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# An Experimental Investigation of Wind Load on a Group of Octagonal Cylinders with Variable Longitudinal Spacing

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## ABSTRACT

***An experimental investigation of wind load on a group of octagonal cylinders with various longitudinal spacing was carried out. The study was performed on group consisting of two cylinders, arranged in staggered form varying longitudinal spacing, one in the upstream and the other in the downstream side. The test was conducted in an open circuit wind tunnel at a Reynolds number of $4.13 \times 10^4$ based on the face width of the cylinder across the flow direction in a uniform flow of velocity 13.2 m/s. The surface static pressures at the different locations of the cylinder were measured with the help of inclined multi-manometers. Then the group of two cylinders were taken into consideration for the study and the surface static pressures were measured for various longitudinal spacing's of 1D, 2D, 3D, 4D, 5D, 6D, 7D and 8D, where D being the width of the cylinder across the flow direction. The pressure coefficients were calculated from the measured values of the surface static pressure distribution on the cylinder. It was observed that the drag coefficients become remarkably smaller compared to those for a sharp-edged square cylinder. After all, it was concluded from the results that wind loading on a building is generally less severe when the building forms part of a group than when it is free- standing.***

**Keywords:** Wind Load, Octagonal Cylinder.

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# 1 INTRODUCTION

## 1.1 General

Wind is air in motion relative to the earth. The primary cause of wind is traced to the earth's rotation and differences in terrestrial radiation. The radiation effects are mainly responsible for convection current either upwards or downwards. The wind generally blows horizontal to the ground at high speeds. Since vertical components of the atmospheric motion are relatively small, the term 'wind' denotes almost exclusively the horizontal wind while 'vertical' winds are always identified as such. The wind speeds are assessed anemometers or anemographs, which are installed at the meteorological observations at heights generally varying from 10 to 30 meters above ground. The subjects of wind load on buildings and structures are not a new one. In the 17$^{th}$ century, Galileo and Newton have considered the effect of wind loading on buildings, but during that period, it did not gain popularity. The effect of wind loading on buildings and structures has been considered for design purposes since late in the 19$^{th}$ century; but starting from that time up to about 1950, the studies in this field have not been considered seriously. Building and their components are to be designed to withstand the code specified wind loads. Calculating wind loads is important in the design of wind force resisting system, including structural members, components, and cladding against shear, sliding, overturning and uplift actions.

In recent years, much emphasis has been given on "The Study of wind Effect on buildings and structures" in the different corners of the world. Even researchers in Bangladesh have taken much interest in this field. Till now, little attention has been paid to the flow over the bluff bodies like square cylinders, rectangular cylinders, hexagonal cylinders etc. and some information is available concerning the flow over them in staggered condition, although this is a problem of considerable practical significance. With the progressing world, Engineering problems regarding wind loads around a group of skyscrapers, chimneys, towers and the flow induced vibration of tubes in heat exchangers, bridges, oil rigs or marine structures need detailed investigation of flow patterns and aerodynamic characteristics. Arising from the increasing practical importance of bluff body aerodynamics, over the past few decades' sufficient effort has been given in research works concerning laboratory simulations, full-scale measurements and more recently numerical calculations and theoretical predictions for flows over bodies of wide variety of shapes. A number of failures of bridges, transmission towers, buildings and housings over the last one hundred years prompted researchers to do research work in this field.

The study of wind effect was first limited to loading on buildings and structures only, possibly because of its most dramatic effects are seen in their collapses. In mid-sixties, researchers started the study of less dramatic, but equally important environmental aspects of flow of wind around buildings. These include the effects on pedestrians, weathering, rain penetration, ventilation, heat loss, wind noise and air pollution etc. The pioneer researcher in this field is Lawson, T.V. [1] of the University of Bristol. A number of works of the environmental aspects of wind was being studied at the Building Research Establishment at Garson and the University of Bristol, UK. It is true that researchers from all over the world have contributed greatly to the knowledge of flow over bluff bodies as published by Mchuri, F. G. [2] but the major part of the reported works are of fundamental nature involving the flow over single body of different profiles. Most of the researchers have conducted works either on single cylinder with circular, square, hexagonal or rectangular sections etc. or in a group with them for various flow parameters. However, the flow over octagonal cylinders has not been studied extensively especially in-groups to date, although this is a problem of practical significance. It is believed that the study on the cylinder with octagonal section will contribute to find the wind load on the single and group of octagonal buildings and the results will be useful to the relevant engineers and architects.

## 1.2 Nature of the Wind

Very strong winds are generally associated with cyclonic storms, thunderstorms, dust storms or vigorous monsoons. A feature of the cyclonic storms over the Bangladeshi region is that they rapidly weaken after crossing the coasts and move as depressions/ lows inland. The influence of a severe storm after striking the coast does not in general exceed about 60 kilometers, though sometimes, it may extend even up to 120 kilometers. Very short duration hurricanes of very high wind speeds called Kal Baisaki or Norwesters occur fairly frequently during summer months over North East Bangladesh. The wind behavior is discussed in this section in brief. The characteristics of the wind, which are more or less related to the present study, have been taken into consideration for discussion in a nutshell.

## 1.3 Wind Velocity

High wind velocity is responsible for the failure of building and structures and it can cause unpleasant side effects also. Strong winds often have special names, including gales, hurricanes and typhoons. The wind speeds recorded at any locality are extremely variable and in addition to steady wind at any time, there are effects of gusts, which may last for a few seconds. Because of the inertia of the building, short period gusts may not cause any appreciable increase in stress in main components of the building and structure. The response of a building to high wind pressures depends not only upon the geographical location and proximity of other obstructions to airflow but also upon the characteristics of the structure itself. Winds are named by the direction they come from. Thus a wind from south, blowing toward the north is called a south wind. Windward refers to the direction a wind comes from, leeward to the direction it blows toward. When a wind blows more frequently from one direction than from any other it is called a prevailing wind. Wind speed increases rapidly with height above the ground level, as frictional drag declines. Wind is commonly not a steady current but is made up of a succession of gusts, slightly variable in direction, separated by lulls. Close to the earth the gustiness is developed due to irregularities in the wind are caused by the conventional currents. All forms of turbulence play a part in the process of transporting heat, moisture and dust into the air aloft. There are various parameters, which control the flow behavior as mentioned by Castro, J.P. [3]. They are (i) vortices in front of the building, (ii) opening through buildings, (iii) spacing of rows, (iv) wakes of buildings, (v) long straight streets, (vi) narrowing streets, (vii) corners and (viii) courtyards. The mean wind speed varies with height. The variation of wind speed has been expressed by Davenport, A. C. [4] as

$$V = V_c(Z/Z_c)^a \quad \ldots \quad \ldots \quad \ldots \quad (1)$$

Where, V is the mean wind speed at a height Z, $V_c$ is the mean wind speed at the gradient height $Z_c$. The value of $V_c$ depends upon the geographical locality, but $Z_c$ is a function of terrain. The values of $Z_c$ and the exponent "a' suggested by Davenport, A. G. [4] are as follows: For open terrain with very few obstacles: a = 0.16, Zc = 300m; For terrain uniformly covered with obstacles of 10-15: a = 0.28, $Z_c$ = 430m. For terrain with large and irregular objects: a = 0.40, Zc = 560m.

## 1.4 Generation of Wind

The source of wind energy is the sun that emits solar radiation, which causes differential heating of the earth surface and the atmosphere. In the atmosphere there is a general convective transport of heat from lower to higher latitudes in order to make the earth's radiation imbalance as mentioned by Lanoville, A. [5].

It is for this reason that the atmosphere is a restless medium in which circulation of all sizes is normal. Wind is simply air moving in a direction that is essentially parallel with the earth's surface. The atmosphere is fixed to the solid-liquid earth in gravitational equilibrium and so moves with the earth in its west to east rotational movement. Wind, therefore is air movement in addition to that associated with rotation. In large-scale circulation covering several thousand miles, horizontal motion greatly exceeds vertical motion. Thus, a wind that takes several days to cross an ocean may move up or down only a few miles. The vertical component of movement is much greater in small-scale circulation such as thunderstorms and tornadoes. In a thunderstorm, air may ascend to the top of the atmosphere in about an hour. Wind is complex in origin. Usually, its direct cause lies in differences between atmospheric densities resulting in horizontal differences in air pressure. That is, it represents nature attempt to rectify pressure inequalities. When these horizontal pressure differences develop, a gradient of pressures exists. But in spite of the direct part played by pressure differences, the ultimate source of average for generating and maintaining winds against the drag is mainly from the differences in heating and cooling between high and low latitudes.

## 1.5 Wind Loading on Structures

The effect of wind on the structure as a whole is determined by the combined action of external and internal pressures acting upon it. In all cases, the calculated wind loads act normal to the surface to which they apply. The pressures created inside a building due to access of wind through openings could be suction (negative) or pressure (positive) of the same order of intensity while those outside may also vary in magnitude with possible reversals. Thus the design value shall be taken as the algebraic sum of the two in appropriate/concerned direction. Furthermore, the external pressures (or forces) acting on different parts of a framework do not correlate fully. Hence there is a reduction in the overall effect. The development of modem materials and construction techniques has resulted in the emergence of a new generation of structures. Such structures exhibit an increased susceptibility to the action of wind. Accordingly, it has become necessary to develop tools enabling the designer to estimate wind effects with a higher degree of refinement than has been previously required. It is the task of the engineer to ensure that the performance of structures subjected to the action of wind will be adequate during their anticipated life from the standpoint of both structural safety and serviceability. To achieve this end, the designer needs information regarding

(i) The wind environment.

(ii) The relation between that environment and the forces it induces on the structures.

(iii) The behavior of the structure under the action of forces.

The action of wind on building considering the load effect may be classified into two major groups; the static effect and the dynamic effect. There are many other effects like generation of noise the risk of the hazard, the penetration of rain and uncomfortable wind for the pedestrians etc. but they are not usually considered for structural design. Since all wind loadings are time-dependent because of varying speeds and direction of winds, wind loading is never steady. For this reason, static load is referred to the steady (time-variant) forces and pressures tending to give the structure a steady displacement. On the other hand, dynamic effect has the tendency to set the structure oscillating. A steady wind load on a building is very difficult to achieve. In fact, always wind loads are of a fluctuating nature because of varying speeds and directions of winds. The type of wind and the stiffness and roughness of the structure determine the nature of loading on a building. When a building is very stiff the dynamic response of the structure may be neglected and only the static leads may be considered. This is because the natural frequency of an extremely stiff building is too high to be excited by wind. In the present study the effect of static loading is taken into account due to the steady wind. Since natural winds are continually fluctuating, it is generally assumed that these fluctuations are so irregular and random that the response of a structure will not differ from that due to a steady wind of the same average speed. Very recently the dynamic response of building has been considered for study because of the modern tendency to build more slender and lighter structures.

## 1.6 Necessity of the Study

Housing and mankind is the basic primary need next to food and clothing, clear air and portable water being very essential for existence. In Bangladesh, strong wind is an annual natural hazard due to its geographical location. On the other hand, most of the existing houses and those which are going to be built in the next few decades are likely to be non-engineered, mostly with thatched roofs and are vulnerable to wind. Strong wind is causing immense losses of rural dwellers by making their houses collapse fully or partially by lifting of roof etc.

Almost 70% of the population in the rural sector and 50% of the population in the urban sector are living below the poverty level with earnings too little to pay for all needs. It is this group of people most impoverished that is to be provided with good housing. About 75% of the dwelling in rural areas is of weak construction (Mud, Bamboo, Woven Bamboo etc.) and that 23% of urban and more than 40% of rural dwellings are of a temporary nature. They can rarely survive against even a moderate intensity storm. Evidence from the field in strong wind-prone areas indicates that there is a socially perceived need of more engineering knowledge and improved construction of domestic dwelling. Bangladesh is a land hungry country. The urban population of this country is increasing at a very fast rate making the housing problem worse every day. One possible solution of the housing problem is to construct multistoried buildings. The knowledge of wind loading on a single tall building or on a group of tall buildings is essential for their economic design. The flow around an octagonal model cylinder can be ideally considered analogous to that of the flow around a tall octagonal-shaped building. Therefore, a study of wind flow around groups of octagonal cylinders would be helpful in this respect. For designing groups of tall buildings, knowledge of the effect of wind loading on a single tall building is not sufficient because the effects of nearby buildings on the loads imposed on a structure would be quite different. In the areas with high-rise buildings, other problems like unpleasant wind conditions may be developed near ground level in passages between and through buildings and many instances of such conditions, causing discomfort for the pedestrians and damage to doors and windows in and near the passage, have been reported. In order to eliminate these nuisances, architects and town-planners of Bangladesh should have a better knowledge of the wind flow around the buildings, which can save the nation from making both loss of lives and properties. In the present study, it has been tried to give an understanding about the variation of wind load pattern imposed on building due to the influence of the nearby buildings. To find the complete solutions of the above-mentioned problems a more detailed study in this regard is needed. There are many examples of failures of buildings and structures in different parts of the world, which has made the enthusiastic investigators puzzled to find the exact causes, and research works are being carried out to find the proper remedial measures for eliminating these failures. The investigators of this country may contribute a lot to the nation by conducting appropriate research work in this field. Though the problem regarding the wind loadings on buildings and structures is common to all parts of the world and it is expected that the solution will not be significantly different from country to country, yet research work should be carried out in this field considering the climatic conditions and problem of this country so that a clear picture about the nature of wind loading can be obtained. The data from these research works should enable to the architects, engineers and town planners of Bangladesh to design buildings and structures more efficiently.

## 1.7 Aim of the Study

In the present experimental investigation, group of octagonal cylinders will be taken into consideration. The objectives of the present study are as follows:

(i) To measure the static pressure distribution around a group of octagonal cylinders at various angles of attack.

(ii) To measure the pressure distributions for different side dimensions of cylinders.

(iii) To measuring the pressure distribution around staggered octagonal cylinders at zero angle of attack.

(iv) Observations of the effects of different longitudinal spacing between the cylinders.

(v) Comparisons of wind loads for various spacing and side dimensions of the octagonal cylinders.

It is expected that the wind load on a group of octagonal cylinders will decrease appreciably compared to that having sharp edge.

# 2 EXPERIMENTAL SET-UP

## 2.1 General

The experimental investigation to find wind load on the octagonal cylinder was conducted at the exit end of a subsonic open circuit wind tunnel. The test was done on a group consisting of two identical cylinders one in the upstream side and another in the downstream side in a uniform cross flow. The surface static pressures at the different locations of the cylinder were measured with the help of an inclined multi-manometer.

## 2.2 Wind tunnel

The test was done in an open circuit subsonic wind tunnel as shown in **Fig.1**. It was the low speed wind tunnel having the maximum wind velocity of 14 m/s in the test section. The tunnel consists of various components such as, fan, valve, silencer, honey comb etc. It is 5.93 meter long with a test section of 460 mm x

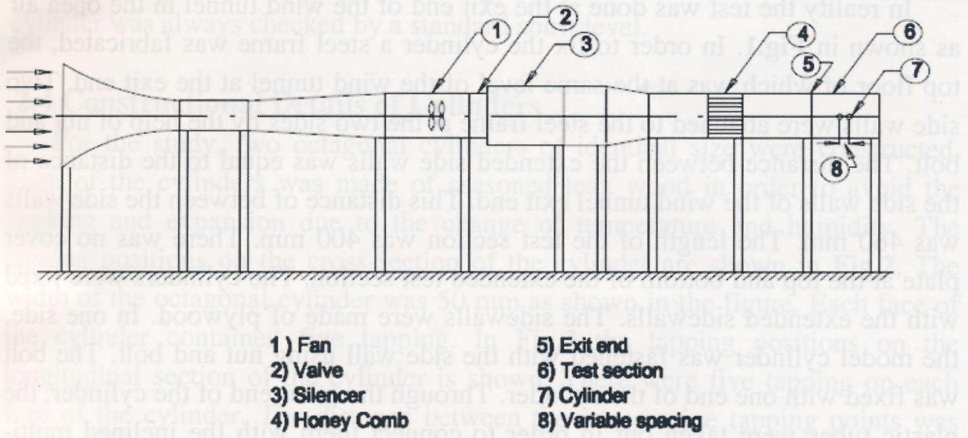
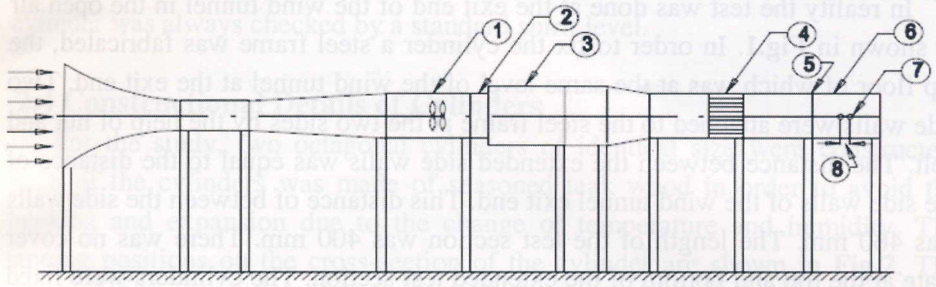



**Figure 1:** Schematic diagram of wind tunnel.

460 mm cross-section. In order to make the flow uniform a honeycomb is fixed near the end of the wind tunnel. There is a converging bell mouth shaped entry. To generate the wind velocity, two axial flow fans are used. Each of the fans is connected with the motor of 2.25 kilowatt and 2900 rpm. There is a butterfly valve to control the wind speed. There is a silencer just after the butterfly valve as shown in **Fig.1**. The central longitudinal axis of the wind tunnel is maintained at a constant height of 990 mm from the floor. The axis of the model coincides with that of the wind tunnel. The converging mouth entry is incorporated in the wind tunnel for smooth entry of air into the tunnel and to maintain uniform flow into the duct free from outside disturbances. The induced flow through the wind tunnel is produced by two-stage rotating axial flow fan of capacity 18.16 $m^3/s$ at the head of 152.4 mm of water and 1475 rpm. A butterfly valve, actuated by a screw thread mechanism, is placed behind the fan and used to control the flow. A silencer is fitted at the end of the flow controlling section in order to reduce the noise of the system. This section is incorporated with a honeycomb. The diverging and converging section of the wind tunnel is 1550mm long and made of 16 SWG black sheets. The angle of divergence and convergence is 7°, which has been done with a view to minimizing expansion and contraction loss and reducing the possibility of flow separation. In each case of the tests, wind velocity is measured directly with the help of a digital anemometer. The flow velocity in the test section was maintained at 13.2m/s approximately. The measured velocity distribution was almost uniform across the tunnel test section in the upstream side of the test models.

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### 2.3 Test Section

In reality the test was done at the exit end of the wind tunnel in the open air as shown in **Fig.1**. In order to fix the cylinder a steel frame was fabricated, the top floor of which was at the same level of the wind tunnel at the exit end. Two side walls were attached to the steel frame at the two sides by the help of nut and bolt. The distance between the extended side walls was equal to the distance of the side walls of the wind tunnel exit end. This distance of between the side walls was 460 mm. The length of the test section was 400 mm. There was no cover plate at the top and bottom of the extended test section. The cylinders were fixed with the extended sidewalls. The sidewalls were made of plywood. In one side, the model cylinder was fastened with the side wall using nut and bolt. The bolt was fixed with one end of the cylinder. Through the other end of the cylinder, the plastic tubes were taken out in order to connect them with the inclined multi-manometer. This end was supported in the groove of the sidewall of the extended portion, compatible with the octagonal end of the cylinder. The capillary tube made of copper was used to make the tapping on the sides of the octagonal model cylinders. These copper tubes were connected with the plastic tubes. The cylinder was leveled and then fixed very carefully so that its top and bottom sides were parallel to the flow direction. There was a provision for rotation of the test cylinder at various angles to obtain the wind load at different angles of attack. The Reynolds number was $4.13\times10^4$ based on the projected width of the cylinder across the flow direction.

Since the top and bottom of the extended part of the wind tunnel was open; as such no correction for blockage was done in the analysis. The test cylinders were placed very close to the end of the wind tunnel so that the approach velocity on the test cylinders was approximately identical as that in the exit end of the wind tunnel. The provision was also kept in the extended wall to fix the two octagonal cylinders side by side along the flow direction. These two cylinders were the part of the group. There was also a scope to change the inter-spacing between the cylinders. The inter-spacing between the two cylinders was varied at 1D, 2D, 3D, 4D, 5D, 6D, 7D and 8D, where D being the width of the cylinder across the flow direction. With a view to achieving this, several groups were made on the side walls of the test section. When the test was conducted, the unnecessary groves were sealed. The cylinders were fixed at one end by the help of bolt and nut and the other ends were fixed in groove. During fixing the cylinders, it was carefully checked whether the top and bottom sides of the cylinders were parallel to the free stream velocity direction. The rear cylinder was fixed behind the front cylinder along the flow direction. Leveling of the test cylinder was always checked by a standard spirit level.

## 2.4 Constructional Details of Cylinders

For the study, two octagonal cylinders of identical size were constructed. Each of the cylinders was made of seasoned teak wood in order to avoid the bucking and expansion due to the change of temperature and humidity. The tapping positions on the cross-section of the cylinder are shown in **Fig.2**. The width of the octagonal cylinder was 50 mm as shown in the figure. Each face of the cylinder contained five tapping. In **Fig.3** the tapping positions on the longitudinal section of the cylinder is shown. There were five tapping on each face of the cylinder. The distance between the consecutive tapping points was equal ($\Delta d$) as shown in the figure. However, the location of the corner tapping was at a distance of $\frac{1}{2}\Delta d$. Each taping was identified by a numerical number from 1 to 40 as can be seen from the figure. It can be seen from the longitudinal section that the tapping were not made along the cross-section of the cylinder.

The cylinders were located with different inter-spacing. On one side of the cylinder a steel plate was attached through which there was a bolt for fixing the cylinder with the side wall of the extended tunnel as shown in **Fig.3**. The other side of the cylinder was hollow through which the plastic tubes were allowed to pass.

The plastic tubes were connected with the copper capillary tubes at one side and at the other side with the inclined multi-manometer. The manometer liquid was water. The tappings were made of copper tubes of 1.71 mm outside diameter. Each tapping was of 10 mm length approximately. From the end of the copper tube flexible plastic tube of 1.70 mm inner diameter was press fitted.

## 2.5 Cylinders in Group

In **Fig.4** the position of the group of cylinders at zero angle of attack is shown in the wind tunnel test section. The inter-spacing between the front cylinder and the rear cylinder was taken as 1D i.e. 50mm. Then static surface pressure distributions were measured on the eight faces of the front and the rear cylinders. Keeping everything identical the inter-spacing was changed to 2D and the experiment was repeated. Next, the inter-spacing was varied to 3D, 4D, 5D, 6D, 7D and 8D and in each case the static pressure distributions on both the front and the rear cylinders were taken. All the measurements were taken at zero angle of attack only.

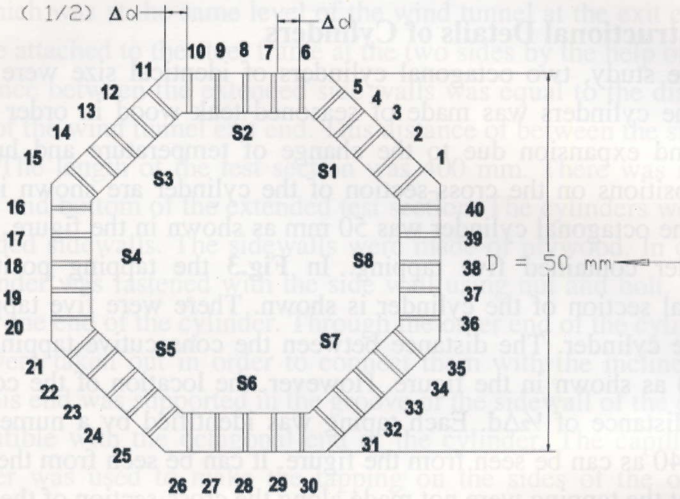


**Figure 2:** Tapping positions shown on cross-section of cylinder.

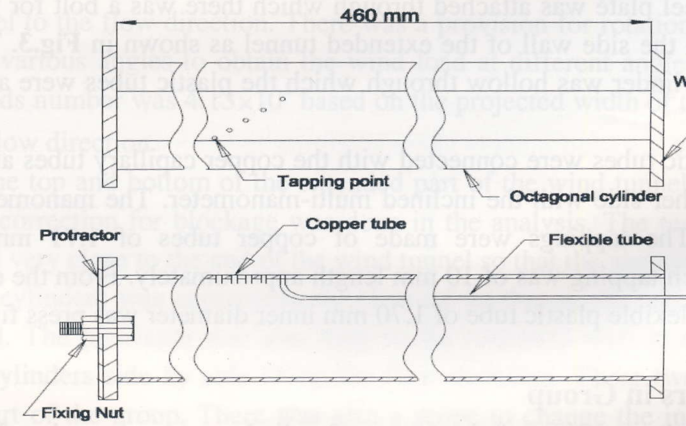


**Figure 3:** Tapping positions shown on longitudinal section of cylinder.

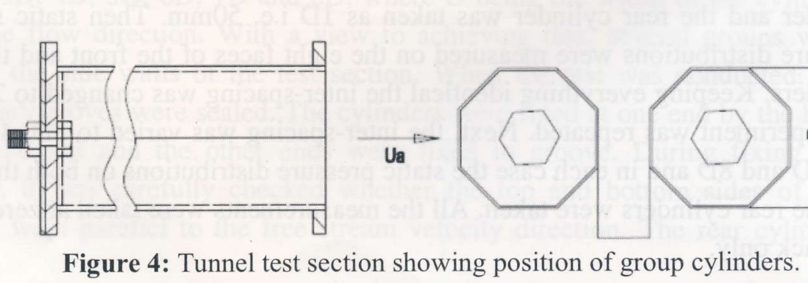


**Figure 4:** Tunnel test section showing position of group cylinders.

## 3 MATHEMATICAL MODEL

### 3.1 General

From the measured surface static pressure on the octagonal cylinder the pressure coefficients are obtained. With the help of numerical integration method drag and lift coefficients are determined.

### 3.2 Determination of pressure coefficient

The pressure coefficient is defined as

$$C_P = \frac{\Delta P}{\frac{1}{2}\rho u_\infty^2} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

Where, $\Delta P = P - P_0$

$P$ is the static pressure on the surface of the cylinder

$P_0$ is the ambient pressure

$\rho$ is the density of the air

$U_\infty$ is the free stream velocity

$\Delta P$ is obtained from

$$\Delta P = \Delta h_w \times \gamma_w \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (3)$$

Where, $\Delta h_w$ is the manometer reading

$\gamma_w$ is the specific weight of manometer liquid, that is water

Next two octagonal cylinders were placed at various inter-spacing along the flow direction at zero of attack only. Then the surface static pressures were measured for each of cylinders with the help of multi-manometer

### 3.3 Determination of Drag and Lift Coefficients

Drag and lift coefficients are defined as follows

$$C_D = \frac{F_D}{\frac{1}{2}\rho u_\infty^2} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (4)$$

and

$$C_L = \frac{F_L}{\frac{1}{2}\rho u_\infty^2} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (5)$$

The detailed calculation of $C_P$ can be found in Mandal, A. C. [6]

## 4 RESULTS AND DISCUSSION

### 4.1 Group of Cylinders

In **Fig.5**, the group of cylinders is shown at zero angle of attack. One cylinder is positioned in the upstream side designated as the front cylinder and another one is positioned in the downstream side designated as the rear cylinder. Both of them are placed along the flow direction. The inter-spacing between them will only be varied at 1D, 2D, 3D, 4D, 5D, 6D, 7D and 8D keeping the angle of attack constant. Tapping points are shown along the cross-section on the eight surfaces $S_1$, $S_2$, $S_3$, $S_4$, $S_5$, $S_6$, $S_7$ and $S_8$ of the cylinder, where the surface static pressures were measured.

### 4.2 Distribution of Pressure Coefficients on Front Cylinder

The Cp-distribution on the front cylinder of the group at the inter-spacing of 1D is shown in **Fig.6**. It can be seen from this figure that the $C_p$-distribution is more or less identical to that of the single cylinder at zero angle of attack. That is, there is little effect on the Cp-distribution of the front cylinder due the presence of the rear cylinder. However, the positive $C_p$ values have been increased slightly on the surfaces $S_1$ and $S_8$ compared to those on the single cylinder. There is more or less uniform distribution of $C_p$ on the Surfaces $S_2$ and $S_6$. In **Fig.7**, the $C_p$-distribution on the front cylinder at the inter-spacing of 2D has been presented. It can be observed from this figure that there has been appreciable increase in the back pressure due to presence of the rear cylinder. The average $C_p$ values on the surfaces $S_2$ to $S_6$ is approximately -0.45 compared that of-0.66 in case of the single cylinder. However, $C_p$-distribution on the surfaces $S_2$ to $S_6$ is of uniform nature approximately. About same pattern of $C_p$-distribution is seen in **Fig.8** at the inter-spacing of 3D on the front cylinder. However, the positive $C_p$ values increase slightly on the surfaces $S_1$ and $S_8$ compared to that from the inter-spacing of 2D. There is remarkable effect on the Cp-distribution at both the inter-spacing of 2D and 3D due to the presence of the rear cylinder. As shown in **Fig.9**, the Cp-distribution on the front cylinder at the inter-spacing of 4D is close to that on the front cylinder at the inter-spacing of 1D, except there is slight rise of $C_p$ values on the surfaces $S_1$ and $S_8$. The surfaces $S_2$ and $S_6$ show uniform Cp-distribution approximately. In **Fig.10**, the $C_p$-distribution at the inter-spacing of 5D on the front cylinder. However, the positive $C_p$ values increase slightly on the surfaces $S_1$ and $S_8$ compared to that from the inter-spacing of 4D. The $C_p$-distribution at the inter-spacing of 5D is almost close to that at the inter-spacing

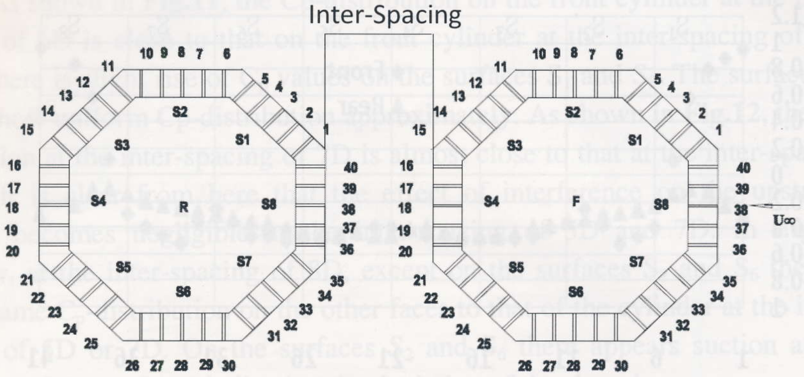


**Figure 5:** Flow over cylinder in group at zero angle of attack.

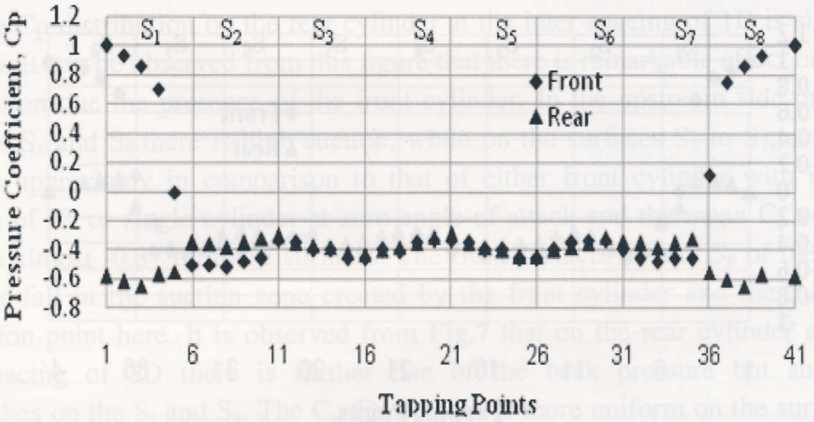


**Figure 6:** Distribution of $C_p$ on front & rear cylinder at inter-spacing of 1D.

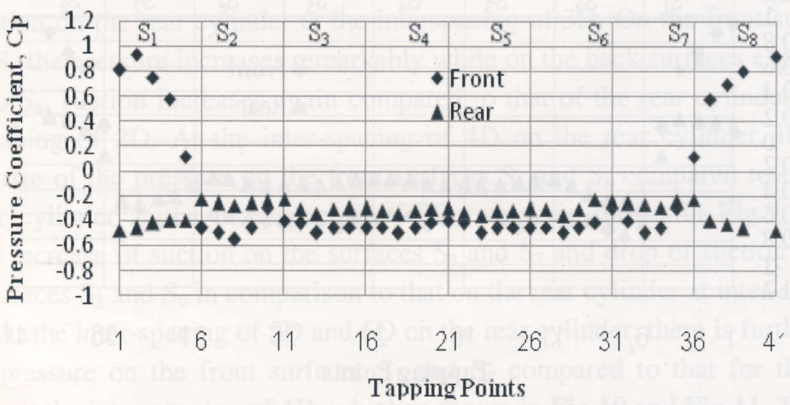


**Figure 7:** Distribution of $C_p$ on front & rear cylinder at inter-spacing of 2D.

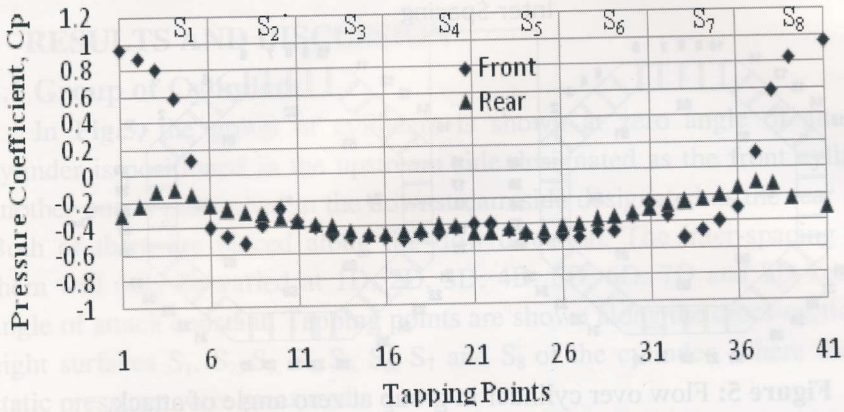


**Figure 8:** Distribution of $C_p$ on front & rear cylinder at inter-spacing of 3D.

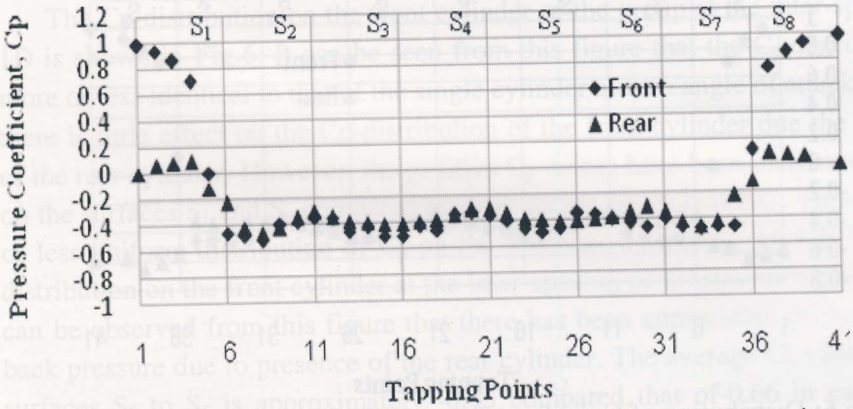


**Figure 9:** Distribution of $C_p$ on front & rear cylinder at inter-spacing of 4D.

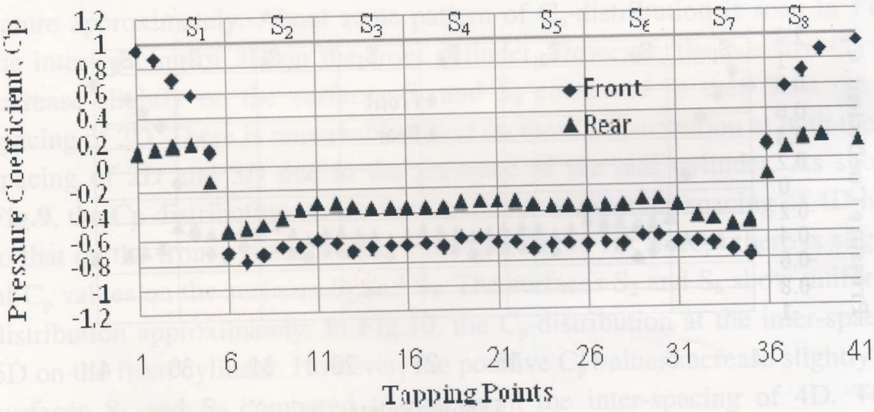


**Figure 10:** Distribution of $C_p$ on front & rear cylinder at inter-spacing of 5D.

of 4D. As shown in **Fig.11**, the Cp-distribution on the front cylinder at the inter-spacing of 6D is close to that on the front cylinder at the inter-spacing of 1D, except there is slight rise of $C_p$ values on the surfaces $S_1$ and $S_8$. The surfaces $S_2$ and $S_6$ show uniform Cp-distribution approximately. As shown in **Fig.12**, the $C_p$-distribution at the inter-spacing of 7D is almost close to that at the inter-spacing of 6D. It is clear from here that the effect of interference on the upstream cylinder becomes negligible at the inter-spacing of 5D and 7D. In **Fig.13**, However, at the inter-spacing of 8D, except on the surfaces $S_2$ and $S_6$ there is almost same $C_p$-distribution on the other faces to that of the cylinder at the inter-spacing of 5D or 7D. On the surfaces $S_2$ and $S_6$ there appears suction at the beginning of the surfaces indicating the deviation of the shear layer.

### 4.3 Distribution of Pressure Coefficient on Rear Cylinder

The Cp-distribution on the rear cylinder at the inter-spacing of 1D is shown in **Fig.6**. It can be observed from this figure that there is remarkable effect on $C_p$-distribution due the presence of the front cylinder. In the upstream side on the surfaces $S_1$ and $S_8$ there is high suction, while on the surfaces $S_2$ to $S_7$, suction reduces appreciably in comparison to that of either front cylinder with inter-spacing of ID or single cylinder at zero angle of attack and the mean $C_p$ values become almost -0.37 on these surfaces. The front surfaces $S_1$ and $S_8$ of the rear cylinder fall in the suction zone created by the front cylinder and there is no stagnation point here. It is observed from **Fig.7** that on the rear cylinder at the inter-spacing of 2D there is further rise of the back pressure but suction diminishes on the $S_1$ and $S_8$. The $C_p$-distribution is more uniform on the surfaces $S_2$ to $S_7$. On the surfaces $S_2$ and $S_7$, there is higher pressure compared to that on the surfaces $S_3$ to $S_6$. However, a noticeable picture is seen in **Fig.8** for the $C_p$-distribution on the rear cylinder at the interspacing of 3D. On the front surfaces $S_1$ and $S_8$ the pressure increases remarkably while on the back surfaces especially on $S_3$ to $S_6$, suction increases again compared to that of the rear cylinder at the inter-spacing of 2D. At the inter-spacing of 4D on the rear cylinder, there is further rise of the pressure on the front surfaces $S_1$ and $S_8$ compared to that for the rear cylinder at the inter-spacing of 3D, which is shown in **Fig.9**. There appears increase of suction on the surfaces $S_2$ and $S_7$ and drop of suction on the back surfaces $S_3$ and $S_6$ in comparison to that on the rear cylinder at inter-spacing of 3D. At the inter-spacing of 5D and 6D on the rear cylinder, there is further rise of the pressure on the front surfaces $S_1$ and $S_8$ compared to that for the rear cylinder at the inter-spacing of 4D, which is shown in **Fig.10** and **Fig.11**. There

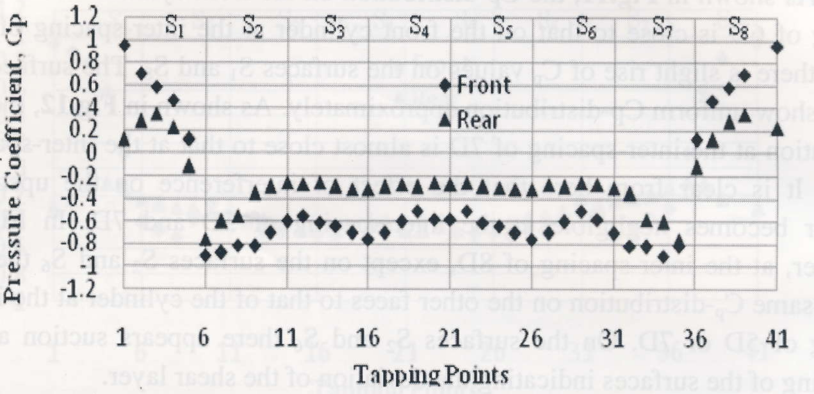


**Figure 11:** Distribution of $C_p$ on front & rear cylinder at inter-spacing of 6D.

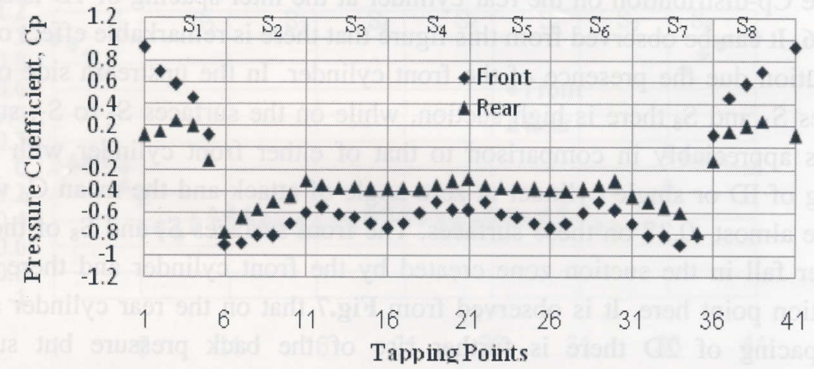


**Figure 12:** Distribution of $C_p$ on front & rear cylinder at inter-spacing of 7D.

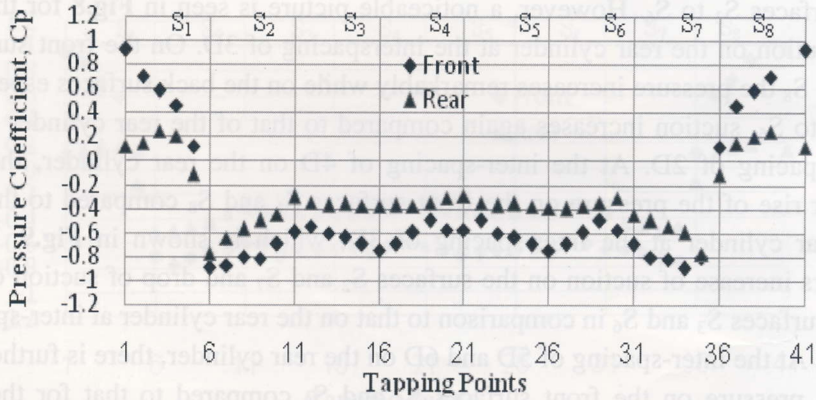


**Figure 13:** Distribution of $C_p$ on front & rear cylinder at inter-spacing of 8D.

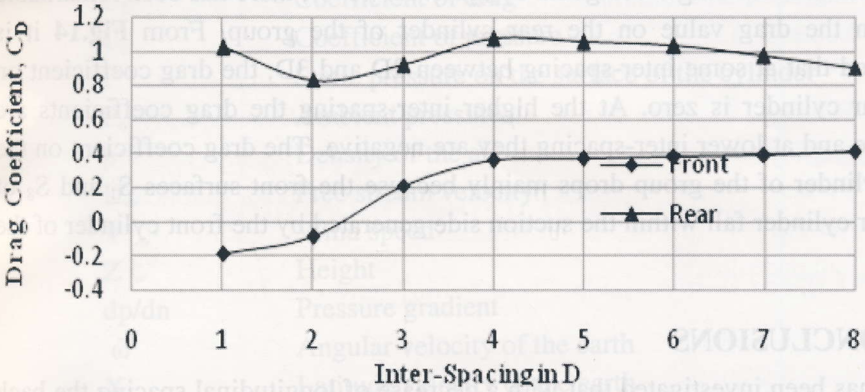


**Figure 14:** Variation of drag coefficient on front & rear cylinders at different inter-spacing.

appears increase of suction on the surfaces $S_2$ and $S_7$ and drop of suction on the back surfaces $S_3$ and $S_6$ in comparison to that on the rear cylinder at inter-spacing of 4D. The Cp-distribution on the rear cylinder at the inter-spacing of 1D is shown in **Fig.12**, about similar pattern of Cp-distribution is seen as that on the rear cylinder at the inter-spacing of 5D. There is further rise of pressure on the front surfaces $S_1$ and $S_8$ and back surfaces $S_3$ and $S_6$. However, more suction is observed on the back surfaces $S_2$ and $S_7$. Finally, the same trend is noticed on the rear cylinder at the inter-spacing of 8D, which is shown in **Fig.13**. The pressure increases appreciably on the front surfaces $S_1$ and $S_8$. There occurs very high suction at the beginning of the surfaces $S_2$ and $S_7$, and then there occurs reattachment at the end of these surfaces, which is obvious from the Cp-distribution. On the rear surfaces $S_3$ and $S_6$, there is further rise of pressure in comparison to that on the rear cylinder at the inter-spacing of 7D and the $C_p$-distribution is almost uniform on these surfaces.

### 4.4 Variation of Drag Coefficient on Front and Rear Cylinder

The variation of drag coefficients on the front and rear cylinders of the group at different inter-spacing at zero degree angle of attack has been presented in **Fig.14**. It can be seen from this figure that the drag coefficient on the front cylinder is about unity. Except at the inter-spacing of 1D, at all other inter-spacing the drag coefficients on the front cylinder of the group are higher than that on the single octagonal cylinder. That is, due to the interference of the flow by the rear cylinder, there has been increase of the drag values on the front cylinder of the group at all inter-spacing except at the inter-spacing of 1D in comparison to the single octagonal cylinder. However, there has been remarkable drop in the drag value on the rear cylinder of the group. From **Fig.14** it is observed that at some inter-spacing between 2D and 3D, the drag coefficient on the rear cylinder is zero. At the higher inter-spacing the drag coefficients are positive and at lower inter-spacing they are negative. The drag coefficient on the rear cylinder of the group drops mainly because the front surfaces $S_1$ and $S_8$ of the rear cylinder fall within the suction side generated by the front cylinder of the group.

## 5 CONCLUSIONS

It has been investigated that with a decrease of longitudinal spacing the back pressure of both the front and rear cylinder increases remarkably thereby decreasing drag coefficient. The Cp values on the front surface of the downstream cylinders for longitudinal spacing, 2D and 6D are negative. The stagnation point is found on the front face of either the single octagonal cylinder or the front cylinder in the group, however no such stagnation point is found in the rear cylinder of the group. There is remarkable drop in the drag coefficient on the rear cylinder of the group as it falls in the suction region generated by the front cylinder. It is observed at some inter-spacing between 2D and 3D, the drag coefficient on the rear cylinder is zero. At the higher inter-spacing the drag coefficients are positive and at lower inter-spacing they are negative. The drag coefficient on the rear cylinder of the group drops mainly because the front surfaces $S_1$ and $S_8$ of the rear cylinder fall within the suction side generated by the front cylinder of the group. Even though the net wind load on an individual cylinder in staggered form decreases; however, some portions of the surfaces experiences high local Cp

## ACKNOWLEDGEMENTS

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## NOMENCLATURE

| | |
|---|---|
| A | Frontal area of the Cylinder |
| I | Net force |
| $F_D$ | Drag force |

| | |
|---|---|
| $F_L$ | Lift force |
| $C_L$ | Coefficient of lift |
| $C_D$ | Coefficient of drag |
| $C_p$ | Coefficient of pressure |
| P | Static pressure on the surface of the cylinder |
| $P_o$ | Ambient pressure |
| $\rho$ | Density of the air |
| $U_\infty$ | Free stream velocity |
| V | Wind speed |
| Z | Height |
| dp/dn | Pressure gradient |
| $\acute{\omega}$ | Angular velocity of the earth |
| X | Latitude velocity of the earth |
| $\Delta P$ | Pressure difference |
| $\Delta h_w$ | Manometer reading |
| $\gamma_w$ | Specific weight of manometer liquid (water) |
| $h_a$ | Air head |
| $\gamma_a$ | Specific weight of air |
| $\alpha$ | Angle of attack |

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