Total Temperature Effects on Centerline Mach Number Characteristics of Freejets

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This paper describes a detailed experimental study of Mach number centerline characteristics of unheated and heated freejets. The jet characteristics were obtained at a range of jet Mach numbes from 0.1 to 0.9 and jet total temperatures up to 900 K. Previously published results showed that the jet total temperature significantly affects the nozzle-exit, boundary-layer characteristics. The results of this study indicate that a strong correlation exists between nozzle-exit, boundary-layer conditions and freejet development. It is clear from this investigation that experimental data on freejet development cannot be meaningfully compared from one facility to another without specific knowledge of nozzle-exit, boundary-layer conditions. It was concluded that direct effect of the jet operating conditions (elevated flow temperature) on freejet development is much less important than the indirect effect due to changed nozzle-exit, boundary-layer characteristics.

Nomenclature

D = nozzle exit diameter, mm
$H_{\delta\theta}$ = displacement-momentum shape factor
M = Mach number
p = pressure, kPa
Re = Reynolds number
T = temperature, K
U = velocity, m/s
x = axial distance, mm
θ = momentum thickness, mm

Subscripts
A = ambient
J = jet
P = probe
T = total
995 = 99.5%

Introduction

HEATED jets are encountered in many engineering applictions dealing with heat and mass transfer. However, reliable conclusions about the effects of jet operating conditions on jet plume characteristics are difficult to formulate because the available experimental data disagree or contradict each other.

Even the experimental data on such a basic jet-plume characteristic as the jet centerline Mach number decay indicate contradictory behavior as a function of the jet total temperature. Experimental data acquired at the United Technology Research Center[1,2] show absolutely no effect of the jet total temperature on the jet centerline Mach number decay. Data gathered by the NASA Lewis Research Center[3,4] and an older set of data acquired at the Lockheed-Georgia Research Center[5,6] indicate an increased rate of Mach number decay with increasing jet total temperature. Finally, the more recent data acquired at the Lockheed-Georgia Research Center[7,8] show different effects of elevated flow temperature for jets at low and high Mach numbers. These contradictory results are discussed in detail in the following subsection.

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Discrepancies Among Experimental Data

Experimental data from Lockheed's work on hot-jet mixing enhancement[7,8] indicate a strong dependence of the jet centerline Mach number at $X/D_J = 9$ on jet operating conditions. A summary of these findings is shown in Fig. 1[1] (Ref. 8). Here, normalized Mach numbers at $X/D_J = 9$ on the jet centerline are plotted as a function of the jet total temperature. The figure shows this dependence for two jet-exit Mach numbers of 0.3 and 0.8. For the jet-exit Mach number of 0.8, as seen in Fig. 1, the normalized Mach number at $X/D_J = 9$ remains practically unchanged up to the total temperature ratio of 1.7 and then steeply decreases with the increasing jet total temperture. For the jet-exit Mach number of 0.3, the results do not show any significant change between the unheated jet and a jet heated to a total temperature ratio of 2.7.

The results for high Mach number jets contradict the approximate substitution principle, introduced by Greitzer et al.,[1] which "predicts congruence of Mach number profiles at any axial station" regardless of the flow temperature. Lockheed's data[7,8] conflict with the experimental data provided by Simonich[1,2] who showed for a freejet at an exit Mach number of 0.6 that "over an axial extent of some forty nozzle diameters, the cold and hot test results are observed to be nearly identical"[1] and that "the heated (810 K) and unheated (304 K) profiles are nearly identical for stations at $X/D_J \leq 9.1$."[2] Further discussion of encountered discrepancies is presented in Ref. 9.

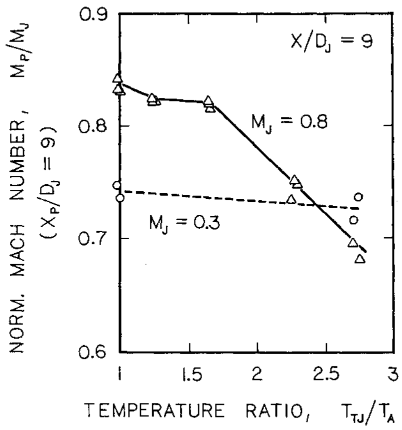

Fig. 1 Total temperature effects on centerline Mach number at $X/D_J = 9$.

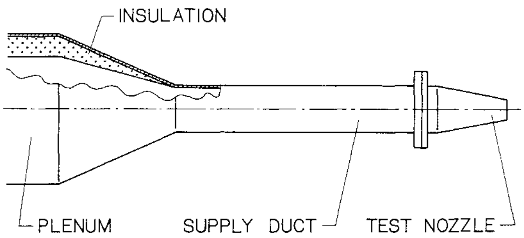

Fig. 2 Test facility.

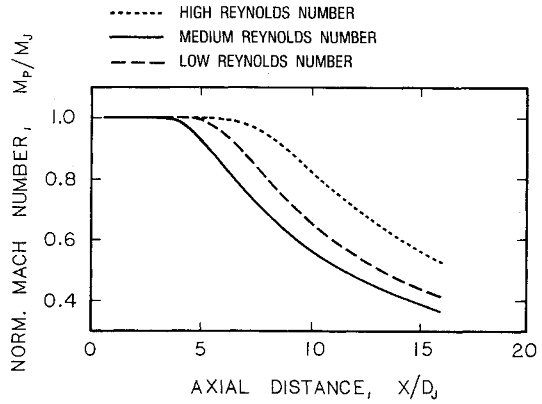

Fig. 3 Mach number centerline distributions. Low Reynolds number: $Re_J = 111{,}060 \pm 2{,}200$; $T_{TJ} = 799.1 \pm 7.3$ K; $M_J = 0.326 \pm 0.003$; $U_J = 180.0 \pm 1.9$ m/s. Medium Reynolds number: $Re_J = 205{,}520 \pm 3{,}000$; $T_{TJ} = 705.6 \pm 4.9$ K; $M_J = 0.904 \pm 0.007$; $U_J = 285.5 \pm 2.1$ m/s.

To clarify the observed discrepancies, a set of centerline Mach number distributions was measured for a variety of jet operating conditions covering a Mach number range from 0.1 to 0.9 and a total temperature ranging from unheated jets up to jets heated to 900°K (total temperature ratio of 3). The tests cover the range of Reynolds numbers from $0.1 * 10^6$ to $1.3 * 10^6$.

Test Facility

The experiments were conducted in Lockheed's Jet Flow Facility shown in Fig. 2. This facility consists of a 256-mm-diam plenum, followed by an initial contraction to a 690-mm-long supply duct 102 mm in diameter. The stainless steel converging test nozzle is mounted on 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. To minimize the wall heat flux, the plenum is lined with a 25-mm-thick Kaowool insulation. The supply duct and the test nozzle are not thermally insulated.

Instrumentation

United Sensor probes were used for the total pressure measurements; probe PAC-12-KL for the plenum total pressure and a Kiel total pressure probe KAL-12 for the jet centerline pressure. Validyne pressure transducers P305D, rated ±220 and ±86 kPa were used with these probes for jet exit Mach numbers above 0.4. For the jet operating conditions below Mach 0.4, tranducers rated at ±8.6 and ±3.5 kPa were used in most of the test.

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

A three-direction positioner moved the Kiel total pressure probe along the jet centerline. Driving electronics for the positioner consisted for a Superior Electric Modulynx motion control system interfaced to a Digital Equipment VAX 11/750 computer.

The entire data acquisition process, including the probe traversing, was fully automated and controlled by the facility-dedicated VAX 11/750 computer. The acquired temperature and pressure data were reduced online and converted to engineering units. Nozzle-exit conditions, Mach number, jet-exit velocity, and flow temperature were continuously displayed on a computer terminal. All of the acquired data were stored in raw, unreduced form for later offline data analysis.

Measurement Uncertainty

Extreme care was exercised to insure the highest possible reliability and accuracy of the acquired data. Each test point in every centerline survey represents an average of five repetitive pressure and temperature readings. The time interval between successive readings was 8 s. Each time the probe was moved to a new position, a settling time period of 20 s was allowed before the new data were recorded. All pressure transducers were carefully calibrated and the calibration data stored in the computer memory. Slope calibration data points for each transducer were curve fitted with a cubic-parabola to improve the pressure conversion accuracy. The largest standard deviations of calibration points from the best cubic-parabola fits were ±13 Pa for the ±3.5 kPa transducer and ±110 Pa for the ±220 kPa transducer. The temperature conversion accuracy of the Digi-Link processor is ±3 K at 900 K and ±1.5 K at 300 K. No temperature recovery or stem corrections were applied to the thermocouple readings of the plenum total temperature.

To eliminate the effect of thermal expansion of the duct work on the position of the probe relative to the exit plane and jet centerline, the test facility was operated for at least 30 min at given jet operating conditions prior to commencement of data acquisition. Vertical and horizontal Mach number profiles at $X/D_J = 9$ and 16 were measured at the start of every test. Peak points of these profiles determined the centerline coordinates at given axial stations. A best-fit straight line through these two points and the nozzle-exit cross-section center was used as the datum for the traversing mechanism to insure that the probe was moved along the jet centerline. Accuracy of the probe positioning was better than ±0.15 mm.

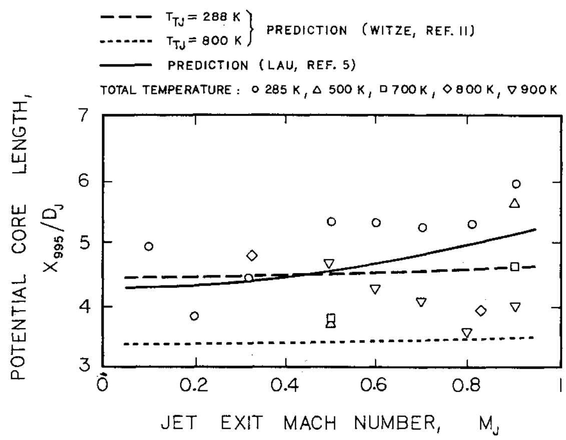

Fig. 4 Potential core length variations with jet exit Mach number.

Potential Core Length

The measured local Mach numbers were normalized with the jet exit Mach number. For a given centerline distribution, all of the discrete experimental points were fitted with an analytical curve based on the parametric cubic-spline-fitting subroutine ICFSKU from the IMSL library.[10] Figure 3 shows the fitted curves for three selected jet operating conditions. Clearly, the jet operating conditions have significant effects on the length of the jet potential core and the rate of decay of the Mach number beyond the potential core. The length of the potential core was determined as the distance from the nozzle-exit plane to the point at which the centerline Mach number falls to 99.5% of the jet exit Mach number.

For comparison purposes, the variation of the potential-core length with jet-exit Mach number is depicted in Fig. 4 in a similar way to Lau et al.[5], and Lau[6] and Simonich.[2] Also included are predictions of potential-core length variation as a function of the jet-exit Mach number. The solid curve is based on Lau's prediction,[5] and the remaining two curves are based on Witze's prediction[11]; the broken curve is for unheated jets, and the dotted curve is for jets heated to 800 K. The prediction of Lau et al.[5] is restricted to isothermal jets only, while Witze's prediction[11] accommodates the effects of jet elevated temperatures on the length of the jet potential core through a ratio of specific density of the ambient air and specific density of the jet stream at the jet exit. As can be seen in Fig. 4, Lau's prediction[6] (solid line) shows a gradual increase in jet potential-core length with increasing jet-exit Mach number. Witze's prediction for unheated jets (broken line) shows a similar trend but predicts a substantially weaker dependence of the jet potential-core length on the jet-exit Mach number. Witze's prediction indicates a strong dependence on the jet temperature (broken line vs dotted line). For jets heated to a total temperature of 800 K, the predicted length of the jet potential core contracts approximately 75% of that predicted for unheated jets.

None of the predictions fits the present experimental data. The experimental data appear to be randomly scattered over the plot domain with unacceptable deviations from the prediction curves. These discrepancies suggest that the jet-exit Mach number may not be the correct parameter to describe the potential-core dependence on jet operating conditions. Thus, the experimental data were replotted as a function of the jet-exit Reynolds number in Fig. 5. Clearly, contrary to Fig. 4, the experimental data show an orderly dependence on the jet-exit Reynolds number. Figure 5 shows that the potential-core length drops sharply as the Reynolds number is raised from $0.1*10^6$ to $0.3*10^6$ and then increases quite rapidly until the Reynolds number reaches $0.6*10^6$; after this Reynolds number up to $1.1*10^6$, the potential core length remains relatively constant. Above Reynolds number of $1.1*10^6$, the potential-core length seems to grow again. This jet potential-core behavior is reflected in the mixing region beyond the jet potential core. Data from this region are presented in the following section.

Mixing Region Beyond Jet Potential Core

Mach number variations beyond the end of the potential core were investigated at two axial stations of $X/D_J = 9$ and 15. The resulting plots are shown in Figs. 6 and 7. As seen in these figures, the normalized Mach number variation at these two axial stations basically reproduces the behavior of the jet potential-core length as a function of the jet-exit Reynolds number (Fig. 5). It can also be seen in Figs. 6 and 7 that the effect of the jet-exit Reynolds number gradually weakens with increasing distance from the nozzle exit.

In general, all of the presented characteristics feature a sharp local minimum at the jet-exit Reynolds number of $0.3*10^6$. This minimum occurs for jet operating conditions for which the nozzle-exit boundary layer undergoes a transition between laminar and turbulent states. This phenomenon is discussed next.

Nozzle-Exit, Boundary-Layer Characteristics

The effects of jet operating conditions on the development and state of the nozzle-exit boundary layer of heated freejets are discussed in detail in Ref. 7. Only a summary of relevant facts is presented in this section.

A distribution of the nozzle-exit momentum thickness as a function of the nozzle operating conditions, expressed in

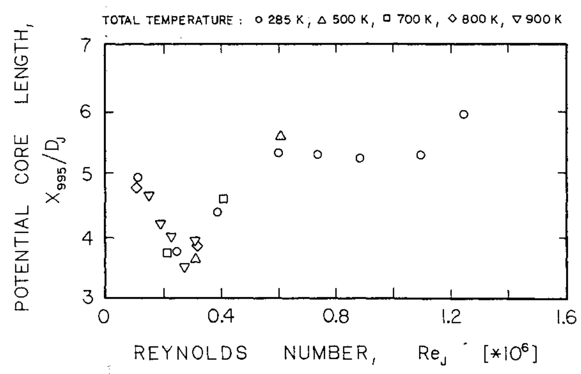

Fig. 5 Reynolds number effects on jet potential-core length.

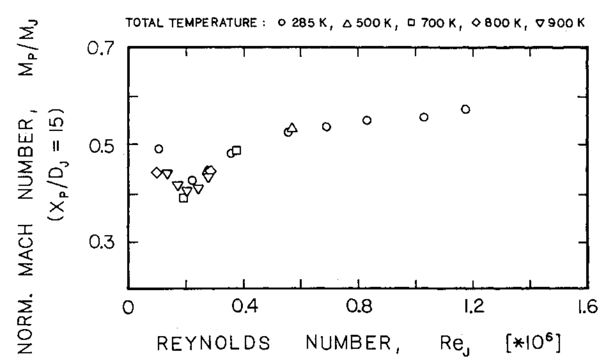

Fig. 7 Reynolds number effects on normalized Mach number at $X/D_J = 15$ on jet centerline.

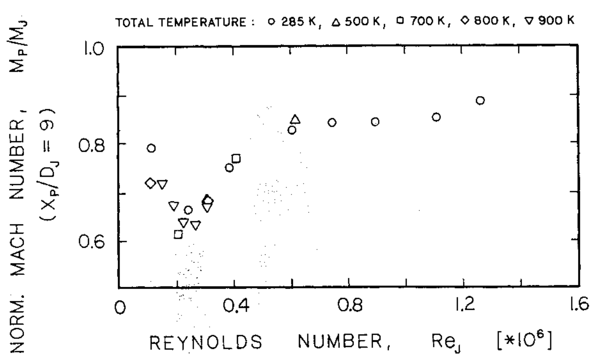

Fig. 6 Reynolds number effects on normalized Mach number at $X/D_J = 9$ on jet centerline.

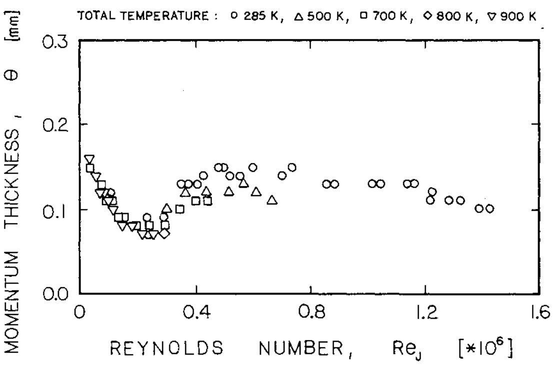

Fig. 8 Reynolds number effects on nozzle-exit, boundary-layer momentum thickness.

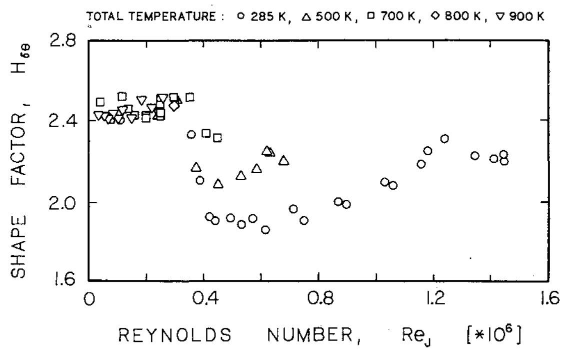

Fig. 9 Reynolds number effects on nozzle-exit, boundary-layer displacement/momentum shape factor.

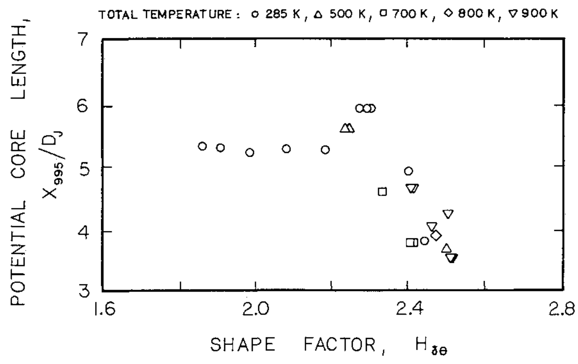

Fig. 11 Correlation between nozzle-exit, boundary-layer shape factor and potential-core length.

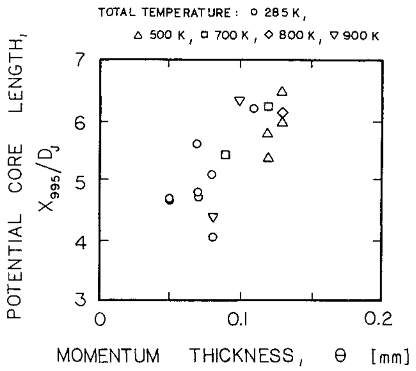

Fig. 10 Correlation between boundary-layer momentum thickness and potential-core length.

terms of the jet-exit Reynolds number, is shown in Fig. 8. The momentum thickness decreases rapidly from an initial value with increasing jet Reynolds number and reaches its minimum at a critical Reynolds number of $Re_J = 0.3*10^6$. Above the critical Reynolds number, the momentum thickness increases and then remains relatively constant until the nozzle-exit velocity approaches the transonic region where the momentum thickness starts to fall slowly.

A displacement-momentum shape factor ($H_{\delta\theta}$) describes the shape of the boundary-layer velocity profile. The significance of this factor lies in detection of boundary-layer transition from laminar to turbulent. As seen in Fig. 9, the displacement-momentum shape factor drops suddently at the jet Reynolds number of $Re_J = 0.3*10^6$. This jet Reynolds number $0.3*10^6$ marks the end of the laminar regime for the nozzle-exit boundary layer.

These results on boundary-layer behavior clearly show that the nozzle-exit boundary layer goes through critical changes (Figs. 8 and 9) at the same jet-exit Reynolds number at which the characteristics along the jet centerline reach extremes (Figs. 5–7).

Relation Between Boundary-Layer and Centerline Characteristics

An apparent similarity between nozzle-exit, boundary-layer, momentum-thickness variation (Fig. 8) and variation of jet potential-core length (Fig 5) as functions of Jet-exit Reynolds number indicates a strong correlation between these two characteristics. Clearly, the nozzle-exit, boundary-layer behavior must be the primary factor and the potential-core length variation follows.

The effect of the initial boundary layer on unheated freejet development has been previously reported in the literature. Bradshaw[12] concluded that "...the effects of the initial conditions are considerably larger than has been generally appreciated in the past." He also pointed out that, as far as freejet development is concerned, "we may be fairly certain that the 'Mach number effects' were really the effect of the exit boundary layer." Hill et al.[13] observed for low-speed, unheated jets that, "The centerline velocity decay is seen to be more rapid with a laminar boundary layer than with a turbulent boundary layer." Finally, Hussain and Zedan[14] also noticed "that free shear flows are noticeably affected by variations of the initial conditions."

The correlation between nozzle-exit, boundary-layer conditions and the jet potential-core variations is shown in Figs. 10 and 11. Nozzle-exit boundary-layer and jet centerline data were acquired independently. The data used for these correlations were selected so that the jet operating conditions (jet Mach and Reynolds numbers and jet total temperature) did not differ more than 5% of their absolute values. Figure 10 shows the effects of nozzle-exit, boundary-layer momentum thickness. As seen here, the thinner the nozzle-exit, boundary-layer momentum thickness, the shorter the jet potential core. The effects of the nozzle-exit, boundary-layer state, laminar vs turbulent, are shown in Fig. 11. Here, the potential-core length is plotted as a function of the nozzle-exit boundary-layer shape factor $H_{\delta\theta}$. Based on the results shown in Fig. 9, the displacement-momentum shape factor value of 2.3 may be considered as borderline between laminar and turbulent states of the nozzle-exit boundary layer. Thus, in Fig. 11, data to the left of $H_{\delta\theta} = 2.3$ are for the turbulent nozzle-exit, boundary layer and data to the right are for the laminar case. The finding tends to support the observations of Hill et al.[13] for low-speed, unheated jets regarding the effects of nozzle-exit, boundary-layer state on the freejet development.

Concluding Remarks

It follows from the preceding discussion that the nozzle-exit, boundary-layer conditions play a dominant role in the freejet plume development. As shown in Ref. 7, the jet operating conditions have a strong effect on the nozzle-exit, boundary-layer state and thickness. This leads to a conclusion that the effects of jet operating conditions, namely the elevated flow temperature on freejet development, is twofold. First, the jet plume development may be influenced directly by heat transfer and momentum interchange by viscous stresses. Second, the jet plume development is affected indirectly due to the profound effect of jet operating conditions on nozzle-exit, boundary-layer characteristics. It is believed that this indirect effect is the dominant factor in jet plume development. The reason for this belief is discussed below.

There is considerable disagreement among correlation predictions of freejet development under different jet operating conditions and experimental data from different test facilities. This can be attributed to the fact that none of the published correlation predictions pays any attention to the effects of nozzle-exit, boundary-layer state and development. The initial nozzle-exit boundary layer and its development are facility dependent. The nozzle-exit boundary layer may be influenced by the nozzle geometry surface roughness, plenum size, initial turbulence intensity, and other factors. This means that the experimental data on Mach number and flow temperature effects on freejet development, acquired in diffferent test facilities are "heavily contaminated" by the effects of nozzle-exit boundary layer peculiar to each facility. It also appears that the published correlation predictions apply only to the particular test facility or the experimental data set without any universal validity.

The conclusion that the direct effect of elevated jet flow temperatures on jet development is relatively insignificant to the effect of nozzle-exit boundary layer seems to support the validity of the approximate substitution principle introduced by Greitzer et al.[1] The substitution principle predicts no effect of elevated flow temperatures on the Mach number characteristics of a freejet and suggests a similarity between flows with different total temperatures. To verify the substitution principle experimentally, the nozzle-exit boundary layer dependence on the jet operating conditions must be eliminated. In essence, the heated and unheated jets must have identical nozzle-exit, boundary-layer conditions. To avoid the problem of transition from turbulent to laminar boundary layer due to heating of the flow, it is suggested experiments be performed on heated jets with suitably modified nozzle-exit boundary layers.

Conclusions

The following conclusions were derived from this study:

1) Jet operating conditions (elevated flow temperatures) strongly affect nozzle-exit, boundary-layer development.

2) A strong correlation between nozzle-exit, boundary-layer conditions and freejet development has been found.

3) Nozzle-exit boundary-layer effects dominate over the direct effects of jet operating conditions (elevated flow temperatures) on freejet development.

4) Experimental data on freejet development, acquired in different test facilities, cannot be meaningfully compared without a knowledge of nozzle-exit, boundary-layer conditions.

5)The relatively insignificant direct effect of jet operating conditions (elevated flow temperatures) on freejet decay seems to support the approximate substitution principle.

6) An experiment with controlled nozzle-exit, boundary-layer conditions should be carried out to investigate the true significance of jet operating conditions (elevated flow temperatures) on freejet development.

Acknowledgment

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