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EXPERIMENTAL STUDY OF A FIVE-HOLE PRESSURE PROBE FOR MEASURING THREE MEAN VELOCITY COMPONENTS

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Abstract. *Multi-hole pressure probes are quite known as instruments to measure magnitude and direction of mean velocity in turbulent flows. They are also used to simultaneously measure the dynamic and total pressures. A five-hole pressure probe is build with a central pressure hole and four circumferential and symmetrical distributed pressure holes in its measuring head. A five-hole pressure probe can be operated in the null detector mode and also in a fixed mode. In the present work the pressure probe is used in the fixed mode and, consequently, it has to be calibrated. The probe was fixed in a transversal axis and calibrated in a wind tunnel test section of known air flow. The yaw and pitch angles was tested from* -25^o *to* $+25^o$. *Two dimensionless coefficients for yaw and pitch angles and other two dimensionless parameters for dynamic and total pressures are defined. Tridimensional surfaces for those dimensionless parameters are fitted for yaw and pitch angles against non-dimensional coefficients that take into account the variation in the probe position in relation to flow direction. Tridimensional surfaces are also fitted for the dimensionless dynamic and total pressure coefficients against the yaw and pitch angles.*

Keywords: *Multi-hole pressure probe, velocity intensity, velocity direction, dynamic and total pressure*

1. INTRODUCTION

The measurement of velocity magnitude, flow direction, dynamic and total pressures with a five-hole pressure probe is well established (Mesquita et al, 1980).In a uniform flow, where the velocity vector direction is known a Pitot tube may be used for measuring the dynamic pressure and consequently, the magnitude of the velocity vector. In a three dimensional flow, where the velocity direction is not known, *a priori*, one have to use multi-hole pressure probes to establish the yaw and pitch angles of the velocity vector and its also its magnitude. In a three dimensional flow one may be also interested in obtain information regarding the pressure field and again, the five-hole pressure probe is a very interesting device to obtain those informations. Laser Doppler Anemometry, Hot Wire Anemometry and Particle Image Velocimetry, all of them, are able to only measure kinematic variables of the flow field. Besides the mean value one can also measure the fluctuating values of the turbulent velocity field with those complex instrumentation devices. None of them, however, can give information on the pressure field. Only multi-hole pressure probes have this particular characteristic. A multi-hole pressure probe may be used in two different modes. In the first one, it is used as a null detector for the yaw and pitch angles. In this null mode, it is placed in a three dimensional flow where the velocity magnitude and direction are not known. A mechanical device is used to rotate the probe in a horizontal plane firstly, until the difference between the two lateral pressure holes is equal zero. The yaw angle is then measured by a protractor. Sequentially, the probe is rotated in a vertical plane until the two vertical pressure holes difference is equal zero. The pitch angle is then measured by a second protractor. In this position, the central pressure hole is measuring the total pressure. With a reference pressure in some reference position of the experimental set up, it is possible to indirectly measure the dynamic pressure and the velocity vector magnitude. In the second method the probe operates in a fixed mode and it has to be calibrated. To do this, the probe is immersed in a known uniform flow. In the calibration process it is rotated in a horizontal plane and also in a vertical plane. The flow conditions are kept unchanged during the calibration. For each yaw angle, one can vary the probe position in order to obtain different pitch angles. A matrix of yaw-pitch positions is then covered during the calibration. In each yaw-pitch position one knows the following variables: velocity flow magnitude, total pressure, static pressure, fluid density, yaw angle and pitch angle. Tridimensional surfaces may be fitted for yaw angle in function of the pressure coefficients that take into account the five pressure values present in the probe head. Three dimensional surfaces for the dimensionless total pressure and the dimensionless dynamic pressure can also be fitted in function of the yaw and pitch angles. With these set of four tridimensional surfaces fitted, the calibration process of the five-hole pressure probe is completed. During the measurement process one needs to know only the five pressure values and the fluid density. With those informations the fitted three dimensional surfaces are used in order to get firstly the yaw and pitch angles. Sequentially, with the known values of yaw and pitch angles, using the other two three dimensional surfaces, one may obtain the dynamic and total flow pressures. The five-hole pressure probe employed in the present experimental study was used in the fixed mode.

2. BIBLIOGRAPHIC REVISION

Huffmann *et al*(1980) in their work on multi-hole pressure probes for measuring the flow direction present a justification for a better understanding of the theoretical and experimental aspects of the multi-hole pressure probes and their importance in the application in many fields of the engineering. They comment that que null detection method is more precise but more complex to operate. The fixed mode, even being less precise and demanding calibration is simpler to operate.They suggest that one theoretical approach for a better understanding of this device could be obtained by numerical tridimensional solution of a potential flow around the multi-hole pressure probe. Ligrani *et al* (1989) inform that fluid dynamicists have dedicated a good deal of attention for the development of very small pressure probes in order to have a good spatial resolution. They produced and also tested a miniature pressure probe with diameter of only 1,22 mm. A wind tunnel test section was used to calibrate their miniature pressure probe. During the calibration the air speed was kept constant and equal to 30 m/s. The influence of the Reynolds number on the dimensionless coefficients was checked. In the range of Reynolds number tested, those dimensionless coefficients are independent of Reynolds number. Mesquita *et al* (1997) present in their work one type of five-hole pressure probe of low cost and report the advantages of this kind of device for measuring important variables in three dimensional flows. In a wind tunnel test section the five-hole pressure probe was calibrated, with the yaw angle and pitch angle varying in the range of $+/-25^o$, and the Reynolds number based on the probe head diameter was fixed in $Re = 8,8 \times 10^3$.Gundocdu *et al* (1998) present a method to measure velocity field with secondary flow with strong rotation (swirling flow), using multi-hole pressure probes with good sensitivity. They pointed out that multi-hole pressure probes combine means for simultaneous measurement of total and dynamic pressure as well as magnitude and direction of the velocity vector. They developed a device to move the probe in a matrix of yaw and pitch positions during the calibration process. The five-hole pressure probe was build by the union of five copper tubes of 1.2 mm of outside diameter. Dimensionless angular pressure coefficients, dynamic and total dimensionless coefficients are defined and calculated in the calibration carried on a wind tunnel test section with air flow of varying from 5m/s to 15 m/s. The results are presented for a velocity of 10 m/s. The pressure coefficients are not very affected by the tested Reynolds numbers. The probe was used to measure velocity components and static pressure in a conventional cyclone. Morrison *et al* (1998) present a refined technique in order to analyze five-hole pressure probes operating in a stationary mode. A computer software is utilized to fit tridimensional surfaces for the respective pressure coefficients. The shape of those surfaces constitute in an important indicator on the probe quality, regarding on the manufacturing aspects or by any operational damage. The tridimensional contours are also good indicators of the angular probe operational range. Pisadelli (2002) applied one model of potential flow around one sphere in order to propose and to avalize the dimensionless angular and pressure coefficients. A theoretical basis to understand the operational probe range is also presented. Mesquita (2005) in one revision on this subject regarding pressure probes for measuring tridimensional and turbulent flows presents the operational principles for multi-hole pressure probes, the mathematical expressions for the dimensionless angular and pressure coefficients, and how the experimental data may be fitted in three dimensional surfaces. The methodology presented by Mesquita (2005) is used in the present work.

3. THE PROBE AND ITS CALIBRATION

Figure 1 shows a photo of the five-hole pressure probe used in the present work. The probe body comprises a 8 mm outer stainless steel tube. Each one of the five small pressure tap tubes has an outer diameter of 1 mm and is also made in stainless steel. The probe is 120 mm long and its tip was chamfered to a 45^o.

Figure 2 shows the details of the five-hole pressure probe head with a central pressure tap 1, and four circumferential pressure taps 2 to 5.

The probe calibration was carried out in a wind tunnel test section. During the calibration the air velocity was kept in 10 m/s. The dynamic and total pressure in the test section were measured and monitored by a Pitot tube placed near the probe, without disturbing the flow in its surrounding. The yaw and pitch angles were measured by two independent protractors and were varied in the range of $+25^o$, from 5 to 5. Seven pressure data, five of them from the probe, the static and total pressure from the Pitot tube were recorded for each pair of yaw-pitch position. Four dimensionless coefficients were defined for angular position, dynamic pressure and total pressure respectively, and calculated as follows:

$$X_1 = \frac{P_2 - P_3}{P_1 - \bar{P}} \tag{1}$$

$$X_2 = \frac{P_5 - P_4}{P_1 - \bar{P}} \tag{2}$$

$$X_D = \frac{\rho V^2}{P_1 - \bar{P}} \tag{3}$$

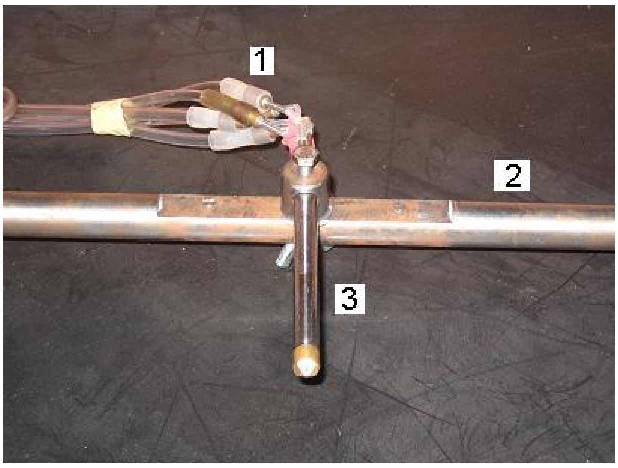

Figure 1. Five-Hole Pressure Probe 1 - Pressure Tap Outputs ; 2 - Horizontal axis; 3- The Probe.

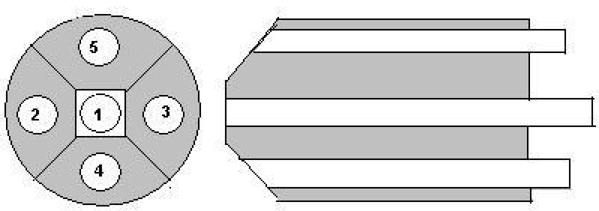

Figure 2. Five-Hole pressure probe; 1 - central pressure tap; 2 - 3 : pressure taps difference strongly affected by the yaw angle; 4 - 5: pressure taps difference strongly affected by the pitch angle

$$X_P = \frac{P_1 - P_t}{P_1 - \bar{P}} \tag{4}$$

Where:
$\bar{P} = 1/4(P_2 + P_3 + P_4 + P_5)$
$P_t = P_{total}$
V= Magnitude of the velocity vector

The dimensionless coefficients X_1 e X_2 are associated to the yaw angle α and pitch angle τ, respectively. X_D is a dimensionless dynamic pressure and X_T is a dimensionless total pressure. With the five pressure readings from the probe head, the total and static pressure readings from the Pitot tube and with the value of the air density, it is possible to calculate all of those coefficients for each yaw-pitch pair position. Tridimensional surfaces were fitted by the least square method using polynomials of third degree in the form $\alpha = g_1(X_1, X_2)$, $\tau = (g_2(X_1, X_2)$, $X_D = X_D(\alpha, \tau)$, and $X_T = X_T(\alpha, \tau)$. X_1 and X_2 are functions only on the five pressures values P_1, P_2 ...., P_5.

Figure 3 shows the fitted three dimensional surface $\alpha = g_1(X_1, X_2)$ and Fig. 4 shows the same procedure for $X_D = X_D(\alpha, \tau)$. Similar surfaces were fitted for $\tau = (g_2(X_1, X_2)$ and also for$X_T = X_T(\alpha, \tau)$.

In order to evaluate the five-hole probe regarding its manufacturing aspects, Morrison *et al* (1998) suggest that the projection of some fitted tridimensional surfaces , like $P_1 = f_1(\alpha, \tau)$ or $P_2 = f_2(\alpha, \tau)$ may constitute in good indicators. Figure 5 shows how the pressure tap P_1 indication behaves as the angular positions of the probe tip is varied in the air flow in the test section. Some lack of symmetry exists due to some basic sources: the first one may be related to the initial probe head angular position; a second may be related to the manufacturing process; and another may be related to the errors in the fitted process itself.

4. EXPERIMENTAL RESULTS

The five-hole pressure probe was fixed in an appropriate displacement system and tested to measure a tridimensional air flow at the exit of a pre-mixing chamber of a Lean Premixed Combustor - LPP, operating without combustion. A photo of this combustor is shown in the Fig. 6.

To do this measurement the combustion chamber was removed and the air flew as a free-rotating jet - swirling flow . The measurement was carried out along a horizontal line covering 9 different positions in the exit free jet. The probe tip

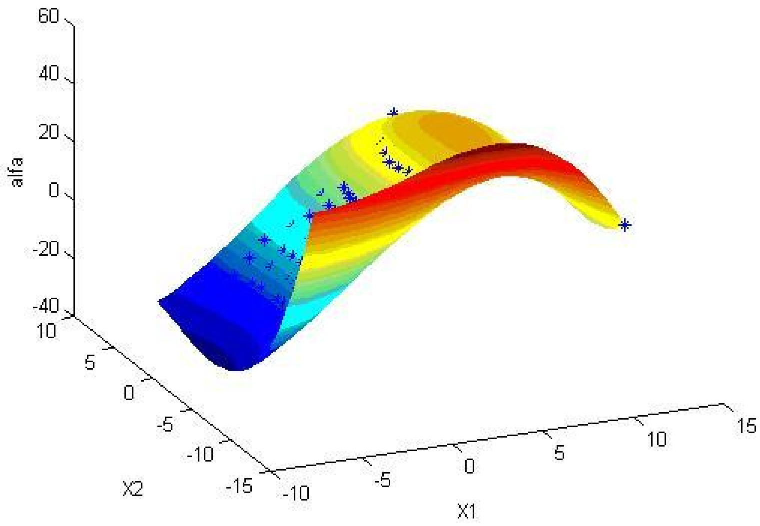

Figure 3. Yaw pitch as a function of X1 end X2 coefficients

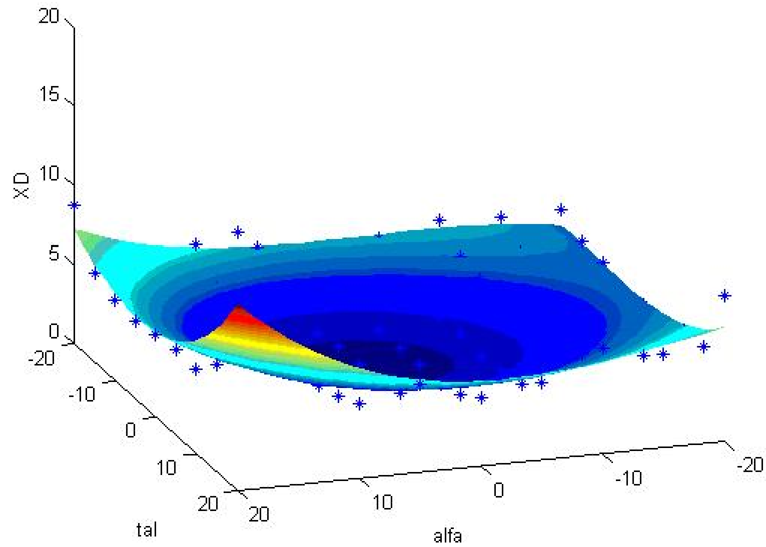

Figure 4. Dynamic pressure coefficient in function of yaw and pitch angles

was positioned $10mm$ from the exit section of the pre-mixing chamber. In this combustor, the swiller vanes are adjustable. The measurement was carried out for a fixed air rate of 27×10^-3 normal cubic meter per second and the swiller vane angle position was fixed at 30^o. The horizontal flow is shown in the plane $x - z$, with velocity components as V_z (the the axial velocity component) and V_x(the transversal component). Figure 7 shows these two velocity components in the 9 measured positions. The pre-mixing chamber inner diameter is equal to 50 mm. The distance between probe tip positions is expressed in mm. In the present set up the air flow is produced by a ventilator where its electrical motor is controlled by a frequency inversor. The air flow rate is measured by a rotameter. In the present experimental set up, the electric motor rotation of the ventilator, and consequently the air flow rate were fixed. The air comes from the test section in a axial movement until it reaches the swirller. After the swirller the air will continues to experiment a axial flow, but also a rotating flow - as a rigid solid rotation - and also a precession vortex in its flow core. Many instabilities are presented in this complex flow. Due to the presence of the rotational movement, the air at the exit of the premixing chamber, when it encounters the atmospheric air at rest, will present a large central recirculating zone, that may comprises more than

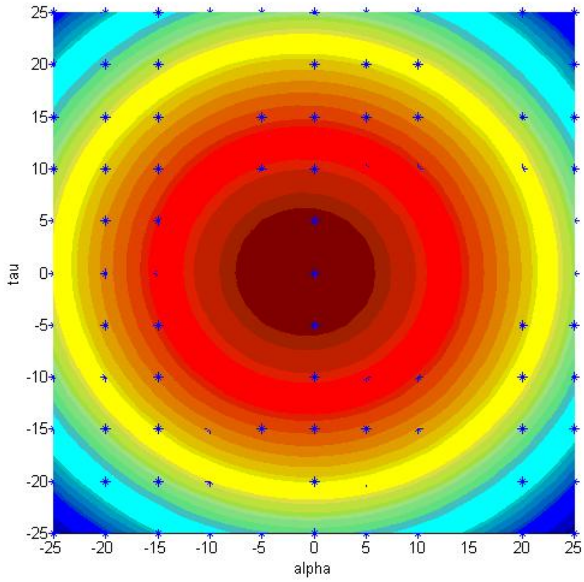

Figure 5. The P_1 behavior with the variation of α and τ

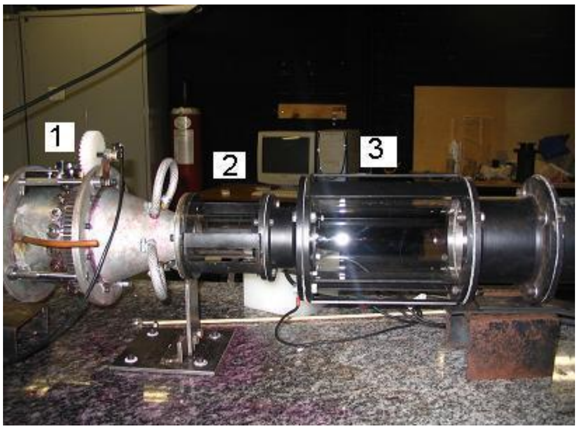

Figure 6. The LPP combustor. 1 - Swiller; 2 - Premixing chamber; 3 - Combustion chamber

50 per cent of the rotating free jet. The size of this recirculating zone is strongly dependent on the angle of the swirller vanes. The five-hole pressure probe adequate to make measurements of three velocity components of a specific flow, but the recirculation may not be present. It is a limitation, as that limitation also found in the hot wire anemometer technique, that is able to measure the velocity vector intensity, but not its sense. When one wants to use the five-hole pressure probe in order to measure three velocity components, the flow direction may vary, but its sense can not. In the choosen flow, unfortunately, only very small angle of the swirller vanes may be choosen, otherwise the air flow, at the exit of the premixing chamber will present a very large recirculating zone, where the velocity sense is negative, and consequently the five-hole pressure probe is not useful anymore. That was a limitation of the present experimental set up. The five-hole pressure probe may be used to measure the three velocity components in a curved flow, for instance. The flow in the present set up, unfortunately, has presented recirculation zone at small values of the swirller angle. Due to this fact only one swirller angle value was tested for the fixed air flow rate.

Figure 8 presents the swirling flow for the same air flow rate and for the same angular vane position in the transversal plane, showing the behavior of the velocity components V_x and V_y. Due to the small value of the test swirller vane angle, the main velocity component is the axial component. The velocity components in the secondary flow, in the transversal section, are small in comparison to the axial velocity component. The free circulating jet presents an axial velocity component in the horizontal plane and also a vertical and transversal components in the secondary flow, that occurs in the transversal section. The velocity components presented in the figures that follows are not in scale. Another air flow will be tested in the future experimental work, in order to get more representative results.

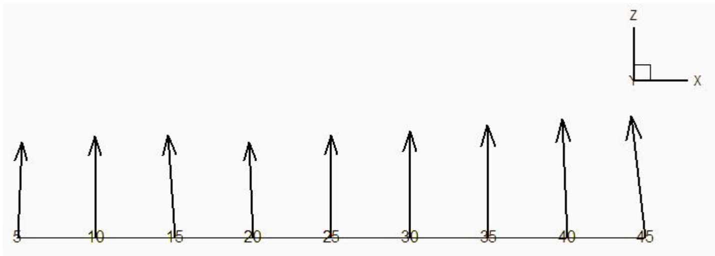

Figure 7. Velocity components in the horizontal plane of the swirling flow

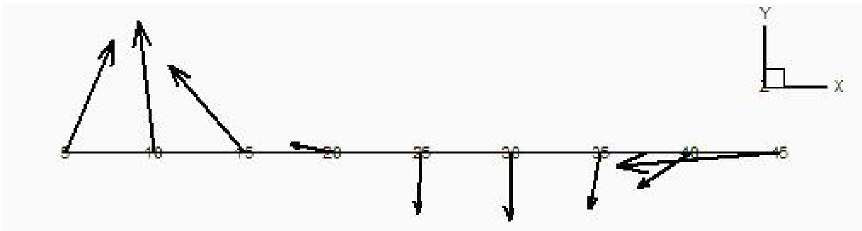

Figure 8. Velocity components in the transversal plane of the swirling flow

5. CONCLUSIONS

A five-hole pressure probe was built with the objective to analyze mean tridimensional air flows. This pressure probe was previously calibrated in a wind tunnel test section and angular coefficients and pressure coefficients for the dynamic and total pressure were measured. Tridimensional surfaces were used to fit the experimental data. The five-hole pressure probe constructed for this purpose presented a good performance, despite its poor spatial resolution. A smaller pressure probe may be now constructed, calibrated and used as a measuring device, following the procedure presented in this experimental work. A numerical solver using a MatLab platform was written to fit the tridimensional surfaces and also to verify how good were those data fitted. Finally, the five hole pressure probe was tested in the measurement of a tridimensional swirling flow at the exit of a pre-mixing chamber.

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