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Comparison Between Hot-Wire and Burst-Mode LDA Velocity Measurements in a Fully-Developed Turbulent Jet

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COMPARISON BETWEEN HOT-WIRE AND BURST-MODE LDA VELOCITY MEASUREMENTS IN A FULLY-DEVELOPED TURBULENT JET

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Abstract

An extensive measurement program was carried out at 70-100 diameters downstream of the exit of a 1 in. axisymmetric turbulent jet. Measurements of all the components of velocity were made and all moments to fourth order were computed. The experiments were performed using hot-wire anemometers and laser Doppler anemometers. Comparisons are made between the LDA and the hot-wire measurements. Considerable discrepancies exist which are largely attributable to the hot-wire errors in high intensity flows.

Nomenclature

$f(\eta)$	Similarity function for mean velocity
M_o	Jet exit kinematic momentum
U, u	Mean and fluctuating axial velocity
U_m, u_m	Axial Velocity measured by hot-wire
$\overline{uv}$	Shear stress
U_c	Centerline velocity
$\overline{u^2}, \overline{u^3}$	2nd and 3rd moment of axial velocity
v	Fluctuating radial velocity
v_m	Radial velocity measured by hot-wire
$\overline{v^2}, \overline{v^3}$	2nd and 3rd moment of radial velocity
w	Fluctuating azimuthal velocity
$\overline{w^2}, \overline{w^3}$	2nd and 3rd moment of azimuthal velocity
η	r/x

Introduction

The axisymmetric turbulent jet is of primary importance for the verification of turbulence closure schemes. The ease with which it can be generated in the laboratory in addition to the fact that it contains most of the mechanisms of importance in turbulent shear flows make it a very attractive flow for investigation. Most investigations to-date were carried out using hot-wire anemometry. Measurements in axisymmetric jets were performed by Corrsin (1), Wygnanski and Fiedler (2), Rodi (3) and numerous others. Corrsin's measurements were made with Pitot tubes while hot-wires were used for the measurements made by Wygnanski and Fiedler and Rodi. Capp (4) reported measurements with burst-mode LDA techniques.

The measurement of the axisymmetric jet is very difficult because of the high turbulence intensity, 25% at the centerline, and specifically because the <u>local</u> turbulence intensity increases with increasing radius. At these turbulence intensities the hot-wire rectification and cross-flow errors cannot be ignored, v. Tutu and Chevray (6) and Beuther et al. (9).

The objective of this paper is to use two sets of comprehensive data collected in the same axisymmetric jet to compare the measurements between hot-wires and the laser Doppler anemometers. Assessment is made of the effect of cross-flow and rectification errors on the velocity moments. These errors are found to cause very large discrepancies in the third and fourth moments.

Experiment

The jet facility was used in a large 5m x 5m x 25m long room to minimize the momentum loss from the external flow generated by the return flow in the enclosure, v. Capp (4). The jet was mounted on a table 2.5 m above the floor to minimize the ground effect. The jet facility has a set of two contractions. The first contraction is 16:1 and made of a third order polynomial. The last contraction reduces the diameter to 1 inch and is a 9:1 fifth order polynomial. This fifth-order polynomial was chosen since it provides a much more uniform mean velocity at the exit (7). The exit velocity was a top-hat profile to within 3%. An exit velocity of 55 m/s was chosen since it gives a high enough Reynolds number while still ensuring the compressibility effects to be negligible. Since the Reynolds number is proportional to the exit diameter a large exit diameter is needed, but it has to be small enough to enable one to obtain measurements at large x/D. Using these two criteria an exit diameter of 1 inch was chosen. This is also large enough to enable one to neglect the boundary layer effect in determining the exit mass and momentum conditions. These conditions correspond to an exit Reynolds number of 100,000 and turbulence Reynolds number $\overline{u^2}^2/\nu\epsilon$ of 19,000.

Measurements were taken at 70 and 100 diameters downstream of the jet. The collapse of the profiles when scaled with the centerline velocity and downstream distance indicates a well established similarity region. Measurements of all the components of the velocity were made and all the moments to the fourth order were computed. Care was taken to ensure that record lengths were long enough to ensure that statistical convergence was achieved, and that the dynamical ranges were adequate to minimize adversely affecting the higher moments by clipping the tails of the probability distributions. The axisymmetry of the jet was very carefully documented. A three dimensional traversing system designed for this experiment was utilized to obtain velocity contours which show very good axisymmetry. These contours were measured at 50, 60 and 70 diameters from the exit of the jet (8). The virtual origin of the jet was found to be 2.7 diameters from the exit. The temperature in the room was monitored throughout the experiments.

The hot-wire measurements were made with single and x-wire configurations. The tungsten wires used were 5 microns in diameter and 1.5 mm in length. The anemometers were operated in a constant temperature mode with an overheat ratio of 0.6. Radial and azimuthal contributions were measured simultaneously by using two x-wire probes in close proximity, but differing by a 90 degree rotation about the streamwise axis. The wires were calibrated for velocity using fourth-order polynomials and for angular dependence using a velocity dependent k-factor. (These techniques were described in detail in George et al.(5) and Beuther et al.(9)). Data were sampled digitally using a PDP 11/84 computer and a 15 bit Phoenix A/D converter. Linearization and component separation were accomplished digitally. Low velocity calibration to 0.3 m/s was accomplished with a very accurate volumetric flow meter since for the values of x/D in this experiment (70-100) the wire is exposed to velocities that are quite low. (For instance the centerline velocity is 3.4 m/sec at x/D = 100.) The hot-wire was calibrated against a pressure transducer for velocities between 1 m/s to 20 m/sec and a manometer for velocities above 20 m/sec.

The LDA measurements were taken using a Dantek 55X two-color Argon ion system with 55L90a counters (4). A Spectra-Physics Argon-ion model 165 laser was mounted on a folded bench with the optical components. Flow reversals were accurately measured by using a 40 MHz frequency shift. The optical bench and the laser were mounted on a computer controlled three-dimensional traversing system. Both single channel and two channel operations were utilized, the latter utilizing a time interval board to assure near simultaneous arrival of the data on both channels. The counters were specially modified to include 10 bit fringe count registers with reset to avoid overflow when used with frequency shift in low velocity regions of the flow. The data were processed using the residence time-weighting described in references (4) and (10). The glycerine smoke used as seeding was generated using a heater in a container of glycerine, and circulated throughout the facility before measuring to insure that the whole environment was uniformly seeded. The seed concentration was carefully monitored throughout the experiment. The particle time constant was estimated to be about 4 x 10^{-4}s, a value sufficiently small to ensure that all scales of motion in the flow were followed by the particles. Care was taken to ensure the absence of biases by using the appropriate amount of frequency shift and residence time weighting of all statistics, and to satisfy the constraints on measuring accuracy described in references (4) and (10).

As shown in Figure [1] the mean velocity measurements were found to be consistently higher than the LDA measurements which is consistent with the expected cross-flow errors on the hot-wires. The mean flow characteristics are summarized as follows:

	Hot-Wires	LDA
Momentum Ratio	1.131	0.952
$\eta_{1/2} = r_{1/2}/x$	0.102	0.094
$c = U_c x/U_o d$	5.9	5.8

where x is the distance measured from the virtual origin of the jet, U_o is the jet exit velocity and U_c is the centerline velocity. The momentum ratio is given by the local momentum integral (obtained by integrating the x-momentum equation including the pressure terms)

$$M = \int_o^\infty \left[U^2+\overline{u^2} - \frac{\overline{v^2}+\overline{w^2}}{2}\right] 2\pi r dr \tag{1}$$

divided by the jet exit momentum $M_o = \pi d^2 \frac{U_o^2}{4}$.

George et al. (11) have shown that the induced back-flow in the enclosed room causes the momentum ratio to be reduced from unity. This has been the source of error in many earlier experiments. As shown above the LDA measurements reasonably satisfy the momentum integral constraint on the flow. The hot wire measurements, on the other hand, show a gain in momentum. This is consistent with the fact that the cross-flow errors cause the measured mean velocity from hot-wires to be higher than the actual velocity.

Figures [2a] and [2b] show the measured shear stress $\overline{uv}/U_c^2$ as a function of $\eta = r/x$ for the hot-wires and LDA respectively. Also shown on the figures is the shear stress determined from the similarity form of the momentum equation.

$$\frac{\overline{uv}}{U_c^2} = \frac{1}{\eta} f \int_o^\eta f\eta d\eta + \eta \left[\frac{\overline{u^2}-\overline{v^2}}{U_c^2}\right] + \eta \int_\eta^\infty \frac{\overline{v^2}-\overline{w^2}}{\eta U_c^2} d\eta \tag{2}$$

where $f = U/U_c$. Both the results from the full equation above and that from only the mean flow (first term on left) are shown. It is seen that for the hot wire (Figure 2a) the mean flow contribution is higher than the measurements of the shear stress. The shear stress determined from the full momentum equation is even higher since the main second-order term (second term on the right hand side of equation (2)) is positive. The peak value indicated by the momentum balance is 23 percent higher than the value measured by the wire. This discrepancy is entirely due to hot-wire errors. The LDA measurements for $\overline{uv}$ are shown in Figure [2b] and are in excellent agreement with the momentum balance determination. This is consistent with the difference in the centerline decay coefficient between the two sets of data. We know that the LDA measurements satisfy the momentum constraint to within a few percent and yield a decay coefficient of 5.8. The hot wire results show the coefficient to be 5.9 which says that the momentum balance is increased by the fact that the wire measured mean velocities are larger than the actual values. These are contrary to the earlier hot-wire results of references [2] and [3] which were presumably contaminated by backflow resulting in both narrower mean profiles and more rapid decay than observed here.

The centerline values for the normal stresses are 0.075, 0.045 and 0.047 from the LDA and are not too different from 0.078, 0.057 and 0.057 from the hot-wire for $\overline{u^2}/U_c^2$, $\overline{v^2}/U_c^2$ and $\overline{w^2}/U_c^2$ respectively. The discrepancies occur off-axis at higher turbulence intensities where the hot-wire profiles decrease much more rapidly with radius. The values are roughly 75% of those from the LDA at a radius of $\eta = 0.1$. These second order moments are subject to much more cross-flow errors than the mean values since the errors enter at only one level higher (third). Equations (5) and (6) in the Appendices show that the leading errors of second-order moments due to the cross-flow errors are negative, hence the LDA values should show higher values than their hot wire counterparts. Figures [3], [4] and [5] all show this at high turbulence intensities. Furthermore the magnitude of these errors are quite close for the azimuthal and normal stress as shown in Figures [4] and [5].

The profile of the axial normal stress measured with the LDA shows a distinct off-axis peak whereas the hot-wire profile is nearly flat near the centerline. This off-axis peak has also been predicted from model calculations, and is consistent with the strong off-axis peak in the production of turbulent energy by the Reynolds stress working against the mean shear.

The triple correlations show considerable discrepency between the hot-wire and LDA measurements. Figure [6] shows that the results for $\overline{u^3}$ are about the same at the centerline but the peak of the LDA value is about twice that of the hot wire. Results for $\overline{uv^2}$ and $\overline{uw^2}$ shown in Figures [7] and [8] respectively are negative near the centerline whereas the hot-wire results are positive. Figures [9] and [10] show that the profiles for the radial transport of $\overline{u^2}$ and $\overline{v^2}$ do not peak at the same η. The LDA results for the radial transport of $\overline{u^2}$ show negative values near the centerline while the hot-wire results do not.These differences are due to cross-flow errors. The results of the $\overline{vu^2}$ term are also negative near the centerline for the LDA measurements while the hot-wire values are positive. These negative regions in the LDA data have not previously been observed, but are consistent with the expected energy fluxes due to the off-axis production peaks. The positive values measured by the hot-wires are due to the relative magnitude of the cross-flows errors and the smaller values of the moments near the axis.

Concluding Remarks

Measurements of velocity moments were made in the far field of an axisymmetric turbulent jet. The experiments were taken using both hot-wires and LDA, and the results for the higher moments show considerable differences. The hot-wire measurements were subject to significant amounts of cross-flow errors and the discrepancies between the two sets of data are attributed to these errors. The integral and differential balances of the momentum constraint are satisfied by the LDA measurements. The third order correlations $\overline{uv^2}$, $\overline{uw^2}$ and $\overline{vu^2}$ all show negative regions in the LDA measurements. This is not the case for the hot-wire results but is consistent with the expected turbulence transport. The results of this paper show that the measurement of high turbulence intensity flows with hot-wires cannot be reliably made with stationary hot-wire probes.

Acknowledgements

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Appendix

Cross-Flow Errors

Beuther et al. (9) and Tutu and Chevray (6) have shown that hot-wire cross-flow errors can amount to significant values in high turbulence intensity flows. Here we will present equations containing the leading error terms obtained from binomial expansions of the measured velocity. These equations break down rapidly for turbulence intensities above 50%, and do not account for rectification effects. Note that the contamination of the shear stress arises entirely from the errors in determining the mean velocity.

Mean Value

Cross Wire:

$$U_m = U\left\{1 + \frac{1}{(1+k^2)}\left[\frac{\overline{w^2}}{U^2} - \frac{\overline{uw^2}}{U^3} + \frac{\overline{u^2w^2}}{U^4} - \frac{\overline{2w^4}}{U^4}\right]\right\} \tag{3}$$

Single Wire:

$$U_m = U\left\{1 + \frac{1}{2}\left[\frac{\overline{w^2}}{U^2} - \frac{\overline{uw^2}}{U^3} + \frac{\overline{u^2w^2}}{U^4} - \frac{1}{4}\frac{\overline{w^4}}{U^4}\right]\right\} \tag{4}$$

Second Moment

Cross-Wire

$$\overline{u_m^2} = \overline{u^2}\left\{1 + \frac{2}{1+k^2}\left[\frac{\overline{uw^2}}{\overline{u^2}U} - \frac{\overline{u^2w^2}}{\overline{u^2}U^2} + \frac{\overline{w^4}}{\overline{u^2}U^2} - \frac{\overline{w^2}^2}{\overline{u^2}U^2}\right]\right\} \tag{5}$$

Single wire

$$\overline{u_m^2} = \overline{u^2}\left\{1 + \left[\frac{\overline{uw^2}}{\overline{u^2}U} - \frac{\overline{u^2w^2}}{\overline{u^2}U^2} + \frac{\overline{w^4}}{\overline{u^2}U^2} - \frac{1}{4}\frac{\overline{w^2}^2}{\overline{u^2}U^2}\right]\right\} \tag{6}$$

Shear Stress

$$\overline{u_m v_m} = \overline{uv} \tag{7}$$

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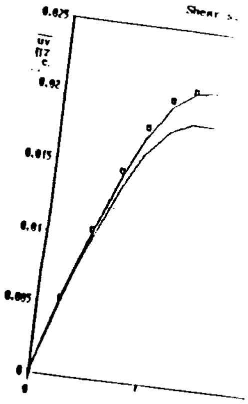

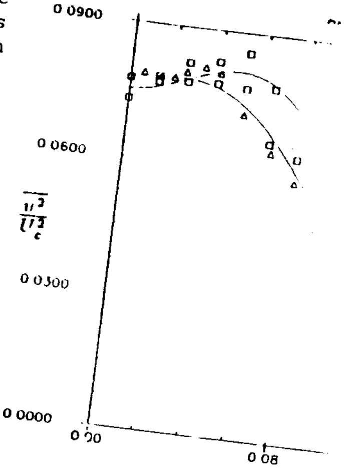

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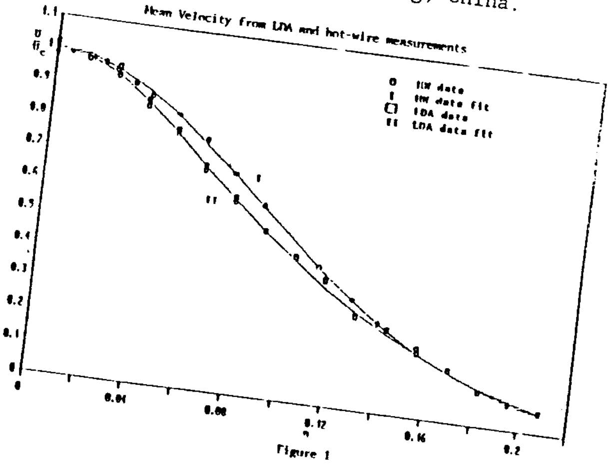
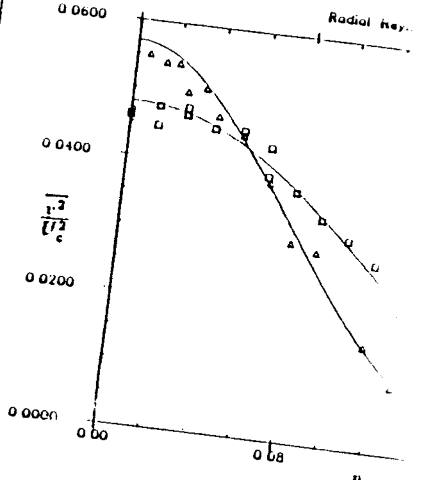


Figure 1



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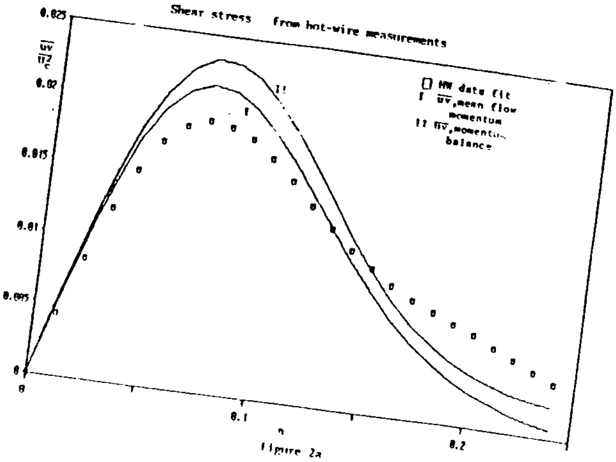

Figure 2a

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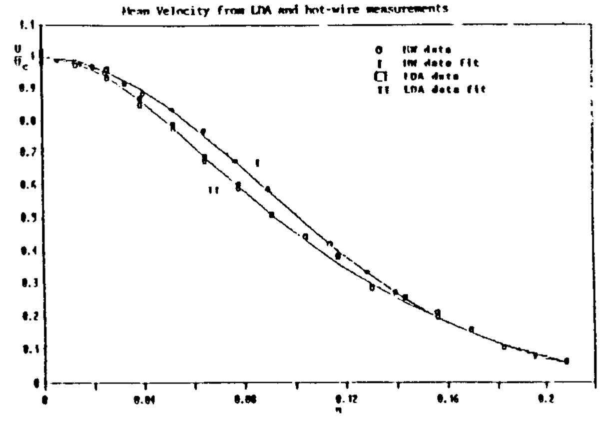
Mean Velocity from LDA and hot-wire measurements

Figure 1

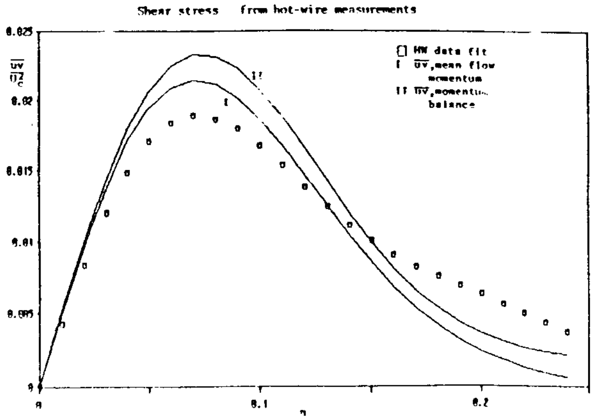
Shear stress from hot-wire measurements

Figure 2a

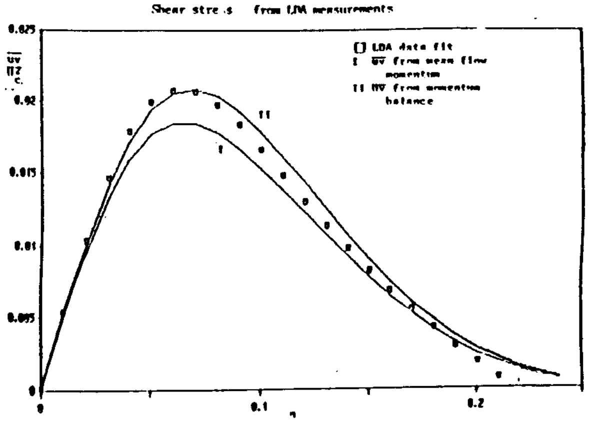
Shear stress from LDA measurements

Figure 2b

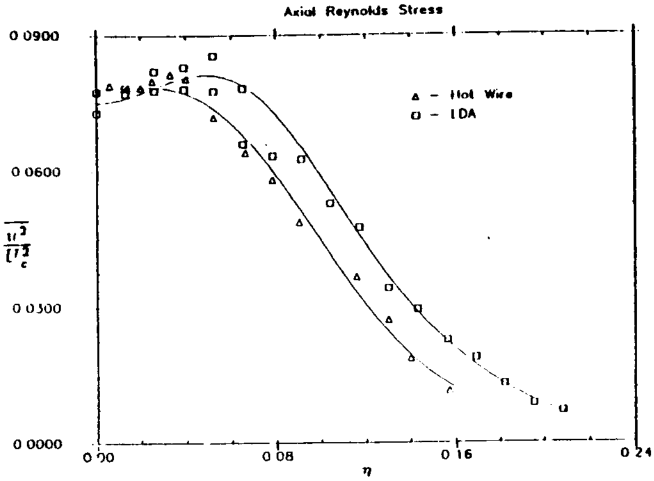
Axial Reynolds Stress

Figure 3

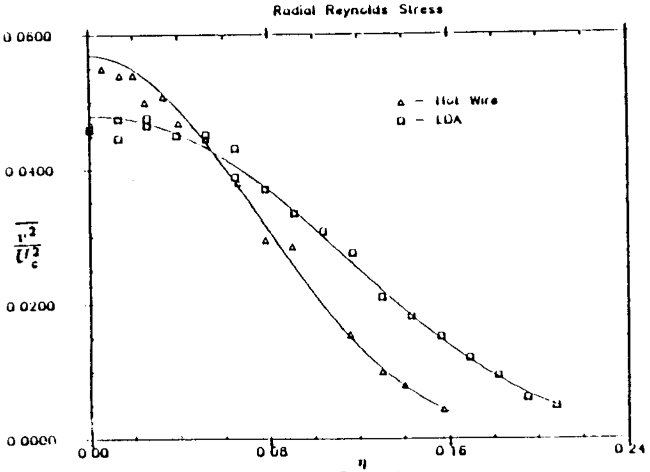
Radial Reynolds Stress

Figure 4

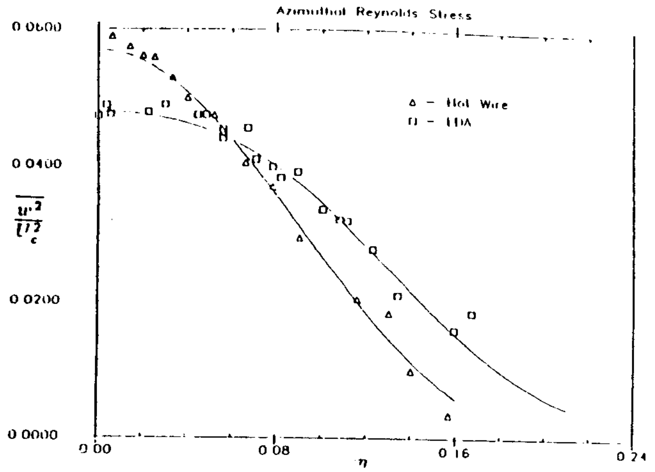

Figure 5

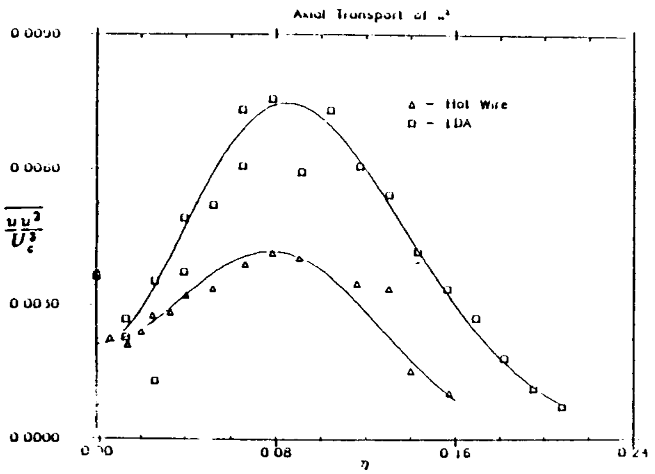

Figure 6

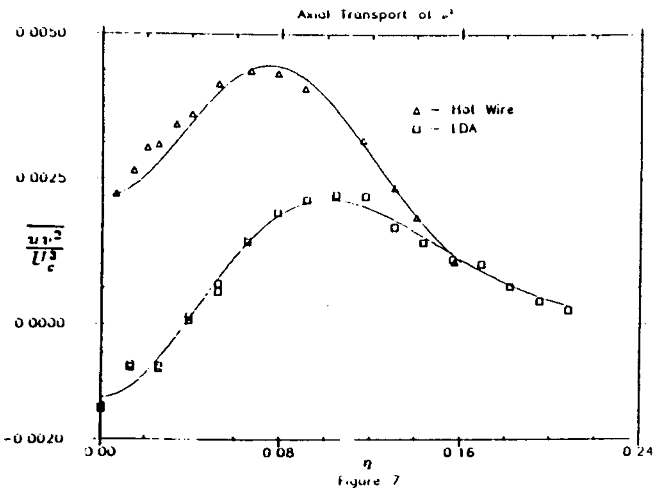

Figure 7

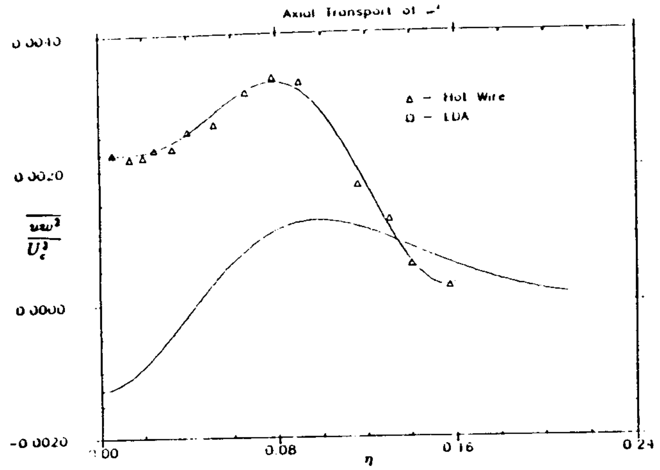

Figure 8

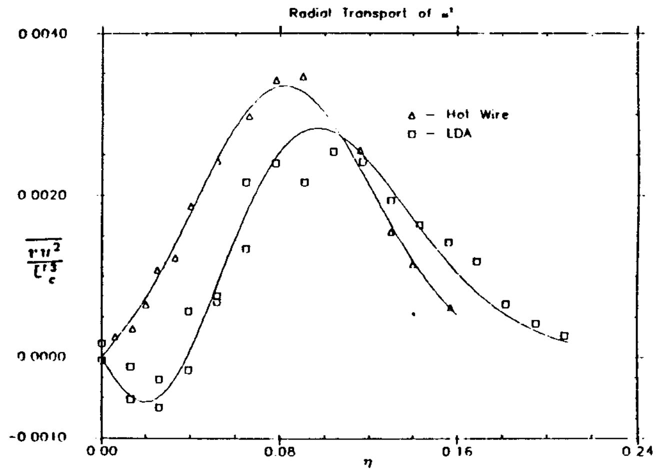

Figure 9

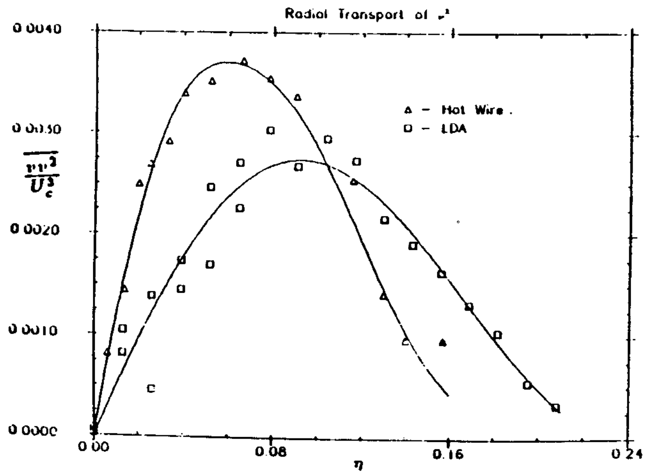

Figure 10