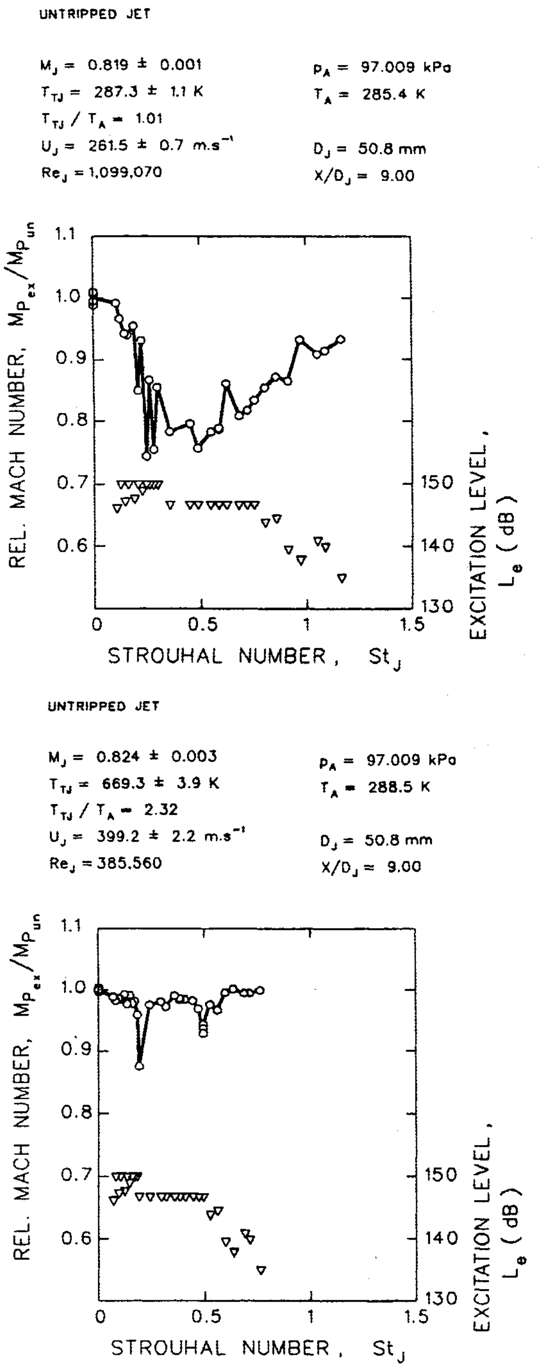

Fig. 4 Excitation Strouhal number effects on relative changes in jet mixing of unheated and heated untripped jets.

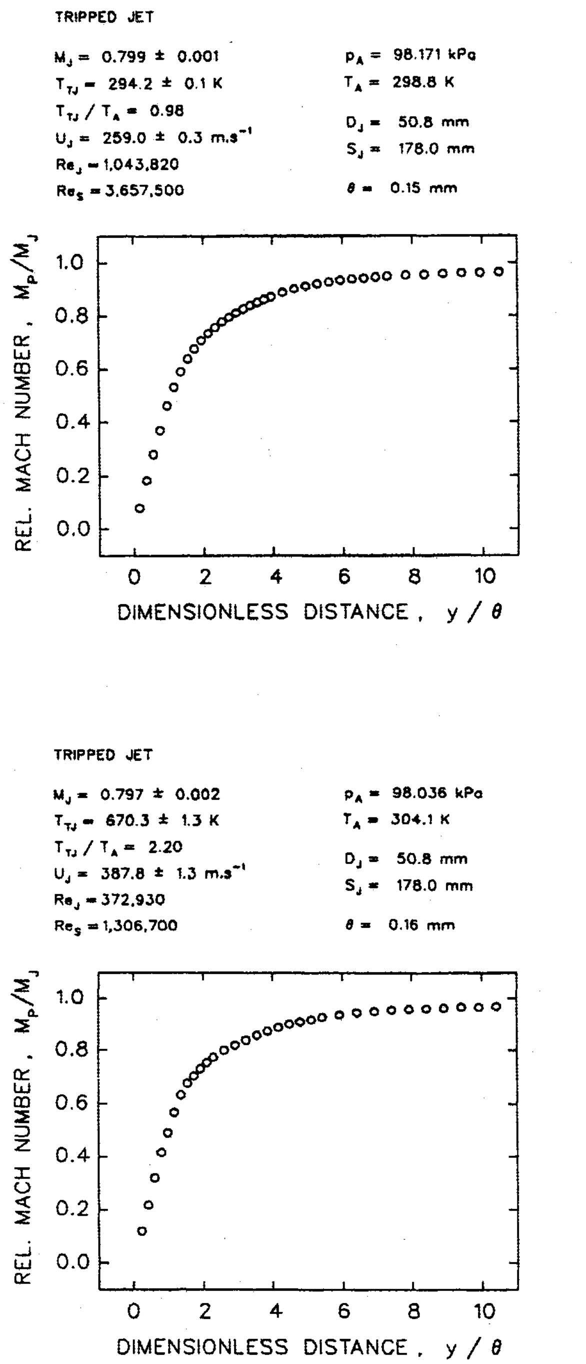

Fig. 5 Nozzle exit boundary-layer profiles of unheated and heated tripped jets.

results, the nozzle exit characteristics for the tripped boundary layer at a Mach number of 0.8 are not significantly modified by a change in jet total temperature. Thus, the selected method of boundary-layer modification satisfied the requirement of elimination of the nozzle exit boundary-layer dependence on jet operating conditions.

Radial Mach number profiles at $X/D_J=9$ for tripped jets are plotted in Fig. 6. A comparison of Figs. 3 and 6 shows that a change in nozzle exit boundary-layer conditions causes changes in the jet flowfield. For the heated jet, the flow Mach number on the centerline at $X/D_J=9$ increased from 75% of the jet exit Mach number for the untripped jet to 82% for the tripped jet. This indicates decreased mixing of the jet having the thicker turbulent boundary layer in comparison with the jet having a thinner laminar nozzle exit boundary layer.

Table 2 Tripped nozzle exit boundary-layer characteristics

M_J	0.80	0.80
T_T, K	294	670
$H_{\delta\theta}$	1.816	1.796
$H_{\delta\epsilon}$	1.717	1.725
δ, mm	0.28	0.29
θ, mm	0.15	0.16
ϵ, mm	0.26	0.28
Re_θ	3157	1167
$Re_J \times 10^6$	1.044	0.373

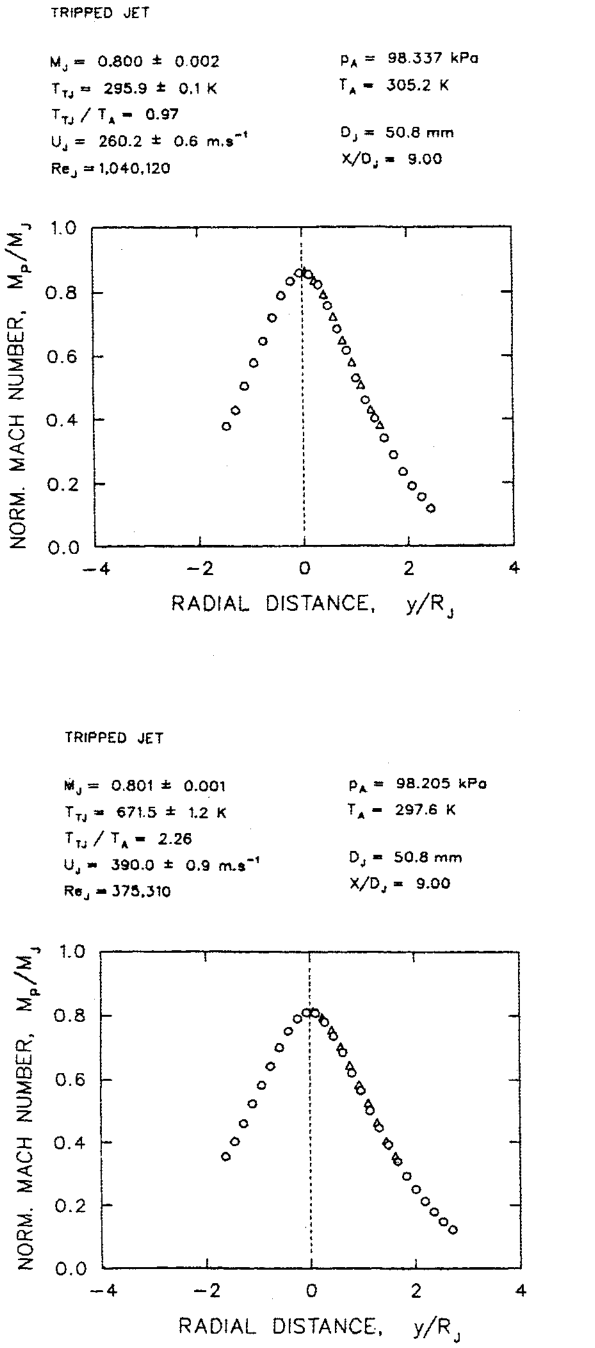

Fig. 6 Radial profiles at $X/D_J = 9$ of unheated and heated tripped jets.

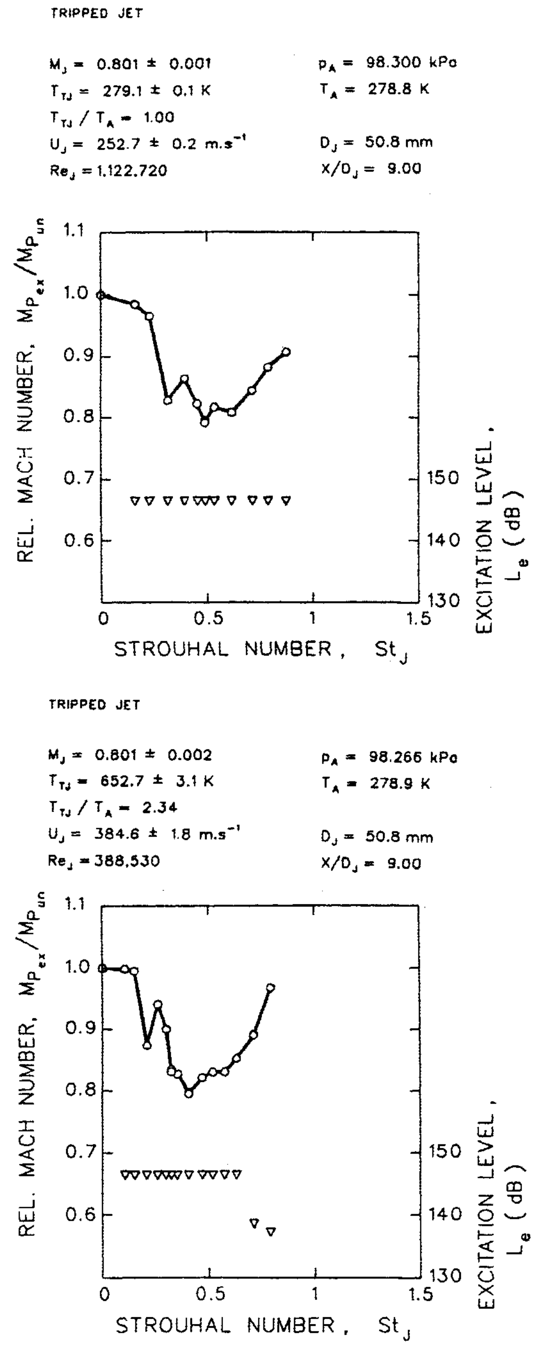

Fig. 7 Excitation Strouhal number effects on relative changes in jet mixing of unheated and heated tripped jets.

Excited, Tripped Jets

Throughout the paper, the excitation Strouhal numbers are based on the nozzle exit diameter. For the sake of completeness, Table 3 contains a conversion chart between Strouhal numbers based on nozzle diameter and those based on momentum thickness for both untripped and tripped jets.

Excitation Strouhal number effects on heated and unheated tripped jets are shown in Fig. 7. Apart from a small shift in the optimum excitation frequency, both jets show the same response to the acoustic excitation. For the optimum excitation frequency, the centerline flow Mach number at $X/D_J = 9$ drops to 80% of the unexcited value, indicating increased mixing due to acoustic excitation. This is a significant result showing that nozzle exit boundary-layer conditions play a key role in jet excitability and mixing. When the nozzle exit boundary-layer conditions were identical, no significant difference was found in the response of heated and unheated jets to the applied acoustic excitations.

Table 3 Strouhal numbers based on nozzle exit diameter and boundary-layer thickness

	St_θ			
	Untripped		Tripped	
St_J	Unheated	Heated	Unheated	Heated
0.5	0.0012	0.0010	0.0015	0.0016
1.0	0.0024	0.0020	0.0030	0.0031
1.5	0.0035	0.0030	0.0044	0.0047

Comparison of Tripped and Untripped Jets

Presented results show that the free jet mixing rate strongly depends on nozzle exit boundary-layer conditions. As shown in Fig. 3. for a constant Mach number unexcited jet, the effect

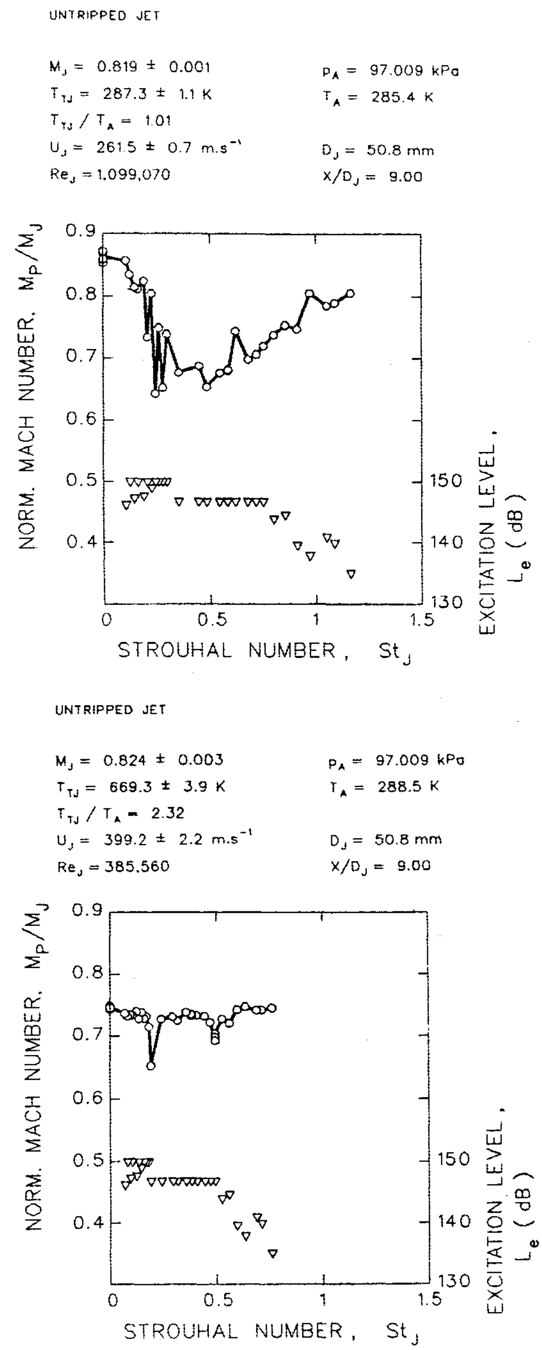

Fig. 8 Excitation Strouhal number effects on absolute changes in jet mixing of unheated and heated untripped jets.

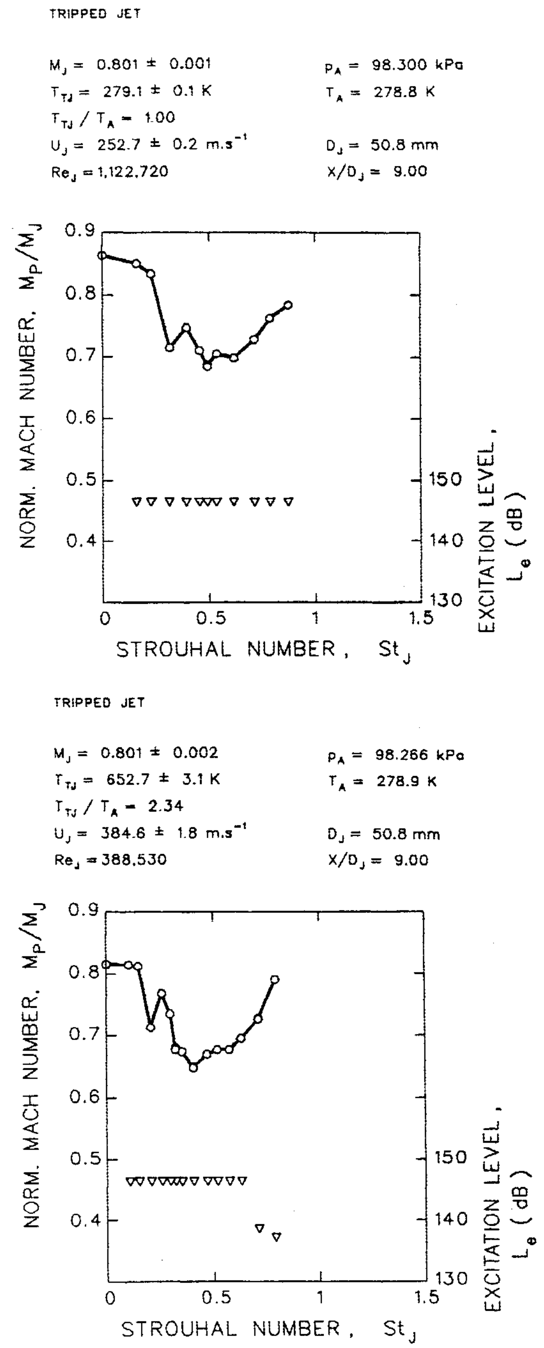

Fig. 9 Excitation Strouhal number effects on absolute changes in jet mixing of unheated and heated tripped jets.

of changing the boundary layer from turbulent to laminar by heating was to reduce the centerline Mach number, M_P/M_J at $X/D_J=9$ from 0.86 to 0.73. When the nozzle exit boundary layer, on the other hand, was tripped and kept turbulent even for the low Reynolds number heated jet (Fig. 6), the change in the centerline Mach number was very small. This indicates that free jet mixing and development may be controlled also by nozzle exit boundary-layer modification.

In Figs. 4 and 7, the jet mixing enhancement was judged on the basis of relative changes between excited and unexcited states. To assess the achieved intensity of mixing, the results are replotted in Figs. 8 and 9 on the basis of local Mach number normalized by the jet exit Mach number. For unheated jets (Figs. 8 and 9), there are no differences between untripped and tripped jets for excitation Strouhal numbers above 0.3. For excitation Strouhal numbers below 0.3, however, the untripped jet seems to be more responsive to excitation than the tripped one. This greater response, however, may be attributable to the higher excitation level applied to the untripped jet in this range of excitation Strouhal numbers. In essence, it may be concluded that for identical excitation levels both jets respond similarly to acoustic excitation.

The tripped heated jet, judged on the relative basis (M_{ex}/M_{un}), seems to be more excitable than the untripped on (Figs. 4 and 7). However, the tripped heated jet's centerline Mach number at $X/D_J=9$ for the no-excitation case was substantially higher than the one for the untripped jet. It appears that the greater relative gain in mixing enhancement of the tripped jet results from the decreased "natural" mixing caused by the boundary-layer tripping, as discussed above. Thus, the jet response must be judged on an absolute basis taking into account the level of "natural" mixing for unexcited cases. A closer inspection of Figs. 8 and 9 reveals that, for the same excitation level of 147 dB, the centerline flow Mach number at $X/D_J=9$ drops to approximately 65% of the jet exit Mach number regardless of the flow temperature or nozzle exit boundary-layer conditions. However, the jet with a thin laminar nozzle exit boundary layer (untripped jet, Fig. 8) responds only to certain excitation frequencies. It appears to be more selective about the optimum excitation frequency than jets with thick, turbulent nozzle exit boundary layers.

Conclusions

The following conclusions were derived from this study.

1) The free jet mixing rate strongly depends on nozzle exit boundary-layer conditions (Fig. 3).

2) Relative gain in mixing enhancement due to flow excitation, in terms of a ratio of flow local Mach numbers of excited and unexcited states at the optimum excitation frequency, is a strong function of nozzle exit conditions (Fig. 4) but seems to be independent of flow temperatures (Fig. 7).

3) Intensity of mixing at the optimum excitation frequency, in terms of the ratio of the flow local Mach number to the jet exit Mach number, appears to be independent of the nozzle exit conditions (Figs. 8 and 9).

4) Jets with a thin laminar nozzle exit boundary layer appear to be more selective as far as the optimum excitation frequency is concerned than those with a thick turbulent nozzle exit boundary layer (Figs. 4 and 8).

5) Free jet mixing and development may be controlled by acoustic excitation as well as by nozzle exit boundary-layer modification (Figs. 3 and 6).

Acknowledgement

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References

[1]Crow, S. C. and Champagne, F. H., "Orderly Structure in Jet Turbulence," *Journal of Fluid Mechanics,* Vol. 48, 1971, pp. 547-591.

[2]Vlasov, E. V. and Ginevskii, A. S., "The Aeroacoustic Interaction Problem" *Soviet Physics—Acoustics,* Vol. 26, 1980, pp. 1-7.

[3]Schmidt, C., "Aerodynamic Characaterization of Excited Jets," *Journal of Sound and Vibration,* Vol. 61, 1978, pp. 148-152.

[4]Ahuja, K. K., Lepicovsky, J., Tam, C. K. W., Morris, P. J., and Burrin, R. H., "Tone-Excited Jet, Theory and Experiments," NASA CR-3538, 1982.

[5]Zaman, K. B. M. Q. and Hussain, A. K. M. F., "Turbulence Suppression in Free Shear Flows by Controlled Excitation," *Journal of Fluid Mechanics,* Vol. 103, 1981, pp. 133-159.

[6]Pavel'ev, A. A. and Tsyganok, V. I., "Influence of Acoustics and Flow Regime in the Boundary Layer on Nozzle Walls on the Mixing of an Immersed Jet," *Izvestiya Akademiii Nauk SSSR, Mekhanika Zhidkosti i Gaza,* No. 6, 1982, pp. 36-42.

[7]Ivanov, N. N., "Acoustic Effect on the Root Part of a Turbulent Jet," *Izvestiya Akademii Nauk SSSR, Mekhanika Zhidkosti i Gaza,* No. 4, 1970, pp. 182-186.

[8]Lepicovsky, J., Ahuja, K. K., and Salikuddin, M., "An Experimental Study of Tone-Excited Heated Jets," *Journal of Propulsion and Power,* Vol. 2, 1986, pp. 149-154.

[9]Lepicovsky, J., Ahuja, K. K., Brown, W. H., and Morris, P. J., "Acoustic Control of Free Jet Mixing," *Journal of Propulsion and Power,* Vol 2, 1986, pp. 3123-330

[10]Hill, Jr., W. G., Jenkins, R. C., and Gilbert, B. L., "Effects of the Initial Boundary-Layer State on Turbulent Jet Mixing," *AIAA Journal,* Vol. 14, 1976, pp. 1513-1514.

[11]Hussain, A. K. M. F. and Zedan, M. F., "Effects of the Initial Condition on the Axisymmetric Free Shear Layer: Effects of the Initial Momentum Thickness," *Physics of Fluids,* Vol. 21, 1978, pp. 1100-1112.