Hot-Wire Accuracy in Supersonic Turbulence from Comparisons with Laser-Induced Fluorescence

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A hot-wire anemometer and a new, nonintrusive, laser-induced fluorescence (LIF) technique are used to survey a turbulent boundary layer in a supersonic channel flow at Mach no. 2.06. The purpose is to test the accuracy of using the hot wire to measure the fluctuation amplitudes of static temperature and density in a compressible turbulent flow by comparing the results with independent and direct LIF measurements. Several methods of hot-wire calibration and analysis are applied. With each method, the hot-wire response can be related primarily to fluctuations of mass flux and total temperature, from which fluctuations of static temperature and density are calculated. However, these calculations are shown to be valid only if the fluctuations in static pressure are negligible. The acquisition and the analysis of the hot-wire data are often simplified further by neglecting the effects of fluctuations in total temperature. Comparisons of the fluctuation amplitudes of temperature and density obtained by hot-wire and LIF measurements demonstrate that such assumptions might not always be warranted, even in apparently simple flows.

Introduction

FOR several decades, turbulent-flow research has relied on the hot-wire anemometer to measure fluctuations owing to the turbulence. However, in applications to compressible flows, the interpretation of its response has remained a subject of study and controversy. The work done in this area has recently been reviewed by Stainback.[1]

To evaluate the hot-wire response, an independent means of measuring fluctuation amplitudes in the flow is desirable. For example, laser-Doppler velocimetry (LDV) can be used to measure velocity fluctuations independently. However, the hot wire responds to a combination of velocity, density, and total temperature, thereby obscuring any direct comparison of the two measurements. On the other hand, if certain assumptions are made about the response of the wire or the magnitude of the pressure and total-temperature fluctuations,[2] then the velocity fluctuations can be calculated from the hot-wire data. While the validity of these assumptions has not been demonstrated conclusively, several comparisons have been reported which show that, under some circumstances, hot-wire and LDV results are consistent.[2–5] For example, Robinson et al.[5] found that their LDV data from a supersonic, turbulent boundary layer agreed well with results from one hot-wire probe configuration tested, but only for the streamwise velocity component. In any case, comparisons of hot-wire and LDV results for velocity measurements do not confirm the accuracy of hot-wire data for determining other flow variables.

Recently, a laser-induced fluorescence (LIF) method was demonstrated in which static temperature, density, and pressure can be measured simultaneously with good spatial and temporal resolution.[6,7] Because LIF is an independent means of measuring the fluctuation amplitudes of these flow quantities, comparisons of the results from both instruments provide a new opportunity to evaluate the hot-wire measurement technique.

In general, the interpretation of the hot-wire data depends on the method of calibration and analysis. Several different procedures have been used,[3,8–10] but few authors have reported a comparison of results using two or more methods. Here, we apply several different calibration and analysis techniques and compare the results with data obtained independently using LIF.

Method of Analysis

Hot-Wire Response

If a hot wire is exposed to small fluctuations in density, velocity, and total temperature, the fluctuating voltage across it can be described by the linearized response equation[11]

$$\frac{E'}{E} = S_\rho \frac{\rho'}{\rho} + S_u \frac{u'}{u} + S_{T_t} \frac{T_t'}{T_t} \tag{1}$$

where the primed symbols denote the instantaneous perturbation from their mean (i.e., time-averaged) value, E is the mean hot-wire voltage, ρ the mean static density, u the mean streamwise velocity, and T_t the mean total temperature. The sensitivities, S_ρ, S_u and S_{T_t}, are defined by $S_\rho = (\partial \ell n E/\partial \ell n \rho)_{u,T_t}$, $S_u = (\partial \ell n E/\partial \ell n u)_{T_t,\rho}$, and $S_{T_t} = (\partial \ell n E/\partial \ell n T_t)_{\rho,u}$. In general, they vary with the overheat ratio, which is defined by $\tau = (T_{\text{wire}} - T_{\text{flow}})/T_{\text{flow}}$ where T_{flow} is the flow recovery temperature. Horstman and Rose[12] have shown that for Mach numbers larger than 1.2 and Reynolds numbers (based on wire diameter) higher than 20, the sensitivities to density and velocity are approximately equal. Thus, at those conditions, they can be combined to define the sensitivity to mass flux by assuming that

$$S_\rho \approx S_u \approx S_m \tag{2}$$

where $m \equiv \rho u$ is the mass flux and $S_m = (\partial \ell n E/\partial \ell n m)_{T_t}$.

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Thus, the calibration of a hot wire for measurements in compressible flows consists of determining the parameters S_m and S_{T_t} as functions of τ.

Hot-Wire Calibration and Analysis Methods

Numerous methods of hot-wire calibration and analysis for compressible flows have been reported. The method selected for a given application will determine the dependence of the results on S_m and S_{T_t} and the wire overheat ratio. The simplest mode of hot-wire operation employs a high overheat ratio. We describe two calibration procedures, both using high overheat ratios, and a separate analysis technique that is appropriate for operation at multiple overheat ratios. All three approaches are suitable for measurements in compressible, turbulent boundary layers. They are applied here to the flow in a small, supersonic, blowdown wind tunnel in which use is made of the variation in time during a run of the mean stagnation temperature and mean pressure.

1. Single High-Overheat Ratio

If the wire is operated at a sufficiently high temperature, it is sensitive only to mass flux, thereby allowing the effects of temperature fluctuations to be neglected. One approach to calibration is then to place the hot-wire probe at the centerline of the test section, where the flow is relatively free of disturbances, and vary the stagnation pressure from run to run. Consequently, the mass flux is varied by a known amount while the Mach number remains constant. Although the stagnation conditions of a blowdown tunnel vary with time, this effect can be ignored if the hot-wire data are acquired for only a short time compared with the time required for a significant change in flow conditions. Then, a simple time average of m and E can be obtained, from which the slope of a plot of $\ell n E$ vs $\ell n m$ determines S_m. We shall refer to this procedure as the "centerline method."

Unfortunately, using the centerline method can lead to errors if the flow in the region to be probed is sufficiently different from the flow where the wire was calibrated. In particular, erroneous results are obtained if the Mach number or the mean total temperature are different. Furthermore, the sensitivity of the wire can change as it ages. To minimize these problems, a second approach to calibration has been suggested by Robinson et al.[5] in which thermocouple and pitot-static probes are used to measure the time-averaged total temperature, static pressure, and Mach-number profiles in the flow. The mean mass-flux profile is calculated from these data using the standard formulas of compressible flow. The hot wire is then traversed through the same region, and its time-averaged voltage output is recorded at each position. Again, the slope, $\partial \ell n E/\partial \ell n m$, determines S_m while, at the same time, the fluctuating wire voltage, E', is also measured, giving the probe calibration data and test data simultaneously. This technique is especially appropriate for boundary-layer flows because their mean mass-flux profiles are relatively simple and easily characterized. We refer to this approach as the "boundary-layer method."

2. Multiple Overheat Ratios

A hot wire that is operated at a single high overheat ratio can measure only mass flux directly. To measure total-temperature fluctuations as well, the wire must be operated at low overheat ratios, so that it also responds to variations in total temperature. However, a more complex method of analyzing the hot-wire response is then required. Such an analysis, which has been described by Kovasznay,[13] begins by squaring and averaging Eq. (1) over time to obtain

$$\left\langle \frac{E'}{E} \right\rangle^2 = S_m^2 \left\langle \frac{m'}{m} \right\rangle^2 + 2 S_m S_{T_t} \left\langle \frac{m'}{m} \right\rangle \left\langle \frac{T_t'}{T_t} \right\rangle R_{mT_t} + S_{T_t}^2 \left\langle \frac{T_t'}{T_t} \right\rangle^2 \tag{3}$$

where $\langle x \rangle$ denotes the root-mean-square (rms) fluctuation-amplitude of x and R_{mT_t} is the correlation coefficient for m and T_t. If S_m and S_{T_t} are obtained by some other means and measurements of $\langle E'/E \rangle$ are made for three or more overheat ratios, then the three flow variables, $\langle m'/m \rangle$, $\langle T_t'/T_t \rangle$, and R_{mT_t} can be determined. This procedure has been used by Kistler[14] to study a supersonic boundary layer, by Mikulla and Horstman[15] for a hypersonic boundary layer, and by Ardonceau[16] for a shock-wave/boundary-layer interaction. We refer to this analysis procedure as the "multiple overheat method."

The accuracy of the values of $\langle m'/m \rangle$, R_{mT_t}, and $\langle T_t'/T_t \rangle$ that are obtained from the solution of Eq. (3) depends on the method used to solve it. One commonly used method[11] begins by normalizing Eq. (3) by $S_{T_t}^2$ and combining the temperature and mass-flux sensitivities into a single parameter, $r = S_m/S_{T_t}$. If r is regarded as the independent parameter and $e = (\langle E'/E \rangle / S_{T_t})^2$ is the dependent parameter, then measured values of e vs r can be analyzed using multiple linear regression. However, such a normalization of Eq. (3) is equivalent to introducing a weighting factor of $1/S_{T_t}^2$ to the analysis. This has the effect of emphasizing measurements made at high overheat ratios where S_{T_t} is small, thereby producing precise calculations of $\langle m'/m \rangle$ at the expense of precision in R_{mT_t} and $\langle T_t'/T_t \rangle$. An alternate approach is to apply a multiple linear-regression analysis to Eq. (3) as written, without normalization, and solve for the three unknowns $\langle m'/m \rangle$, R_{mT_t}, and $\langle T_t'/T_t \rangle$. This approach does not degrade the precision of $\langle T_t'/T_t \rangle$ and R_{mT_t}, and it is preferred in this application.

To implement the multiple overheat method, $S_m(\tau)$ and $S_{T_t}(\tau)$ must be known. $S_m(\tau)$ can be measured using either the centerline or boundary-layer methods. However, the influence of total-temperature fluctuations on the determination of S_m at low overheat ratios must be considered. To prevent large errors in S_m, the mean total-temperature must be kept constant throughout all of the calibration runs. As before, this can be accomplished if the initial stagnation temperature of the wind tunnel is consistent from run to run and the data-acquisition time is kept short compared with the time over which significant temperature changes occur. Furthermore, if the boundary-layer method is to be used, the total-temperature profile must be constant throughout the region where the wire is calibrated. In our flow, all of these conditions were satisfied within 1%, permitting either the centerline or the boundary-layer method of finding S_m to be used.

A more difficult problem is the measurement of $S_{T_t}(\tau)$. This requires that the probe be exposed to flows with various total temperatures while maintaining a constant mass flux. Ardonceau[16] accomplished this using a special calibration tunnel with an electrically heated flow. However, in most wind tunnel facilities, the total temperature is not easily controlled. Also, the fragility of a hot-wire probe often limits the number of calibration runs that can be successfully conducted. Therefore, S_{T_t} is more often calculated, rather than measured, using variations of a procedure outlined by Morkovin.[8] Nevertheless, the most accurate way to determine S_{T_t} is by direct measurement. The behavior of a blowdown wind tunnel allows such measurements to be made.

Measurement of Hot-Wire Total-Temperature Sensitivity

In a blowdown wind tunnel, both total temperature and stagnation pressure decrease as the reservoir discharges. Consequently, the mean flow conditions within the test section will vary with time. If these variations are consistent and can be accurately characterized, then the response of the hot wire to them can be used to determine its sensitivity to total temperature.

For an ideal gas, the time dependence of total pressure, total temperature, and mass flux in a blowdown wind tunnel can be described by[17]

$$p_t(t) = p_t(0)(1 + b_p t)^{-2\gamma/(\gamma-1)} \tag{4}$$

$$T_t(t) = T_t(0)(1 + b_T t)^{-2} \tag{5}$$

$$m(t) = m(0)\frac{1 + b_T t}{(1 + b_p t)^{2\gamma/(\gamma-1)}} \tag{6}$$

where γ is the ratio of the specific heats. If the expansion in the reservoir is an ideal adiabatic process, then $b_p = b_T$ and they both can be calculated using an analytic expression.[17] However, better accuracy is obtained if b_p and b_T are determined experimentally from measurements in the test section using pressure and thermocouple probes.

Once the time dependence of the wind tunnel mean-mass-flux and mean-total-temperature are accurately characterized, the sensitivity of the hot wire to total-temperature at constant mass-flux, i.e., $S_{T_t} = [\partial(\ell n E)/\partial(\ell n T_t)]_m$, can be evaluated. Since the mass-flux, which varies with reservoir pressure and total temperature, decrease simultaneously for any given run, pairs of wind tunnel runs with different initial reservoir pressures are compared to identify an instant in time for each of the two runs when their mean mass-fluxes are the same. The value of S_{T_t} is then computed from the corresponding mean values of T_t and E.

Conversion of Hot-Wire Data to Static Temperature and Density

To compare the hot-wire and LIF results, the fluctuations of mass-flux and total-temperature that are obtained from the hot-wire data must be converted to those of those of the static density, ρ, and the static temperature, T, which are measured by the LIF technique. The static pressure and its fluctuations can also be obtained from the LIF data by using the equation of state, $p = \rho RT$, where R is the appropriate gas constant. The necessary expressions for the fluctuations, ρ' and T', can be written as follows[18]

$$\left\langle \frac{T'}{T} \right\rangle^2 = \frac{1}{(\alpha+\beta)^2}\left[\beta^2\left\langle \frac{m'}{m}\right\rangle^2 - 2\beta\frac{\overline{m'T'_t}}{mT_t} + \left\langle \frac{T'_t}{T_t}\right\rangle^2 + 2\beta(\alpha+\beta)\frac{\overline{T'p'}}{Tp} - \beta^2\left\langle \frac{p'}{p}\right\rangle^2\right] \tag{7}$$

$$\left\langle \frac{\rho'}{\rho} \right\rangle^2 = \frac{1}{(\alpha+\beta)^2}\left[\beta^2\left\langle \frac{m'}{m}\right\rangle^2 - 2\beta\frac{\overline{m'T'_t}}{mT_t} + \left\langle \frac{T'_t}{T_t}\right\rangle^2 + 2\alpha(\alpha+\beta)\frac{\overline{\rho'p'}}{\rho p} - \alpha^2\left\langle \frac{p'}{p}\right\rangle^2\right] \tag{8}$$

where $\alpha = 1/[1 + (\gamma-1)M^2/2]$, $\beta = (\gamma-1)M^2\alpha$, and M is the Mach number.

If the multiple overheat method is used in conjunction with Eq. (3), then the terms in Eqs. (7) and (8) that contain $\langle m'/m\rangle$, $\langle T'_t/T_t\rangle$, and $(m'T'_t/mT_t)$ can be determined, but not those containing pressure. In many flows, these pressure terms are assumed to be small compared to the others and are neglected. This assumption that $\langle p'/p\rangle \ll \langle m'/m\rangle$ then leads to

$$\left\langle \frac{T'}{T} \right\rangle^2 \approx \left\langle \frac{\rho'}{\rho} \right\rangle^2 \approx \frac{1}{(\alpha+\beta)^2}\left[\beta^2\left\langle \frac{m'}{m}\right\rangle^2 - 2\beta\frac{\overline{m'T'_t}}{mT_t} + \left\langle \frac{T'_t}{T_t}\right\rangle^2\right] \tag{9}$$

Furthermore, if the hot wire is operated only at high overheat ratios, it is sensitive only to $\langle m'/m\rangle$, thereby leading to the further approximation

$$\left\langle \frac{T'}{T} \right\rangle \approx \left\langle \frac{\rho'}{\rho} \right\rangle \approx \frac{\beta}{(\alpha+\beta)}\left\langle \frac{m'}{m}\right\rangle \tag{10}$$

For Eq. (10) to be valid, $\langle T'_t/T_t\rangle \ll \langle m'/m\rangle$ must also be true.

Experimental Arrangement and Methodology

To assess the accuracy of the hot-wire calibration and analysis methods just described, hot-wire and LIF measurements were made in the supersonic flow in a small blowdown wind tunnel. The flow entering the test section first expanded through a two-dimensional nozzle that was followed by a 76-cm-long rectangular channel that allowed a turbulent boundary layer to develop. At the test section, the channel cross section was 65 by 32.5 mm, and the boundary layers on the top and bottom walls each filled about one-third of the 32.5-mm height with a nonturbulent core flow in the center. Properties of the boundary layer on the bottom wall, the region of interest for this study, are summarized in Table 1. Windows were located in the two side walls to provide optical access for the laser, and on the top wall for observation of the fluorescence. In the region of the test section, the pressure gradient was effectively zero and the freestream Mach number was 2.06. The useful run time of the tunnel was limited to 13 s, during which the static pressure and temperature dropped by 30% and 5%, respectively.

The LIF method has been described in detail elsewhere.[6,7] It requires the use of a nitrogen flow that is seeded with approximately 100 ppm of the fluorescent species, nitric oxide. The technique provides simultaneous measurements of the instantaneous static temperature, density, and pressure in a cylindrical sample volume about 0.5 mm in diameter and 1 mm long. The sample volume can be located anywhere in the flow having optical access. Normally, 65 measurements are obtained during a 13-s wind tunnel run. A statistical analysis of the LIF data produces mean values of the measured variables in absolute units and the rms amplitude of their fluctuation about the mean value. Data from numerous identical runs can be collected together to improve the statistical accuracy of the rms amplitudes.

The accuracy of the LIF measurements is limited primarily by the statistical photo-electron noise in the radiometric signals (so-called instrument noise). For these experiments, the instrument noise produced a consistent uncertainty in the temperature measurements of approximately 1% rms and in the density and pressure measurements of approximately 2% rms. Thus, contributions owing to fluctuations in the flow with lower amplitudes are not resolved. However, the rms fluctuations in the LIF signal from the instrument noise and from the flow combine as the square root of the sum of their squares. Thus, fluctuation amplitudes in the flow that are more than twice the instrument noise amplitudes have errors of less than 12% of the combined amplitude, and the noise contribution decreases significantly for larger amplitudes. Furthermore, since the instrument noise is consistent, the measured fluctuation amplitudes can by corrected to remove it.

The Mach number profile in the boundary layer and the time dependence of pressure during a wind tunnel run were determined using a pitot tube in combination with a wall-pressure port. The mean total-temperature profile across the

Table 1 Boundary-layer properties

M_∞	2.06
u_∞	530 m/s
δ	12.1 mm
Displacement thickness	2.3 mm
Momentum thickness	0.68 mm
C_f	1.9×10^{-3}
Re_x	2.7×10^7
Re_δ	4.4×10^5
T_t	295 K
p_t	3.0 atm

boundary layer and its time dependence during a run were measured with a probe similar to the one described by Kussoy et al.[19] Shadow photography was also used to verify that no strong shock waves were observable in the region of interest and that the introduction of intrusive probes into the channel did not exert any global influence on the boundary layer.

The hot-wire probe configuration is shown in Fig. 1. It incorporated a tungsten wire which was 8 μm in diameter and 1 mm in length. The wire was positioned parallel to the wall and perpendicular to the mean flow direction. It was supported by an epoxy backing to reduce vibration and mounted with a small amount of slack to avoid the effects of flow-induced strain. Since the bulk flow contained no oxygen, there was no danger of wire oxidation, thereby allowing the wire to be operated at temperatures up to 800°K. The probe was operated by a DISA 55M10 constant-temperature anemometer system, and the signal was recorded with a Physical Data 515A waveform digitizer having a frequency response up to 250 kHz.

The low-pass filter and gain on the anemometer were adjusted to give the best possible frequency response at each overheat ratio without exciting any resonances within the amplifier-probe system. The frequency response of the system was tested using a square-wave input signal. The results showed an upper limit of better than 160 kHz for all overheat ratios, which corresponds to an eddy size of one-fourth the boundary-layer thickness. Spectra of the hot-wire output with the probe in the flow showed very little turbulent energy above 100 kHz.

Results

Main-Flow Features

Measurements of the decay of pressure and temperature in the test section during a wind tunnel run were found to correspond well with the time-dependent behavior predicted by Eqs. (4) and (5). However, while the experimental values of b_p and b_T were very consistent from run to run, they differed from each other by about 40% and were found to be functions of the stagnation pressure. Also, b_T varied with the distance of the thermocouple probe from the wall. Nevertheless, these departures from ideal behavior do not compromise the results of these experiments if the time-dependent decay of the flow variables in the test section is characterized accurately. Hence, the experimental values of b_p and b_T were used to determine the hot-wire-sensitivity values.

The Mach number profile is shown in Fig. 2, and the total-temperature profile at a selected time during the run interval is shown in Fig. 3. A high degree of consistency in these mean flow variables was obtained from run to run, making possible the method of finding S_{T_t} described previously. The corresponding velocity profile, which is calculated from these mean flow profiles, is shown in Fig. 4. It is seen to be similar to that described by Coles' law of the wall, as modified for compressibility.[20] This agreement with the Coles profiles is an indication that the boundary layer is similar to a two-dimensional, fully developed turbulent layer. Although not essential to this work, the thickness, δ, was then determined by extrapolating the data to $u/u_\infty = 1$, and the associated skin-friction coefficient was computed by fitting the experimental profile to Coles' curves (see Fig. 4).

Measured Hot-Wire Sensitivities

When the centerline and boundary-layer methods of hot-wire calibration were applied to probes operated at high overheat ratio, both methods yielded the same S_m, within the limits of error. The results for two probes are shown in Fig. 5 where S_m is determined by the slope of the line through each data set. The only deviation in slope is near the wall where the Mach number approaches unity. Otherwise, the sensitivity to mass-flux appears to be independent of the Mach number, which agrees with the results of Horstman and Rose.[12]

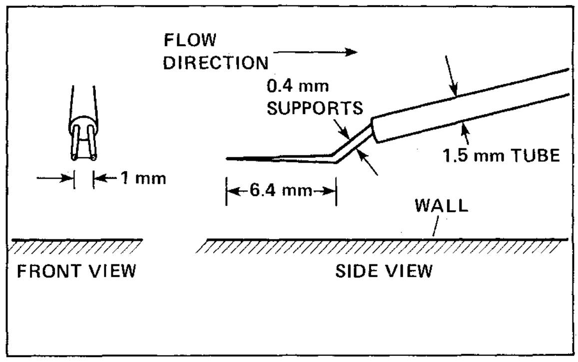

Fig. 1 Hot-wire probe configuration.

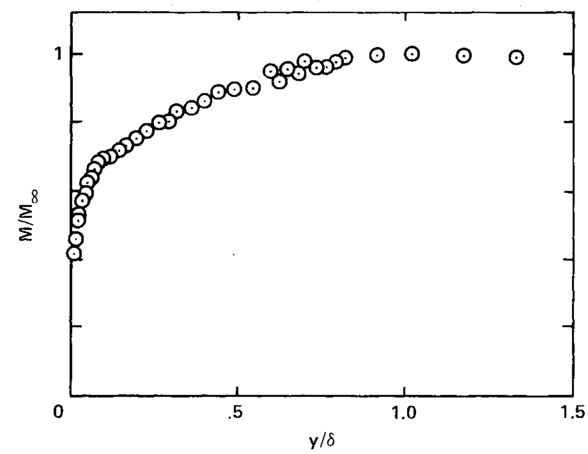

Fig. 2 Distribution of mean Mach number within the boundary layer.

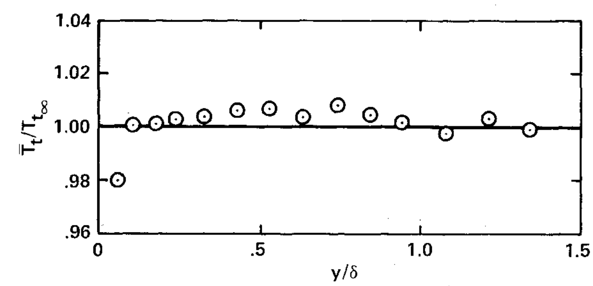

Fig. 3 Distribution of mean total temperature within the boundary layer.

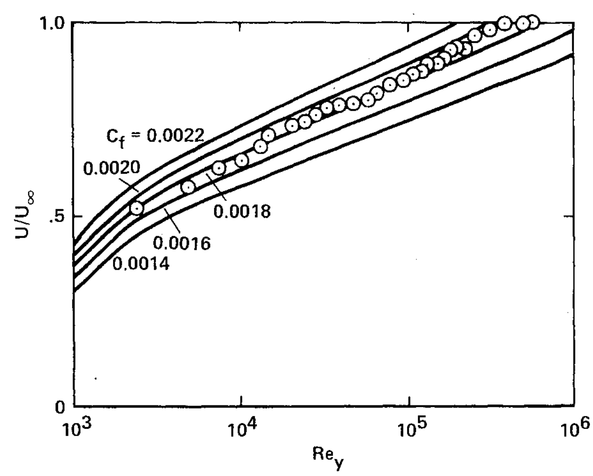

Fig. 4 A comparison of the experimental velocity profile with those predicted by Coles' modified law of the wall for various skin-friction coefficients. Re_y is the Reynolds number based on distance from the wall.

Measurements of S_{T_t} and S_m were made for five wire-overheat ratios. In principle, only two runs at each overheat ratio are needed to compute S_{T_t}. In practice, the accuracy was improved by making at least five runs and then computing S_{T_t} for all possible pairings. The resulting sensitivity plot is shown in Fig. 6, and the dependence of both sensitivities on the overheat ratio is shown in Fig. 7. Ardonceau,[16] who calibrated a 5-μm wire, obtained qualitatively similar results.

Boundary-Layer-Fluctuation Profiles

The profiles of mass-flux fluctuation amplitudes obtained from the two methods of hot-wire analysis are compared in Fig. 8. The profile obtained with the single high-overheat method is in good agreement with that obtained from the multiple overheat method, thereby showing that either method of analysis leads to consistent measurements of mass-flux fluctuations.

The profiles of $\langle T'/T \rangle$ and $\langle \rho'/\rho \rangle$ obtained from the LIF technique are compared in Fig. 9 with those calculated from the hot-wire data. Considering first the comparison of the hot-wire results with the temperature fluctuations obtained from LIF, the hot-wire measurements obtained with a single high-overheat ratio are shown to be in poor agreement with the LIF measurements in the region where $y/\delta < 0.6$. In contrast, the measurements using a multiple overheat analysis show much better agreement with the LIF measurements throughout the boundary layer. The only difference between the two hot-wire approaches is that the former completely neglects total-temperature fluctuations, thereby suggesting that the neglect of $\langle T_t'/T_t \rangle$ and R_{mT_t} are responsible for the error in the hot-wire measurements of $\langle T'/T \rangle$ made with a single high-overheat ratio. That conclusion is supported by the multiple-overheat measurements of $\langle T_t'/T \rangle$ and R_{mT_t} that are shown in Fig. 10. They are seen to be largest near the wall where the error is greatest.

The ability of the hot-wire profiles to represent $\langle \rho'/\rho \rangle$, as Eq. (9) suggests, can also be considered. Figure 9 shows that in the middle of the boundary layer, the $\langle \rho'/\rho \rangle$ amplitudes from the LIF data are significantly larger than those that are derived from the hot-wire data using the multiple overheat analysis. An indication of the source of the error in the hot-wire results can be found in the amplitudes of $\langle p'/p \rangle$ that were obtained from the LIF data and are shown in Fig. 11. Although the resolution of the pressure data is very poor because of the instrument noise, $\langle p'/p \rangle$ appears to peak at the same positions in the boundary layer where the discrepancy in $\langle \rho'/\rho \rangle$ is the largest. From this observation, we are led to conclude that the pressure-dependent terms that affect $\langle \rho'/\rho \rangle$ in Eq. (8) cannot be neglected for our flow. On the other hand, the neglect of the pressure terms that affect $\langle T'/T \rangle$ in Eq. (7) does not produce a similar error. An explanation of these results is proposed in the next section.

Effects of a Weak, Unsteady Shock Wave on Flow Fluctuations

One explanation of the discrepancies between the hot-wire and LIF measurements of $\langle \rho'/\rho \rangle$, but not $\langle T'/T \rangle$, is based on the presence of a weak, unsteady shock wave in the flow that passes back and forth across the sample volume. Such a wave might be caused by an oscillation in the boundary layer that is upstream of the test section. In the neighborhood of such an unsteady wave, a nonintrusive probe records measurements corresponding to conditions both upstream and downstream of the wave.

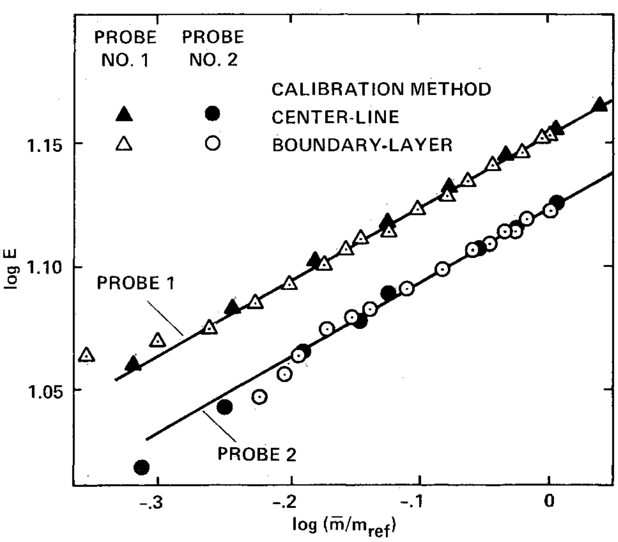

Fig. 5 Calibration diagrams for the mass-flux sensitivity of two probes using the centerline method and the boundary-layer methods of calibration; $m_{ref} = 400$ kg^2/ms.

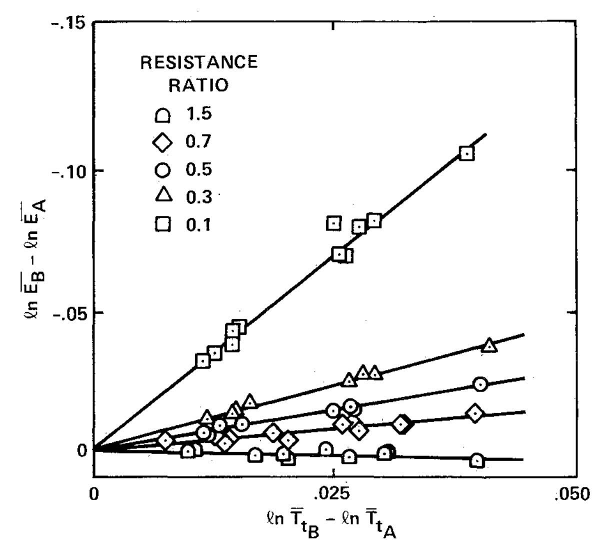

Fig. 6 Calibration diagrams for the total temperature sensitivity of a probe at several resistance ratios. The resistance ratio, $(R_{wire} - R_o)/R_o$, is determined by the overheat ratio used. R_o is the wire resistance at the flow-recovery temperature.

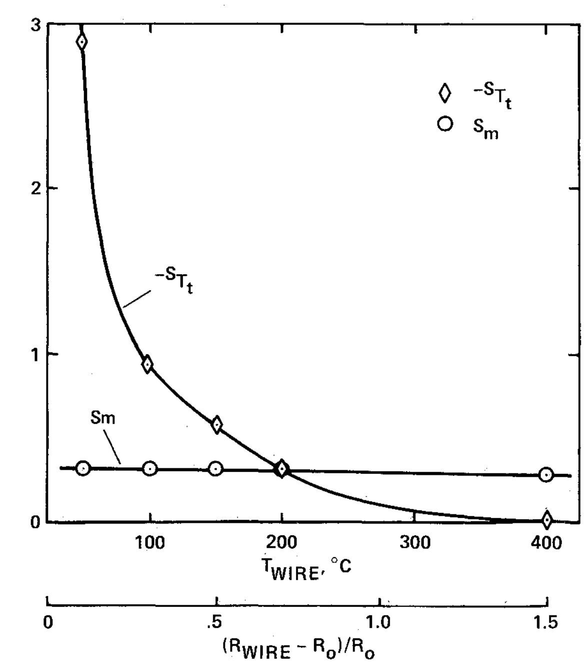

Fig. 7 Variation of the hot-wire sensitivities, S_m and S_{T_t}, with wire temperature and resistance ratio.

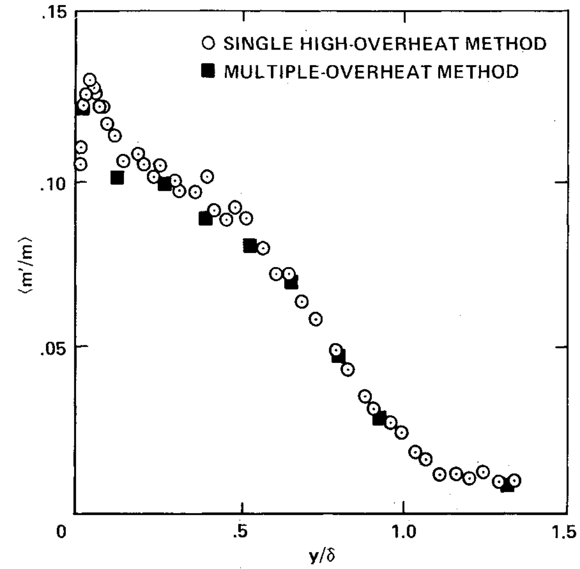

Fig. 8 A comparison of the distribution of rms fluctuation amplitudes in mass flux within the boundary layer as measured using a hot wire operated with a single high-overheat ratio and with multiple overheat ratios.

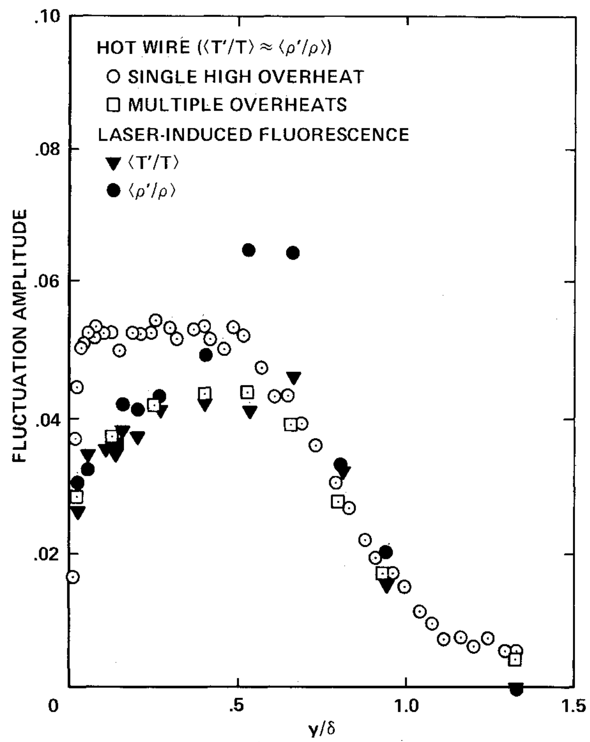

Fig. 9 A comparison of the distribution of rms fluctuation amplitudes in static temperature and density within the boundary-layer obtained using a hot wire at single and multiple overheat ratios with direct measurements obtained using laser-induced fluorescence (LIF). The LIF data have been corrected for instrument noise.

The effect of such a wave on the LIF measurements can be analyzed using the weak-shock equations.[21] For a weak wave, the pressure and density jumps are identical to those for isentropic flow and can be described by

$$\frac{\Delta p}{p} = \left(\frac{\gamma}{\gamma - 1}\right)\frac{\Delta T}{T} \qquad \text{and} \qquad \frac{\Delta \rho}{\rho} = \left(\frac{1}{\gamma - 1}\right)\frac{\Delta T}{T} \tag{11}$$

For $\gamma = 1.4$, the terms in brackets are 3.5 and 2.5, respectively. Thus, a weak wave produces fluctuations in density and pressure that are significantly larger than those in tempera-

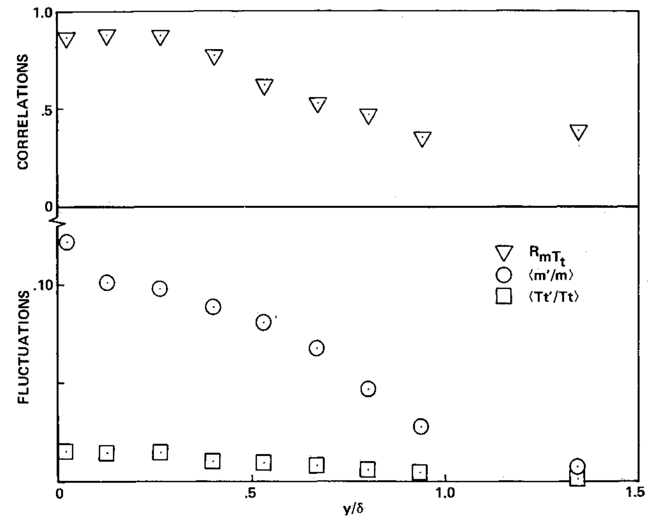

Fig. 10 The distribution of rms fluctuation amplitudes of mass flux, total temperature, and their correlation, measured using a hot wire with multiple overheat ratios.

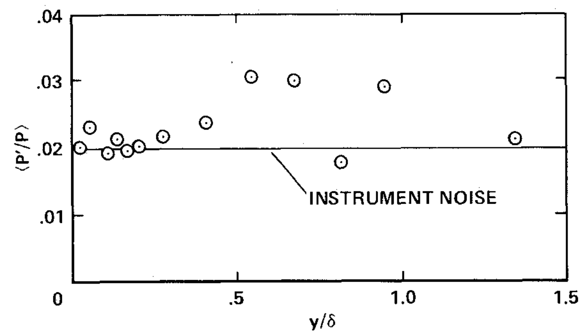

Fig. 11 The distribution of rms fluctuation amplitudes in static pressure, measured using LIF. The amplitudes are not corrected for instrument noise.

ture. The discrepancies shown in Fig. 9 can then be explained if the presence of the hot-wire probe in the flow stabilizes the wave motion. The existence of a wave and the possibility that the presence of the probe stabilizes its oscillation is supported by the fact that the fluctuation amplitudes measured with the LIF change when the probe is present in the flow.

Conclusions

By comparing measurements of the fluctuation amplitudes of static temperature, density, and pressure that were obtained using a laser-induced fluorescence technique with measurements of mass-flux and total-temperature that were obtained using a hot-wire probe, the following conclusions are made regarding the applicability of hot wires to unsteady compressible flows.

1) A hot wire that is operated either at a single high-overheat ratio or at multiple overheat ratios will obtain the same measurements of fluctuation amplitudes in mass-flux.

2) The centerline and boundary-layer methods of hot-wire calibration lead to the same results for the sensitivity to mass-flux fluctuations. In flows were the distribution of mean mass-flux can be measured with consistency, the boundary-layer method is preferred because it is not affected by errors associated with the use of separate calibration and test flow conditions.

3) If a hot wire at a single high-overheat ratio is used to measure only mass-flux fluctuations, then the fluctuation amplitudes of temperature and density cannot be accurately determined. The error is caused mainly by the neglect of the effects of total-temperature fluctuations.

4) If measurements of the mass-flux, the total-temperature, and their correlation are made using a hot wire at

multiple overheat ratios, and if there are no sources of pressure fluctuations such as unsteady waves in the flow, then the fluctuation amplitudes of temperature and density can probably be determined accurately. However, in the flow tested, pressure fluctuations that would not have been observed without the LIF measurements are believed to be the cause of significant errors in the density fluctuation amplitudes determined from the hot-wire data.

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