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PRESSURE PROBE MEASUREMENTS OF THE MEAN AND TURBULENT STRUCTURE OF A SWIRLING JET

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ABSTRACT:

The use of a four-hole directional pressure (or Cobra) probe in mapping the turbulent and mean flow structure of a swirling free jet is described. The probe determines all components of the mean and turbulent velocities, together with the mean and dynamic static pressure. Current measurement techniques yield a frequency response to 1.5 kHz.

1. INTRODUCTION.

The simultaneous experimental determination of all mean and turbulent velocity components, together with the dynamic and mean component of the local fluid static pressure at a point in a turbulent single phase flow, has been achieved through the use of a four-hole directional pressure (or Cobra) probe. This work follows the development of the Cobra probe by Shepherd (1981), and the further refinement of the experimental techniques by Hooper and Musgrove (1991). Further work by the authors has succeeded in converting the probe into a device having a frequency response of 1.5 kHz, and thus being able to resolve the local fluid velocity to this frequency limit. The rugged nature of the probe, and the highly stable nature of the calibration surfaces (Hooper and Musgrove, 1991) used to interpret the probe pressures in terms of the magnitude of the local fluid velocity, flow pitch and yaw angles and static pressure ensure that the probe can be used in both laboratory and industrial flows.

Historically, the hot-wire anemometer and in the last 20 years, the Laser-Doppler Anemometer (LDA) have been the major instruments for the measurement of the mean and turbulent quantities in gas or liquid flows. The Pitot probe, and generalised pressure probes have been limited almost exclusively to the determination of the mean velocity vector. Both the hot-wire anemometer and the LDA have significant defects and limitations which the extended or high frequency Cobra probe overcomes. The limitations of the hot-wire anemometer include the fragile nature of the sensor wire (a few microns in diameter), and the calibration drift due to the change in resistance with time. The transformation of the fluctuating bridge voltages from the hot wire anemometer bridge circuit to the turbulent velocity components is generally possible only in turbulent flows below approximately 30% intensity, due to the highly non-linear response of the device (Perry, 1982).

The LDA (or velocimeter) overcomes the restriction of the hot wire anemometer to low and medium intensity turbulent flows (Durst et al, 1981) but has attendant limitations. These include the need to seed the flow with light scattering particles of approximately 1.5 micron diameter, and the need to frequency shift one beam of the laser and so obtain directional velocity information on one axis. The signal from the LDA is random in time, and in highly turbulent flows requires large velocity bias correction. A three axis system capable of measuring all three velocity components at a point in space requires a complex optical set-up. The counting system has to be of very high frequency response, leading to a capital cost of approximately \$350,000 (Aust.). Neither the LDA nor the hot-wire anemometer have the ability to sense simultaneously the local mean and fluctuating pressure.

The use of the high frequency Cobra probe in mapping the flow field generated by a highly swirled free jet is presented by this paper, as a means of demonstrating the capability of the device.

2. EXPERIMENTAL RIG AND TECHNIQUE.

A 20 kPa two-stage centrifugal blower, rated at 1 m^3s^{-1} air flow, was used to supply air to a 6.0 m long rigid wall pipe, of 142 mm internal diameter. The flow through the pipe was swirled near to the exit section by a single start Archimedes spiral, having a pitch to diameter ratio of 1.52. The swirler had five turns, with the last turn of the swirler projecting from the end of the pipe. The swirler was formed on a 50 mm diameter tube, which was open at both ends and thus allowing an axial component of flow past the swirler. A four hole Cobra probe, mounted in a stepper motor driven axial and radial traverse system, was used to map the flow structure from 25 to 300 mm downstream of the end of the swirler. The probe also was able to be rotated through 360 degrees, with all the axis of traverse, measurement and data reduction being under the control of a dedicated 386 computer.

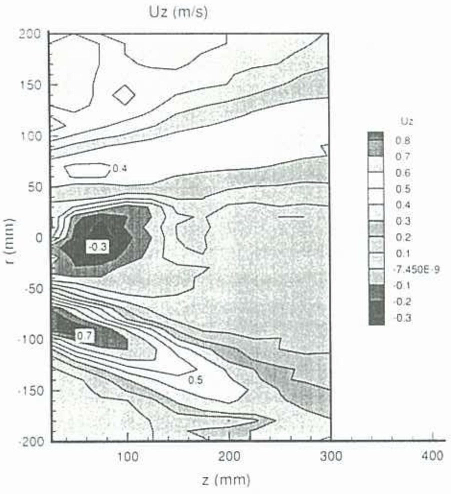
The calibration of the Cobra probe, and the experimental method of determining the axis of the mean velocity vector, are described by Hooper and Musgrove (1991). The flow was scanned at 10 mm increments in the radial position, and for 25 mm increments in the axial station, leading to a possible matrix of 480 points encompassing the expanding free swirling jet. Outside the jet the probe recognises the absence of valid experimental data, thus defining the outer boundary of the flow.

It is interesting to contrast the speed of measurement attained by this system with that expected from hot-wire anemometers and laser-Doppler velocimetery. A fully automated hot-wire anemometer system, used to measure the mean velocity distribution and all components of the Reynolds stresses in a reactor subchannel model, required approximately 50 hours to characterise the developed flow region (Hooper, 1980). This flow was less than 30% turbulence intensity (standard deviation to mean), and apart from secondary flow components less than 1% of the local axial velocity, the mean velocity vector was aligned with the axis of the rig. The hot-wire anemometer would not operate in the above free swirling jet, due to the high turbulence levels invalidating the small signal expansion of the hot-wire probe fluctuating voltages, and the relatively shallow acceptance angle of the probe before the wake of the forks further distorts the response. The use of a single axis LDA system in a similar free swirling jet required two weeks (approximately 70 hours) of experimental time, with a total of some 150 points of the three mean velocity components together with the local turbulence intensity being measured. A major problem in this study was in the poor seeding of the highly turbulent mixing zones, and the poor count rate.

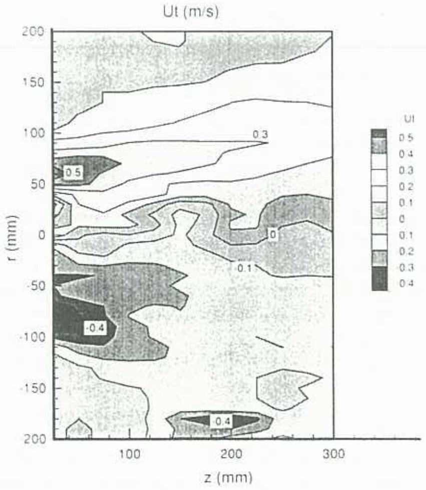
In contrast to these techniques, the high frequency Cobra probe can characterised the mean velocity distribution and turbulence structure within 4 hours for the above flow. The spatial resolution of the probe is governed by the head geometry, currently approximately 5 mm in height and of triangular cross-section.

3. EXPERIMENTAL RESULTS.

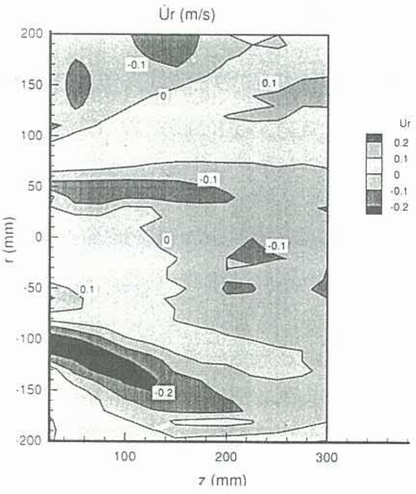
The mean velocity distribution, normalised by the maximum total velocity of 80 ms^{-1}, generated by the swirler is shown by figs. 1(a), (b) and (c) for the axial, tangential and radial mean velocity components respectively. It is apparent that the expanding swirling jet is far from symmetrical about the swirler z axis, an effect to be expected due to the single start nature of the swirler. The swirler blade was in a vertical position at the end plane of the swirler, and positioned upwards or in the positive radial direction at this location. The swirler projected 210 mm (one pitch) outside the pipe, and the centre of the co-ordinate axis was taken as the end of the swirler. It is clear that the mean flow diverges rapidly from the solid body of the swirler. The data in fig. 1(a) show a zone of axial flow reversal extending to approximately 150 mm downstream of the swirler.



Axial mean velocity.
Figure 1(a).



Tangential mean velocity.
Figure 1(b).

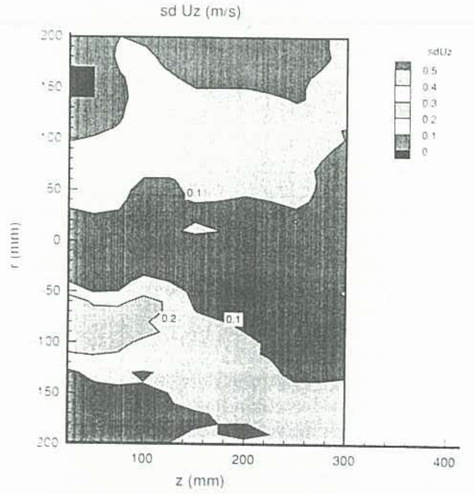


Radial mean velocity.
Figure 1(c).

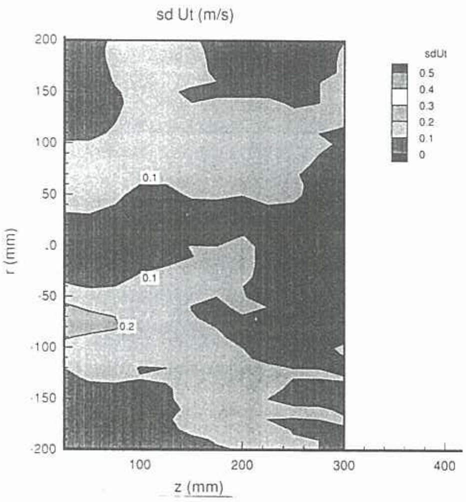
The tangential velocity component, fig. 1(b), shows the expected distribution, having a maximum positive value of 0.5 and a negative minimum of -0.4 on the opposite side of the jet. The radial velocity component, fig. 1(c), shows where the entrainment regions of the jet are high.

The normalised turbulent velocities (standard deviation of the mean velocity component) are shown by figs. 2(a) to 2(c) for the corresponding axis. These are directly related to the normal component of the Reynolds' stresses. There is a clear correlation between these plots and the mean velocity data, showing low turbulence velocities in the recirculation zone and a relatively high turbulence intensity in regions where the entrainment, and mean velocity gradients, are high.

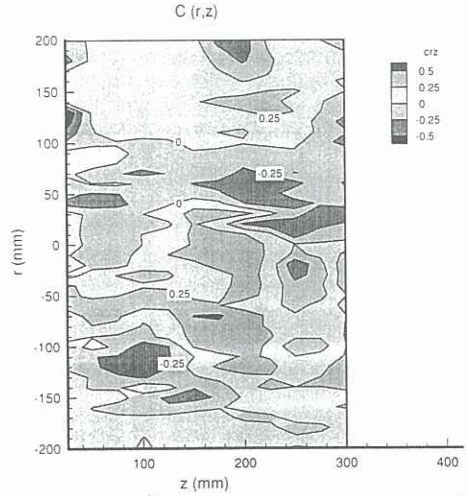
Figures 3(a) to 3(c) show the correlations between the fluctuating velocities which can be related to the cross-product terms of the Reynolds' stresses. It is apparent that the entrainment process generates a large scale turbulent structure that manifests a high coherence (above 50%) between the axial and tangential velocity components, as shown by fig. 3(a). The largest correlations occur, in general, in regions where the mean velocity is low at the margins of the jet stream. The remaining correlations, figs. 3(b) and 3(c), show somewhat lower but still significant values between the corresponding velocity components.



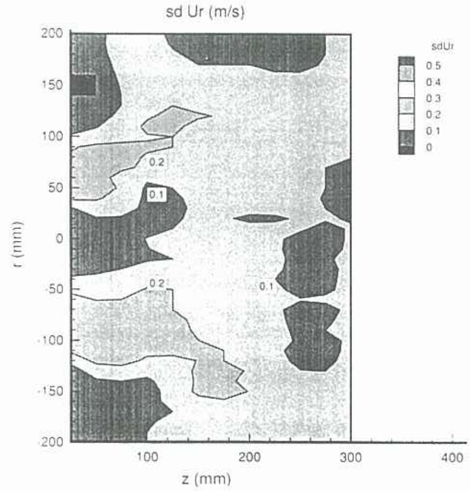
Axial turbulence velocity.
Figure 2(a).



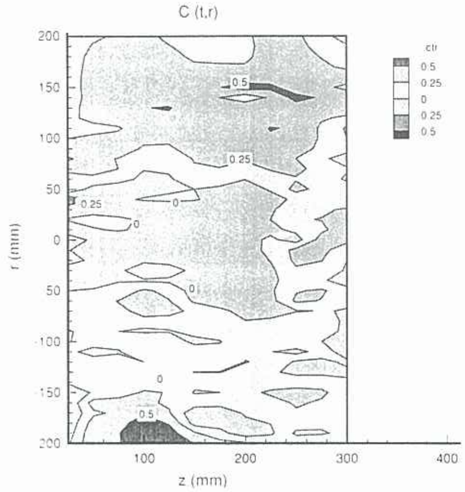
Tangential turbulence velocity.
Figure 2(b).



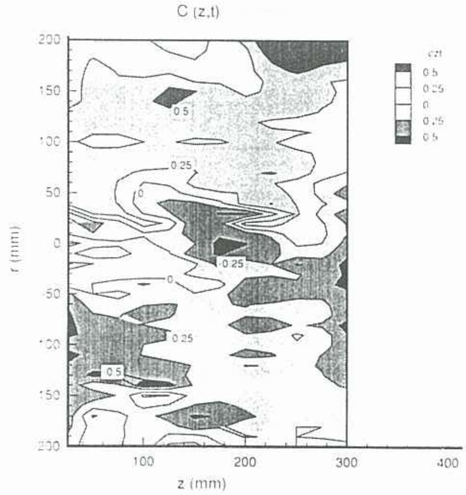
Correlation $C(U_zU_r)$.
Figure 3(b).



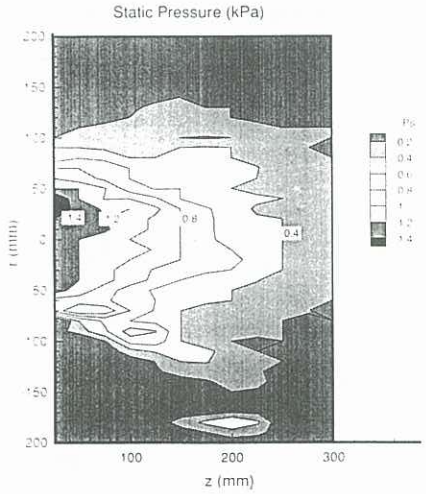
Radial turbulence velocity.
Figure 2(c).



Correlation $C(U_tU_r)$.
Figure 3(c).



Correlation $C(U_zU_t)$.
Figure 3(a).



Static pressure (kPa).
Figure 4.

The static pressure distribution appears in fig. 4. where it can be seen that the jet has significantly reduced static pressure values within the recirculation zone, and these low values persist over the whole of the jet boundary. The experimentally determined time record of the static pressure and turbulent velocity components allows the calculation, in principle, of any moment of these components. This includes the pressure-rate of strain term needed by various closure hypotheses for the computational modelling of turbulent flow, as described by Launder et al (1975).

4. CONCLUSION.

The high frequency Cobra probe has been developed to a level allowing the rapid characterisation of complex, high turbulence intensity flows. All components of the mean and turbulent velocity, together with the corresponding mean and dynamic static pressure, are resolved by the probe, subject to the spatial and temporal resolution of the probe. The new measurement system should allow the computational modelling of turbulent flows to be tested more extensively.

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