An Experimental Study of Tone-Excited Heated Jets

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The objective of this investigation was to obtain detailed experimental data on the effects of upstream acoustic excitation on the mixing of heated jets with the surrounding air. Based on the information gathered in the literature survey, a technical approach was developed to carry out a systematic set of mean flowfield measurements for a broad range of jet operating and acoustic excitation conditions. Most of the results were obtained at Mach numbers of 0.3 and 0.8 and total temperatures of up to 800 K. Some measurements were made also for the fully expanded supersonic jet of $M_j = 1.15$. The maximum level of excitation was $L_e < 153$ dB and a range of excitation frequencies up to $f_e = 4$ kHz was used. The important results derived from this study can be summarized as follows: 1) the sensitivity of heated jets to upstream acoustic excitation varies strongly with the jet operating conditions, 2) the threshold excitation level increases with increasing jet temperature, and 3) the preferred Strouhal number does not change significantly with a change of the jet operating conditions.

Nomenclature

D_j = nozzle exit diameter
f_e = excitation frequency
$H_{\delta\theta}$ = shaped factor
L_e = excitation level
M_j = jet Mach number
M_{ex} = local Mach number, tone-excited jet
M_{un} = local Mach number, unexcited jet
Re_j = Reynolds number, based on nozzle exit diameter
Re_θ = Reynolds number, based on boundary-layer momentum thickness
St_j = Strouhal number, based on nozzle exit diameter
St_θ = Strouhal number, based on boundary-layer momentum thickness
T_0 = ambient temperature
T_t = jet total temperature
U_j = jet velocity
X = axial distance
δ = boundary-layer displacement thickness
θ = boundary-layer momentum thickness

Introduction

ALTHOUGH jet mixing processes are encountered in many engineering applications, there is still a lack of well-understood and controllable methods of promoting mixing for a given flow situation. It is now generally acknowledged that large-scale structures are the key element in controlling mixing of the adjacent streams of fluid. Using the proper flow excitation, the amplitude of the large-scale structures increases, which may promote the mixing.

Unheated Jets

The measurements on acoustically excited, unheated jets performed by Crow and Champagne,[1] Sarohia and Massier,[2] Schmidt,[3] Vlasov and Ginevskii,[4] Zaman and Hussain,[5] and Ahuja et al.,[6,7] among others, showed the possibility of mixing enhancement for moderate excitation Strouhal numbers ($0.3 < St_j < 1.0$). On the other hand, high-frequency acoustic excitation ($St_j = 2 \div 5$) of a turbulent jet attenuates the turbulent mixing, as reported by Vlasov and Ginevskii.[4] Similar results were obtained also by Zaman and Hussain,[8] who found that a noticeable suppression occurs over the Strouhal number range $0.008 < St_\theta < 0.024$. In this case, the Strouhal number St_θ was based on the initial shear layer momentum thickness rather than on the jet diameter.

Heated Jets

As mentioned briefly above, the effects of acoustic excitation on the behavior of unheated jets are well documented in the open literature. However, there is a serious lack of experimental data on the subject of the effects of acoustic excitation on hot jet mixing. Jubelin[9] and Lu[10] investigated the effects of acoustic excitation on heated jets, but they acquired only acoustic data and no flow measurements were obtained. Ivanov[11] and Vermeulen et al.[12] showed that, for the certain flow situations, the hot jet mixing can be improved by acoustic excitation. Nevertheless, no firm general conclusions, as to trends due to acoustic excitation in hot jet mixing, can be drawn from the results discussed above. A detailed and comprehensive study to understand better the potentials of acoustic excitation in hot jet mixing is clearly needed, since the mixing of hot jets is involved in many important practical applications.

Method of Approach

The main objective of this study was to obtain detailed experimental mean flow data on the effects of relatively strong upstream acoustic excitation on the mixing of heated jets with the surrounding air. From measurements in unheated jets, it is known that the excitability of the jets depends on the excitation conditions and also on the nozzle exit boundary thickness and profile (laminar or turbulent). Therefore, the effects of the jet operating conditions on the nozzle exit boundary-layer thickness and type were investigated first. Then, an optimization of the Strouhal number effect on jet behavior was made. Finally, the investigations of the excitation level effects were conducted for those Strouhal numbers that indicated a significant effect of upstream acoustic excitation on the jet behavior.

Test Facility

All experiments were conducted in Lockheed's jet flow facility. The facility, shown in Fig. 1, consists of a 256 mm diam plenum, followed by an initial contraction to 102 mm

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diam, 340 mm long source-section duct. The 50.8 mm diam test nozzle is attached to the source-section duct. The plenum to nozzle area contraction ratio is 25. Two precisely machined stainless steel nozzles were used in the present program. One of the nozzles is convergent, while the other one is convergent-divergent with fully expanded design Mach number of 1.2. The flow in this facility may be heated by a through-flow propane burner up to 1000 K at pressure ratio exceeding 4.

The source section consists of eight acoustic drivers, coupled in pairs, equally spaced along the circumference of the nozzle supply duct. The source section utilizes 100 W Altec model 290E acoustic drivers. The sound is funneled to the nozzle supply duct through four 25.4 mm diam tubes. Each tube is connected to a pair of acoustic drivers through a "Y" connector.

United Sensor probes were used for flow measurements as well as for experiments in the nozzle exit boundary layer. The flow survey was made with the combined pressure and temperature probe DAT-187-12-CD-C/A-36. The boundary-layer probe BR-.020-12-C11-.120 was used for boundary-layer measurements. Pressure transducers Validyne P305D, rated for pressure ranges of ±86 and ±350 kPa, were used in connection with the above mentioned probes.

Further details about the test facility and data acquisition and reduction procedures are given in Ref. 13.

Nozzle Exit Boundary-Layer Experiments

Mach Number Effects

The effects of jet Mach number on the nozzle exit boundary-layer behavior were studied by measuring the boundary-layer velocity profiles for various jet exit Mach numbers in the range $M_j = 0.16$-0.9. The measurements were made for the unheated jet. The boundary-layer profiles are shown in Fig. 2. It was found that the nozzle exit boundary layer gradually changed from laminar at low Mach numbers to turbulent at high Mach numbers. This becomes clearer on examining the variation of the nozzle exit boundary-layer displacement thickness δ with the Reynolds number, based on the nozzle exit diameter, as shown in Fig. 3.

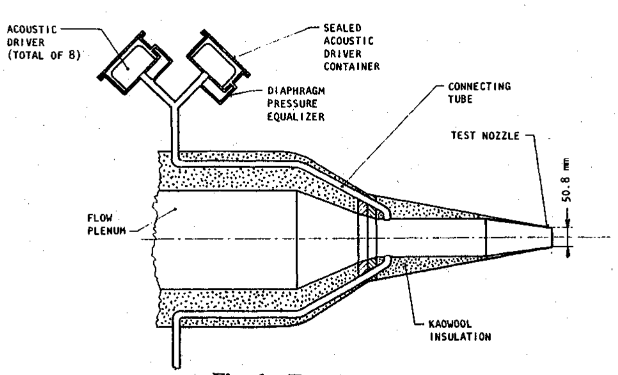

Fig. 1 Test facility.

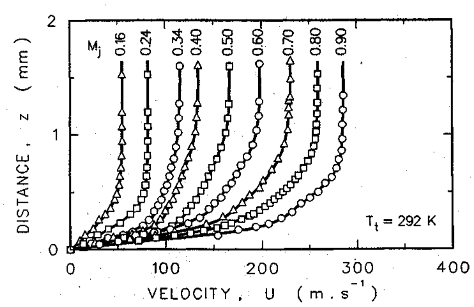

Fig. 2 Jet Mach number effects on nozzle exit boundary-layer profiles.

The process of boundary-layer transition, from laminar to turbulent boundary-layer profile, is characterized by a large decrease in a value of the boundary-layer shape factor $H_{\delta\theta} = \delta/\theta$. In the case of the present nozzle exit boundary layer, a sudden change in the shape factor value from 2.4 to 1.8 occurs at $Re_j \cong 350{,}000$, as seen in Fig. 4. Thus, it appears that the transition of the laminar boundary layer to a turbulent one occurs at a jet Reynolds number of $Re_j \cong 350{,}000$.

Total Temperature Effects

The effects of the jet total temperature on nozzle exit boundary-layer behavior were studied mostly at a jet exit Mach number of $M_j = 0.8$. At this Mach number and for the unheated jet, the exit boundary layer was found to be turbulent, as it was shown above. On raising the plenum total temperature gradually from $T_t = 290$ K (unheated case) to $T_t = 809$ K, the nozzle exit boundary layer changed from turbulent to laminar. A family of nozzle exit boundary-layer profiles for different jet total temperatures and jet Mach numbers

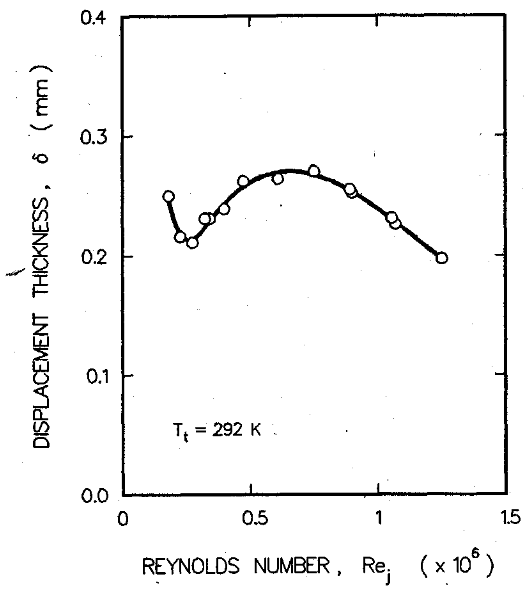

Fig. 3 Jet Mach number effects on nozzle exit boundary-layer displacement thickness.

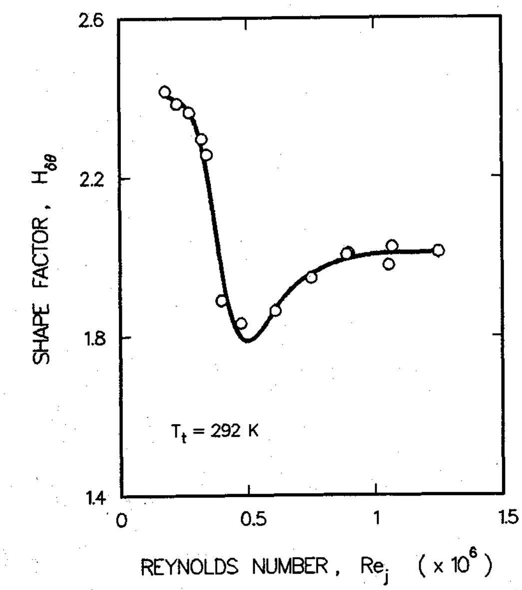

Fig. 4 Jet Mach number effects on nozzle exit boundary-layer shape factor.

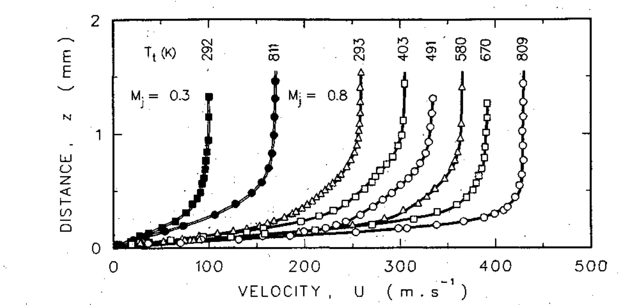

Fig. 5 Jet total temperature effects on nozzle exit boundary-layer profiles.

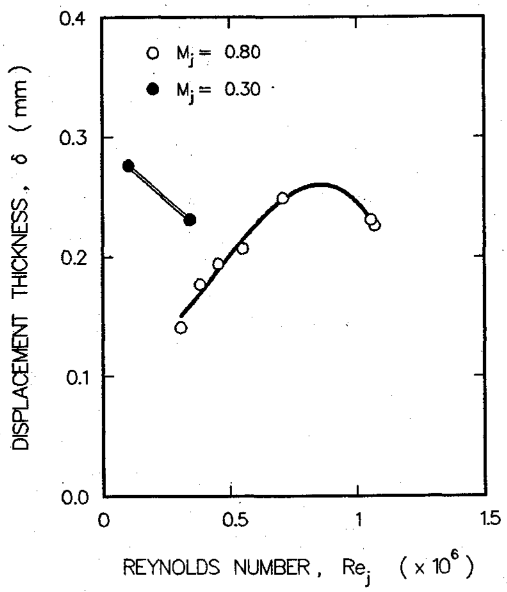

Fig. 6 Jet total temperature effects on nozzle exit boundary-layer displacement thickness.

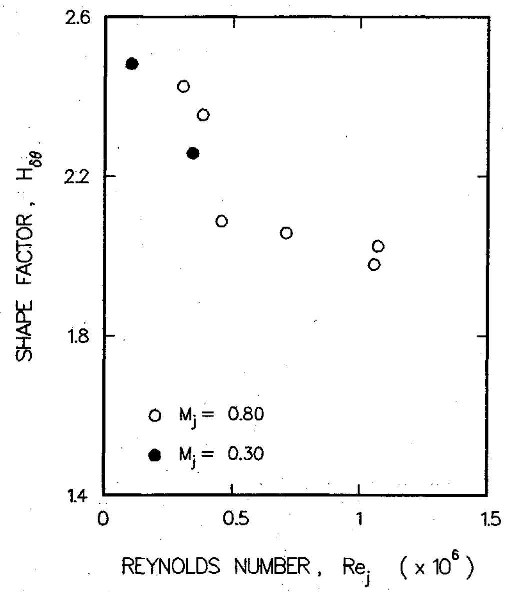

Fig. 7 Jet total temperature effects on nozzle exit boundary-layer shape factor.

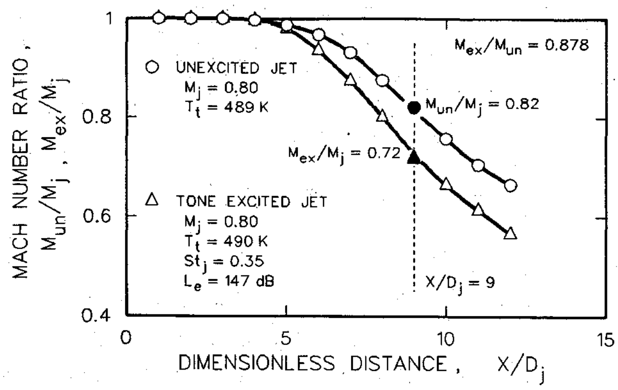

Fig. 8 Acoustic excitation effects on centerline velocity variation.

of $M_j = 0.8$ and 0.3 is shown in Fig. 5. The effect of temperature on the nozzle exit boundary layer can best be summarized by plotting the variations of the boundary-layer displacement thickness δ and shaped factor $H_{\delta\theta}$ as shown in Figs. 6 and 7.

On comparing the variations of the boundary-layer thickness and shape factor for jet Mach number and jet total temperature changes, it is seen that for a given Reynolds number, the boundary layer is thinner for heated flows. The experiments thus show clearly that the effects of jet Mach number and jet total temperature do not scale universally as a function of Reynolds number based on the nozzle diameter.

Excitation Strouhal Number Effects

Experiments were carried out to determine the excitation Strouhal number that caused the greatest changes in the jet flowfield. The Strouhal number optimization was based on changes in the local Mach number along the jet centerline at nine nozzle exit diameters downstreams of the nozzle exit plane. The local Mach number at this point was compared with the Mach number at the same point in the jet flowfield, but in the absence of upstream acoustic excitation, as indicated in Fig. 8. The excitation sound pressure levels were the maximum levels of excitation achievable at the particular Strouhal number.

It should be mentioned that the excitation levels existent in the nozzle exit plane are measured indirectly using a microphone located outside the flow. The levels in the flow during the tests are deduced from the readings of the outside microphone and from the predetermined relationship between the outside microphone and a microphone located at the jet centerline. In addition, this exercise is carried out only for the unheated jet, but it is assumed to remain the same for the heated jet. The levels measured by the outside microphone may be affected by a particular layout of the test room, especially because the free jet facility is not located in an anechoic environment.

The optimization exercise for the Strouhal number effects was carried out in three parts: unheated subsonic jets, heated subsonic jets, and supersonic jets. The results for each of these jets are described below.

Unheated Subsonic Jets

The distributions of relative Mach numbers as a function of excitation Strouhal number for low and high jet Mach numbers are plotted in Figs. 9 and 10. In the same figures the excitation levels existent at the nozzle exit are also plotted. The nonuniformity of the excitation levels partially affects the relative Mach number distributions; however, the general trend is clearly indicated. In general, the responses of both jets to upstream acoustic excitation are similar. The differences are probably due to the different excitation levels applied at particular Strouhal numbers. As seen in Figs. 9 and 10, the most effective Strouhal numbers are in the range of 0.4-0.5 for both low and high Mach number unheated jets.

It should be mentioned here that the nozzle exit boundary-layer thicknesses were approximately the same in both cases, as shown in Fig. 3. However, the high Mach jet of $M_j = 0.8$

had a fully developed turbulent nozzle exit boundary layer, as indicated in Fig. 4, while the low Mach number jet of $M_j = 0.3$ was in the transition region between laminar and turbulent boundary-layer profile.

Heated Subsonic Jets

The effects of excitation Strouhal number on heated jets were not consistent at different Mach numbers. For example, as may be seen by comparison of Figs. 9 and 11, the excitability of the jet at $M_j = 0.3$, which was heated to $T_t = 811$ K, has improved significantly with respect to the unheated one. However, at a high Mach number of $M_j = 0.8$ at this total temperature, no effects of the upstream acoustic excitation on the jet were observed at all. This was rather a surprising result, so additional experiments were carried out to clarify this inconsistency. The results are shown in Figs. 12-15. The sequence of Figs. 10 and 12-15 clearly shows the effect of increasing jet total temperature on the jet excitability at the jet Mach number of $M_j = 0.8$. The higher the jet total temperature, the less the jet is affected by upstream acoustic excitation.

It is to be noted that the nozzle exit boundary layer decreases in thickness for high Mach numbers and increases in thickness for low Mach numbers due to the heating of the

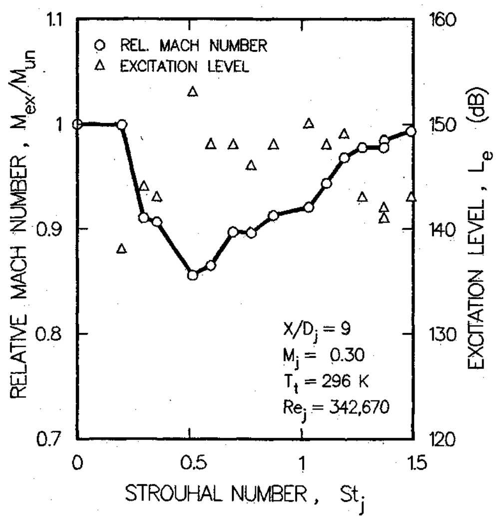

Fig. 9 Excitation Strouhal number effects on low Mach number unheated jet.

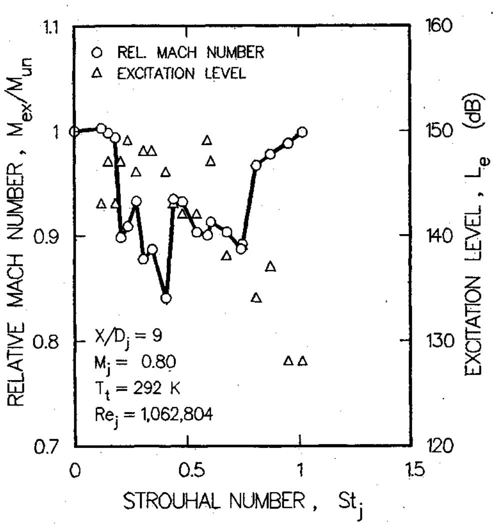

Fig. 10 Excitation Strouhal number effects on high Mach number unheated jet.

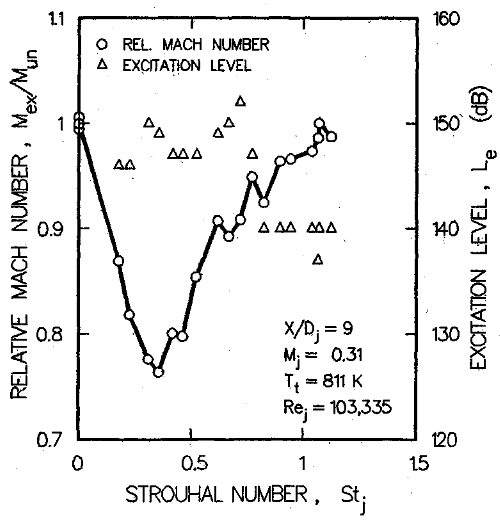

Fig. 11 Excitation Strouhal number effects on low Mach number heated jet.

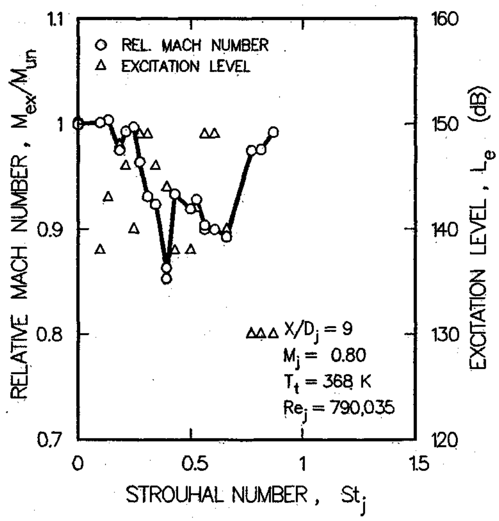

Fig. 12 Excitation Strouhal number effects on high Mach number heated jet.

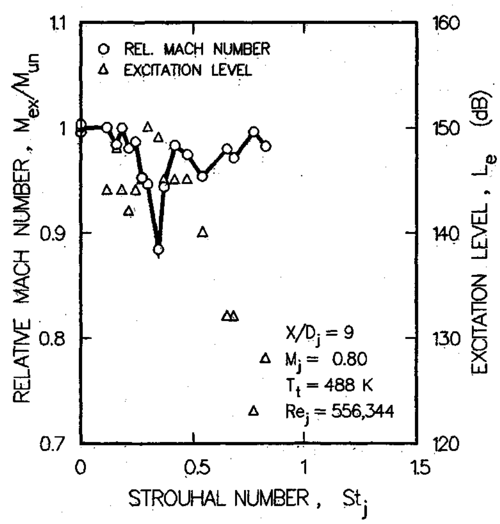

Fig. 13 Excitation Strouhal number effects on high Mach number heated jet.

flow, as seen in Fig. 6. It appears, from Fig. 7, that both jets showed the tendency toward the relaminarization of the nozzle exit boundary-layer profile due to the increased jet total temperature. While the low-speed heated jet ($M_j = 0.3$, $T_t = 811$ K) reached the laminar boundary-layer profile, the high-speed heated jet ($M_j = 0.8$, $T_t = 809$ K) reached just the region of transition from turbulent to laminar nozzle exit boundary-layer profile.

Supersonic Jets

The experiments were aimed at revealing the effects of upstream acoustic excitation on a supersonic, fully expanded, heated jet. The jet operating conditions were $M_j = 1.15$ and $T_t = 489$ K. Jet noise spectra measurements revealed that shockless expansion for the nozzle used occurred actually at a jet Mach number of $M_j = 1.15$, which was slightly lower than the nozzle nominal Mach number 1.2.

The Strouhal number optimization experiment shows that a supersonic heated jet of $M_j = 1.15$ and $T_t = 489$ K is practically unaffected by upstream acoustic excitation, as seen in Fig. 16. An additional experiment was carried out for supersonic unheated jet. As shown in Fig. 17, the unheated supersonic, fully expanded jet response to upstream acoustic excitation is similar to that of high-speed subsonic jets. In accordance with previously acquired results for high-speed subsonic jets, it appears that the excitation levels used may not be high enough to enhance the mixing of supersonic jets heated above the total temperature of $T_t < 500$ K in the range of excitation Strouhal numbers up to $St_j = 0.6$.

Excitation Level Effects

The excitation level effect experiments were carried out for jet Mach number of $M_j = 0.8$ and four jet total temperatures of $T_t = 291$, 367, 488, and 672 K. Similar to the Strouhal number optimization experiments, the excitation level effect experiments were also based on the changes of the centerline local Mach number at $X/D_j = 9$ as described in the previous section. The excitation Strouhal number at each test point was selected in accordance with the results of the Strouhal number optimization experiments presented above.

The excitation level effects on jets of different total temperatures are shown in Fig. 18. From this figure, it appears that higher temperature jets require higher excitation levels for the flow to respond to this excitation. Probably due to this trend, no effects of upstream acoustic excitation were observed at the jet operating conditions corresponding to Figs. 14 and 15. The maximum excitation level that could be generated in our test facility was 153 dB (rel. 2 × 10^5 Pa) or

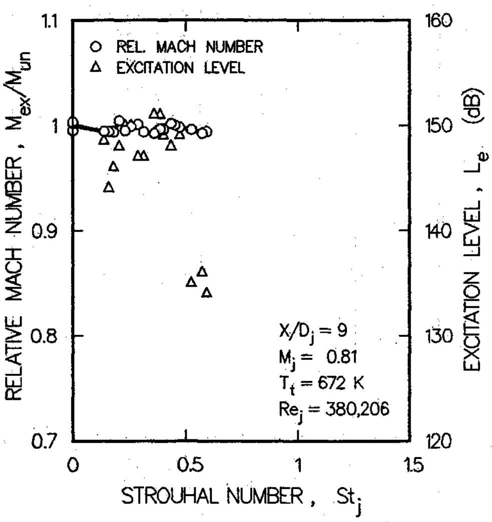

Fig. 14 Excitation Strouhal number effects on high Mach number heated jet.

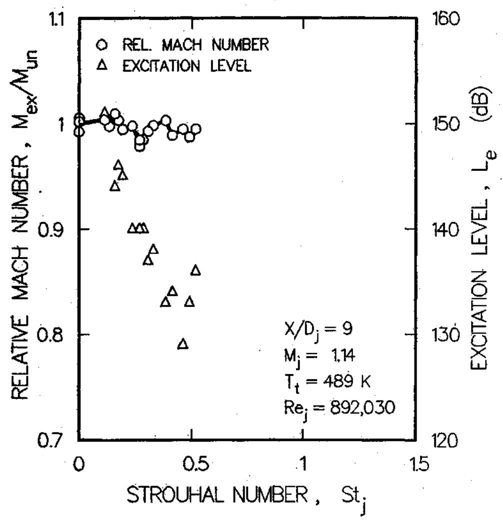

Fig. 16 Excitation Strouhal number effects on supersonic heated jet.

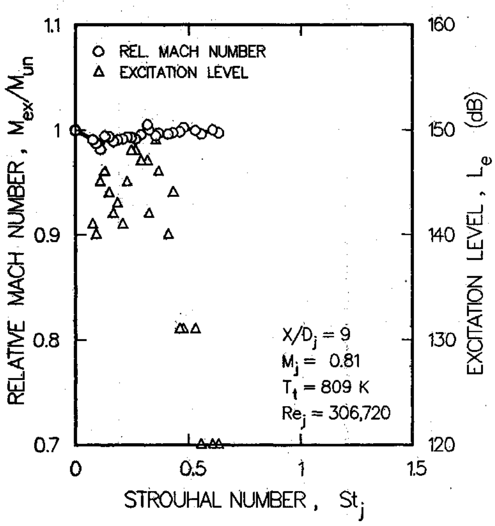

Fig. 15 Excitation Strouhal number effects on high Mach number heated jet.

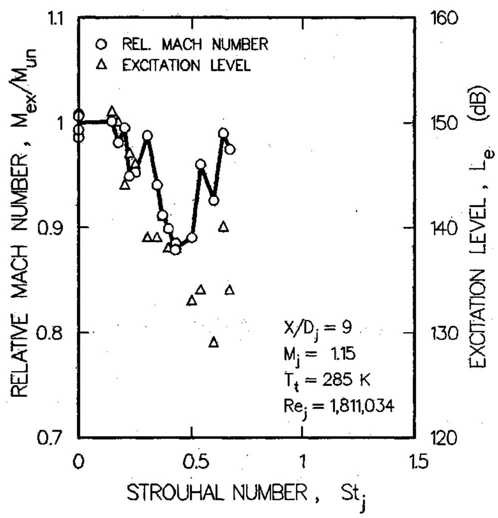

Fig. 17 Excitation Strouhal number effects on supersonic unheated jet.

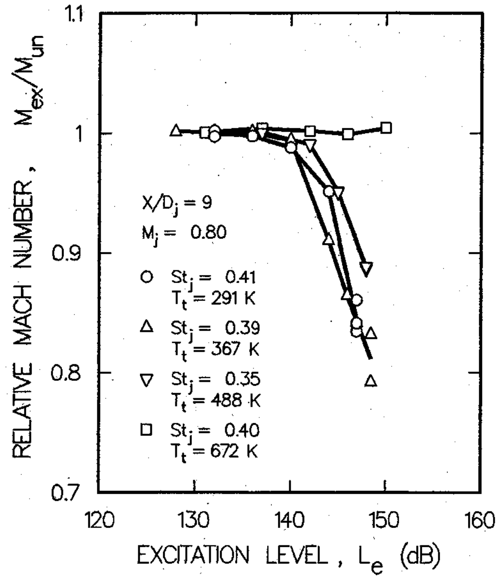

Fig. 18 Excitation level effects on high Mach number heated jets.

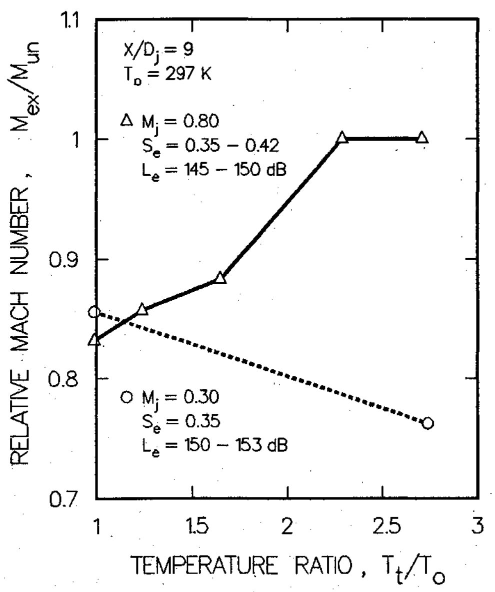

Fig. 19 Jet total temperature effects on acoustically excited jets.

lower at high M_j and T_t; this may not be high enough to produce measurable flow changes at the high-velocity, high-temperature conditions.

Conclusions

A summary of key observations is given below. Of course, the validity of the conclusions presented here is restricted to the range of investigated jet operating and flow excitation conditions.

1) The sensitivity of heated jets to upstream acoustic excitation strongly varies with the jet operating conditions.

2) A low Mach number jet ($M_j = 0.3$) shows increased sensitivity to upstream excitation as the jet temperature is raised, but the high Mach number jet ($M_j = 0.8$) exhibits a decrease in the jet excitability as the jet temperature rises, as shown in Fig. 19.

3) The threshold excitation level increases with increasing jet temperature.

4) The measurements indicate that, in the case of heated jets, the excitation level is of prime importance. Higher-temperature jets require higher excitation levels for the flow to respond to this excitation.

5) The preferred excitation Strouhal number does not change significantly with a change of the jet operating conditions.

6) The excitation Strouhal number that produces the maximum changes in the jet flowfield varies little with the jet operating conditions. As shown above, the most effective excitation Strouhal number remained in the range 0.35-0.5 at all of the examined jet operating conditions.

The results obtained in this experimental investigation have pointed out some differences between heated and unheated jets as far as their excitability and consequently their rates of mixing are concerned. In addition, it has provided an experimental data base on heated jets under the upstream acoustic excitation.

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