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Enhancement of Mixing in High-Speed Heated Jets Using a Counterflowing Nozzle

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An experimental study was conducted to examine the effect of annular counterflow on the mixing of high-speed subsonic jets and slightly underexpanded supersonic jets. Suction was applied to a collar placed concentrically about a converging nozzle to create a counterflowing stream around the jet periphery. The primary jet was operated at exit Mach numbers between 0.4 and 1.2, for stagnation temperatures from 20 to 400°C. The results show that moderate levels of counterflow can be used to enhance the mixing between the jet and surrounding fluid. Furthermore, the counterflow control technique becomes more effective as the jet temperature is increased.

Nomenclature

D = jet exit diameter
L = length of extension collar
M = Mach number
r = radial coordinate
T = temperature
U = mean streamwise velocity
w = gap width of secondary stream
x = streamwise coordinate

Subscripts

ns = no suction
s = with suction
0 = stagnation conditions
1 = primary stream conditions in jet exit plane
2 = secondary stream conditions in jet exit plane

Introduction

RESEARCHERS have been plagued for years with the problem of enhancing mixing in supersonic heated jets. In high-speed combustion chambers, for instance, the extent of mixing between the hot product gases and a secondary airstream will in large part determine the amount of NO_x formed in the chamber. Enhanced mixing in a jet engine exhaust can lead to significant suppression of jet noise as well as reductions in the temperature signature of the exiting stream. Advancing these technologies will require the development of novel jet mixing schemes that are efficient as well as sufficiently robust to survive outside the laboratory. The aim of the present research was to explore a new approach to the mixing problem in compressible heated jets, based on recent studies of countercurrent mixing in low-speed flows.

Despite the practical motivations for detailed investigations of high-speed heated jets, there remains only a handful of studies reported in the literature. Lepicovsky,[1,2] Lepicovsky and Brown,[3] and Lepicovsky et al.[4] have undertaken the most complete examination of the high-speed heated jet problem, considering the jet response to nominally random background forcing, the so-called "natural" jet, as well as jet control using monochromatic plane wave excitation. By systematically varying the initial conditions in heated and unheated jets, they identified a velocity gradient parameter in the nozzle exit boundary layer as the single most important condition determining the jet development farther downstream.[1,3] At a Mach number of 0.8 in a typical laboratory jet, for instance, a highly heated jet will usually have a thin laminar exit boundary layer that develops organized shear layer structure and intense mixing in the jet downstream. By comparison, the cold fluid properties of an unheated jet often give rise to a turbulent exit boundary layer that tends to display less shear layer structure and reduced mixing in the jet downstream. The role of initial conditions observed in high-speed compressible jets is consistent with those described by Hussain and Zedan[5] in low-speed jets.

Lepicovsky and Brown[3] also examined the influence of acoustic excitation on the mixing of heated and unheated jets. The principal finding of this research was that compressible jets, up to Mach numbers of at least 0.8, could be effectively forced with monochromatic plane wave acoustic excitation *independent of the jet stagnation temperature*. The extent to which the excitation could be used to enhance jet mixing did depend on the nature of the jet initial conditions. However, the level of acoustic excitation necessary to achieve reasonable mixing augmentation was substantial, and research indicates that further elevations of acoustic power probably will not lead to significantly higher levels of mixing, at least in the presence of plane wave forcing.[6,7]

Experiments conducted at low Mach numbers in relatively clean laboratory jets[8–10] indicate that the jet can be effectively excited by creating a countercurrent mixing region in the jet near field. This *self-excitation* is believed to be a consequence of the absolutely unstable nature of the velocity field established using peripheral counterflow. Depending on nozzle design, the self-excitation can be used to enhance mixing or, under special circumstances, inhibit mixing between the jet and ambient fluids. Furthermore, the counterflow technique does not appear to depend sensitively on the jet initial conditions, being equally effective in jets with laminar or turbulent separating boundary layers.[10] In the present context we concern ourselves only with nozzle configurations suitable for mixing enhancement and explore the effect of the counterflow control technique under compressible flow conditions in heated and unheated circular jets.

The counterflowing nozzle-collar configuration used in the experiments is shown in Fig. 1. The main jet stream is characterized by the conditions in the nozzle exit plane, namely, by the nominally uniform forward velocity stream U_1, static temperature T_1, and exit Mach number M_1. The measurements were made relative to a coordinate system having an origin in the nozzle exit

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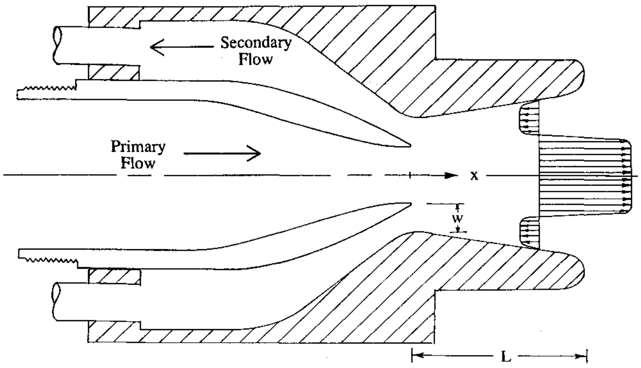

Fig. 1 Nozzle-collar configuration used to establish counterflow around the jet periphery.

plane, where the x direction is assumed to be positive in the direction of U_1. A regenerative pump is connected to the suction collar to create the counterflowing stream U_2 at a temperature T_2. The magnitude of U_2 is taken as the average velocity across the annular slot in the nozzle exit plane obtained by measuring the mass flow rate through the suction system. The sketch of the streamwise velocity profile in the collar region, shown in Fig. 1, is representative of the flow conditions examined during this study. (A more complete discussion about the nature of the counterflowing stream will be given shortly.) The control parameter used to characterize the effect of reverse flow on jet development is the velocity ratio, given by the expression $-U_2/U_1$, which is positive in the present problem owing to the chosen coordinate system. We investigated the influence of the velocity ratio on jet mixing in a parameter space including jet Mach number and temperature ratio T_1/T_2.

The nozzle geometry imposes a number of constraints on the flow that will influence the jet response to the counterflow. Nozzle design studies at low Mach numbers[10,11] indicate that jet mixing is particularly sensitive to the selection of the collar extension length L and annular slot width w, holding invariant other features of the collar geometry, such as divergence angle and curvature; see Fig. 1. In the limit of large L, small w, or combinations thereof, the flow from the primary jet stream will decelerate and create an annular stagnation flow.[11] Under these conditions, the countercurrent axisymmetric mixing layer sketched in Fig. 1 does not exist, and the suction system draws fluid entirely from the primary jet. The fluid remaining in the primary jet that exhausts into the laboratory is then distributed across the collar exit diameter at a reduced Reynolds number. The entire primary jet will eventually be drawn backward into the secondary flow stream as the vacuum pressure is reduced further.

There were several techniques used in the low-speed jet experiments to determine conditions at the onset of annular stagnation flow, including hot-wire surveys, smoke-wire and laser-sheet visualization, static pressure measurements, and audible tones.[8–11] The latter is perhaps the most convenient indication of the transition from counterflow to stagnation flow, due to the annoying low-frequency "flutter" sound accompanying the intermittent attachment and reattachment process. (We have not explored the applicability of this effect, but it certainly generates a violent flowfield!) As stated earlier, the present experiments were operated at conditions well removed from those necessary to create an annular stagnation flow. This was determined by laser sheet flow visualization, the absence of audible tones, and static pressure surveys within the collar. In fact, at Mach numbers above approximately 0.6 it was not possible to achieve annular stagnation flow for the nozzle-collar configuration shown in Fig. 1 due to limitations of our vacuum system. For all experiments reported here, the nozzle-collar geometry was fixed under the following conditions: the collar extension length was $L/D = 3$, the annular width was $w/D = 0.4$, and a divergence half-angle was 7 deg. The nozzle exit diameter was $D = 2.26$ cm.

We continue our discussion in the next section with a brief description of the flow facilities used to make the measurements. The jet data will be presented in two parts. First we will describe the effect of counterflow on jet development in an unheated jet at a Mach number of 0.8. This will serve to outline the basic features of counterflow control by identifying the relationship between velocity ratio $-U_2/U_1$ and jet mixing. Then the heated jet data will be presented to examine the influence of jet temperature ratio on the effectiveness of counterflow control. Heated jets were studied at stagnation temperatures up to ≈400°C for Mach numbers between 0.4 and 1.2.

High-Speed Jet Facility

All measurements were made in the high-speed jet facility at Florida State University. This blowdown facility consists of four high-pressure storage tanks with a total capacity of 360 ft^3 and is driven by a high-displacement reciprocating air compressor. The air can be diverted through an array of resistive heaters having a maximum power output of 450 kW providing stagnation temperatures up to 750 K. To simulate the forward flight effect, a secondary cold stream is available but was not employed during the course of this investigation. The primary mass flow provided by the facility is quite sufficient to supply air at a pressure ratio of 2.42 ($M = 1.2$) to an axisymmetric fifth-order converging nozzle, having an exit area of 4 cm^2, continuously for about 1 h. Because of expansion of the facility during prolonged heating, care was taken to periodically realign the traversing mechanism with the true jet axis by taking radial and azimuthal velocity surveys sufficiently downstream and along the jet exit.

A regenerative vacuum pump was connected through a 12-port manifold to the suction collar to establish the counterflowing stream. Detailed azimuthal velocity profiles taken immediately downstream of the suction collar indicated that no regular azimuthal structure was imposed on the jet owing to the presence of the suction manifold. At maximum throughput the vacuum pump could deliver 100 CFM, corresponding to a secondary stream velocity in the nozzle exit plane of $-U_2 = 50$ m/s using the configuration shown in Fig. 1. The power requirements necessary to drive the secondary stream relative to the primary stream are quite modest. With the exception of the low-speed case examined at $M_1 = 0.4$, the power requirements of the secondary stream were less than 1% of the primary stream.

The jet mixing behavior was examined by measuring time-averaged axial and radial total pressure profiles and axial temperature profiles. All data acquisition was automated using a Dell 286 workstation. Total head and recovery probes for measurement of Mach number and temperature, respectively, were mounted on a three-dimensional traversing system having a resolution of 10^{-5}m.

Unheated Jet Response to Counterflow

The effectiveness of counterflow on jet mixing was examined in an unheated jet at an exit Mach number of 0.8. The effect of the velocity ratio was studied by fixing the primary jet velocity U_1 and

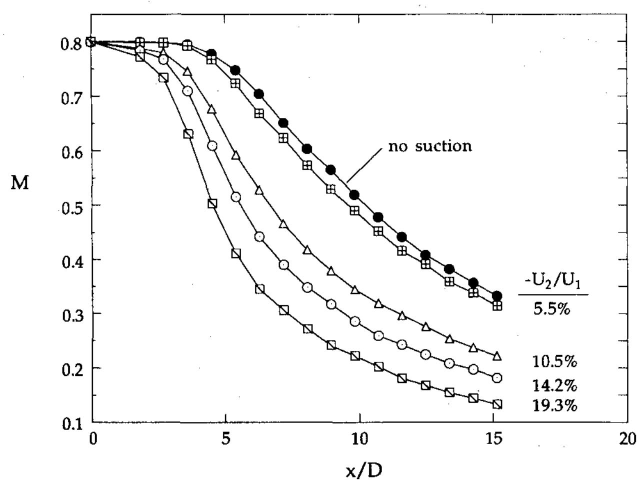

Fig. 2 Axial Mach number profiles at $M_1 = 0.8$ and $T_0 = 20$°C.

varying the reverse velocity U_2. The primary jet enters an adverse pressure gradient in the collar region due to the counterflowing stream. Consequently, the static pressure in the nozzle exit plane was slightly lower than atmospheric pressure; however, this had an insignificant effect on the jet exit Mach number in the present experiments.

Axial Mach number profiles taken at several velocity ratios at $M_1 = 0.8$ are shown in Fig. 2. In the absence of reverse flow, the jet potential core extends to $x/D \approx 5$ and is followed downstream by axial decay in good agreement with results previously reported.[2,4] Axial profiles at velocity ratios up to 20% are also shown in Fig. 2 and indicate the strong effect that counterflow has on jet mixing. The effect of counterflow is seen to be relatively small in the jet near field for streamwise distances less than $x/D \approx 2$. The slight deceleration in the jet potential core in the region immediately downstream of the nozzle exit is believed to be a consequence of the slight adverse pressure gradient within the collar due to counterflow. However, the rapid decay observed farther downstream is due to increased mixing in the countercurrent shear layers of the jet. This latter effect can be seen most clearly by examining radial profiles over this same streamwise distance.

Radial Mach number profiles with and without counterflow are presented in Figs. 3 and 4, respectively, at an exit Mach number of 0.8. The top-hat nature of the jet without suction can be seen in the profiles near the nozzle exit in Fig. 3. At larger streamwise distances, the mixing layers are seen to encroach on the jet potential core, which is essentially absent at $x/D \approx 5$, consistent with the axial data presented in Fig. 2. The radial profiles in Fig. 4, taken with 14% counterflow, indicate that potential flow deceleration is

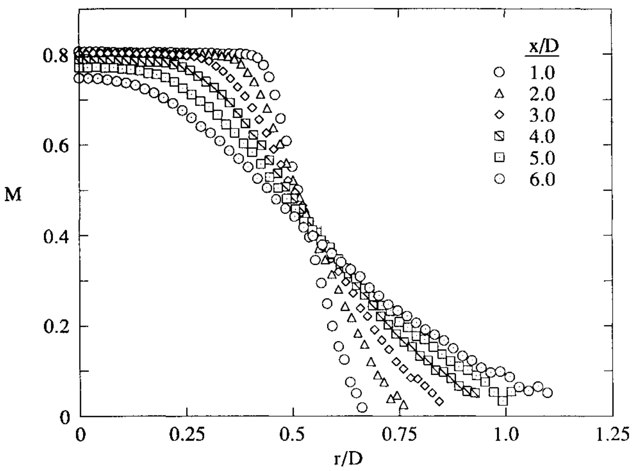

Fig. 3 Radial Mach number profiles without counterflow at $M_1 = 0.8$ and $T_0 = 20°C$.

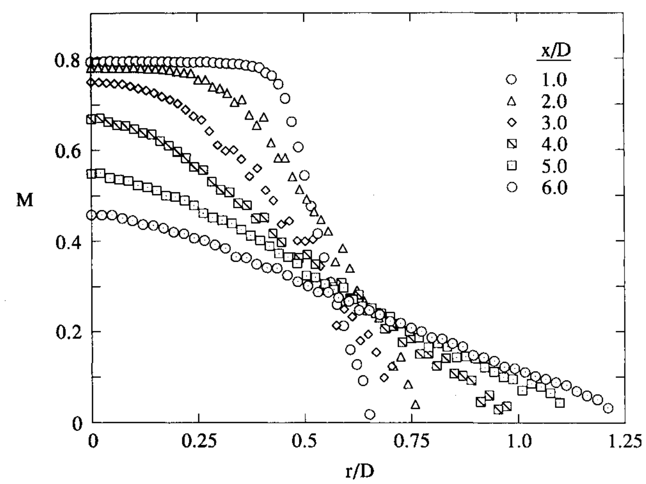

Fig. 4 Radial Mach number profiles with 14% counterflow at $M_1 = 0.8$ and $T_0 = 20°C$.

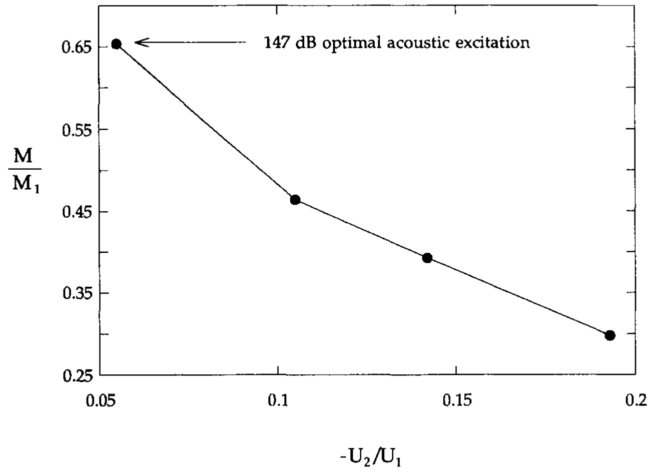

Fig. 5 Mach number ratio on the jet axis at $x/D = 9$ for $M_1 = 0.8$ and $T_0 = 20°C$.

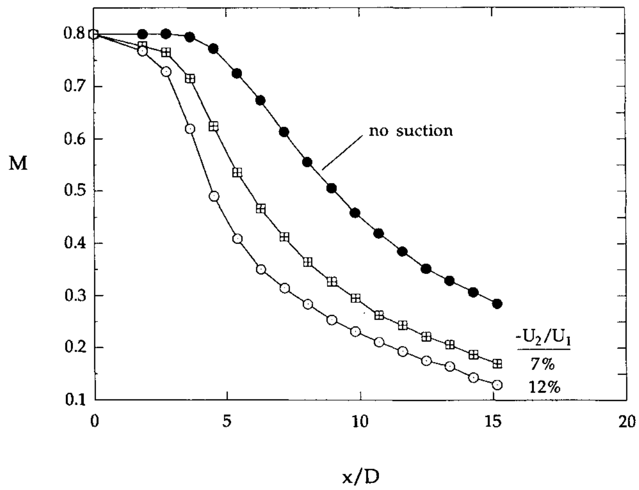

Fig. 6 Axial Mach number profiles at $M_1 = 0.8$ and $T_0 = 400°C$.

not responsible for the rapid decay observed downstream of $x/D \approx 3$ in Fig. 2 but rather is a consequence of intense mixing in the jet shear layers. Notice, for instance, that the jet potential core is consumed already at $x/D \approx 3$ in the case with 14% counterflow. A similar radial profile does not occur until $x/D \approx 6$ in the jet without counterflow.

To appreciate the effectiveness of the jet control using counterflow, we compared our mixing data in Fig. 2 with the acoustically forced jet data of Lepicovsky and Brown[3] made in an unheated jet at a Mach number of 0.8. They reported that the jet response to monochromatic plane wave acoustic excitation—the optimal Strouhal number of excitation was dependent on the particular flow conditions—could be expressed independently of jet initial conditions if the data were normalized by the jet exit Mach number M_1. Lepicovsky and Brown selected the axial Mach number at $x/D \approx 9$ to be representative of the global mixing behavior in the jet under the influence of optimal excitation at a forcing level of 147 dB. For heated and unheated jets, as well as jets with laminar and turbulent boundary layers, they measured a mixing parameter $M/M_1 = 0.65$. We computed this parameter from our data in Fig. 2 and have presented it in Fig. 5. The jet response to counterflow is quite striking and suggests that the technique may hold promise of significant mixing augmentation at more realistic operating conditions as well. We should emphasize that no systematic effort was made during the course of this study to optimize the nozzle-collar geometry. Our experience at much lower Mach numbers indicates that changes in geometry can significantly reduce the amount of

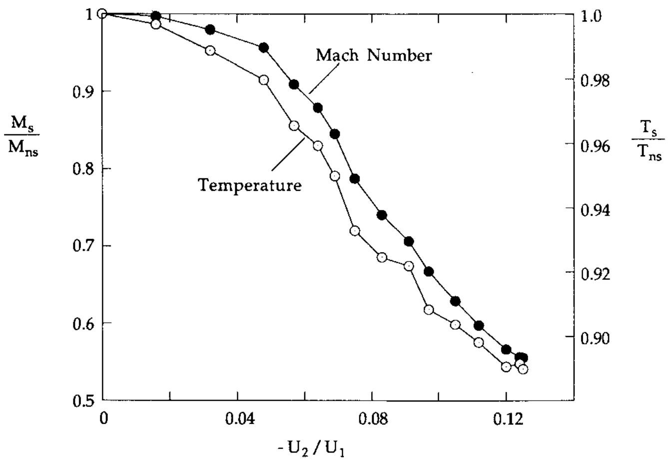

Fig. 7 Mach number and temperature ratios at $M_1 = 0.8$ and $T_0 = 400°C$.

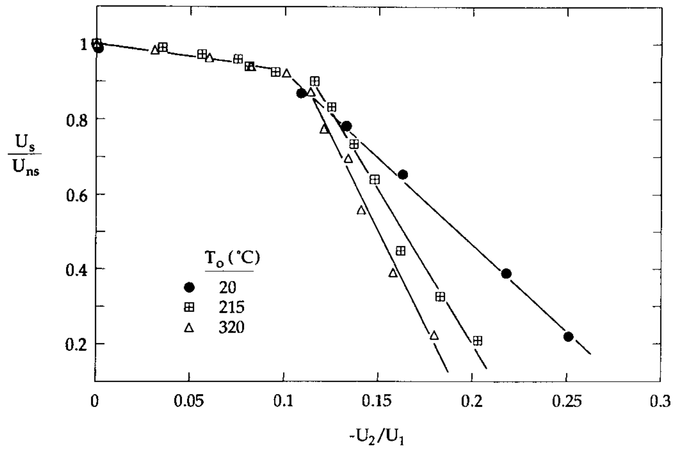

Fig. 8 Normalized mean velocity on the jet centerline at $x/D = 5$ and $M_1 = 0.4$.

counterflow necessary to achieve a particular level of mixing enhancement.[10,11]

Heated Jet Response

Axial Mach number and temperature data were obtained in heated air jets for Mach numbers between 0.4 and 1.2. To elucidate the important effect of temperature ratio T_1/T_2 at a fixed Mach number, we begin by presenting results obtained at a Mach number of 0.8 for stagnation temperatures up to 400°C. Axial Mach number profiles are shown in Fig. 6 at $T_0 = 400$ for velocity ratios of 7 and 12%. The data reflect the trends reported earlier in Fig. 2 and indicate that counterflow control is not limited to unheated jets. A careful comparison of the axial profiles taken without counterflow from Figs. 2 and 6 shows that the heated jet experiences slightly more mixing than the unheated jet at the same Mach number. Lepicovsky and Brown[3] made similar observations at $M_1 = 0.8$, attributing the disparity principally to differences in the initial conditions of the nozzle boundary layer. Employing the mixing parameter M/M_1 measured at $x/D = 9$, suggested by these authors, we can compare the effectiveness of counterflow control independent of jet initial conditions. In the heated jet, the parameter M/M_1 takes the values of 0.4 and 0.3 at velocity ratios of 7 and 12%, respectively. Comparing these values with those shown earlier in Fig. 5 suggests that counterflow control will be more effective as the jet temperature is increased. (A careful examination of the effect of initial conditions on the jet response to counterflow[10] confirms that the technique is robust and insensitive to the separating boundary-layer characteristics.) More will be said about this important trend shortly.

The relationship between velocity ratio and jet mixing was investigated by measuring the local Mach number ratio M_s/M_{ns} and absolute static temperature ratio T_s/T_{ns} on the jet centerline at $x/D = 5$. Figure 7 reveals that the Mach number at $x/D = 5$ is reduced by almost a factor of two at a velocity ratio of 12%. Furthermore, the decreasing temperature ratio with increasing velocity ratio reinforces our expectation that cold ambient fluid is rapidly drawn into the jet core in the presence of counterflow even at the relatively small axial distance of $x/D = 5$; this location corresponds approximately to the end of the potential core in the jet without counterflow.

To further examine the relationship between velocity ratio, temperature ratio, and Mach number, we made a series of measurements at Mach numbers from 0.4 to 1.2 over a range of stagnation temperatures between 20 and 410°C. The highest Mach number jet examined was at an underexpanded pressure ratio of 2.42, corresponding to an ideally expanded Mach number of 1.2. To accommodate a parametric study, the jet mixing was characterized by a single spatial measurement of mean velocity on the jet axis at $x/D = 5$, namely, by the relative ratio U_s/U_{ns}. This required that total pressure and temperature be acquired at each operating condition.

Data obtained at Mach numbers of 0.4, 0.8, and 1.2 are given in Figs. 8, 9, and 10, respectively. Several important observations can be drawn from these data sets: 1) all data display a characteristic "break" in their slopes at a critical velocity ratio, the magnitude of which is relatively insensitive to jet temperature ratio at a fixed Mach number; 2) below the critical velocity ratio the jet dynamics are essentially unaffected by counterflow, but above this critical value the jet mixing is strongly dependent on $-U_2/U_1$ and T_1/T_2;

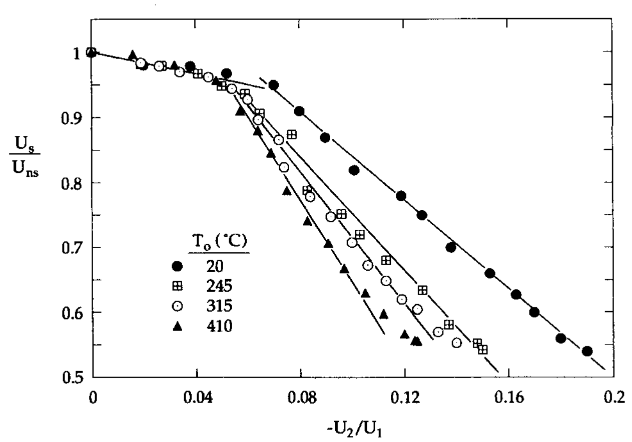

Fig. 9 Normalized mean velocity on the jet centerline at $x/D = 5$ and $M_1 = 0.8$.

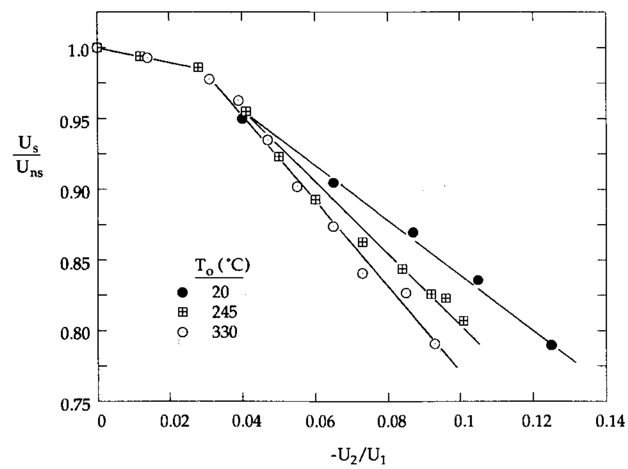

Fig. 10 Normalized mean velocity on the jet centerline at $x/D = 5$ and $M_1 = 1.2$.

and 3) the critical velocity ratio decreases with increasing Mach number.

We can begin to glean a physical understanding of the role of counterflow from the information contained in Figs. 8–10. The slope discontinuity suggests that the mechanism responsible for mixing enhancement in the jet shear layers is fundamentally altered at elevated velocity ratios. At low velocity ratios we expect that the mixing layer will experience spatial growth proportional to $\Delta U/U_c$, where $\Delta U = (U_1 - U_2)$ and U_c is the convection velocity of structures in the layer. As suction is increased, the shear across the layer will increase and the convection velocity will decrease, giving rise to higher total spatial amplification at any fixed location. This scaling, based on spatial theory, was verified in countercurrent mixing layers at low velocity ratios by Strykowski and Niccum.[8] In this earlier work the spatial theory was satisfied only up to a critical velocity ratio, and above this value the spatial theory alone was inadequate to completely describe the flow development. It was argued that a global instability, due to the absolutely unstable nature of the flow at elevated velocity ratios, was responsible for the discrepancy. Although satisfactory shear layer measurements have not been made in jets with counterflow under the high-speed conditions examined here, we speculate that a convective-absolute transition may explain the discontinuous behavior observed in Figs. 8–10 at the critical velocity ratio; additional comments regarding this connection are provided later.

An important observation above the critical velocity ratio is that counterflow becomes more effective as the jet is heated. To elucidate this effect, the data at $M_1 = 0.8$ were replotted as a function of temperature ratio. These data, shown in Fig. 11, were obtained by intersecting the curves from Fig. 9 at $U_s/U_{ns} = 0.6$. The selection of this particular value of U_s/U_{ns} was arbitrary but reflects a similar level of mixing in the jet. The curve in Fig. 11 clearly shows that the jet becomes more "controllable" at higher temperature ratios; i.e., less counterflow is required to attain comparable levels of mixing. The behavior shown in Fig. 11 is consistent with the measurements made at the other Mach numbers as well and is in general agreement with the trend we would expect if the flow were absolutely unstable. Several studies[12–14] have shown, for instance, that the flow will tend toward absolute instability as the temperature ratio T_1/T_2 is increased at a fixed Mach number.

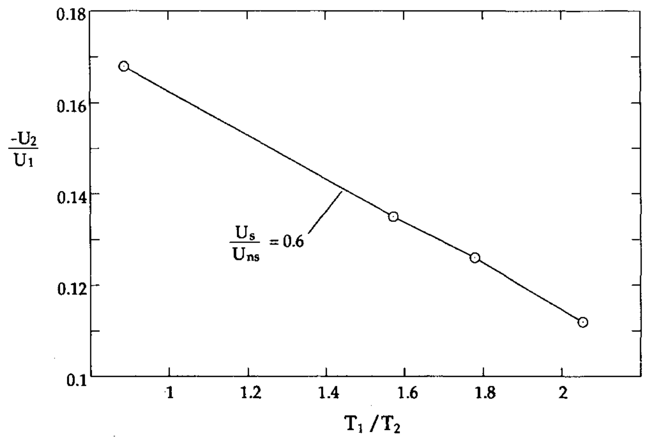

Fig. 11 Relationship between velocity ratio and temperature ratio at $M_1 = 0.8$.

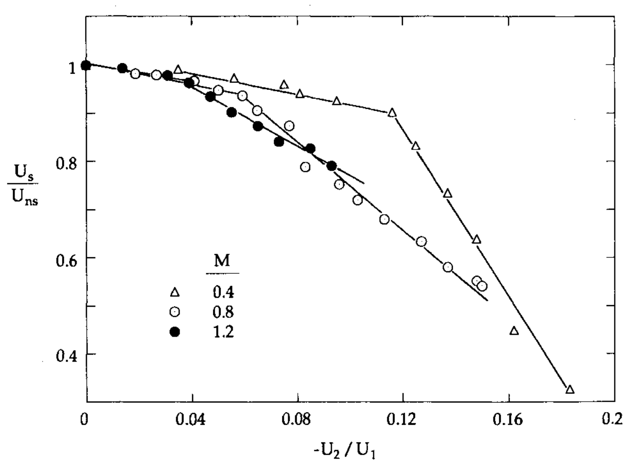

Fig. 12 Normalized mean velocity on the jet centerline at $x/D = 5$ and $T_1/T_2 \approx 1.6$.

Finally, the relationship between velocity ratio and Mach number was examined by combining data from Figs. 8–10 at a fixed temperature ratio of $T_1/T_2 \approx 1.6$ and is shown in Fig. 12. The slope discontinuity occurs at lower velocity ratios as the Mach number is increased, suggesting that counterflow will be more effective in higher speed jets. However, above the critical velocity ratio, the slopes of the curves decrease with increasing Mach number, indicating the opposite trend. Although more work needs to be done here, we note that this latter trend is consistent with the spatiotemporal theory of compressible mixing layers.[12–14] These studies show that the transition from convective to absolute instability occurs at higher velocity ratios as the Mach number is increased.

Concluding Remarks

This research was motivated by studies of incompressible jets[10] that indicated that annular counterflow could be used to augment jet mixing. The present investigation was designed to establish whether this technique could be extended to a more realistic range of operating conditions. Data were taken to include Mach numbers between 0.4 and 1.2 at stagnation temperatures ranging from 20 to 400°C. The principal finding of the research was that the counterflow technique is an effective approach to mixing control in high-speed heated jets. Although our physical understanding of counterflow control remains incomplete, many of the present observations in high-speed jets are in qualitative agreement with those made earlier under incompressible flow conditions, indicating that a global instability of the flowfield may be responsible for the robustness of the technique.

Despite significant mixing augmentation in the present experiments, some concern may be raised about the excessive amount of suction needed to achieve the control. We re-emphasize two important points:

1) We believe that the efficiency of the technique can be improved through a systematic nozzle-collar design. Because of the expense of manufacturing several stainless steel collars to cover a wide geometric parameter space, no attempt was made to optimize the nozzle-collar geometry during the course of this study. We have learned from our experience with low-speed jets[10] that a narrower suction slot width will lead to greater efficiency by reducing the velocity ratio necessary to achieve a given level of mixing. However, we did not push this limit in the present collar design owing to other constraints, in particular to avoid an annular stagnation point flow.

2) Although suction levels up to 20% were employed to achieve mixing enhancement, the corresponding power ratio was indeed small. Under the most extreme counterflow conditions presented here, the power developed in the secondary stream was less than 1% of the power demands in the primary stream.

Acknowledgments

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