Experimental Comparison of Two Hot-Wire Techniques in Supersonic Flow

D. A. Walker* and W. F. Ng†
Virginia Polytechnic Institute and State University, Blacksburg, Virginia
and
M. D. Walker‡
State University of New York, Stony Brook, New York

The performance of two constant-temperature normal hot-wire techniques for resolution of turbulent mass flux and local stagnation temperature in a supersonic flow is examined. The first technique used a single wire and the rapid scanning of multiple overheat ratios. Time averages of the signals at all overheats were used to separate the mean and rms mass flux, stagnation temperature, and their cross-correlation. The second technique used a dual-wire probe with each wire operated at different overheat ratios, giving instantaneous mass flux and stagnation temperature. In spite of a small separation distance (0.18 mm) between the wires in the dual-wire probe and high correlation between their signals, the rms mass flux inferred from the dual-wire technique was a factor of two higher than that from the single-wire technique. A consistency check based on data from one of the wires indicated that the dual-wire method produced results that were too high.

Nomenclature

A_i, B_i	= hot-wire dc calibration constants
d	= hot-wire diameter
e	= instantaneous hot-wire voltage with zero mean
e'	= rms hot-wire voltage
$\bar{E}$	= mean hot-wire voltage
f_i	= sensitivity coefficient to mass flux
g_i	= sensitivity coefficient to stagnation temperature
G	= matrix of coefficients
H	= height of injection flow (splitter plate), = 1.27 cm
i	= index corresponding to ith wire temperature
k_0	= molecular conductivity at stagnation conditions
Kn	= Knudsen number, = λ/d
ℓ	= hot-wire length
M	= freestream or local Mach number
m	= mass flux, = ρu
N	= number of wire operating temperatures
Nu	= hot-wire Nusselt number, = $E^2/[R_w \pi 1 k_0(T_w - T_e)]$
Re	= hot-wire Reynolds number
R_w	= operating resistance of wire
T_e	= local wire equilibrium temperature, $\approx T_t$
T_{t_0}	= stagnation temperature in settling chamber
T_t	= local stagnation temperature
T_w	= hot-wire temperature
u	= local streamwise component of velocity
X	= axial distance measured from the slot
Y	= distance of probe from floor of the tunnel
λ	= molecular mean free path
ρ	= local density
τ	= temperature loading factor, = $(T_w - T_e)/T_t$

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*Assistant Professor, Department of Aerospace and Ocean Engineering. Member AIAA.

†Associate Professor, Department of Mechanical Engineering. Member AIAA.

‡Assistant Professor, Department of Mechanical Engineering. Member AIAA.

Introduction

INTEREST has again greatly increased in measurements of the turbulent mixing in supersonic shear layers. Since the pioneering works of Kovasznay[1,2] and Morkovin[3] on hot-wire anemometry in supersonic flows, many papers have been published on the subject and vast improvements have been made in electronics and computerized data acquisition. To benefit from the electronic improvements in supersonic applications, both the wind tunnel (run sequence, stagnation pressure) and instrumentation (probe position, hot-wire overheat ratio, data acquisition) should be computer controlled. Currently available commercial hot-wire anemometers can be computer operated, but operating conditions can be changed only slowly. If a fast sequence of changes is needed, one must custom-build the hot-wire anemometer.

Measurement by hot-wire anemometry in supersonic turbulent flow is far more demanding than the corresponding measurements in low-speed applications. First, the highest possible frequency response is insufficient to resolve the smallest scales of the turbulence. When large turbulence intensities are encountered, the nonlinear response of the anemometer requires high-frequency response to obtain even the mean flow variables. Second, the hot-wire anemometer responds to flow parameters that usually have greater fluctuations in high speed flow than in low-speed flow, e.g., density, pressure, and stagnation temperature. These variables are difficult to separate.[4] Third, most supersonic flow facilities, like the one used here, are "blowdown" tunnels with relatively short operating times (less than 10 s) and unsteady stagnation temperatures. The short run times make it impossible to scan the overheat ratios using the commercial hot-wire anemometer during one run. Fourth, fast-responding hot-wire probes are quite fragile and particularly vulnerable to the harsh starting and stopping conditions of a supersonic wind tunnel.

It is well known that signals from hot-wire anemometers can be used to resolve mass flux and local stagnation temperature in supersonic flow. This can be done in several ways. In the multiple-wire method, two or more hot-wire probes are placed very close together in the flow. These wires are operated at different overheat settings to permit conversion of the signals to instantaneous mass flux and stagnation temperature.[5] The multiple overheat method requires operation of a single wire at three or more overheat settings. Time averages of the signals at all overheats are used to separate the mean

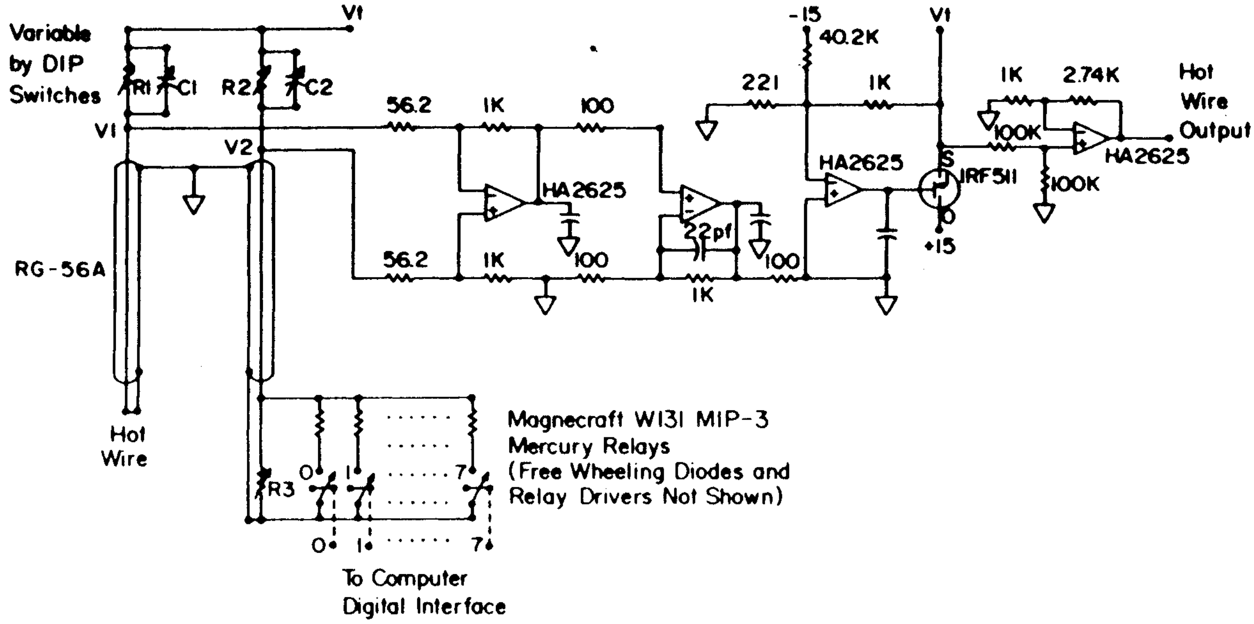


Fig. 1 Schematic diagram of the custom-built hot-wire anemometer.

and rms mass flux, stagnation temperature, and their cross-correlation.

The advantage of the multiple-wire method is that time averages are not needed to reconstruct mass flux and stagnation temperature from the hot-wire signals. Because data conversion by a calibration curve can be made on instantaneous signals, even statistically unsteady flows may be examined. Instantaneous conversion also allows nonlinearities in the calibration to be eliminated. The difficulty is that all of the wires must detect the same instantaneous flow (mass flux and stagnation temperature) or errors are introduced in the data reduction.

Use of multiple overheats to separate flow variables is well established.[1-3,6-8] Attempts have been made to separate density, velocity, and stagnation temperature and their correlations with six overheat ratios without success.[4] Except possibly for the case of transonic flow,[6] the explanation is given by Dewey[9] that distinct density and velocity sensitivities generally exist only in free molecular or slip flows (low Knudson number). Kovasznay[1] resolved the fluctuations into acoustic, entropy, and vorticity contributions. In the absence of substantial acoustic mode fluctuations, he demonstrated that density, velocity, stagnation temperature, and their correlations can be decoupled at high Knudson numbers by careful selection of the overheat ratios used. For the present investigation, this was not likely to be a good approximation. However, the mean square values of the mass flux ρu, stagnation temperature T_t, and their correlations can be separated by using at least three overheat ratios to solve for the coefficients.

In this paper, the application of both hot-wire techniques for resolution of turbulent mass flux and local stagnation temperature in supersonic shear layers is presented. The experimental setup is discussed briefly, followed by a description of each hot-wire technique. Typical results are presented and compared. A discussion with final conclusions is then given.

Apparatus and Experimental Background

The probe used for the single-wire multiple overheat method was the DANTEC miniature wire probe (55P11). It is a straight general-purpose type using Pt-plated tungsten wire with a diameter of 5 μm and a length of 1.25 mm. The probe was connected to a custom-built, constant-temperature anemometer.

Figure 1 is a schematic diagram of the hot-wire anemometer circuit that was constructed to permit the hot-wire to be

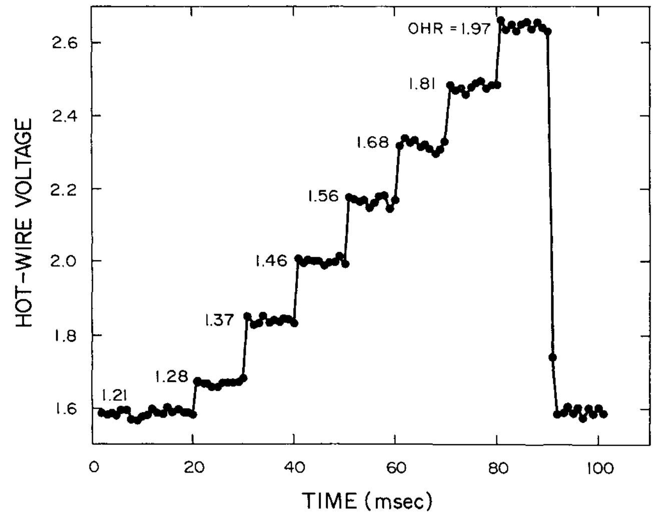


Fig. 2 Hot-wire signals with stepped overheat ratios (10 ms per overheat level).

stepped through eight operating temperatures at 10 ms/temperature (reported in Walker et al.[10]). Ten milliseconds was sufficient time to permit averages to be made (approximately 1000 integral times) but short enough so that the mean flow remained constant.

The temperature stepping was performed under computer control (IBM PC) with a Metrabyte DAS-16F A/D-D/A converter board, which was also used to operate the wind tunnel, to specify the operating pressure, to traverse the probes, and to acquire data. Thus, wire temperature stepping was synchronized with data sampling. The temperature was increased from step to step until the maximum temperature was reached. Then the temperature was allowed to return to the lowest value. Equilibrium was reached nearly instantly (approximately 10 ms) at each step as the temperature was increased, but an extra 10 ms interval was required during the return to allow the wire to reach equilibrium at the lowest temperature. Separate calibration tests were made at fixed temperatures to assure that no data were affected by the stepping time.

A segment of the resulting hot-wire signal is shown in Fig. 2. The numbers above the curve indicate the overheat ratio at each step, where here the overheat ratio is defined as the ratio of the operating wire resistance to the wire resistance at 20°C. Shown are 10 samples per step; however, for the data that follow 156 samples were taken during the 10 ms at each step.

The probe used for the dual-wire method was a modified DANTEC parallel-array probe (55P71). It is a straight probe using the same sensor as the single-wire probe. Spacing between the two parallel wires was 0.18 mm. The probe was connected to two DISA 55D01 constant-temperature anemometers. The anemometers were used with 1:1 bridges for higher-frequency response.

The anemometer outputs from the dual-wire probe were digitized with a LeCroy analog/digital system. Two types of data were taken. For the first, data were taken while the probe traversed across the shear layer to measure the mean profiles and rms values. Here, data were sampled at 10 kHz for a duration of approximately 1.6 s. The second type of data was taken at a fixed point in the shear layer to evaluate the autocorrelations and cross-correlations of two wires operating at the same overheat setting. Data of the second type were digitized at 1.0 MHz.

For both the single- and dual-wire methods, the frequency response was optimized by adjusting the anemometer gain and filter settings. All wires were checked for strain gaging, and those found to be suspect were discarded.

The experiments were performed in the 23 × 23 cm blowdown supersonic wind tunnel at the Virginia Polytechnic Institute and State University. The experimental setup consisted of a tangential supersonic slot injection into a supersonic stream. The injector was a rearward facing step slot designed to provide a slot freestream Mach number of 1.7. The slot height H was 1.27 cm. The freestream Mach number of the mainstream of the nozzle block was 2.93. All measurements presented in this paper were taken at an axial station (X/H) of 4. Further detail on the experimental setup is given in Ref. 11.

Single-Wire Technique

Principle of Operation

The heat loss of a hot-wire anemometer in supersonic flow in general depends on the following dimensionless groups:

$$Nu = f(Re, M, \tau) \tag{1a}$$

$$Nu = g(Re, Kn, \tau) \tag{1b}$$

since $Kn \sim M/Re$.

Independent variation of Nu with density and velocity (or equivalently either Mach number or Knudson number) in supersonic flow requires that the wire be in the slip flow[6] or free[5] molecular domain. In the current investigation, this was not the case. Thus, here the density and velocity sensitivities may not be distinguished. Modal analysis[1,3] is not helpful either, since the flow was deliberately chosen so that both vorticity and acoustic modes would contribute. Instead, the task is only to separate the mass flux and the total temperature contributions to the hot-wire signal. For the ith wire temperature,

$$Nu_i = A_i\sqrt{Re} + B_i \tag{2}$$

The method of separation of the rms values is by now well known,

$$\left(\frac{e}{E}\right)_i = f_i\left(\frac{m}{\bar{m}}\right) + g_i\left(\frac{T_t}{\bar{T}_t}\right)$$

where

$$f_i = \frac{1}{4\left(1 + \dfrac{B_i}{A_i}\dfrac{1}{\sqrt{Re}}\right)} \tag{3a}$$

$$g_i = \frac{-\bar{T}_t}{2(T_{w_i} - \bar{T}_t)} \tag{3b}$$

then

$$\left(\frac{\overline{e'^2}}{\bar{E}^2}\right)_i = f_i^2\left(\frac{\overline{m'^2}}{\bar{m}^2}\right) + g_i^2\left(\frac{\overline{T_t'^2}}{\bar{T}_t^2}\right) + 2f_ig_i\left(\frac{\overline{mT_t}}{\bar{m}\bar{T}_t}\right), \quad (i = 1,2,3)$$

which can be solved for the unknown flow variables in matrix form:

$$\begin{bmatrix} (\overline{m'^2}/\bar{m}^2) \\ (\overline{T_t'^2}/\bar{T}_t^2) \\ (\overline{mT_t}/\bar{m}\bar{T}_t) \end{bmatrix} = [G]^{-1} \begin{bmatrix} (\overline{e'^2}/\bar{E}^2)_1 \\ (\overline{e'^2}/\bar{E}^2)_2 \\ (\overline{e'^2}/\bar{E}^2)_3 \end{bmatrix} \tag{4}$$

where

$$[G] = \begin{bmatrix} f_1^2 & g_1^2 & 2f_1g_1 \\ f_2^2 & g_2^2 & 2f_2g_2 \\ f_3^2 & g_3^2 & 2f_3g_3 \end{bmatrix}$$

The difficulty lies in the matrix of coefficients G. It is ill conditioned, i.e., its determinant is usually small. Experimentally, this translates into great sensitivity to small changes in signal levels. The problem is aggravated by the fact that the matrix depends on the mean flow at each location and time. To improve this, redundancy has been introduced by taking measurements at more hot-wire temperatures. This technique, suggested by Kovasznay[1] and used by Laderman and Demetriades,[12] among others, requires the flow to remain constant while the hot wire is operated at all of its selected temperatures.

Thus, in a blowdown wind tunnel, where the hot wire is operated at a different temperature in each of several runs, the flow conditions must not vary by even a small amount from run to run or errors are introduced into the already sensitive problem. The way around the difficulty of flow variation is to vary the temperature of one wire fast enough so the mean properties of the flow have not changed.

Least Squares Separation of Mean and RMS Quantities

If more than three wire temperatures are used, the calibration data may be used to obtain linear least squares fits for both mean and rms quantities. The procedure differs for the two cases in that the mean equation is nonlinear in the flow variables of interest, whereas the rms equation is best linearized in the flow variables:

$$\text{mean} \left(\frac{E_i^2}{A_iR_{w_i}\pi\ell k_0T_{w_i}} - \frac{B_i}{A_i}\right) = \sqrt{Re} - \left(\frac{B_i}{T_{w_i}A_i}\right)T_t - \left(\frac{1}{T_{w_i}}\right)(T_t\sqrt{Re}) \tag{5}$$

which is of the form

$$z_i = \beta_1 - \beta_2y_i - \beta_3x_i$$

for flow variables

$$\beta_1 = \sqrt{Re}, \qquad \beta_2 = T_t, \qquad \beta_3 = T_t\sqrt{Re}$$

where β_3 was treated as if it were independent of β_1 and β_2. (To improve separation of mean quantities, total temperature was computed in units of 100 K instead of degrees K.) Then, least squares analysis produces the matrix equation that can be solved for β_1, β_2, and β_3:

$$\begin{bmatrix} -N & \sum_{i=1}^{N} y_i & \sum_{i=1}^{N} x_i \\ -\sum_{i=1}^{N} y_i & \sum_{i=1}^{N} y_i^2 & \sum_{i=1}^{N} x_i y_i \\ -\sum_{i=1}^{N} x_i & \sum_{i=1}^{N} x_i y_i & \sum_{i=1}^{N} x_i^2 \end{bmatrix} \begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{bmatrix} = \begin{bmatrix} -\sum_{i=1}^{N} z_i \\ -\sum_{i=1}^{N} y_i z_i \\ -\sum_{i=1}^{N} x_i z_i \end{bmatrix} \tag{6}$$

Least squares analysis applied to Eq. (3) produces the following matrix equation for the rms fluctuations:

$$\begin{Bmatrix} \sum_{i=1}^{N} f_i^4 & \sum_{i=1}^{N} f_i^2 g_i^2 & 2\sum_{i=1}^{N} f_i^3 g_i \\ \sum_{i=1}^{N} f_i^2 g_i^2 & \sum_{i=1}^{N} g_i^4 & 2\sum_{i=1}^{N} g_i^3 f_i \\ 2\sum_{i=1}^{N} f_i^3 g_i & 2\sum_{i=1}^{N} g_i^3 f_i & 4\sum_{i=1}^{N} f_i^2 g_i^2 \end{Bmatrix} \begin{Bmatrix} \overline{\left(\dfrac{m'}{\bar{m}}\right)^2} \\ \overline{\left(\dfrac{T_t'}{\bar{T}_t}\right)^2} \\ \overline{\left(\dfrac{mT_t}{\bar{m}\bar{T}_t}\right)} \end{Bmatrix} = \begin{Bmatrix} \sum_{i=1}^{N} f_i^2 \overline{\left(\dfrac{e'}{\bar{E}}\right)_i^2} \\ \sum_{i=1}^{N} g_i^2 \overline{\left(\dfrac{e'}{\bar{E}}\right)_i^2} \\ 2\sum_{i=1}^{N} f_i g_i \overline{\left(\dfrac{e'}{\bar{E}}\right)_i^2} \end{Bmatrix} \tag{7}$$

Calibration

For calibration, the hot-wire probe was traversed across a shear flow produced by two supersonic streams separated by a splitter plate ($M_1 = 2.93$, $M_2 = 1.7$). Only the uniform parts of each stream were used for calibration. It was necessary to use both flows in order to obtain a large enough range in wire Reynolds number. Two operating pressures were also used to further increase the variation in wire Reynolds number. The signal produced during a typical 7 s traverse was sorted by wire temperature and is shown in Fig. 3.

Mean flow measurements were made by miniature Pitot probe, cone static probe, and diffuser-type thermocouple probe. From these, the mean wire Reynolds number and stagnation temperature were found. The calibration curves for one wire are shown in dimensionless form in Fig. 4. No corrections for temperature loading or wire length were required since each wire was calibrated at its own operating conditions.

Dual-Wire Technique

Principle of Operation

For a constant-temperature hot wire, the voltage output from the anemometer is proportional to the convective heat loss through the Nusselt number

$$E^2 \propto Nu\,(T_w - T_t) \tag{8}$$

The Nusselt number depends only on the wire temperature ratio and Reynolds number of the wire, which is the dimensionless form of the mass flux ρu across the wire. Thus, the measured voltage is a function of the total temperature and the mass flux of the fluid and the calibration constants for the specific wire,

$$E^2 \propto (\rho u)\,(T_w - T_t) \tag{9}$$

By operation of two constant-temperature hot wires at different wire temperatures T_w, two simultaneous signals are produced from which the two unknowns, ρu and T_t can be determined.

Calibration

The procedure for calibrating the dual-wire probe was similar to that for the single-wire probe. The two hot wires were operated at overheat ratios of 1.95 and 1.67, while the probe was traversed across the dual-stream flow. Only data from the uniform parts of each stream were used. The calibration curves of the two wires were combined to yield the overall probe response. See Fig. 5.

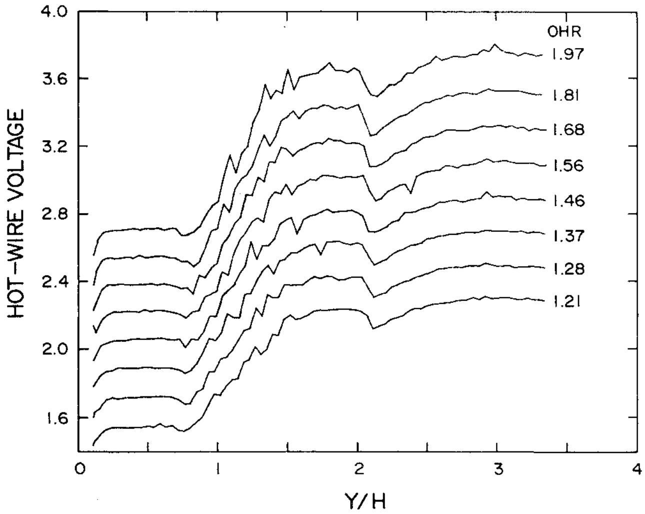


Fig. 3 Mean hot-wire signals at different overheat ratios during a traverse across the shear layer.

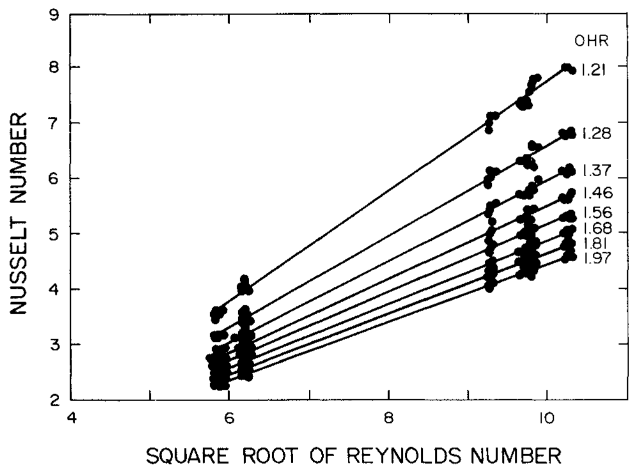


Fig. 4 Single-wire calibration at different overheat ratios.

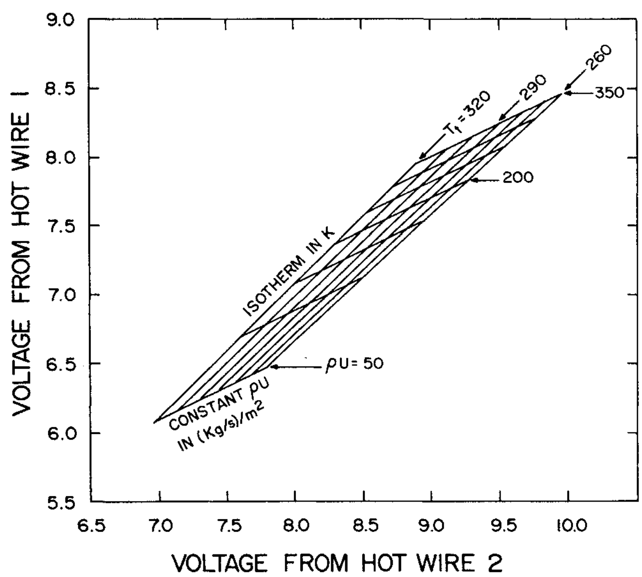


Fig. 5 Dual hot-wire probe calibration.

Repeatability of the calibration was checked by calibrating the dual-wire probe before and after the experiments. The change in Nusselt number was less than 3% over the range of experimental Reynolds numbers.

Cross-Correlation

An assumption basic to the dual-wire probe is that the flowfield is spatially uniform at the wire plane. It is only to the degree to which this is true that the probe can yield meaningful data. This assumption can be violated if the flowfield contains disturbances whose length scales are small compared to the spacing between the hot wires. To test the assumption, the wires were operated at the same wire temperature and their signals compared. Such a comparison, made at an axial station of $X/H = 4.0$ and $Y/H = 1.00$, is shown in Fig. 6. (This Y/H location corresponds to about the lower edge of the shear layer and just above the wake coming off from the splitter plate.) The signals from the wires appear very similar. The cross-correlation of the two signals is shown in Fig. 7. The high correlation coefficient of 0.97 indicates that the two wires detected nearly the same flowfield. A high correlation also was found at the other positions in the flowfield.

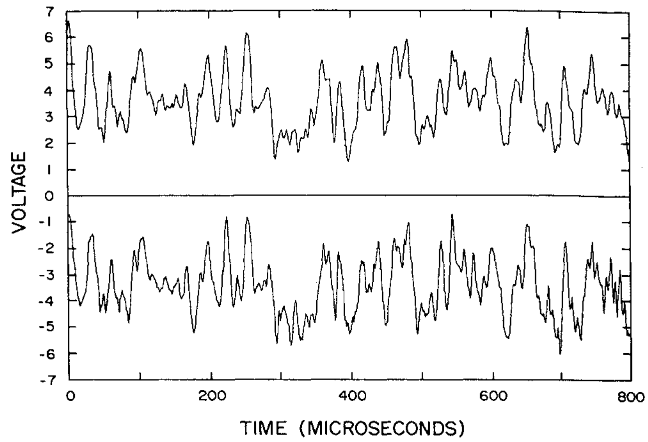


Fig. 6 Simultaneous output from dual hot-wire probe, wires operated at the same temperature.

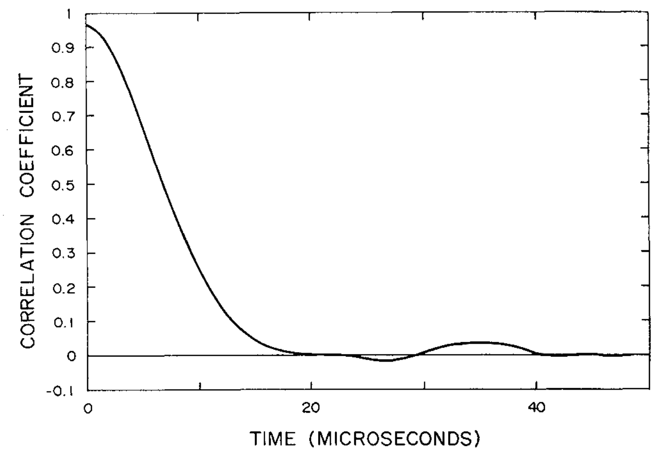


Fig. 7 Cross-correlation of dual hot-wire probe signals.

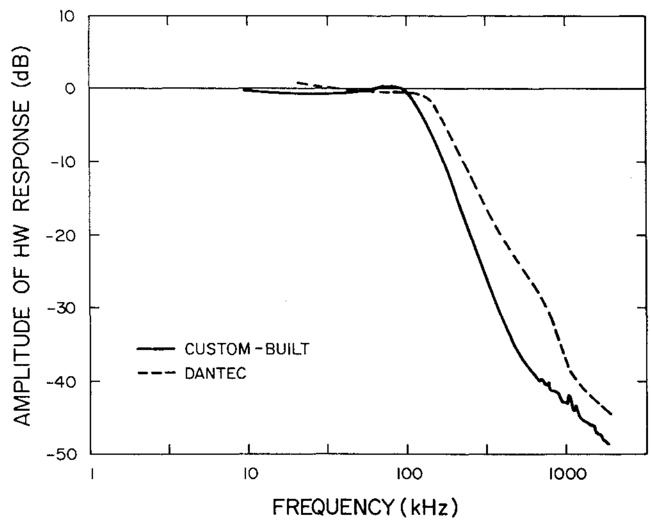


Fig. 8 Frequency response of the two hot-wire anemometers.

Results

Frequency Response

Calibration is not complete without determination of the frequency response. Since a knowledge of the transfer function allows a correction of the measured spectrum and hence a high-frequency correction of the rms data, it is useful to know more than square wave pulse width response. Sine wave tests[13] were performed during a single 7 s run at Mach 2.93 to obtain the frequency response curves shown in Fig. 8. Details of the circuits used are reported elsewhere.[14] For the sine wave test, overheat ratio of the custom-built anemometer was set at 1.20, the lowest overheat setting used during stepping. For the DANTEC anemometer, the overheat ratio was set to 1.67, which was the lower overheat ratio setting of the two wires.

It can be seen from Fig. 8 that, at these overheat settings, the frequency response of the custom-built anemometer was down 3 dB at 121 kHz, while the -3 dB point of the DANTEC system was 158 kHz. A rough estimate shows that 90% of the turbulent kinetic energy in the flowfield can be obtained with the custom-built anemometer, whereas the DANTEC system can obtain up to 95% of the turbulent kinetic energy.

Measurement of the hot-wire frequency response allows the data to be corrected to a frequency where the signal-to-noise ratio becomes one. It may be possible to correct the rms levels beyond this point if a $-5/3$ roll-off can be assumed. However, no corrections were made here.

Mean Flow Results

Separation of the data shown in Figs. 3 and 4 resulted in the mean mass flux and stagnation temperature profiles given in Figs. 9 and 10. Also shown in Fig. 9 are the mean flow data used to calibrate the wire. The data were taken with conventional cone static and Pitot probes. Data reduced from the dual-wire probe are also presented in Figs. 9 and 10. The measurements were taken at $X/H = 4$. The singlewire profiles shown represent one 7 s run. Multiple runs (or increased sampling rate) can be used to increase the number of samples and decrease the uncertainty of the results. The advantage of rapidly scanning the wire temperatures would still exist, since resolution of the flow variables is completed in each run.

It can be seen in Fig. 9 that the mean mass flux profiles agree reasonably well. This is a consistency check of the data reduction procedure, since the nonturbulent freestreams of the slot flow and the mainstream, as measured using conventional probes, are used to calibrate the hot wires.

Figure 9 shows that the freestream of the slot flow is between Y/H of 0.35–0.75. Between Y/H of 0.90–1.50 is the shear layer. At Y/H of approximately 2.00, the mean mass flux profile shows a sudden decrease. This is due to the presence of a weak oblique shock wave originated from the trailing edge of the splitter plate. The discrepancy between the location of the sudden decrease as measured by the single wire with that from the dual wire may be due to a slight difference in the axial length of the probes themselves. Later, a technique was developed to match probe lengths to within approximately 0.08 mm. Tunnel repeatability from run to run was confirmed,[11] and hence the differences shown are not likely to be caused by changes in the tunnel operating conditions.

Figure 10 shows the mean stagnation temperature ratio, nondimensionalized by the stagnation temperature in the settling chamber. Because of the blowdown nature of the tunnel, the stagnation temperature is less repeatable than the mass flux. Although the stagnation temperature profiles measured by the single and dual wires do not agree in detail, they both show variation of temperature of about 10°C across the shear layer. Since the temperature was nearly uniform across the flowfield, fluctuation was expected to be small. Thus, retrieval of mean and rms temperature profiles in the flowfield from the hot-wire data was expected to be a different task.

RMS Flow Results

Figure 11 shows the mass flux profiles. The data are nondimensionalized by the local mean mass flux. Although the profiles appear similar, rms mass flux measured by the dual-wire probe is about two times higher than that measured from the single-wire probe. It is interesting to see that in the freestream of the tunnel, where the errors due to the dual-wire separation were expected to be reduced, the results still differ by a factor of two.

In Fig. 11, the maximum at Y/H of 1.2 is due to the shear layer produced downstream of the splitter plate. At Y/H of about 2.0, the local maximum is due to the weak oblique shock that originated from the trailing edge of the splitter plate.

Profiles of the rms total temperature are shown in Fig. 12. Since both streams were at approximately the same stagnation temperature, fluctuation levels were small over most of the flow.

Measurements of rms stagnation temperature from the dual-wire probe (Fig. 12) show a similar shape compared to the measurements of rms mass flux from the same probe (Fig. 11). A maximum of 12°C is shown at the wake of the splitter plate and another local maximum of 8°C at Y/H of about 2.0. The rms stagnation temperature measured by the single wire were somewhat lower, with a peak of 8°C at Y/H of one and a 3°C peak at Y/H of 2.

Single-Wire, Single Overheat

To try to resolve the discrepancy between the measurements of rms mass flux from the two techniques, another approach was taken. Since the total temperature fluctuations were known to be relatively small, data were reduced from one of the dual wires at high overheat ratio (2.0) and from the single-wire probe at its maximum overheat ratio, with the assumption that total temperature fluctuations could be neglected. If some temperature fluctuations were present, the actual rms mass flux would be less than the value indicated. Thus, the values represent an upper bound on the rms mass flux. The results are shown in Fig. 13. In Fig. 13a, the measurements from one of the wires of the dual-wire probe lie far below dual-wire results that were based on the same data plus data from the other wire, indicating that the dual-wire data are too high. Data were also reduced from the other wire of the dual-wire probe at a low overheat ratio of 1.7. The results are similar to those shown in Fig. 13a.

In contrast, as shown in Fig. 13b, the data from the maximum overheat of the single wire probe lie on top of the least squares data from the same wire, indicating that neither temperature fluctuations nor nonlinearities in rms data introduced significant errors. The data from one wire of the dual wire probe were still above all data from the stepped overheat probe. This latter difference is still unresolved. Nevertheless, the conclusions about the methods are unaffected.

Discussion

Generally, errors in the single-wire multiple overheat approach are due to two effects: 1) nonlinearity in the calibration for high fluctuation intensities and 2) drift in the operating conditions of the supersonic wind tunnel before averages at all the overheat settings can be obtained. The resulting errors due to both of these were small here.

Error in the dual-wire technique is introduced by the wire separation distance. As shown in this paper, the error was expected to be small in most of the flow, but it cannot be neglected. The explanation seems to be ill conditioning in the flow variable separation process; i.e., although the flow seen by the two wires is very nearly the same, even small differences or small amounts of noise result in large errors in the computed results, with the effect of increasing both indicated rms mass flux and indicated rms total temperature. The single wire with multiple overheat ratios is not subjected to the same sort of spatial separation error and the least squares analysis with redundant overheats helps compensate for ill conditioning.

For both techniques, improvements are needed in the system frequency response.

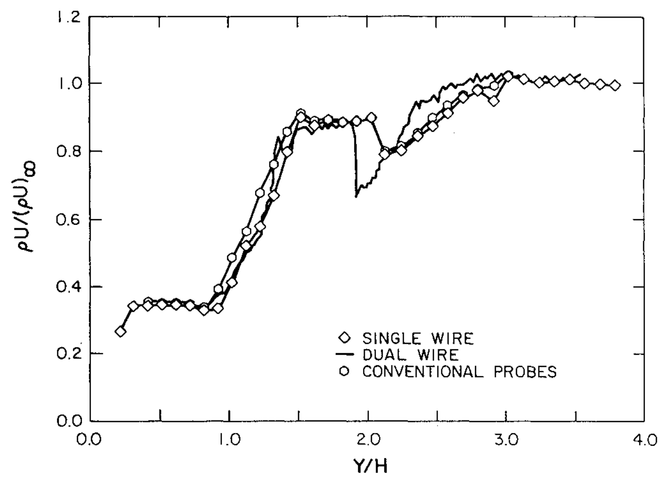


Fig. 9 Profile of the mean mass flux.

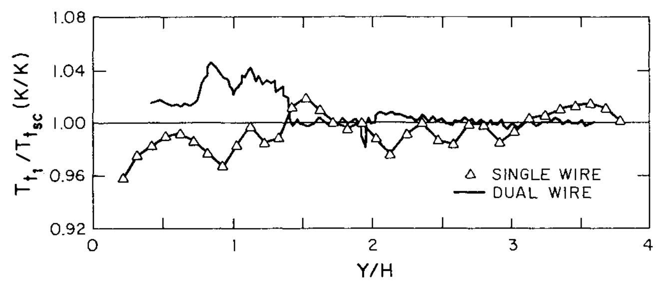


Fig. 10 Profile of the mean stagnation temperature.

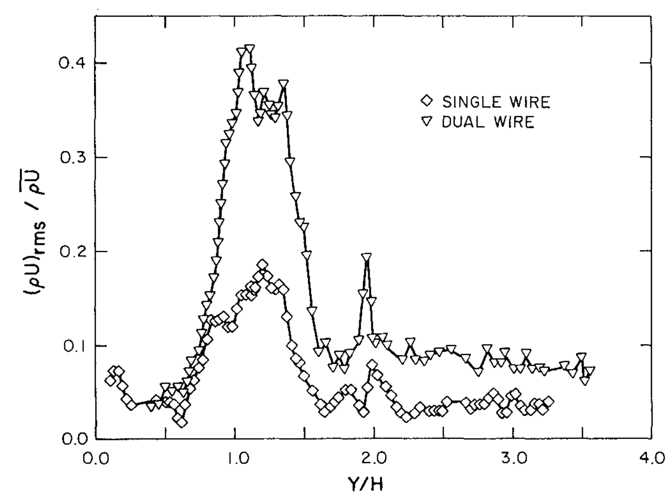


Fig. 11 Rms mass-flux fluctuation intensity.

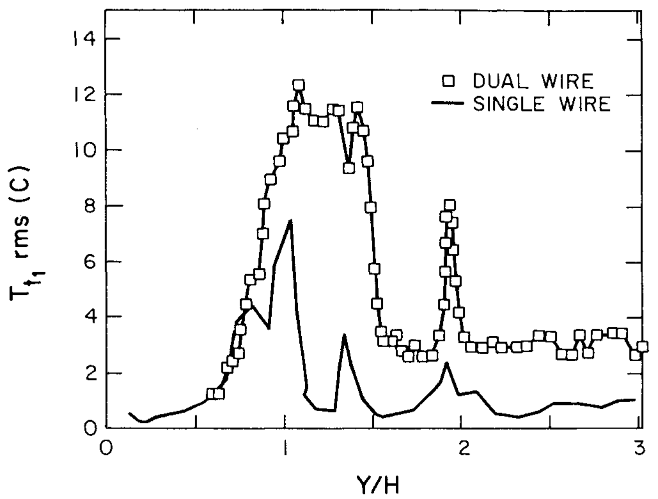
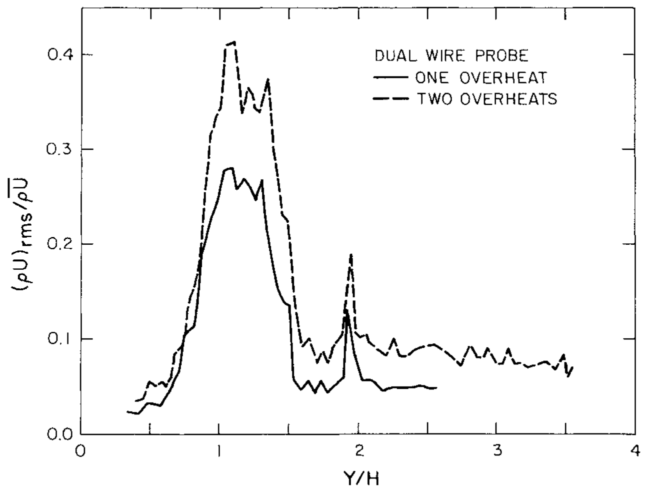
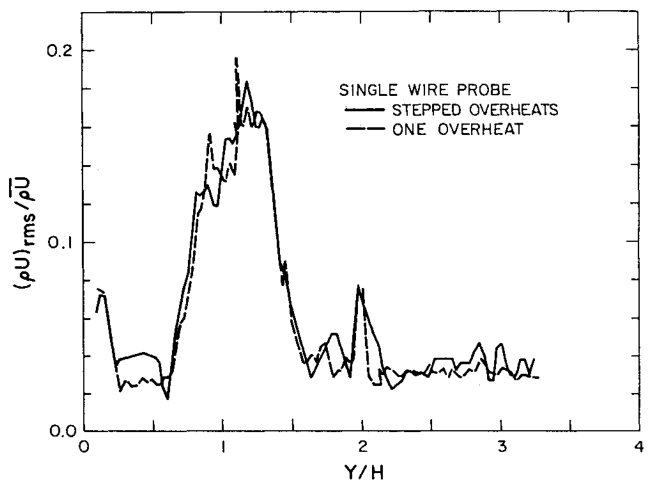


Fig. 12 Rms stagnation temperature fluctuation intensity.



a) One wire of dual wire probe compared to dual wire results



b) One wire temperature of single-wire probe compared to stepped temperature results

Fig. 13 Rms mass flux estimated from a single wire at a single overheat ratio.

Conclusions

Two methods for resolving mass flux and total temperature had been tested. For the single-wire multiple overheat method, redundancy had been introduced by using eight rapidly scanned wire operating temperatures. Separate least squares analysis was used for the mean and rms quantities. The results were encouraging.

For the dual-wire technique, cross-correlations of two wires operated at the same overheat setting show that the two wires see almost the same flowfield in the shear layer. Thus, the error introduced by the wire separation distance was expected to be small. However, comparison of the two techniques showed that the rms mass flux measured from the dual-wire probe was a factor of two higher than the measurements from the single-wire probe even in the freestream.

With the assumption that the temperature fluctuations were small, data from one wire at one overheat ratio were analyzed, producing a surprising result: an upper bound on the rms mass flux was well below the results from the dual wire method. The conclusion is that the two-wire technique must be considered error prone, even in situations where the profile is not rapidly changing.

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References

[1]Kovasznay, L. S. G., "The Hot-Wire Anemometer in Supersonic Flow," *Journal of the Aeronautical Sciences,* Vol. 17, Sept. 1950, pp. 565–584.

[2]Kovasznay, L. S. G., "Turbulence in Supersonic Flow," *Journal of the Aeronautical Sciences,* Vol. 20, Oct. 1953, pp. 657–682.

[3]Morkovin, M., "Fluctuations and Hot-Wire Anemometry in Compressible Flow," AGARDograph 24, 1956.

[4]Smits, A. J., Hayakawa, K., and Muck, K. C., "Constant Temperature Hot-Wire Anemometer Practice in Supersonic Flows," *Experiments in Fluids,* Vol. 1, No. 2, 1983, pp. 83–92.

[5]Stainback, P. C., "Some Influences of Approximate Values for Velocity, Density, and Total Temperature Sensitivities on Hot-Wire Anemometer Results," AIAA Paper 86-0506, Jan. 1986.

[6]Horstman, C. C. and Rose, W. C., "Hot-Wire Anemometry in Transonic Flow," *AIAA Journal,* Vol. 15, March 1977, pp. 395–401.

[7]Kistler, A., ""Fluctuation Measurements in a Supersonic Turbulent Boundary Layer," *Physics of Fluids,* Vol. 2, May–June 1959, p. 220.

[8]Stetson, K. F., Thompson, E. R., Donaldson, J. C., and Siler, L. G., "Laminar Boundary Layer Stability Experiments on a Cone at Mach 8, Part 1: Sharp Cone," AIAA Paper 83-1761, July 1983.

[9]Dewey, C. F., "A Correlation of Convective Heat Transfer and Recovery Temperature Data for Cylinders in Compressible Flow," *International Journal of Heat Transfer,* Vol. 8, Dec. 1965, pp. 245–252.

[10]Walker, D. A., Ng, W. F., and Walker, M. D., "Hot-Wire Anemometry in Supersonic Shear Layers," AIAA Paper 87-1372, Jan. 1987.

[11]Walker, D. A., Campbell, R. L., and Schetz, J. A., "Turbulence Measurements for Slot Injection in Supersonic Flow," AIAA Paper 88-0123, Jan. 1988.

[12]Laderman, A. J. and Demetriades, A., "Mean and Fluctuating Flow Measurements in the Hypersonic Layer over a Cooled Wall," *Journal of Fluid Mechanics,* Vol. 63, Pt. 1, 1974, pp. 121–144.

[13]Freymuth, P., "Electronic Testing of Frequency Response for Thermal Anemometers," *TSI Quarterly,* Vol. 3, No. 4, 1977, pp. 5–12.

[14]Walker, D. A., and Walker, M. D., "Method for Fast Sine Wave Calibration of Hot Wire Frequency Response," *Review of Scientific Instruments* (submitted for publication).