*13th Australasian Fluid Mechanics Conference*
*Monash University, Melbourne, Australia*
*13-18 December 1998*

# VALIDATION OF THE COBRA PROBE USING TURBULENCE MEASUREMENTS IN A FULLY DEVELOPED PIPE FLOW

**Jiajun CHEN, David F. FLETCHER and Brian S. HAYNES**
Department of Chemical Engineering
University of Sydney, NSW 2006, AUSTRALIA

**John D. HOOPER**
Turbulent Flow Instrumentation PTY. LTD.
1 Blackbutt Place, Engadine, NSW 2233, AUSTRALIA

## ABSTRACT

This paper is concerned with the validation of a four-hole pressure probe, known as a Cobra probe, for turbulence measurement. Here the probe measurements are compared with established data for fully developed pipe flow, and good agreement is found. Improvements to the data acquisition and processing systems, and probe calibration methodology are also presented.

## INTRODUCTION

Multi-hole pressure probes have long been used in various forms to measure mean velocity components and the local pressure field in three-dimensional flows (Bryer and Pankhurst, 1971). The subject of this study is a four-hole Cobra probe. The Cobra probe was first proposed by Shepherd (1981) for mean flow measurements and further developed by Hooper (Hooper and Musgrove, 1997) for resolving turbulence structure. A schematic diagram of the probe head is presented in Fig 1. The probe has a truncated triangular pyramid head of width 2.8 mm, tap holes of diameter 0.5 mm and pressure tubing 210 mm in length connecting the probe tip to the transducers.

In the previous applications using the probe, sectoring schemes have been adopted. In these schemes the flow direction at the tip of the probe relative to the probe axis divides the calibration surface into several zones (six and three zones in Shepherd's and Hooper's method, respectively), according to the relative magnitude of the side hole pressures. Different combinations of pressure coefficients were used in each zone. The sectoring scheme, when used for a seven-hole probe, allows optimum combinations of the tap pressures to be used for each zone, and therefore greatly extends the useful flow angle range of the probe (Zilliac, 1993). On the other hand, for the four-hole Cobra probe all the tap pressures must be used in each zone. The sectoring approach is not necessary, and may not be beneficial in this case. In the present effort, a single surface method is implemented for the Cobra probe in order to simplify the calibration and interpolation process. Improvements to the data acquisition and processing method are also presented.

In a previous study, two Cobra probes with different sizes have been tested in a developed pipe flow (Hooper and Musgrove, 1997). Higher accuracy was found for the smaller probe. In this paper, a further validation study for the smaller probe, using the new method, is carried out in a fully developed pipe flow. CFD simulations are also presented to help to understand the pipe flow under study.

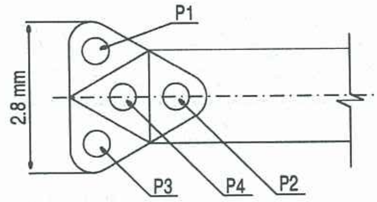


**Figure 1**: Schematic diagram of the Cobra probe head

## NEW APPLICATION METHOD

To orient the reader and to facilitate the presentation of the new method, a brief description of the application method developed by Hooper is presented here. It is basically a non-nulling method that requires pre-determined calibration functions. The calibration involves positioning the probe at known angles to the flow and then measuring the four pressures. Two dimensionless pressure coefficients, based on combinations of differences between the four measured pressures, are formed. These pressure coefficients are only dependent on the flow direction and are independent of Reynolds number, providing the Reynolds numbers are sufficiently high. Therefore the inverse relations exist and the calibration functions for two flow directions based on the two pressure coefficients are then determined. The same type of Reynolds number invariant coefficients for total and static pressures can be formed and the calibration functions for these coefficients can be determined based on the two directional coefficients.

When applying the Cobra probe in an unknown flow, instantaneous velocity components are measured in order to derive turbulence velocities. However, in fine pressure lines, such as those in the Cobra probe, the high frequency signals are distorted both in amplitude and in phase. The pressures sensed by the transducers are not those at the head, therefore the pressures have to be corrected. This is achieved using the transfer function representing the probe frequency response (Hooper and Musgrove, 1997). It is these corrected pressure signals that are mapped onto the calibration surfaces. Upon obtaining a set of instantaneous velocities and pressures

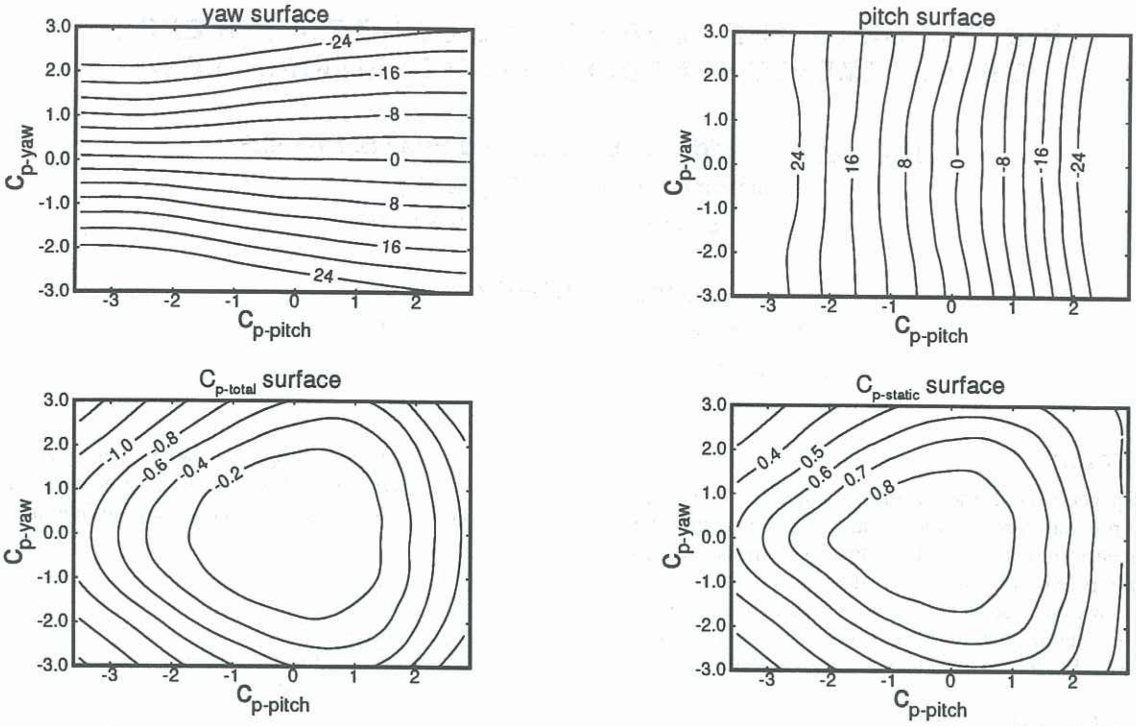


**Fig 2**: Calibration surfaces for the Cobra probe

for a sufficient length of time, the mean and turbulence terms for the velocity and pressure are then deduced using standard methods. At present, the three components of the mean velocity, the static pressure and the six Reynolds stress terms are readily obtained in one measurement.

### Developments in the Data Processing Methods

In the previous method of using the Cobra probe, the pressure signals were recorded and processed in a block manner. Up to 20 blocks of pressure data with 4096 sets of data in each block were recorded. The pressure correction was applied to each block. The effect of this finite data length, known as the window effect, may cause errors. In this study, new software has been developed for continuous data streaming, which allows virtually unlimited data to be recorded, only subject to the computer disk space. The time series pressure data are then corrected as a whole rather than in separated blocks. Consequently, the effective data length is increased enormously. Note that the transfer function needs to be re-interpolated according to the sampling rate and the actual data length, e.g. 5 kHz and 65536 ($2^{16}$) samples in this study.

### New Calibration Surfaces

As stated previously, the sectoring schemes employed by Shepherd and Hooper are not necessary and they may show no net benefit. In this paper, a simplified method suggested by Sitaram (1985) for a similar four-hole probe is implemented. In this method no sectoring scheme is needed and the same set of calibration functions is used over the entire calibration range. The proposed calibration functions are as follows:

$$C_{p-pitch} = \frac{P_2-(P_1+P_3)/2}{P_4-\overline{P}} \qquad C_{p-yaw} = \frac{P_1-P_3}{P_4-\overline{P}}$$

$$C_{p-static} = \frac{\overline{P}-P_S}{P_4-\overline{P}} \qquad C_{p-total} = \frac{P_4-P_t}{P_4-\overline{P}}$$

where $\overline{P}=(P_1+P_2+P_3)/3$, $P_t$ and $P_s$ are static and total pressure and $P_1$ - $P_4$ are tap pressures, as shown in Fig 1. The Cobra probe was calibrated in the potential core of a round free air jet of low turbulence level. A computer-controlled device was used to rotate the probe in the pitch and yaw planes by ±24° in both directions at 2° angular increments. This calibration range has been found adequate for the current study. Calibrations were done at several air velocities from 13m/s to 30m/s, corresponding to Reynolds numbers of 2200 to 5200 based on the width of the probe head. No systematic Reynolds number effect was found. The sensitivity of the Cobra probe using this new method is higher than the old three-zone method. In the region of zero pitch and yaw angles, $C_{p\text{-yaw}}$ and $C_{p\text{-pitch}}$ have sensitivities of about 0.10 and 0.11 per degree, respectively. For the three zone methods, the two angular coefficients have a mean sensitivity of about 0.06 per degree in three zones. Sample calibration surfaces, obtained at an air velocity of 22m/s, are presented in Fig 2.

## EXPERIMENTAL APPARATUS

A schematic of the flow rig is shown in Fig 3. It consists of an inlet section, test section, flowmeter, baffle box and a variable speed blower. Smooth aluminum tube with a diameter of 146 mm is used as the test section. The inlet section includes a contraction cone, tube-bundle flow conditioner, two screens and an orifice trip, all serving to reduce the entrance length for a fully developed pipe flow. The baffle box, containing two 1.5mm wire mesh screens, is used as a buffer to eliminate the pressure fluctuation induced by the blower. Flexible tubes, used to isolate the tube system from the baffle box and the baffle box from the blower, have proved to be necessary to eliminate mechanical vibration that would distort the pressure signal. The air is discharged out of the room via flexible tube to ensure a stable pressure field inside the room. The probe is mounted on a trolley with its axis perpendicular to the pipe axis. A computer controlled traverse system allows the probe to traverse along and rotate about its axis.

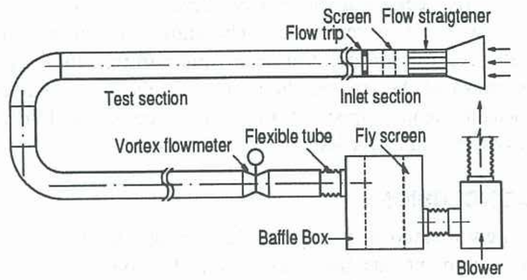


**Figure 3**: Schematic diagram of experimental set-up

## FLOW DEVELOPMENT

In the experimental rig, the last measuring station is about 33D downstream of the trip, which is shorter than some previous experiments, e.g. L/D=60 was used by Lawn (1971). However, the orifice trip located in the inlet section generates extra turbulence and therefore should accelerate the flow development. The effect of the trip was studied using Computational Fluid Dynamics (CFD) simulations, using a commercial software package CFX4 (CFDS, 1996). In the simulation, a 2-D geometry and Differential Reynolds Stress model were used. A uniform velocity distribution and very low turbulence intensity were assumed at the inlet, based on the Cobra probe measurements. The CFD results confirmed that with the flow trip at the inlet section, the flow developed much quicker than the flow without the trip. The entrance lengths required for the mean velocity to become within ±2.5% of the fully developed value are about 15D and 33D with and without the trip, respectively. For the turbulence stress terms, longer lengths are needed, i.e. 33D and 45D with and without the trip, respectively.

## TRAVERSE TEST RESULTS AND DISCUSSIONS

Fully developed pipe flow is used for the validation of the Cobra probe because it is well understood and theoretical results are available. Measurements were made at a plane 33D downstream of the inlet of the pipe for $0 \leq r/R \leq 0.9$. The Reynolds number of the flow was $10^5$ based on the pipe diameter and the bulk velocity. Comparison was made with well documented hot-wire data (Lawn, 1971), which was obtained at 60D downstream in a smooth pipe of diameter 144.3mm.

### Wall Shear Stress and Wall Shear Velocity

Static pressure drops in the direction of the flow were measured through wall static taps located every 0.5 m along the pipe using a pressure transducer. A straight-line regression fit of these data showed the measured pressure drop to be in excellent agreement with the following standard expression:

$$f = 0.079 R_e^{-0.25}, \quad R_e \leq 10^5 .$$

### Mean Velocity

The mean axial velocity profiles measured at 33D downstream of the inlet are shown in Fig 4. The

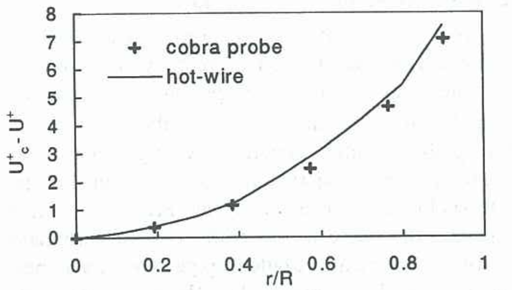


**Figure 4**: Mean axial velocity distribution

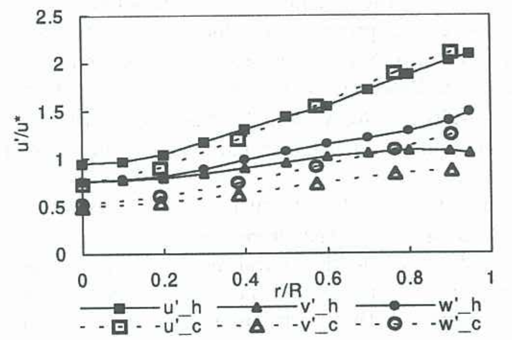


**Figure 5**: Turbulence intensity distribution

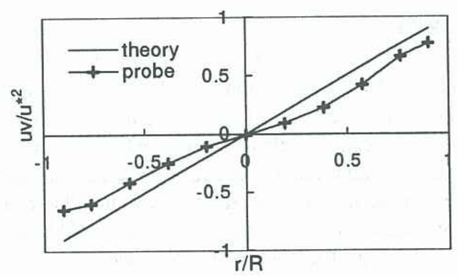


**Figure 6**: Reynolds shear stress $\overline{uv}$ distribution

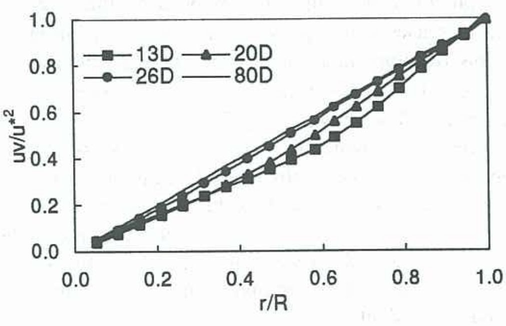


**Figure 7**: $\overline{uv}$ distribution at different axial Positions from CFD simulation

normalized velocity defect plot was chosen because according to Lawn there was no systematic Reynolds number effect for $0 \leq r/R \leq 0.9$ at the Reynolds number between $3\times10^4$ and $3\times10^5$. It can be seen that the velocity profile of a fully developed turbulent pipe flow has been reproduced by the probe. There is good agreement between the results from the hot-wire and the Cobra probe, though the Cobra probe gave slightly higher axial velocities in the region $r > 0.5R$.

**Turbulence Levels and Shear Stress**

The three components of the turbulence intensity, normalized using the wall shear velocity, are shown in Fig 5. The axial, radial and tangential components are denoted by 'u'', 'v'' and 'w'', with the hot-wire and Cobra probe results denoted by '_h' and '_c', respectively. According to Lawn these coefficients are also Reynolds number independent. From Fig 5 it is evident that the shape of the profiles of the turbulence intensity in a typical turbulent pipe flow have been reproduced by the Cobra probe. However, the probe results in lower values than the hot-wire data except for u' at r/R>0.5. The v' and w' terms are similar to the previous Cobra probe data (Hooper and Musgrove, 1997) obtained 5 mm downstream of the pipe exit (L/D=128). However, in the previous test the Cobra probe results of u' term are higher than the hot-wire data and consequently higher than the results in the current test.

The distribution of the turbulence shear stress $\overline{uv}$ is presented in Fig 6. The probe results are smaller in magnitude than the theoretical prediction for a fully developed pipe flow, and a linear distribution has not been achieved. This distribution is similar to the previous test. However, in the current test much better symmetry is found than in the previous Cobra probe results of Hooper.

**Discussion**

The lack of linearity in the distribution of the turbulence shear stress $\overline{uv}$ indicates that the flow at the measuring position may not be fully developed. The flow development can be clearly observed from the CFD simulation results, shown in Fig 7. Accurate prediction of the turbulence development may not have been achieved due to the lack of detailed inlet conditions and the use of a high Reynolds number model which has no detailed wall treatment. However, the CFD results are helpful for understanding the process of flow development. From Fig 7 it can be seen that the $\overline{uv}$ stress increases and approaches a linear distribution as the flow develops along the pipe. The $\overline{uv}$ distribution measured by the Cobra probe is similar to an undeveloped flow shown in Fig 7.

The difference between the Cobra probe results and the hot-wire data in mean velocity and turbulence intensity can be attributed to the lack of fully developed flow as well. Whilst the differences between the current and the previous Cobra probe results indicate the influence of the flow conditions, improvements using the new method are evident.

**Error Analysis**

Measurement errors may also contribute to the differences between the Cobra probe results and the established developed pipe flow data. The uncertainty due to errors in calibration surfaces is 2% in velocity and 2 degrees in the yaw and pitch angles. For the flow studied, which is the centre core of a pipe flow, errors due to a velocity gradient across the probe tip, the wall vicinity effect and turbulence are small. The error caused by probe misalignment is also found to be negligible. Error from the mean static pressure may cause an error in the local wall shear velocity and consequently the normalized turbulence terms. We are currently seeking a method of direct wall shear stress measurement to verify this. The sampling rate and the data length were found to be adequate in this study. The accuracy of the transfer function will also influence the measurements, especially the turbulence terms. Further investigation is needed to clarify this issue.

## CONCLUSION

A new method of using the Cobra probe for turbulence measurement has been presented. The performance of the probe is verified in a nearly developed pipe flow. The differences between the Cobra probe results and those from a hot-wire and the analytical solution are mainly attributed to the lack of development of the flow, while further investigation is needed for the influence of the error in wall friction measurements and the probe transfer function. We are currently extending our study to swirl flow.

## ACKNOWLEDGMENTS

This project was funded by an ARC Collaborative grant in association with BHP Research and TFI.

## REFERENCES

BRYER, D. W. and PANKHURST, R. C., "Pressure-probe methods for determining wind speed and flow direction", HMSO (Lond.), 1971.

CFDS, AEA TECHNOLOGY, "CFX 4.1 Flow Solver: User Guide", Harwell Laboratory, Didcot, Oxon., UK, 1996.

HOOPER, J. D. and MUSGROVE, A. R., "Reynolds stress, mean velocity and dynamic static pressure measurement by a four-hole pressure probe", *Exp. Thermal and Fluid Science*, 15, 375-383, 1997.

LAWN, C. J., "The determination of the rate of dissipation in turbulent pipe flow", *J. Fluid Mech.*, 48, 477-505, 1971.

SHEPHERD, I. C., "A four hole pressure probe for fluid flow measurements in three dimensions", *J. Fluids Eng.*, 103, 591-595, 1981.

SITARAM, N. and TREASTER, A. L., "A simplified method of using four-hole probes to measure three-dimensional flow fields", *J. Fluids Eng.*, 107, 31-35, 1985.

ZILLIAC, G. G., "Modelling, calibration and error analysis of seven-hole pressure probe", *Exp. in Fluids*, 14, 104-120, 1993.