required at approximately x/s of 17 (see Fig. 3) to maintain $\epsilon \geq 0.8$. As illustrated by numerical studies,[7] the slot spacing can be increased with each additional slot because of the "multiple slot effect." However, it should be obvious that the slot spacing will reach some asymptotic value (although not shown in this Note).

In summary, the current study shows that, for a given coolant mass flow rate, thermal protection over the maximum surface area can be accomplished best by injecting the coolant flow through multiple slots. It is of interest to note that numerical studies[11] indicate that skin-friction reduction by slot injection is most effective when the total available mass is injected from one slot as far upstream as possible.

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Turbulence Measurement in Transonic Flow

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Nomenclature

a_w = overheat parameter $(R_w - R_r)/R_r$
d = wire diameter
E = wire voltage
h = film coefficient
k = thermal conductivity
K = $d \ln R_w / d \ln T_w$
l = wire length
m = $d \ln \mu / d \ln T$
M = Mach number
n = $d \ln k / d \ln T$
Nu = Nusselt number, hd/k
p = static pressure
R = resistance
R_s = series resistance in anemometer bridge
Re_δ = Reynolds number, $\rho u \delta / \mu$
Re_t = Reynolds number, $\rho_t u d / \mu_t$
S = sensor sensitivity coefficient
T = temperature
u = streamwise velocity
y = distance normal to wall
α = $1/\{1 + [(\gamma - 1)/2]M^2\}$
δ = boundary-layer thickness
η = recovery factor T_r/T_t
μ = viscosity
ρ = density
τ_{wr} = temperature overheat $(T_w - T_r)/T_r$
$\langle ( ) \rangle$ = root mean square

Superscripts

$( )'$ = fluctuating value
$\bar{( )}$ = time-averaged value

Subscripts

e = boundary-layer edge
r = recovery or adiabatic wall
t = total or stagnation conditions
u = velocity
w = wire
ρ = density
ρu = mass flux

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Introduction

TWO instrumentation systems are presently practical to use in turbulence measurements. The laser velocimeter can measure fluctuating velocities while the hot-wire anemometer, in principle, can be used to obtain both kinematic and thermodynamic fluctuations. In addition, the hot-wire anemometer gives an analog signal output that is convenient for use in time-space correlation studies and spectral analyses. The laser velocimeter has been used successfully in all flow regimes, whereas the hot wire has not been exploited in transonic flows, where the wire response has not been well-understood. The purpose of this Note is to examine the response and calibration of a constant-temperature, hot-wire anemometer in transonic flow and to present turbulence measurements, obtained in a transonic boundary layer.

Results and Discussion

Any discussion of hot-wire anemometry in transonic flow must consider past work in that area of interest. In particular, one must consider how little activity has existed in an area of such technological importance. Twenty years have passed since the significant work of Morkovin[1] was published which outlined the basic considerations of hot-wire anemometry applied to transonic flows. Although Morkovin indicated the possible difficulty in interpreting the wire's signal, he certainly did not indicate that it was impossible to do so.

In order to recount the problems discussed by Morkovin, the following discussion is presented. The nomenclature used, and the ideas considered, follow those of Morkovin and Kovasznay[2] closely. Generally, the fluctuating voltage given by a hot-wire anemometer E' referenced to its mean value $\bar{E}$ is a function of the heat transfer from the wire, which is directly related to fluctuations in the physical variables of the flow. One such relationship involves the fluctuating velocity, density, and total temperature, and can be written as

$$E'/\bar{E}=S_u(u'/\bar{u})+S_\rho(\rho'/\bar{\rho})+S_{T_t}(T_t'/\bar{T}_t) \qquad (1)$$

where S_u, S_ρ, and S_{T_t} are the respective sensitivity coefficients. It is in the determination and behavior of these sensitivity coefficients that the problem of transonic hot-wire anemometry lies.

In general, S_u may be written in terms of S_ρ, following Morkovin's terminology, as

$$S_u=S_\rho+\frac{1}{2\alpha}\left(\frac{\partial \ell n Nu}{\partial \ell n M}-\frac{1}{\tau_{wr}}\frac{\partial \ell n \eta}{\partial \ell n M}\right) \qquad (2)$$

For supersonic flow (and incompressible flow), the derivatives with respect to Mach number are negligible, and the well-known situation of $S_u=S_\rho$ is obtained. However, for transonic flows, Morkovin indicated a possible behavior of $\partial \ell n Nu/\partial \ell n M$, which would make calibration of S_u difficult.

The present study was undertaken to calibrate a wire directly to determine exactly how the sensitivity coefficients vary, and then to use this calibration in measuring turbulence in a transonic boundary layer. The sensitivity coefficients for a constant-temperature anemometer follow directly from Eq. (1) as

$$\left.\begin{aligned} S_u&=\left.\frac{\partial \ell n E}{\partial \ell n u}\right|_{\rho,T_t,R_w}\\ S_\rho&=\left.\frac{\partial \ell n E}{\partial \ell n \rho}\right|_{u,T_t,R_w}\\ S_{T_t}&=\left.\frac{\partial \ell n E}{\partial \ell n T_t}\right|_{u,\rho,R_w}\end{aligned}\right\} \qquad (3)$$

In order to evaluate S_{T_t} without actually varying T_t and determining $\partial \ell n E/\partial \ell n T_t$, a relationship given by Morkovin was used involving the (presumably known) values of S_u and S_ρ and information obtained during the actual use of the wire:

$$S_{T_t}=\frac{1}{2}\left\{n_t+1-2k\left[\frac{\partial \ell n E}{\partial \ell n R_w}+\left(\frac{1}{2}-\frac{R_w}{R_w+R_s}\right)\right]\right\}$$
$$-m_t S_\rho-\frac{1}{2}(S_u-S_\rho)$$

The derived value for S_{T_t}, since it is obtained solely from information about the specific wire and does not rely on any other information, is considered to be a directly calibrated value.

Now S_u and S_ρ still must be evaluated. This requires a flow facility in which the velocity and density can be varied independently. Such a facility[3] became available for use here. The wires were operated in the freestream flow of the test section of the ejector-driven, high Reynolds number pilot wind tunnel at Ames Research Center. The range of flow variables of this tunnel allowed calibrations to be obtained at total pressures from 7 to 100 psia (0.5 to 6.8 atm) for the full range of Mach numbers from 0.3 to 1.2, with the total temperature held at about 500°R (278 K).

The direct calibration technique makes sense only if the wires have a relatively long life expectancy. Wires used in this study were constructed essentially as those discussed in Ref. 4, and consisted of 5-μm-diam uncoated tungsten wire with a length/diameter ratio in the range $75 \leq l/d \leq 100$. These wires sustained several hours of operation at near sonic conditions and the highest pressure condition. These same wires were used later in a boundary-layer-turbulence study in another facility.

A typical behavior of the directly calibrated sensitivities S_u and S_ρ with increasing overheat ratio is shown in Fig. 1. For the highest overheat ratio ($a_w \approx 0.8$), S_u and S_ρ are essentially the same. At this condition, Eq. (1) reduces to

$$E'/\bar{E}=S_{\rho u}[(\rho u)'/\bar{\rho}\bar{u}]+S_{T_t}(T_t'/\bar{T}_t) \qquad (4)$$

Further, the temperature sensitivity S_{T_t} decreases rapidly at high overheat ratios and, if the product $S_{T_t}(T_t'/\bar{T}_t)$ is much less than $S_{\rho u}[(\rho u)'/\bar{\rho}\bar{u}]$, as in most transonic aerodynamic boundary layers, the wire response [Eq. (4)] reduces to

$$E'/\bar{E}=S_{\rho u}[(\rho u)'/\bar{\rho}\bar{u}] \qquad (5)$$

In order to use Eq. (5) and simplify the calibration procedure for high overheat ratio, the wire voltage E may be plotted against ρu, as in Fig. 2, and the logarithmic slope $\partial \ell n E/\partial \ell n \rho u=S_{\rho u}$ found. The data shown in Fig. 2 are from the present study. A single curve fits the data quite well, indicating a single sensitivity to ρu despite the fact that many of the data were taken near sonic conditions.

In another study, at Ames,[5] a sensor was operated in a transonic boundary layer. A single sensitivity to ρu also was found for a high sensor temperature. The direct calibration curve was obtained in Ref. 5 by a so-called "process" calibration, in which E^2 was determined as a function of ρu, by moving the sensor through the boundary layer. The results of this calibration indicate that passage from $M=1.5$ through $M=1.0$ to about $M=0.8$ is achieved without significantly altering the sensitivity to ρu alone.

It should be emphasized that, although the overheat parameter a_w is used, in fact the wire resistance was held constant during the calibrations in correspondence with Eq. (3). The curves should be considered to apply at high or low wire temperatures, rather than at the exact overheat ratios. In transonic flow, since the recovery factor is changing significantly, there is a great difference between a calibration at constant wire resistance and one at constant overheat ratio. In fact, early in the study, a calibration was run at constant overheat ratio, producing behavior of the velocity sensitivity coefficient that ranged from unusual to bizarre, including a negative sensitivity to velocity near $M=1$. One therefore must evaluate the sensitivities, holding the correct variables constant if meaningful results are to be obtained.

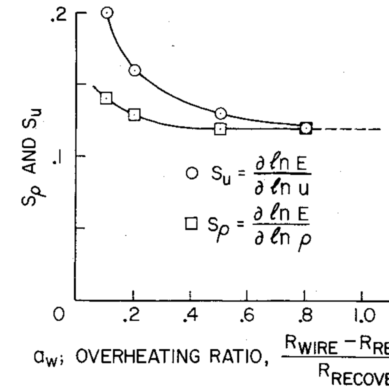

Fig. 1 Variation of S_u and S_ρ with overheat ratio.

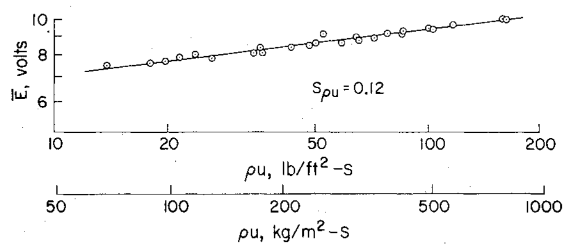

Fig. 2 Variation of $\bar{E}$ with ρu at high overheat ratio, $a_w \approx 0.8$.

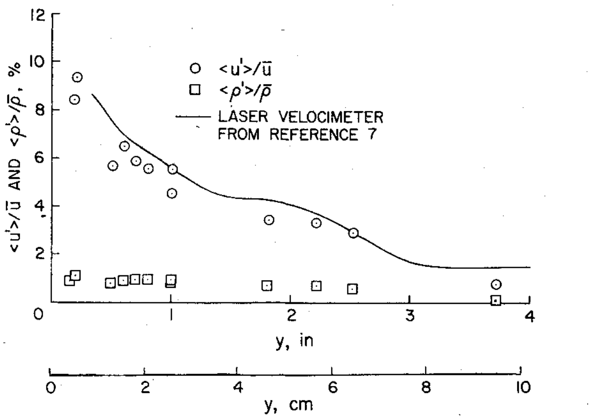

Fig. 3 Fluctuations of velocity and density through a $M_e = 0.8$ boundary layer.

Boundary-Layer-Turbulence Measurements

An application of the calibrations described in the preceding to measure the fluctuating velocity and density in a transonic boundary layer is discussed in the following. The boundary layer investigated was initially artificially thickened, and then allowed to develop on a flat-plate model in a $M = 0.8$ freestream flow in the Ames 6×6 ft wind tunnel. The characteristics of the boundary layer have been documented in Ref. 6, in which the model was denoted "configuration 5." The freestream unit Reynolds number was 4×10^6/ft (1.3×10^7/m), and the boundary-layer thickness was about 3.5 in. (9 cm); thus, $Re_\delta > 10^6$. The total temperature of the flow was near 530°R (295 K), and the surface of the flat-plate model was essentially adiabatic. The DISA model 55M constant-temperature system was used to drive the 5-μm tungsten wire, giving an upper frequency response in excess of 100 kHz for all flow conditions.

The fluctuating hot-wire data were reduced in the following manner. Since the total temperature fluctuations $T_t'/\bar{T}_t$ were everywhere less than about 0.3%,[6] the effect of these fluctuations on the wire's signal was neglected, and Eq. (5) was used to give $(\rho u)'/\bar{\rho}\bar{u}$. In order to separate $(\rho u)'$ into ρ' and u', an assumption about the fluctuating static pressure is required. Following the usual assumption of $p' = 0$, the technique of Kovasznay[2] can be used to obtain the following:

$$\frac{\langle u'\rangle}{\bar{u}} = \frac{1}{1+(\gamma-1)M^2}\,\frac{\langle(\rho u)'\rangle}{\bar{\rho}\bar{u}}$$

$$\frac{\langle \rho'\rangle}{\bar{\rho}} = \frac{(\gamma-1)M^2}{1+(\gamma-1)M^2}\,\frac{\langle(\rho u)'\rangle}{\bar{\rho}\bar{u}}$$

The maximum uncertainties in the previous values for u' and ρ', due to the presence of pressure fluctuations, are given by plus or minus $\langle p'\rangle/\bar{p}$. The pressure fluctuations[6] for the present boundary layer are about 0.4% throughout the boundary layer. Thus, the values of $\langle u'\rangle/\bar{u}$ and $\langle \rho'\rangle/\bar{\rho}$, shown in Fig. 3 as a function of the distance across the boundary layer, could contain this ±0.4% uncertainty. There are no direct measurements of the density fluctuations to compare with the present measurements. However, the observed density fluctuations appear to be reasonable when considering the mean gradient of density in this flow. For comparison, the velocity fluctuations obtained by Johnson and Rose,[7] using a laser velocimeter to study the same boundary layer, also are shown in Fig. 3. The agreement between these two independent measurement techniques gives credence to the hot-wire anemometer measurements and, in particular, to the calibrations and data-reduction procedures used here.

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Similarity in Vortex Asymmetries over Slender Bodies and Wings

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Introduction

WHEN a body of revolution is pitched to high angles of attack at zero sideslip angle, a side force can occur. This asymmetric force is associated with the separation-induced vortex flowfield on the lee side of the body becoming asymmetric. At moderate angles of attack, the location of the flow separation and the resulting vortex flowfield are symmetric, but at high angles of attack, the flow separation and vortex flowfield can become asymmetric. When the flowfield is asymmetric, an asymmetric force (side force) can occur.

Because the configuration of the forebody plays an important role in the spin characteristics of aircraft, a comprehensive wind-tunnel test program was conducted at Ames Research Center in which static aerodynamic data were obtained for forebody-alone models. The tests covered a wide range of forebody shapes, Reynolds numbers, and Mach numbers.[1-6]

The results of these tests showed that the side forces are largest at subsonic speeds and that the magnitude of the side force can be larger than the maximum normal force. Furthermore, there was a well-defined angle of attack for the onset of side force; this onset angle varied only with forebody geometry and could be correlated with the semiapex angle of the nose by a simple formula: onset $\alpha = 2\delta_N$.

One consideration in the analysis of the experimental results was the cause of the vortex asymmetry, which is not understood completely. There are at least two possible causes for the flow becoming asymmetric: 1) a boundary-layer-induced asymmetry in the location of flow separation that causes the vortex flowfield to become asymmetric, or 2) a hydrodynamic (inviscid) instability in the pair of symmetrically separated vortices which causes the asymmetry.

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