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Calibration and Use of a Five-Tube Pressure Probe in the Swirling Flow Field

Mehmet Yaşar GÜNDOĞDU, Ömer Turgay GÖKSEL
Department of Mechanical Engineering,
University of Gaziantep
27310, Gaziantep-TURKEY

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Abstract

In this paper; construction, calibration and then the measurement of flow velocity and angularity in a swirling flow field by a fixed five-tube pressure probe are presented. A novel orientation mechanism was designed to achieve the calibration of the probe. Non-interference with the flow field, simplicity of manipulation and construction are the main advantages of this orientation mechanism over other mechanisms mentioned in the available literature. This mechanism enables to rotate the probe about its tip in two planes perpendicular to each other with a precision of $\mp$ 0.25°. A variable speed, blower type wind tunnel was used during the calibration process. Calibration of the probe was done in the ranges of $\mp$ 45° in pitch and $\mp$ 35° in yaw. The calibration charts thus obtained were used to measure the flow direction, dynamic pressure and total pressure in a swirling flow field of a vertical air cyclone by fixing the probe axis approximately in line with the θ-direction of the cylindrical co-ordinate system.

Key Words: Pressure, Probe, Yaw, Pitch, Swirl.

Beş Tüplü bir Basınç Sondasının Dönel Akım Alanı İçerisinde Kalibrasyonu ve Kullanımı

Özet

Bu makalede; beş tüplü bir basınç sondasının imalatı, kalibrasyonunu ve sonra, dönel bir akım alanı içinde akım hız ve yönünün ölçümü sunulmuştur. Sondanın kalibrasyonunu yapabilmek için orijinal bir açılandırma mekanizması tasarlandı. Açılandırma mekanizmasının akım alanı içinde olmaması, imalatının ve kumandasının kolay olması bu mekanizmaya kaynaklarda sözü edilen diğerlerine göre kullanım ve ölçü hassasiyeti avantajları sağlamaktadır. Bu mekanizma, sondayı ucu etrafında birbirine dik iki düzlemde, $\mp$ 0.25°'lik bir hassasiyetle döndürmeyi mümkün kılar. Sonda kalibrasyonu için değişken hızlı, üfleme tipi rüzgar tüneli kullanıldı. Sondanın kalibrasyonu $\mp$ 45°'lik düşey sapma açısı ve $\mp$ 35°'lik yanal sapma açısı aralıklarında yapıldı. Bu şekilde elde edilen kalibrasyon şemaları, dik bir hava siklonunun dönel akım alanı içine yerleştirilen basınç sonda ekseninin silindirik kordinat sisteminin yaklaşık θ-yönünde tesbit edilmesiyle akım yönü, dinamik basınç ve toplam basınç ölçümü yapıldı.

Anahtar Sözcükler: Basınç, Sonda, Yanal sapma açısı, Düşey sapma açısı, Dönü

1. Introduction

The five-tube pressure probes have been conveniently used to determine flow speed and flow direction after suitable calibration. A five-tube pressure probe is one of the devices that can be used for this purpose in a three-dimensional flow field. The five-tube pressure probe combines the means for simultaneous measurement of total pressure, dynamic pressure and flow direction by one instrument. While LDV and hot-wire probes can be used for measuring mean velocities and flow direction, but additional measurements are required for static pressure as stated by Bryer and Pankhurst [1971], Yajnik and Gupta [1973], Bradshaw and Christiansen [1981].

As reported by Bryer and Pankhurst [1971], Yajnik and Gupta [1973], and Gaillard [1983], the five-tube probes can be used for investigation of three-dimensional flow fields by two distinct methods. In the first method, which is known as the "null-reading" method, the probe orientation is changed in explored flow field until the same pressures are recorded at each hole of the four side tubes of the probe. Thus, at this position it is possible to determine the flow direction and speed of main stream. In the second method, the probe is firstly calibrated to determine its sensitivity to pitch and yaw angles in a known uniform rectilinear flow field. The calibration of the probes is carried out by recording the pressures sensed from individual tubes of the probe when it is oriented about its tip in two planes normal to each other. The difficulty of the probe orientation is due to the fundamental difficulty of having no convenient mechanical axis about which the motion can be described; therefore, the required orientation mechanisms for the calibration has often a complex structure. After the calibration of the probe is completed then the probe axis is fixed approximately in line with main flow direction of the flow field to be explored. The dynamic pressure, total pressure and the exact direction of explored flow are obtained from the calibration charts by using the recorded pressures from each of the five tubes of the probe.

The null-reading method is especially suitable for two-dimensional flow measurements requiring probe rotation about only around one axis where only flow yaw angle and resultant flow velocity is to be measured. This method tends to become less practicable when flow angularity in two planes perpendicular to each other is to be measured. In this case a simple rotation of the probe about a convenient axis or axes do not suffice. The use of the probe by the second method mentioned above is successfully applied for investigating three-dimensional flow fields where the resultant flow velocity as well as flow pitch angle and flow yaw angle is to be measured.

2. Construction of the Probe

The five-tube pressure probe was constructed from copper tubes having 1.2 mm OD and 0.7 ID. It consists of a forwad facing pitot-tube at the centre, two chamfered side tubes in horizontal axis and two chamfered side tubes in vertical axis as shown in Figure 1. The tips of four side tubes were separately chamfered to ∓ 45° by means of a special forming jig designed for this purpose. This was followed by careful stoning after which burrs were removed. The four chamfered tubes were assembled by a small amount of solder around the central square-ended tube. The symmetry of the side tubes was checked by a Leitz PP 500 contour measuring projector by using magnification scale of 50:1. The shape of the probe assembly was formed according to the "cranked" design as described in British Standards [BS 1042].

3. Design and Construction of the Probe Orientation Mechanism

The calibration of the five-tube probes requires an orientation mechanism which enables to rotate the probe about its tip in two planes perpendicular to each other. A probe orientation mechanism which enables 360° yaw wise (Ψ) and ∓ 45° pitch wise (α) rotation with an accuracy of ∓ 0.25°, was designed and constructed. The orientation mechanism was mounted on the test section of a wind tunnel which was constructed from 1.5 mm thick sheet iron having a rectangular crossection of 140×210 mm. Detailed views of the probe orientation mechanism and the wind tunnel test section are shown in Fig. 2 and Fig. 3.

The orientation mechanism is mainly composed of a pitching gear set, an L-shaped arm and a coupling ring. The pitching gear set is composed from the mesh of a helical gear and a worm gear on the vertical side of the portable test section. The worm gear is fixed to the L-shaped arm. The worm gear and the arm can be actuated simultaneously pitch wise when the helical gear is driven by hand. The pitch angle (α) given to the arm, is read by a protractor fixed on the vertical side of the test section through a visualization hole drilled on the arm. The four groove coupling ring is fixed to short side of the L-shaped arm at the top of the test section. The probe held by the coupling ring, can now be rotated yaw wise by loosening the grip of the coupling ring. The yaw angle given to the probe is read by an other protractor with the aid of an angle vernier fixed on the arm. The yaw angle measuring protractor is coaxially fitted with the probe on the coupling ring. The yaw and pitch angle measuring protractors have a resolution of 0.5 °.

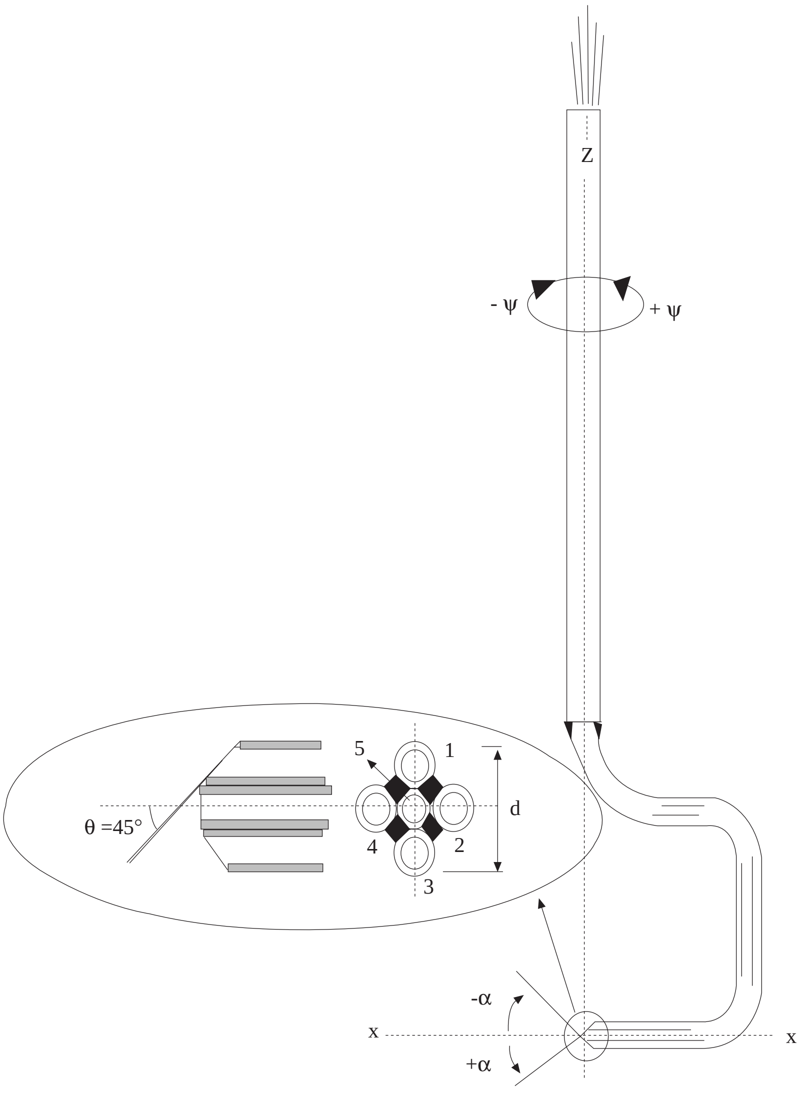


Figure 1. The Constructed Five-tube Pressure Probe.

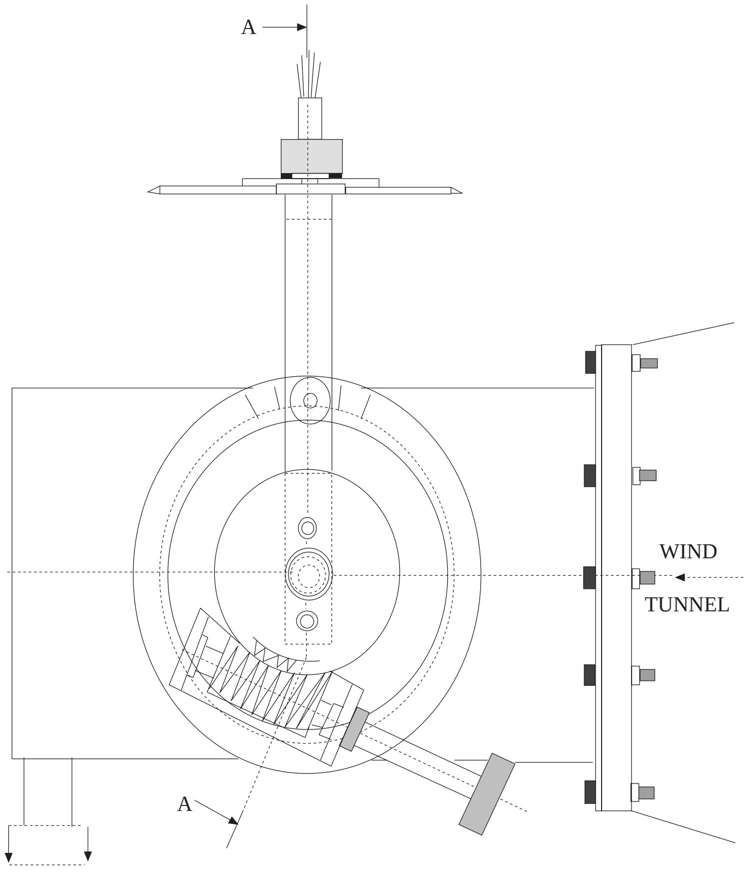


Figure 2. The Probe Orientation Mechanism and the Test Section of Wind Tunnel.

The main advantages of the designed orientation mechanism are that, the construction and manipulation of the mechanism are very simple as compared with the mechanisms designed by Todd [1954], Bryer [1956], Bryer and Pankhurst [1971] and Gaillard [1983], in which fork-ended shafts, segmented guides, parallel-linkage systems, or pantograph systems were installed to provide the pitch wise rotation of the probe tip. There was no interference of the designed orientation mechanism with the flow field. This decreased pressure reading errors of the probe. The orientation mechanisms used in references mentioned above causes blockage of the flow field and thus recorded pressures from the tubes of the probes could be in error throughout the calibration. All orientation mechanisms have some degree of backlash, however worm and worm-wheel drives which were used in the designed orientation mechanism presented in this paper are suitable to prevent the backlash caused by vibration and aerodynamic loading.

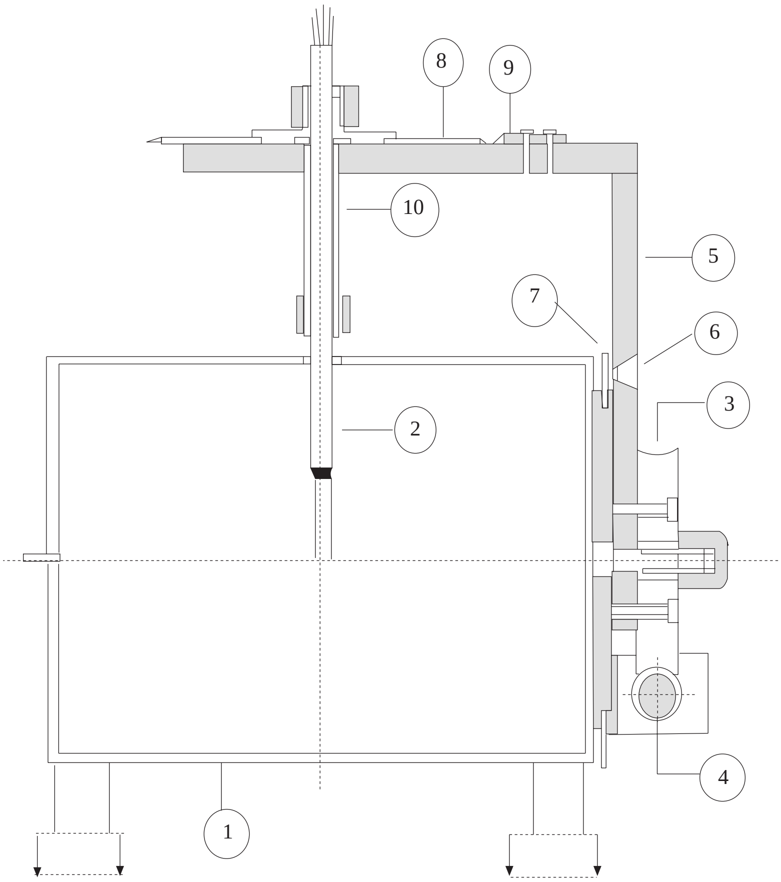
4. Calibration of the Probe

The calibration of the probe was conducted in the portable test section of a blower type wind tunnel designed and constructed by Uskaner [1991]. The wind speed in the test section of the tunnel can be changed from 1 m/s to 10 m/s by means of a Simovert P.6SE2001-1AA00 AC motor speed controller unit coupled to the driving motor of the tunnel propeller. The total pressure, dynamic pressure and flow direction in the flow to be explored are determined by using pressure reading from the probe and the calibration charts.

To form the calibration charts a proper reference position in the test section of the tunnel was needed, and it had to be chosen as the position where the center-line of the probe tip is aligned parallel to the main flow direction. This choice was done for simplifying the calibration of the probe. After the probe axis was set at this position, the pressures from the side tubes of the probe was read and the probe orientation was changed until these readings were equal to each other. This reference position of the probe tip was maintained throughout of the calibration and it was regarded as zero position for the yaw and pitch angles. The flow field in the tunnel is known through the flow investigation of wind tunnel test section carried by Uskaner [1991].

The pressure measured from the central tube of the probe is the total pressure of flow when the probe tip is at the reference position. The static pressure was measured by means of a static pressure tapping on the side wall of the tunnel test section. The static pressure tapping was located at a position where it was in line with the tip of the probe. The dynamic pressure of flow was then measured by an inclined-tube micro-manometer which was joined by flexible tubes to the centre tube at one end, and to the static pressure tapping at the other end. The pressure read from micro-manometer had an accuracy of ∓ 0.025 mm of methyl alcohol column. The wind speed at the position of the probe tip was set to a desired value by means of the AC motor speed controller unit of the wind tunnel. Using the probe orientation mechanism, the pitch and yaw angles of the probe were changed by 5° increments in a range of ∓ 45° and ∓ 35°, respectively. The pressures sensed from the five tubes of the probe are recorded separately for each yaw and pitch angle setting given to the probe with respect to the reference position.

The following dimensionless parameters were used to form the calibration charts of the probe similar to those given by Bryer and Pankhurst [1971], and Gaillard [1983];



1. Portable test section
2. Five-tube pressure probe
3. Worm gear
4. Helical gear
5. L-shaped arm
6. Visualization hole
7. Pitch angle protractor
8. Yaw angle protractor
9. Yaw angle vernier
10. Four-groove coupling

Figure 3. Section View (A-A) of the Probe Orientation Mechanism and the Test Section of Wind Tunnel.

$$f(\alpha) = (P_3 - P_1)/(P_5 - P_m) \quad (1)$$

$$f(\Psi) = (P_2 - P_4)/(P_5 - P_m) \quad (2)$$

$$Q_p = (P_5 - P_m)/(\rho V^2/2) \quad (3)$$

$$S_p = (P_T - P_5)/(P_5 - P_m) \quad (4)$$

where P_1, P_2, P_3, P_4, P_5 are the pressures sensed from the individual tubes of the probe (see Figure 1), P_m is the arithmetic mean of the pressures recorded from the four side tubes of the probe, i.e. $(P_1 + P_2 + P_3 + P_4)/4$, V is the resultant flow velocity, P_T is the total pressure, and ρ is the density of air.

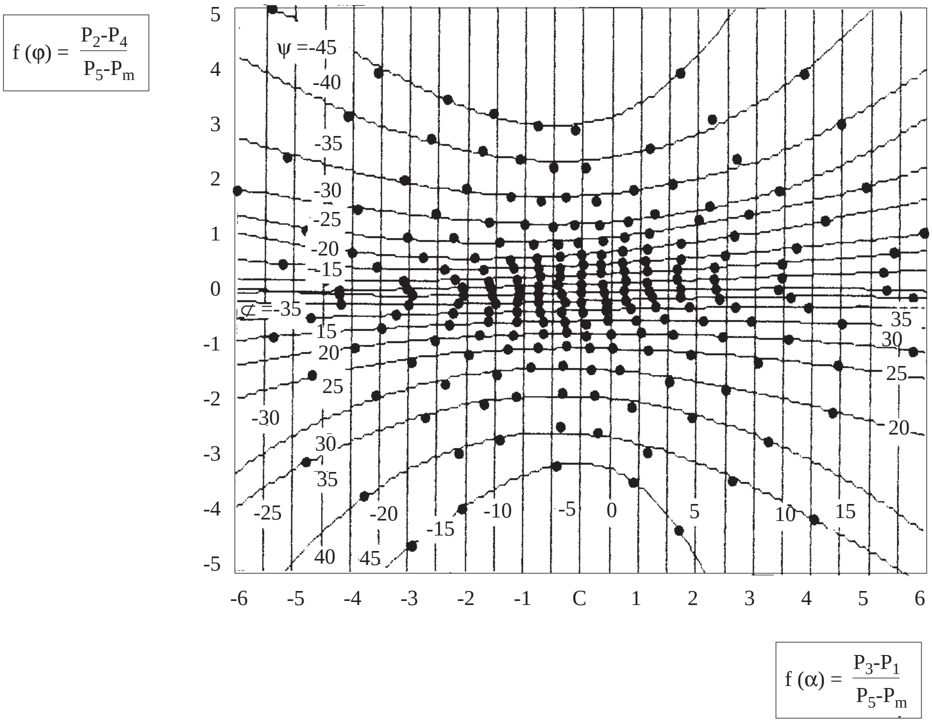


Figure 4. Variation of the Calibration Parameters, $f(\alpha)$ and $f(\Psi)$ with α and Ψ.

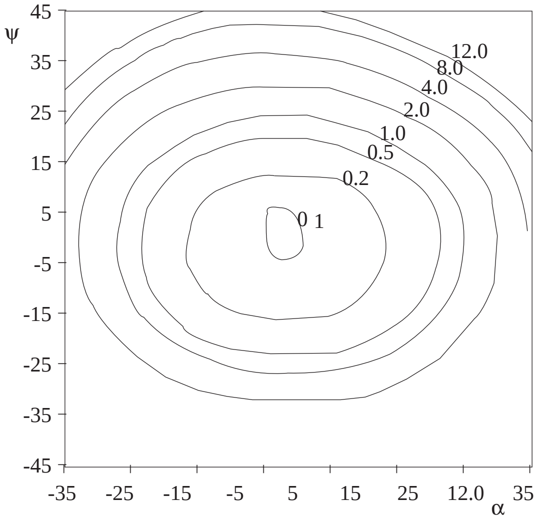


Figure 5. Variation of the Calibration Parameter, S_p with α and Ψ.

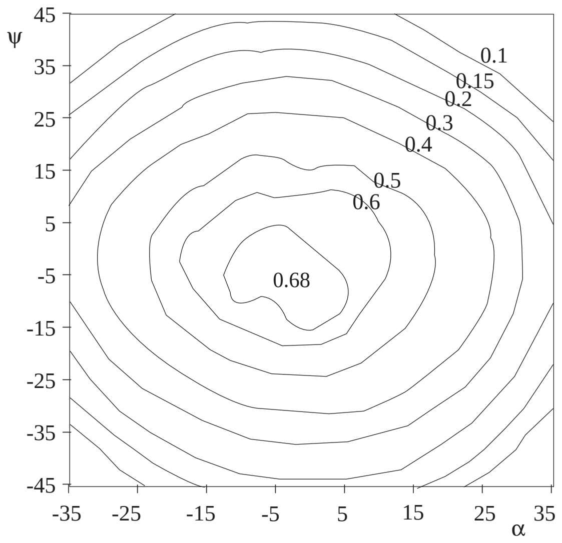


Figure 6. Variation of the Calibration Parameter, Q_p with α and Ψ.

As shown in Fig. 4, Fig. 5, and Fig. 6, the calibration charts were plotted in terms of the above mentioned dimensionless parameters. The calibration results of the probe at wind tunnel test section velocities of 5 m/s, 7.5 m/s and 10 m/s showed that the calibration charts of the probe were essentially the same within measurement accuracy. This impiled that the probe calibration charts were not dependent upon flow velocity or the Reynolds number based on probe diameter, d. Ineffectiveness of flow velocity on the calibration charts of the five-tube probes have been reported by Bryer and Pankhurst [1971], and Gaillard [1983]. It is seen from the calibration charts of the probe that, the symmetricity of side-tubes around the center-tube of the probe is excellent. The probe can be used with the particular method to give results with an accuracy of about ∓ 2 percent in the measurement of the resultant flow velocity provided that α and Ψ angles are within $-20° \leq \alpha \leq +20°$ and $-25° \leq \Psi \leq +25°$. It can be seen from Fig. 4 that the accuracy diminishes rapidly outside the above mentioned ranges of α and Ψ. The constant α and constant Ψ lines become more and more curvilinear when the flow angles are outside of the specified ranges. However, the calibration charts can be used up to range of α values of -45° $\leq \alpha \leq$ +45° if an accuracy of about ∓ 5 percent on the resultant velocity is acceptable . The accuracy of the particular method of use can be increased when the determination of the desired flow quantities from the calibration data is obtained by means of a computer interpolation programme using the probe readings.

5. A Typical Test Case: Swirling Flow Measurements in a Conventional Funnel-Shaped Air Cyclone

The calibrated probe was used for measurement of the velocity components in principle directions of the cylindrical polar co-ordinates, (r, θ, z) and the static pressure in a swirling flow field. As shown in Fig. 7, a conventional funnel-shaped air cyclone with 240 mm body diameter was designed and used by Gündoğdu [1995] for this purpose. The cyclone is capable of delivering flows between, Re=$V_i D_i/$v ranges of 15000≤ Re ≤ 125000. The measurements were carried out radially in the cylindrical body of the cyclone. The probe was traversed in radial direction without any rotation of the probe by means of a probe traversing mechanism. The traversing mechanism was mounted perpendicularly on the cyclone body. It was designed and constructed to enable radial traversing on the whole cyclone cross-section with a precision of ∓0.025 mm. The static pressure at the cyclone wall was measured by means of wall static pressure tappings. The pressures sensed by the individual tubes of the probe were measured separately by micro-manometers.

The recorded pressures are first used to calculate the values of f(α) and f(Ψ) by means of the equations 1 and 2. Then the flow pitch angle, α and yaw angle,

Ψ are read from the probe calibration chart shown in Fig. 4 corresponding to the calculated values of f(α) and f(Ψ). Thus by using the determined values of α and Ψ, the values of S_p and Q_p are read from the probe calibration charts shown in Fig. 5 and Fig. 6, respectively. The magnitude of the resultant flow velocity, total pressure, and static pressure are then calculated by using eq. 3, eq. 4, and the Bernoulli's equation. Hence;

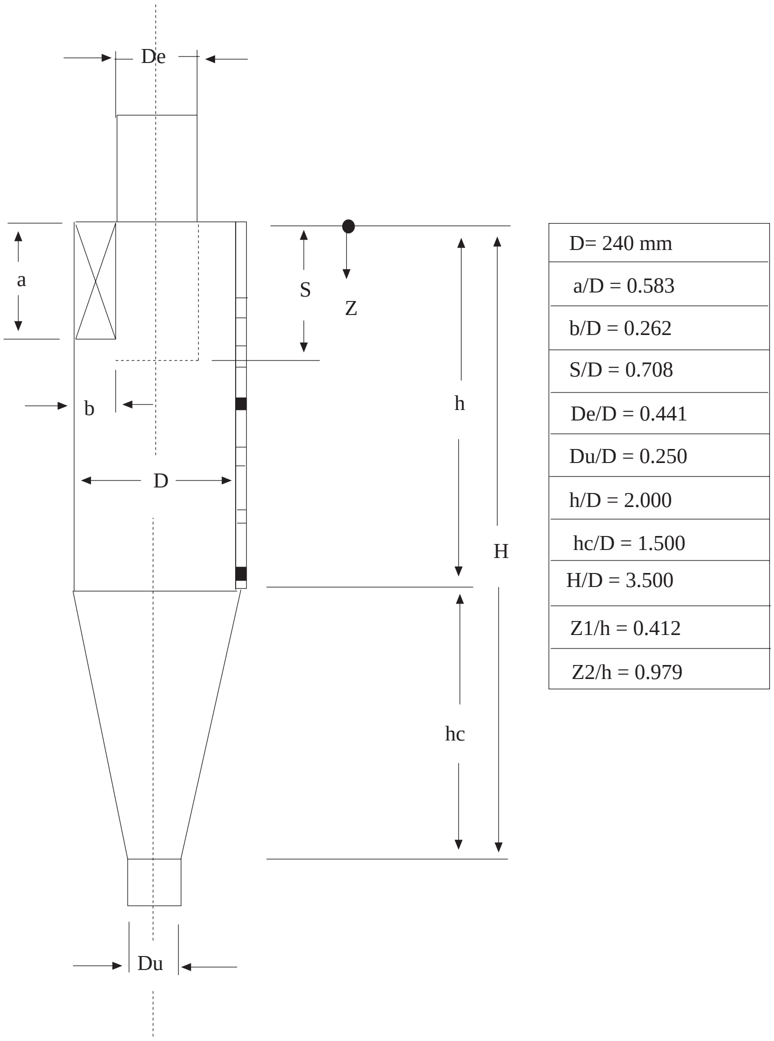


Figure 7. Shape and Principal Dimensions of the Cyclone.

$$V = [(P_5 - P_m)/(1/2\rho Q_p)]^{1/2} \tag{5}$$

$$P_T = S_p(P_5 - P_m) + P_5 \tag{6}$$

$$P_S = P_T - (\rho V^2/2) \tag{7}$$

The components of the resultant flow velocity, V in principle directions of cylindrical polar coordinates are calculated by using the determined pitch and yaw angles of the flow;

$$V_\theta = V \cos\Psi \cos\alpha \tag{8}$$

$$V_r = V \cos\Psi \sin\alpha \tag{9}$$

$$V_Z = V \sin\Psi \tag{10}$$

The determined values of the velocity components and the static pressures were made dimensionless by dividing the mean inlet velocity and the inlet dynamic pressure of the cyclone, respectively. The radial distributions of the dimensionless velocities

V_θ^+, and V_z^+, and the dimensionless static pressure, P_S^+ in the cyclone are shown in Fig. 8, Fig. 9, and Fig. 10, respectively. These figures contain the results of measurements in the cyclone at the vertical stations of Z/h=0.412 and Z/h=0.979 for the cyclone inlet Reynolds number of $V_i D_i / v = 1.24 \times 10^5$. The measurement results of flow angularity and velocity by using five-tube pressure probe without rotation of the probe, and the Laser Doppler Velocitimeter (LDV) measurement results of Zhou and Soo [1990], and Hwang et al. [1993] are shown in Fig. 8 and Fig. 9.

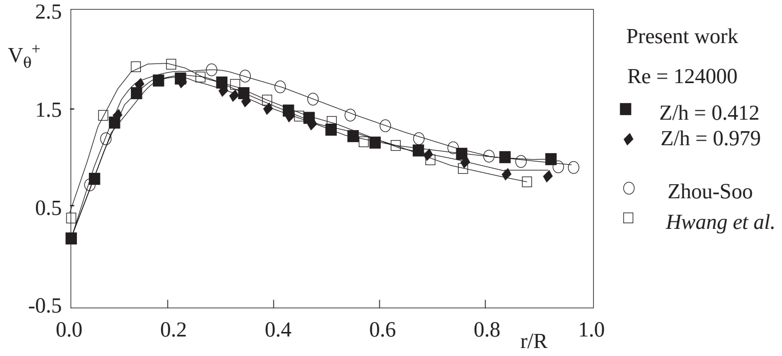


Figure 8. Radial Distribution of Dimensionless Tangential Velocity.

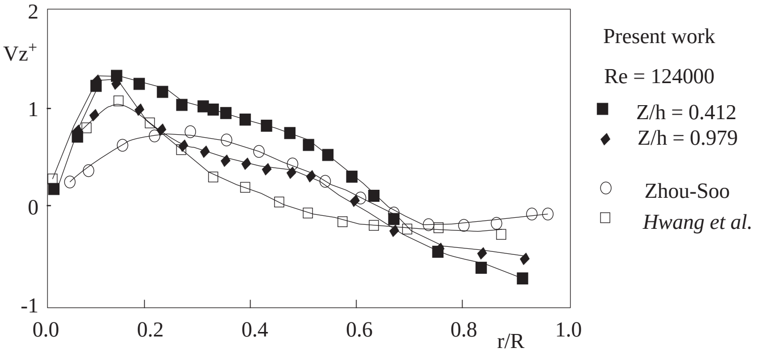


Figure 9. Radial Distribution of Dimensionless Axial Velocity.

The results of the present work and the results of Zhou and Soo were obtained in air cyclones compared to the results of Hwang et al. which were obtained in a hydro-cyclone. As is seen from Fig. 8, the dimensionless tangential velocity profile results of Zhou and Soo, Hwang et al., and the results of this work are in good agreement over all radial positions in the cyclone. This agreement of tangential velocity profile results obtained from air and hydro-cyclones is due to the fact that the effect of the centrifugal forces are far greater than the effect of gravitational forces on the tangential velocity distribution. Therefore the great difference in magnitude of the densities of the fluids used in respective cyclones did not cause a significant effect in the radial distribution of the tangential velocity.

As shown in Fig. 9, the agreement of the dimensionless axial velocity profile results of the present work and Zhou and Soo are in reasonable agreement in the range of 0.25< r/R <0.75. Whereas out of this specified region the agreement between these results is poor which may be due to differences in test-rig used by Zhou and Soo and the test-rig used by the authors. The radial distribution of axial velocity is found to be significantly dependent upon the length of the discharge pipe of the cyclone by Gündoğdu [1995]. The S/D ratio of the experimental cyclone was 0.708, on the other hand the S/D ratio of the cyclone used by Zhou and Soo was 0.367. Furthermore Zhou and Soo did not state the vertical station at which they conducted their measurements. In addition the results of Zhou and Soo, and Hwang et al.

are not in agreement with each other for the radial distribution of axial velocity. This disagreement of the dimensionless axial velocity profiles measured by Hwang et al., and the other results shown in Fig. 9 also show the effect of gravitational forces on the axial velocity profiles of the vertically installed air and hydro-cyclones. The acceptable agreement between the present measurements and the measurements taken by using LDV was mainly due to the non-interference of the probe orientation mechanism with the flow throughout the calibration and experimental measurements.

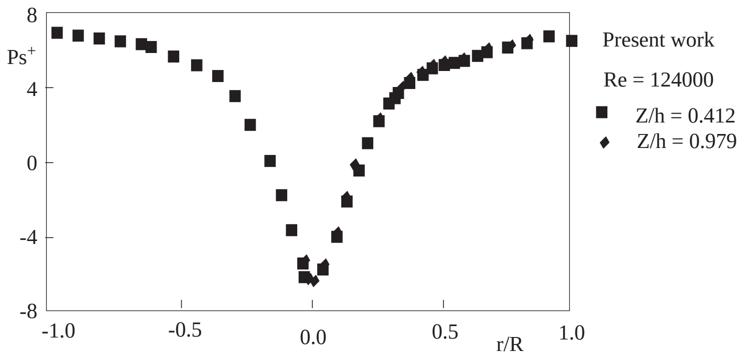


Figure 10. Radial Distribution of Dimensionless Static Pressure.

6. Conclusions

When the experimental uncertainty were taken into account the calibration charts of the probe were essentially independent from the flow velocity in the test section. The probe can be used along with the calibration charts with an accuracy of about ∓ 2 percent in the measurement of resultant flow velocity provided that α and Ψ angles are within the ranges of $-20° \leq \alpha \leq +20°$ and $-25° \leq \Psi \leq +25°$, respectively. If an accuracy of about ∓ 5 percent in the measurement of resultant flow velocity is acceptable, the probe can be used up to range of $-45° \leq \alpha \leq +45°$ and $-35° \leq \Psi \leq +35°$.

The calibrated probe has been tested in the swirling flow field of an air cyclone. It has been found that, a five-tube probe calibrated with the method explained in this paper can be used to measure the radial distributions of total pressure, dynamic pressure and flow direction with an acceptable accuracy in a swirling flow field.

Nomenclature

a	height of the cyclone inlet, m
b	width of the cyclone inlet, m
d	outer diameter of the probe, m
D	diameter of the cyclone body, m
D_e	diameter of the discharge pipe of the cyclone, m
D_i	hydraulic diameter of the cyclone inlet, a.b/2, m
D_u	under flow diameter of the cyclone, m
h	height of the cyclone body, m
h_c	height of the cyclone cone, m
H	total height of the cyclone, m
LDV	Laser Doppler Velocitimeter
P_1, P_2, P_3, P_4, P_5	pressures sensed from the individual tubes of the five-tube pressure probe, (Pascals)
P_m	arithmetic mean of pressures P_1, P_2, P_3, P_4, P_5 (Pascals)
P_S	static pressure, (Pascals)
P_T	total pressure, (Pascals)
Re	Reynolds number at the inlet of the cyclone, $V_i D_i / v$
S	discharge pipe length of the cyclone, m
V_i	mean velocity of flow at inlet of the cyclone, m/s
V	resultant velocity, m/s
V_r	radial velocity, m/s
V_θ	tangential velocity, m/s
V_Z	axial velocity, m/s
P_S^+	dimensionless static pressure

V_θ^+	dimensionless tangential velocity, V_θ/V_i.
V_Z^+	dimensionless axial velocity, V_Z/V_i.
$f(\alpha)$	dimensionless calibration parameter related to (α).
$f(\Psi)$	dimensionless calibration parameter related to (Ψ)
S_p	dimensionless calibration parameter related to P_T
Q_p	dimensionless calibration parameter related to V
θ	chamfer angle of the probe tip, deg.
Ψ	yaw angle, deg.
α	pitch angle, deg.

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