TECHNICAL NOTE

SUB MINIATURE KIEL PROBE FOR TOTAL PRESSURE MEASUREMENTS IN THREE DIMENSIONAL BOUNDARY LAYERS

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Abstract

The design, fabrication and calibration details of a sub miniature Kiel probe for three-dimensional boundary layer measurements are presented in this paper. The probe has a nominal measurement dimension of 0.3 mm and a shroud size of 0.7 mm in the boundary layer direction thus minimizing spatial and flow gradient errors. The probe is calibrated in a calibration tunnel at a velocity of 50 m/s in the yaw and pitch angle ranges of ± 45° and ± 25° at 5° interval respectively. The non-dimensional pressure measured by the probe is plotted as contours. The non-dimensional pressure has a value within ± 1% of total pressure in the yaw and pitch angle ranges of ± 40° and ± 15° respectively. The probe is used to measure total pressure at the exit of a centrifugal impeller at four volume flows. The total pressure measured is found to follow expected trends.

***Keywords**: Sub Miniature Kiel Probe, Total Pressure, Three Dimensional Boundary Layer*

Introduction and Motivation

Kiel probes are used to measure total pressure in three dimensional flows with large flow angles. A well designed Kiel probe [1] can measure total pressure with 1% of dynamic pressure error in flow with angle variation upto ± 50° (Fig.1). The actual angles are 44° for the high velocity of 53 m/s and 48° for the other two low velocities. The 1% error is shown as a horizontal line in magenta. However one of the major disadvantages of Kiel probe is its relatively large size. The size of the shroud of a Kiel probe is usually two to three times the diameter of inner Pitot tube. Because of this large shroud, the errors due to wall vicinity and flow gradients are large. However in three dimensional boundary layers and some flows such as centrifugal compressor diffuser flows, the flow gradi-

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ents are large in only one direction. A standard Kiel probe used in such flows will result in large gradient errors. Hence it is necessary to develop a sub miniature Kiel probe to measure total pressure in such flows. The probe should have good angle insensitivity in the plane where total pressure varies rapidly and reasonable angle insensitivity in the other plane normal to this plane.

Objective

The objective of the present investigation is to design, fabricate, calibrate and validate a sub miniature Kiel probe to measure total pressure accurately in three dimensional boundary layers.

Design and Fabrication Details of Sub Miniature Kiel Probe

Design Details

The major design requirement for the sub miniature Kiel probe is minimum possible dimension in the boundary layer direction to minimize the gradient errors. Hence a very small hypodermic tube (0.3 mm dia.) is used for pressure measurement. To minimise the response time, this small tube inserted in a larger tube (0.5 mm dia.), which is inserted in a much larger tube (0.8 mm) which is inserted in a 1.3 mm dia. tube followed by 2 mm dia. tube and 3 mm dia. tube of 400 mm length. The lengths of the intermediate tubes are relatively small about 3 to 15 mm. The small tube is inserted in a shroud. The shroud is made of 1.2 mm OD x 0.8 mm ID tube of 6 mm length. One end of the tube is flattened to minimise the disturbance to the flow in the direction where the flow is likely to have large gradients. The measuring area of the probe tip is oblong of approximate rectangle shape of 0.7 mm x 1.4 mm. The sensing dimension is 0.3 mm dia. A schematic of the probe tip is shown in Fig.2a and the probe is shown in Fig.2b.

Fabrication Details

All the required tubes are cut to the required length and the internal and external burrs are removed by using a fine emery paper. Stainless steel hypodermic tubes are used except for the external shroud. A brass tube of 1.2 mm OD and 0.8 mm ID is used for the shroud, as it is easy to flatten the tube. All joints are made using Araldite, as it is very difficult to silver braze or solder the small diameter thin tubes used for fabrication. The most important criterion is that the inner tube at the probe tip should be symmetrical with the external shroud.

Calibration Tunnel, Calibration Device, Instrumentation, Calibration Procedure and Program

Calibration Tunnel

The probe is calibrated in the calibration tunnel available in Thermal Turbomachines Laboratory of Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai. The calibration section has a diameter of 200 mm and the maximum velocity is 100 m/s. A photo of the calibration tunnel with calibration device, instrumentation and the probe is shown in Fig.3.

Calibration Device

A calibration device is mounted on the calibration section of calibration tunnel. The maximum diameter of the probe that can be inserted in the calibration device is 14 mm. The probe can be rotated in the yaw direction by ± 180° and in the pitch direction by ± 30°. The probe is mounted such that the probe tip is at the centre of the calibration section to minimize the boundary layer and the tunnel duct wall effects.

Instrumentation

The 20 channel single selection box and the FC012 digital micro manometer manufactured by Furness Control Ltd., Bexhill, London are used to measure probe pressure. The scanning box has 20 channels, which are numbered sequentially. The pressures to be measured are connected to the numbered inputs. The outlet channel is connected to the micro manometer. A particular channel is selected manually in the selection box and its corresponding pressure can be read from the micro manometer. The micro manometer used is sensitive to differential air pressure of 0.1 mm resolution with a range of ± 200 mm of water gauge. The accuracy of the micro manometer is 0.1 mm of the water column. The output of the selection box is connected to the micro manometer and it gives reading directly in terms of velocity in m/s or gauge pressure in mm of water. Time constant potentiometer is used to get time averaged pressures.

Calibration Procedure and Program

The calibration procedure should give the yaw and pitch angle range in which the total pressure measured by the probe is within ± 1% of true total pressure which in this case is taken as the settling chamber static pressure. The probe stem vertical position is taken as zero reference pitch angle. As the Kiel probe has relatively large range of angle insensitivity, it is very difficult to find the zero reference yaw angle. The probe is rotated in the yaw direction, so that the measured total pressure is about half the settling chamber pressure. The probe is rotated in the opposite direction, so that the probe measures pressure measured in the previous position. The average of these two positions is taken as zero reference yaw angle. Once the probe is set at reference zero yaw and pitch angles, the probe is calibrated at a velocity of 50 m/s in yaw and pitch angle ranges of ± 45° and ± 25° respectively. The pitch angle is kept constant and the yaw angle is changed in 5° interval. When the pitch angle is 0°, it is observed that the pressure measured by the probe reduces rapidly when yaw angle is ± 45°. Hence this range is selected. Similarly when pitch angle is ± 25°, it is observed that the pressure measured by the probe reduces rapidly when yaw angle is 0°. Hence this range is selected.

Calibration Results

The measured probe pressures are normalized with the measured total pressure. An excel file with yaw and pitch angles and non-dimensional probe pressure is generated and this file is transported to the graphic package ORIGIN. The pressure contours are presented in Fig.4. For the sake of clarity only contours above the value of 0.5 are presented.

The graph is replotted with yaw and pitch angle ranges of ± 40° and ± 15° respectively and presented in Fig.5. From the graph, it can be seen the pressure measured by the probe gives total pressure within ± 1 % for yaw and pitch angle ranges of ± 40° and ± 15° respectively. In most three dimensional boundary layers and some flows such as diffuser for centrifugal compressors, the pitch angle varies slightly about ± 10°. The yaw angle may vary more than ± 40°. To allow for this large variation in yaw angle, the following procedure may be adopted. The probe can be placed at some reference position (for example in the centre of the diffuser passage) and at an expected yaw angle. Probe traverses can be taken at this yaw angle and at two other yaw angles, which are at ± 20° from this yaw angle position. The maximum value obtained from curve fitting of the three positions can be taken as the true total pressure.

Application of the Probe

The sub miniature Kiel probe is used to measure total pressure at the exit of a centrifugal impeller at four values of flow coefficients, viz. $\phi = 0.23$ (below design value), $\phi = 0.34$ (design value) and $\phi = 0.45$ and 0.60 (above design value). The probe is aligned with the flow direction at the mid span where the probe measures maximum pressure. The probe is traversed in axial direction in intervals of 1 mm near the diffuser walls and 2 mm in the mid passage of the diffuser. In addition measurements are taken with the probe along the axial direction at two angular positions, corresponding to ± 30° from this angular position. The pressure data from the three positions are compared and the maximum value is taken as the total pressure at the corresponding axial position. The total pressure is non-dimensionalised with the dynamic head based on the impeller tip speed. The axial distribution of the total pressure coefficient is plotted against the non-dimensional axial distance and shown in Fig.6. The total pressure distribution shows expected trends.

The total pressure coefficient is area averaged and plotted against the flow coefficient (Fig.7). The variation of the area averaged total pressure coefficient shows expected trends with the maximum value occurring at the design flow coefficient.

Further applications of this probe can be measurement of blade-to-blade variation of total pressure in the vaneless diffuser passage by inserting a fast response pressure transducer of suitable range in the stem of the probe. The frequency of the pressure transducer will be reduced a little. One such probe was designed, fabricated, calibrated and used in Ref.2. However the probe tip is relatively large, about 3.2 mm causing large spatial gradient and wall vicinity errors. Hence a sub-miniature fast response Kiel probe based on the present design will minimize these errors.

Conclusions

A sub miniature Kiel probe with minimum size in the boundary layer direction is designed for minimum gradient errors, fabricated and calibrated. The probe measures total pressure accurately in yaw and pitch angle ranges of ± 40° and ±15° respectively. A method is presented for the use of the probe when the yaw angle exceeds ± 40°. The probe is used to measure total pressure at the exit of a centrifugal impeller at four volume flows. The total pressure measured is found to follow expected trends. The area averaged total pressure coefficient is plotted against the flow coefficient. The variation of the area averaged total pressure coefficient shows expected trends with the maximum value occurring at the design flow coefficient.

Acknowledgement

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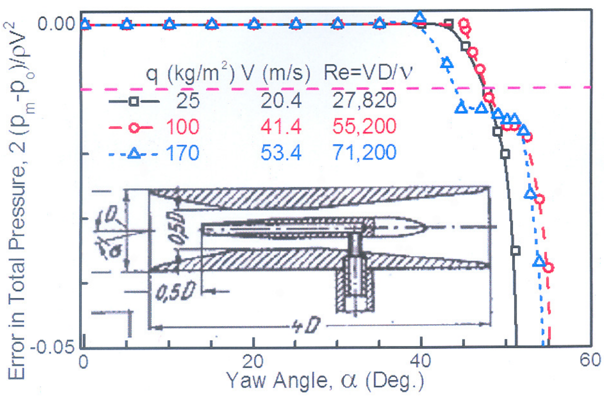

Fig.1 Schematic of Best Kiel Probe and Total Pressure Error Ref : Kiel [1]

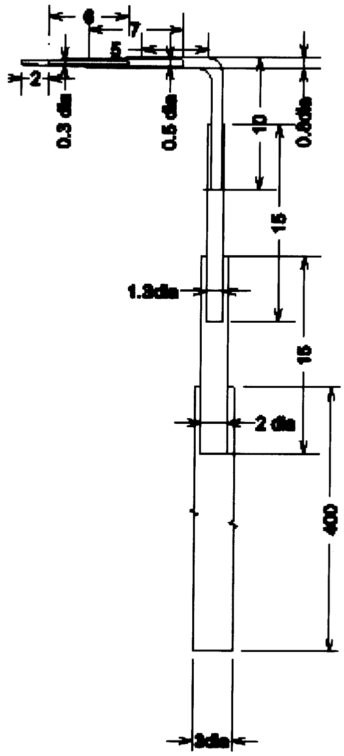

Fig.2b Autocad Drawing of Sub Miniature Kiel Probe (All dimensions in mm)

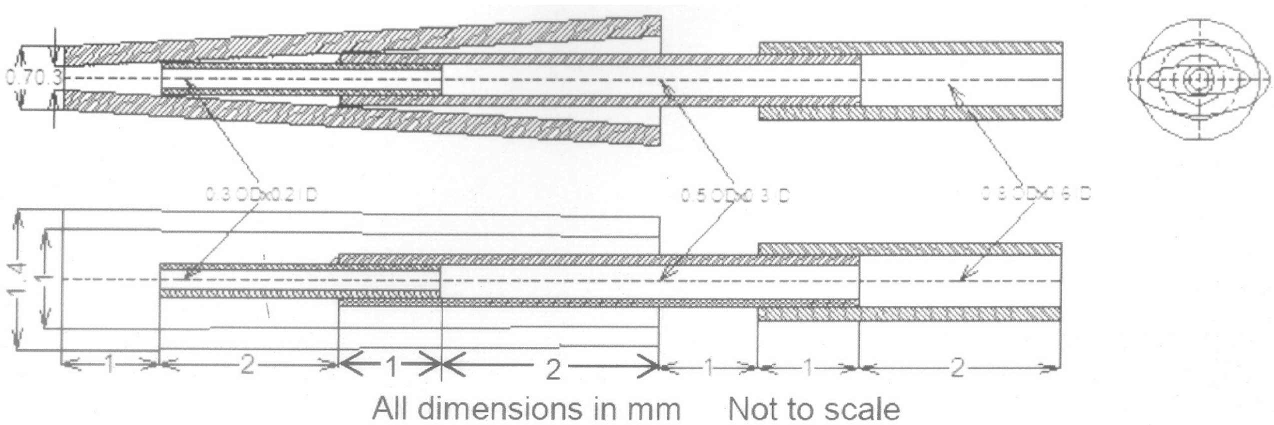

Fig.2a Autocad Drawing of Sub Miniature Kiel Probe Tip

Fig.3 Calibration Tunnel, Calibration Device, Instrumentation and Probe

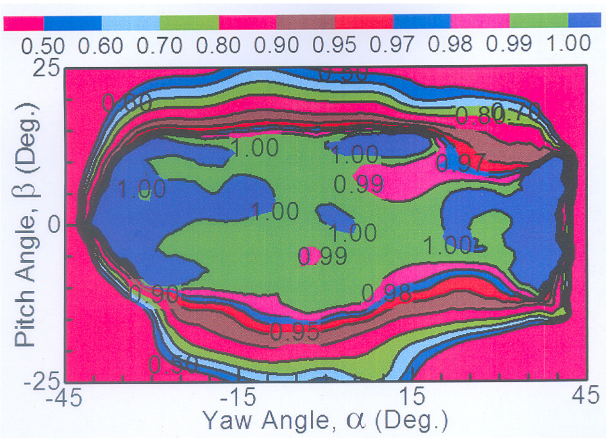

Fig.4 Contours of Non-dimensional Probe Pressures (All data points are shown)

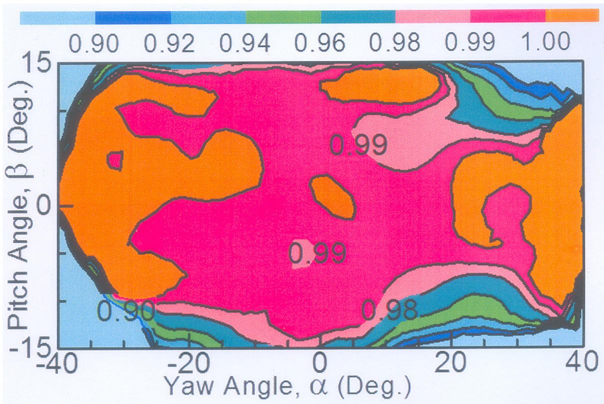

Fig.5 Contours of Non-dimensional Probe Pressures (Limited data points are shown)

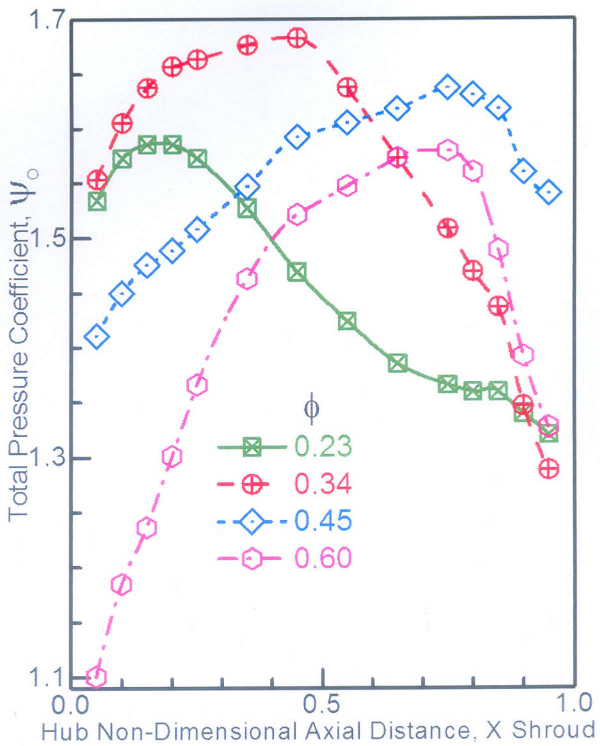

Fig.6 Axial Distribution of Total Pressure Coefficient at the Exit of a Centrifugal Impeller

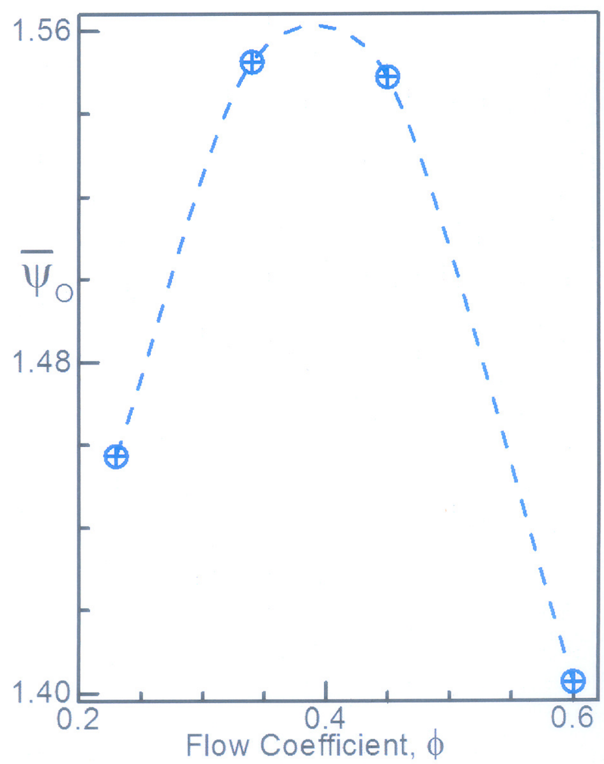

Fig.7 Variation of Area Averaged Total Pressure Coefficient with Flow Coefficient