AN EXPERIMENTAL INVESTIGATION OF FLOW OVER OCTAGONAL CYLINDERS WITH ROUNDED CORNERS

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Abstract: *The static pressure distributions on a single of cylinder with octagonal cross-section having rounded corners are presented. The test was conducted in an open circuit wind tunnel at a Reynolds number of 4.13×10^4 based on the face width of the cylinder across the flow direction in a uniform flow velocity of 13.2 m/s. The experimental test was carried out on a single cylinder at various angles of attack from 0° to 40° at a step of 5°. It was observed that with the rounded corners the drag on the cylinders reduces remarkably in comparison to that on the sharp-edged cylinders. It was also observed that at various angles of attack, the values of the lift coefficients were insignificant compared to those for a sharp-edged square cylinder. The results are applicable to combination of tall buildings one behind the other along the wind velocity direction and each building of square or octagonal cross-section having rounded corners. The wind load on the downstream cylinder decreases remarkably due to the presence of the cylinder in the upstream side.*

Keywords*: Wind load, Octagonal cylinder, Pressure distribution, Tall building*

NOMENCLATURE

A	Frontal area of the Cylinder	V	Wind speed
I	Net force	Z	Height
F_D	Drag force	dp/dn	Pressure gradient
F_L	Lift force	ώ	Angular velocity of the earth
C_L	Coefficient of lift	X	Latitude velocity of the earth
C_D	Coefficient of drag	ΔP	Pressure difference
C_p	Coefficient of pressure	Δh_w	Manometer reading
P	Pressure on the surface of the cylinder	γ_w	Specific weight of manometer liquid (water)
P_o	Ambient pressure	h_a	Air head
ρ	Density of the air	γ_a	Specific weight of air
U_∞	Free stream velocity	α	Angle of attack

INTRODUCTION

The subjects of wind load on buildings and structures are not a new one. In the 17th 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 19th 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.

It is the great challenge of the engineers and architects to reduce the wind load on the tall buildings. Now a day, due to huge population pressure, emphasis on design and construction of the tall buildings is being given in many places. Especially, the design of the group of tall buildings is the most important consideration to take care of the housing problem of the huge population. As the building becomes tall, it is necessary to take into consideration the effect of wind on its design. Keeping this in mind the study on the group of octagonal cylinders has been conducted, which will be applicable to obtain the wind load on the group of tall buildings. 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. There are various parameters, which control the flow behaviour 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). The wind in the atmospheric boundary layer varies in time and space. 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. Lee (6) performed study on the effect of turbulence on the surface pressure field on a square prism. In his study measurements were presented of the mean and fluctuating pressure field acting on a two dimensional square cylinder in uniform and turbulent flows. In his investigation he showed that the addition of turbulence reduces the drag on the cylinder. Mandal and Farok (7) measured the static pressure distributions on the single cylinder with square and rectangular cross-section having rounded corners in a uniform cross flow. The experiment was conducted for different corner radii and side dimensions of the cylinders at zero angle of attack. The experimental results reveal that the corner radius of the cylinder has significant effect while the side dimension has some effect on the drag coefficient.

Mandal and Islam (8) made an experimental investigation of mean pressure coefficients on square cylinders. They measured the pressure coefficients on single square cylinder at various angles of attack and on a group of square cylinders with sharp edge at zero angle of attack. Islam and Mandal (9) performed an experimental investigation of static pressure distributions on a group of rectangular cylinders in a uniform cross flow. The effect of longitudinal spacing as well as the side dimension of the cylinder was taken into consideration in the study.

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 behaviour of the structure under the action of forces. 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. The wind in the atmospheric boundary layer varies in time and space. It depends on the terrain roughness, the local wind climate and on variations in temperature. Usually, the effects of temperature are assumed negligible, when studying wind loads relevant are the proper simulation of the wind speed with height and the turbulent characteristics.

The wind tunnel testing provides information regarding the dependence of particular response parameters on wind speed and direction. In order to make the most rational use of this aerodynamic information, it is necessary to synthesize it with the actual wind climate characteristics at the site. The characteristics necessary to define are those governing wind speed and direction at a suitable height above ground level at the site. The joint probability distribution of wind speed and direction then defines the wind climate, whereas all of the aerodynamic information, which includes sensitivities to building orientation and to its surroundings, is contained in the wind tunnel data. 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.

The scale difference between wind tunnel model and prototype is found in the high frequency fluctuation. High peaks found on the cladding in full-scale are not found in the wind tunnel. Those effects may be caused by structural details that are not simulated in the wind tunnel model. Now-a-days, both the studies with models and full-scale buildings are being performed to compare the result for varying the validity of the former. But full-scale experiments are both costly and difficult to perform. For the present study with staggered buildings full- scale experiments will not only be complex and costly but it would be difficult to record reliable pressure distribution simultaneously on the group of buildings as there will be variation of speeds and direction of wind with time.

EXPERIMENTAL SET-UP

Wind tunnel

The test was conducted at the exit end of an open circuit subsonic wind tunnel. In Figure 1 the schematic diagram of the wind tunnel is presented showing the position of the cylinders at the exit end of the wind tunnel. The wind tunnel was 6 m long with a test section of 460 *mm* x 460 *mm* cross section. The cylinders were fixed to the side walls of the extended portion at the exit end.

In the side wall the cylinder was fastened rigidly at one end and through the other end of the cylinder the plastic tubes from the tapping were taken out and were connected with the inclined manometer, which contained water as the manometer liquid. The cylinder was leveled in such a way that the flow direction was parallel to its top and bottom sides and perpendicular to the front side. The axis of the cylinder was at the same level to that of the wind tunnel. 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. 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.

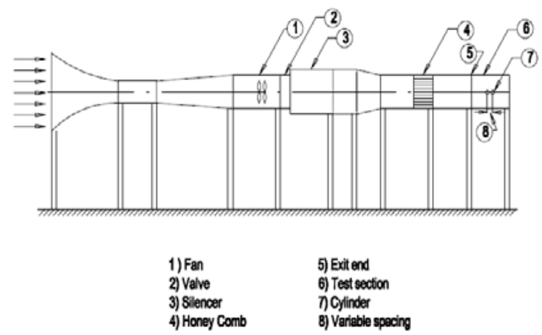

Figure 1. Schematic diagram of wind tunnel

Constructional details of cylinders

The tapping positions on the cross-section of the cylinder are shown in Figure 2. The width of the octagonal cylinder was 50mm as shown in this figure. Each face of the cylinder contained five tappings.

In Figure 2 the tapping positions on the longitudinal section of the cylinder is shown. There were five tappings on each face of the cylinder. The distance between the consecutive tapping points was equal (Δd) as shown in the figure. However, the location of the corner tapping was at a distance of $½\Delta d$. 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 tappings were not made along the cross-section of the cylinder.

They were located within some span of the cylinder as shown in Figure 3. 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 Figure 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 multimanometer. The manometer liquid was water. The tappings were made of copper tubes of 1.71 mm outside diameter. Each tapping was of 10mm length approximately. From the end of the copper tube flexible plastic tube of 1.70 mm inner diameter was press fitted.

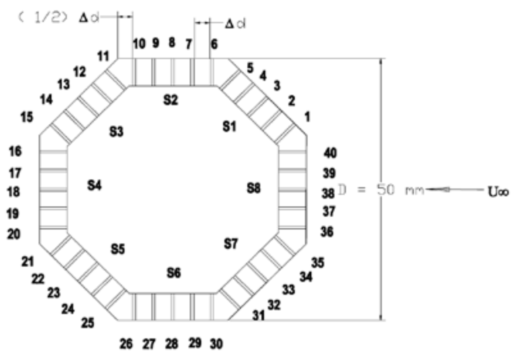

Figure 2. Tapping positions shown on cross-section of cylinder

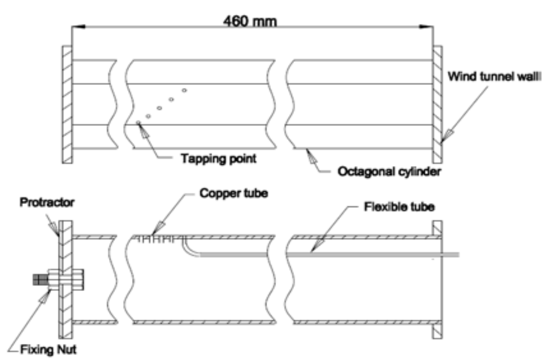

Figure 3. Tapping positions shown on longitudinal section of cylinder

Single cylinder

The upstream velocity was assumed to be uniform and the flow occurred across the cylinder. In Figure 4 the position of the single cylinder at zero angle of attack is shown in the wind tunnel test section.

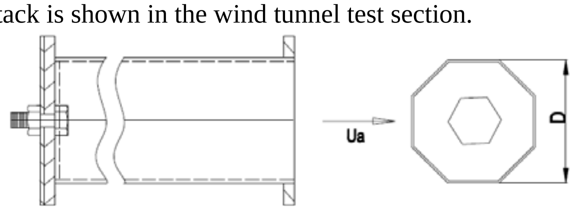

Figure 4. Tunnel test section showing position of single cylinder

The surface static pressure distributions on eight faces of the cylinder were measured in this position. Then the cylinder was rotated at an angle of 5^0 and the static pressure distributions on each face of the cylinder were measured again. The same test procedure was repeated to measure the surface static pressure distributions of the cylinders with angles of attack of 0^0, 5^0, 10^0, 15^0, 20^0, 25°, 30°, 35° and 40°.

MATHEMATICAL MODEL

The pressure coefficient is defined as

$$C_P = \frac{\Delta P}{\frac{1}{2}\rho u_\infty^2} \tag{3.1}$$

Drag and lift coefficients are defined as follows

$$C_D = \frac{F_D}{\frac{1}{2}\rho u_\infty^2} \tag{3.2}$$

and $$C_L = \frac{F_L}{\frac{1}{2}\rho u_\infty^2} \tag{3.3}$$

The detailed calculation of C_P can be found in Mandal, A. C. [7]

RESULTS AND DISCUSSION

Single Cylinder

The distributions of the pressure coefficients, drag and lift coefficients have been taken into consideration for discussion for a single octagonal cylinder at different angles of attack. Pressure coefficients have been calculated from the measured values of the surface static pressures. All the coefficients are determined for the uniform cross flow on the cylinder at Reynolds of 4.13 x 10^4 based on the width of the cylinder across the flow direction at zero angle of attack. Before going to discuss the results of the experimental investigation, it will be relevant here to present the typical flow pattern over a single square cylinder at zero, small and moderate angles of attack as shown in Figure 5.

Although the octagonal cylinder will give a bit different flow pattern, formation of the vortex pair will be similar. Therefore, the typical flow over the single square cylinder has been discussed. As the angle of attack increases, the path of the shear layers is altered from their point of origin at the front corners of the square cylinder to the vortex formation region as shown in Figure 5. The pressure developed on the back surface depends on the distance of the vortices. The longer is the distance of the vortices from the body, higher is the back pressure and vice versa. For the above reasons, pressures increase at the rear surface of the model cylinder around the angle of attack of 15°, while in the higher range of angle of attack, decrease**.**

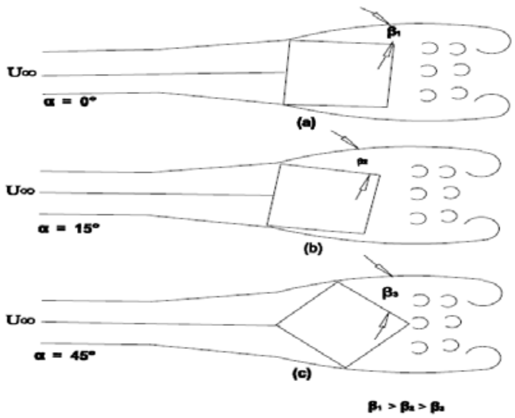

Figure 5. Typical vortex patterns in the downstream of square cylinder

Distribution of pressure coefficients

The cross-section of the single octagonal model cylinder with 40 numbers of tapping's, eight numbers on each surface of the cylinder at an angle of attack has been shown in Figure 6.

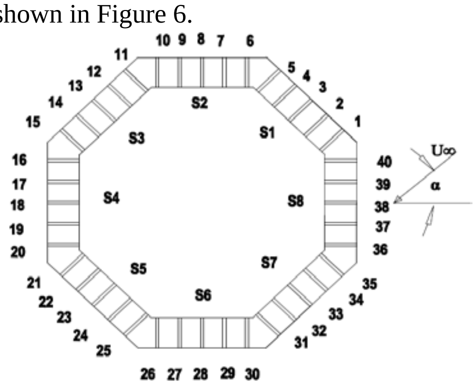

Figure 6. Flow over single cylinder at an angle of attack

The eight surfaces have been identified with S_1, S_2, S_3, S_4, S_5, S_6, S_7 and S_8. Pressure coefficient for each tapping point has been determined from the measured surface static pressure. In Figure 7, the distributions of static pressure coefficients for angles of attack of 0° to 40° with a step of 5° have been presented respectively. While in Figure 7, the distributions of pressure coefficients for all angles of attack have been shown for relative comparison. From Figure 7 one can observe that the distribution of the pressure coefficients is symmetric at zero angle of attack.

It can be further noticed from this figure that nowhere there is stagnation point. It is due to the fact that the location at the stagnation point has not been selected for the tapping. The pressure coefficient values are positive on the surfaces S_1 and S_8, while on the surfaces S_2 to S_7 there are negative pressure coefficients. However, one interesting point can be seen from this figure that almost uniform pressure coefficient distributions are found on surfaces S_2 to S_7. Baines, W. D. (1963) has stated that, velocities in the wake region are much smaller than the mean flow, and hence, almost uniform pressures exist on the body surfaces.

In Figure 8, at angle of attack of 5°, the value of the pressure coefficient has increased slightly on surface S_1, while it has dropped slightly on surface S_8. However, on the other six surfaces S_2 to S_7, the distributions of pressure coefficient are almost uniform. At $\alpha = 5°$, the Cp-distribution is close to that at $\alpha = 0°$. From Figure 9, at angle of attack of 10°, the pressure coefficient values are positive on the surface S_1 to S_8. It occurs high suction at the beginning of the surface S_2 to S_7 and uniform distribution. From Figure 10, it is due to the fact that the location at the stagnation point has not been selected for the tapping. The pressure coefficient values are positive on the surfaces S_1 and S_8, while on the surfaces S_2 to S_7 there are negative pressure coefficients. However, one interesting point can be seen from this figure that almost uniform pressure coefficient distributions are found on surfaces S_2 to S_7 In Figure 11 at angle of attack of 20°, there is further rise of C_p values on surface S_1 and further drop of C_p values on surface S_8. However, on surfaces S_3 to S_7 almost uniform C_p-distribution occurs. While on surface S_2 there is high suction near the tapping point 6. Probably the shear layer deviates much in the outward direction near this point. At $\alpha = 25°$, an interesting point can be observed from Figure 12, where on surface S_1, there is stagnation point on tapping point 3. The distributions of C_p on surfaces S_2 and S_8 are symmetric, which is expected at this angle of attack. On surfaces S_2 and S_8 near the tapping points 6 and 40 respectively, there are high suction, which indicates the high deviation of the shear layer in the outward direction from the body.

In Figure 13 at angle of attack of 30°, while reattachment is seen to occur at the downstream side of the surfaces S_2 and S_8, However, there is almost uniform Cp-distribution on the surfaces S_3 to S_7. It is observed from Figure14 that, there is still stagnation point on surface S_1, but it occurs at tapping point 4. Due to further rotation the surface S_2 shows positive values of C_p. However, on the surfaces S_3 to S_7, there is more or less uniform distribution of C_p. While on surface S_8 the C_p values become less negative. There appears reattachment near the tapping point 37 on the surface S_8. Finally, from Figure 15 at $\alpha = 40°$, it is seen that the stagnation point still occurs at tapping point 4 and there is further rise of positive C_p values on the surface S_2 and all values are positive on this surface. On the surfaces S_3 to S_7, the C_p values are more or less uniform. While on the surface S_8, there is very high suction. Further rotation of the cylinder has not been made because at $\alpha = 0°$ and $\alpha = 45°$, they are identical.

Variation of drag coefficient

Variation of drag coefficient at various angles of attack on single octagonal cylinder is shown in Figure 16. The drag coefficient at different angles of attack on a single square cylinder at uniform flow obtained by Mandal, A. C. [7] is also presented in this figure for comparison. It can be noticed from this figure that there is significant drop in the drag coefficient values for the octagonal cylinder in comparison to that of the square cylinder and the values approach to that of the circular cylinder. It is seen from this figure that at zero angle of attack, the drag coefficient is about 0.99 and at all other angles of attack, the values are close to 0.90 except at angle of attack of 5°, where the value is about 0.60. The values of the drag coefficient at various angles of attack for the octagonal cylinder can be explained from the Cp-distribution curves.

Variation of lift coefficient

In Figure 17 the variation of lift coefficient at various angles of attack on single octagonal cylinder is shown. The lift coefficient at different angles of attack on a square cylinder at uniform flow obtained by Mandal, A. C. [7] is also presented in this figure for comparison. It can be noticed from this figure that the variation of the lift coefficient on the single octagonal cylinder is not appreciable; they are close to zero value except at angles of attack of 30° and 40°, where some insignificant values are observed. For the single square cylinder the variation of lift coefficient with angle of attack is remarkable. The values of the lift coefficients for the single octagonal cylinder can be explained from the Cp-distribution curves.

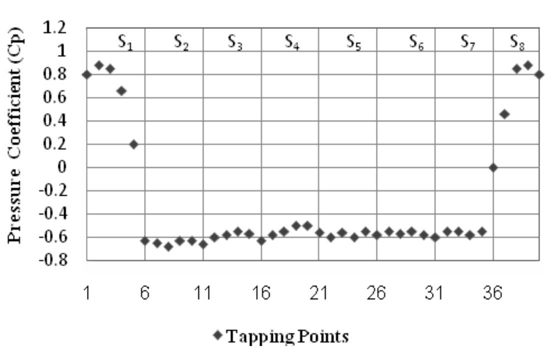

Figure 7. Distribution of C_p at angle of attack of 0°

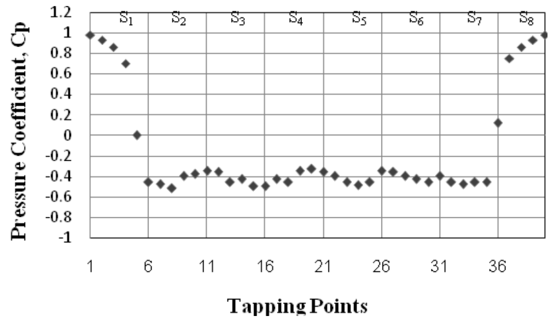

Figure 8. Distribution of C_p at angle of attack of 5°

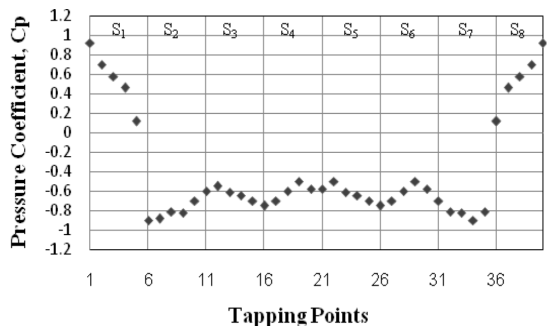

Figure 9. Distribution of C_p at angle of attack of 10°

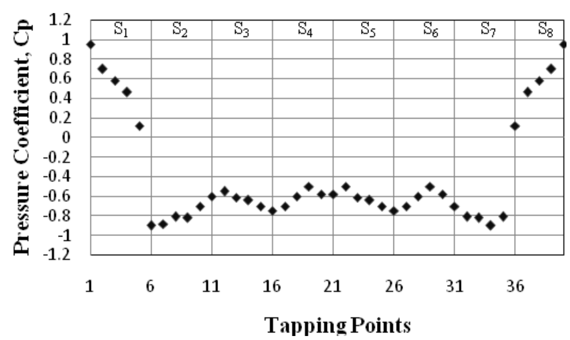

Figure 10. Distribution of C_p at angle of attack of 15°

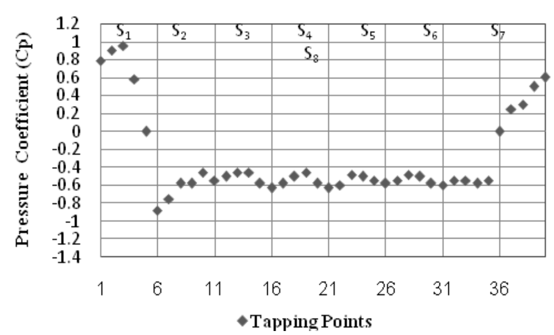

Figure 11. Distribution of C_p at angle of attack of 20°

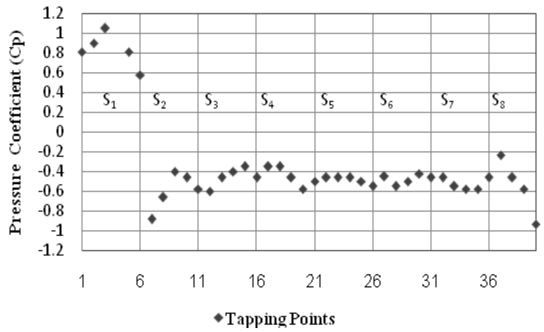

Figure 12. Distribution of C_p at angle of attack of 25°

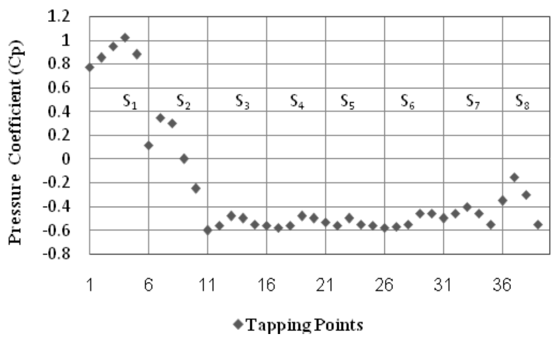

Figure 13. Distribution of C_p at angle of attack of 30°

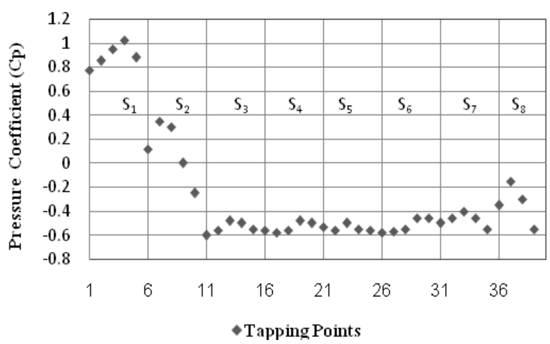

Figure 14. Distribution of C_p at angle of attack of 35°

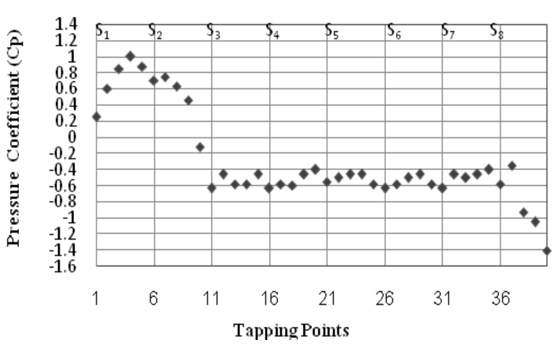

Figure 15. Distribution of C_p at angle of attack of 40°

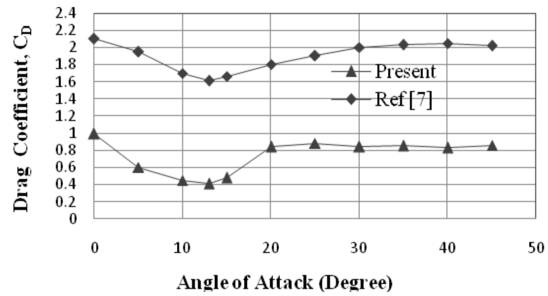

Figure 16. Variation of drag coefficient at various angles of attack on single cylinder

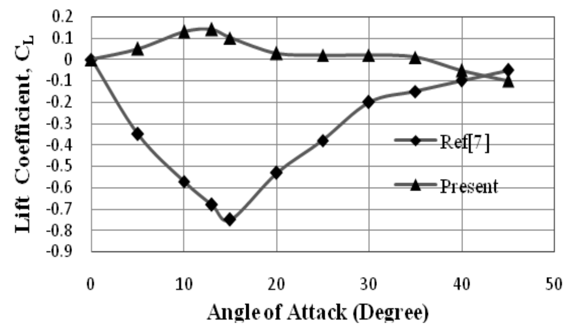

Figure 17. Variation of lift coefficient at various angles of attack on single cylinder

CONCLUSIONS

The following conclusions are drawn in regard to the wind effect on the single octagonal cylinder. The drag coefficient on the rear cylinder with either square or octagonal cross-section having rounded corner decrease significantly compared to that on the single cylinder. There is significant drop in the drag coefficient values for the single octagonal cylinder in comparison to that of the single square cylinder and the values approaches to that of the circular cylinder. The drag coefficient for a single octagonal cylinder at zero angle of attack is about 0.97 in contrast to that of 2.0 for a single square cylinder at the same angle of attack. The variation of the lift coefficient on the single octagonal cylinder is not appreciable and they are close to zero value except at angles of attack of 30^0 and 40^0, where some insignificant values are observed.

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