Turbulence Measurements in Confined Jets Using a Rotating Single-Wire Probe Technique

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Abstract

A SIX-ORIENTATION single hot-wire technique is described and applied to the complex flowfield of a swirling confined jet. The flowfield, which contains a sudden expansion with recirculation zones, is typical of those found in gas turbine and ramjet combustors. The present study focuses on nonreacting flows and gives details of how the method allows time-mean velocities and turbulent normal and shear stresses to be deduced. Flowfield surveys are presented for both nonswirling and swirling axisymmetric confined jets in the full paper, with only the key results presented here.

Contents

As part of a research program program aimed at the understanding and modeling of mixing processes in combustion chambers, a six-orientation single normal hot-wire technique is being used in an axisymmetric geometry under low-speed, nonreacting, swirling flow conditions. The flow enters the test section and proceeds into a large chamber (the expansion ratio D/d is 2) via a sudden expansion with a sidewall angle α of 90 deg. The large chamber is 30 cm in diameter and 150 cm long and constructed of plexiglass so as to aid flow visualization studies. The airflow exits directly into the laboratory; there are no film cooling or dilution air holes. Inlet swirl vanes (whose downstream face is located 3.2 cm upstream of the expansion station) are adjustable to a variety of swirl vane angles ϕ with $\phi=0$ (swirler removed) and 38 deg being emphasized in the present study.

Analysis

Multiorientation of a single hot-wire is a novel way to measure the three components of a velocity vector and their fluctuating components. King[1] modified a technique developed by Dvorak and Syred.[2] This method calls for a normal hot wire to be oriented through six different positions, each orientation separated by 30 deg from the adjacent one. Orientation 1 is normal to the facility centerline, orientation 2 is rotated 30 deg from this, etc. Mean and rms voltages are measured at each orientation. The data reduction is performed using some assumptions regarding the statistical nature of turbulence, making it possible to solve for three time-mean velocities, the three turbulent normal stresses, and the three turbulent shear stresses.

The six-orientation hot-wire technique requires a single, straight, hot wire to be calibrated for three different flow directions in order to determine the directional sensitivity of the probe. In the following relationships, tildes signify components of the instantaneous velocity vector in coordinates on the probe. Each of the three calibration curves is obtained with zero velocity in the other two directions. The calibration curves demonstrate that the hot wire is most efficiently cooled when the flow is in the direction of the $\tilde{u}$ component (which is normal to both the wire and the supports). The wire is most inefficiently cooled when the flow is in the direction of the $\tilde{w}$ component (which is parallel to the wire). Each of the calibration curves follows a second-order, least-square fit of the form

$$E_i^2 = A_i + B_i \tilde{u}_i^{1/2} + C_i \tilde{u}_i \tag{1}$$

which is an extension of the familiar King's law. In this equation, A_i, B_i, and C_i are calibration constants and $\tilde{u}_i$ can take on a value of $\tilde{u}$, $\tilde{v}$, and $\tilde{w}$ for the three calibration curves, respectively.

When the wire is placed in a three-dimensional flowfield, the effective cooling velocity experienced by the hot wire is

$$Z^2 = \tilde{v}^2 + G^2 \tilde{u}^2 + K^2 \tilde{w}^2 \tag{2}$$

where G and K are the pitch and yaw factors defined by Jorgensen[3] and deduced from the calibration curves. Hence, equations for the effective cooling velocity can now be ob-

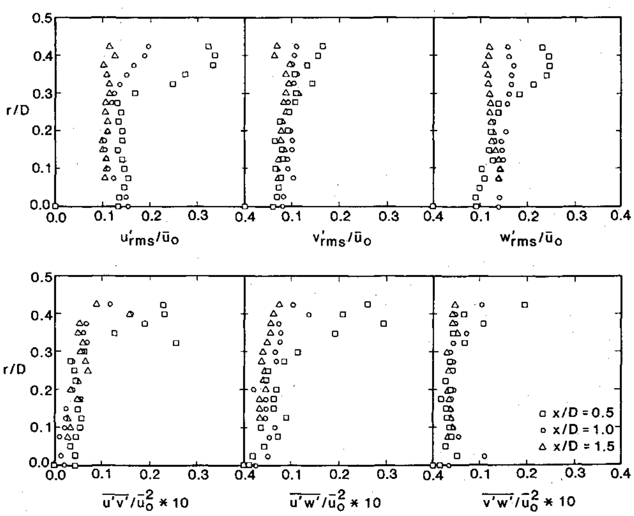

Fig. 1 Distribution of normalized directional turbulence intensities and shear stresses in swirling confined jet with $\phi = 38$ deg.

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Table 1 Effect of input parameters on turbulence quantities in the swirling flow with $\phi = 38$ deg at a representative flowfield position ($x/D = 1$, $r/D = 0.25$)

		Change in time-mean and turbulence quantities, %								
Parameter	Change in parameter, %	$\bar{u}$	$\bar{v}$	$\bar{w}$	u'_{rms}	v'_{rms}	w'_{rms}	$\overline{u'v'}$	$\overline{u'w'}$	$\overline{v'w'}$
$\bar{E}_1$	+1	+16.10	+0.66	+4.98	+15.75	−2.06	+2.75	+6.0	+51.43	+11.94
$\bar{E}_5$	+1	+2.19	−2.21	+11.49	−6.50	+2.42	+12.88	+4.0	+14.29	+7.46
$\bar{E}_6$	+1	−10.59	−0.36	−8.50	−1.88	+7.07	−9.54	−6.0	−54.29	−11.94
E'_{1rms}	+1	+0.27	−0.06	+0.14	+1.63	+0.13	+0.39	+2.0	+2.86	+1.49
E'_{5rms}	+1	+0.05	0.0	+0.14	0.0	−0.13	+1.57	0.0	0.0	+1.49
E'_{6rms}	+1	−0.16	+0.18	−0.14	−0.63	+1.03	−1.08	−2.0	−5.71	0.0
G	+1	−1.02	0.0	−1.01	−1.0	0.0	−0.98	−2.0	−2.86	−1.49
K	+1	+0.01	−0.04	+0.01	+0.01	0.0	+0.01	0.0	0.0	0.0
$\gamma_{Z_P Z_Q}$	+1	+0.05	0.0	+0.14	−0.13	−0.13	−1.77	0.0	−2.86	+1.49
$\gamma_{Z_Q Z_R}$	+1	+0.21	+0.01	+0.05	−1.63	+0.13	−0.79	0.0	−5.71	+1.49
$\gamma_{Z_P Z_R}$	+1	−0.16	+0.18	−0.08	+0.13	0.0	+0.69	−2.0	+2.86	0.0

tained for each of the six wire orientations. Simultaneously solving any three adjacent equations provides expressions for the instantaneous values of the three velocity components (u, v, and w in the facility x, r, and θ coordinates, respectively) in terms of the equivalent cooling velocities. It is then possible to obtain the three time-mean velocity components and the six different components of the Reynolds stress tensor, in the manner described in the full paper.

Results

Uncertainty Analysis

The uncertainty analysis includes a determination of the sensitivity of the six-orientation hot-wire data reduction to various input parameters that have major contributions in the response equations. Pitch and yaw factor values are discussed further in the full paper. Table 1 summarizes the sensitivity analysis performed on the data reduction program at a representative position in the swirling flow with $\phi = 38$ deg. The table demonstrates the percent change in the output quantities for a 1% change in each of the important input quantities individually, while the others are held at their standard values. For the data presented in Table 1, only quantities calculated from the probe orientations 5, 6, and 1 are used, for simplicity. This combination was chosen because the mean effective cooling velocity exhibited a minimum in orientation 6, and it is expected[1] that in this case the combination 5, 6, and 1 will produce more accurate estimates of calculated turbulence quantities. The data of Table 1 demonstrate that the most serious inaccuracies in the measurement and data reduction technique are in estimates of turbulent shear stresses, the most inaccurate output term being $\overline{u'w'}$.

Flowfield Surveys

Radial distributions of time-mean velocities, turbulent normal stresses, and other stresses have been obtained for both nonswirling and swirling conditions at various axial locations in the flowfield. Because of lack of directional knowledge, data were obtained from an average of the values found in each of the six possible combinations of three adjacent wire orientations. As an example of the results obtained, Fig. 1 shows turbulence data associated with the six components of the Reynolds stress tensor, with radial distributions given at three axial stations in the confined swirling jet with $\phi = 38$ deg. At axial locations closer to the inlet, the axial turbulence intensity is fairly high, up to 32% for $x/D = 0.5$, because of large axial velocity gradients closer to the wall. However, in the case of radial turbulence intensity, the profiles are rather flat. The mean swirl velocity also experiences sudden changes in gradients and, hence, the outcome is a large azimuthal turbulence intensity closer to the wall at $x/D = 0.5$. The figure also shows turbulent shear stresses for which the sensitivity analysis showed that large uncertainties might be expected in the deduced values. Nevertheless, the values portrayed are certainly to be expected, with large values close to the wall in locations where time-mean axial and swirl velocity gradients are also large. Nevertheless, in nonswirling flows, the measured shear stresses are in good agreement with previous measurements made with a cross-wire probe.[4] In closing, it may be noted that the six-orientation single hot-wire technique is a novel cost-effective tool for use in complex turbulent flow situations.

Acknowledgments

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