WIND EFFECT ON STAGGERED CYLINDERS OF SQUARE AND RECTANGULAR SECTIONS WITH VARIABLE LONGITUDINAL SPACINGS

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Abstract: *An experimental investigation of mean pressure distributions on a group of cylinders with square and rectangular cross-sections in a uniform cross flow is presented here. The group consists of one rectangular and two square cylinders of identical dimension. The rectangular cylinder is placed centrally in the upstream side and the other two square cylinders are placed symmetrically in the downstream side with respect to tunnel axis. Surface pressure distributions on the cylinders are measured for various longitudinal spacings of the cylinders. Wind loads are obtained in terms of drag coefficients, lift coefficients and total force coefficients. The drag on an isolated cylinder is higher in general than that on the same cylinder while it becomes part of a group.*

Keywords: *Wind load, staggered cylinders.*

INTRODUCTION

In recent years, studies of wind load on buildings and structures are being performed in the different parts of the world. Certain disastrous events, such as the collapse of suspension bridges and damage to towering buildings due to wind effects have proved that the effects of wind loads should not be taken lightly and consequences of wind loading should be a major criterion for design purposes of tall buildings and structures. Extensive research work on isolated bluff bodies have been done in many places giving less emphasis in the staggered ones, even after this has the practical significance. Till now little information is available concerning the flow over staggered cylinder consisting of square and rectangular cross-sections.

Mandal and Islam[1] described in their studies the wind effect on square cylinders. The pressure distributions were measured on a single square cylinder at various angles of attack and a group of square cylinders at various longitudinal spacing. It was mentioned in their works that the model study of wind effect around a group of square cylinders would be helpful to find the wind load on a group of tall square shaped buildings. It was also observed from the experimental results that the wind load on the individual cylinder of the group was less severe than that on a single cylinder in most of the cases. Mandal and Islam[2] described in their studies the wind effect on staggered square cylinders. The pressure distributions were measured on a group of square cylinders at various transverse and longitudinal spacing. Bearman and Truman[3] investigated the base pressure coefficients, drag coefficients and Strouhal number of rectangular cylinders with one face normal to the flow direction. Barriga *et al.*[4] and Lee[5] carried out research works on single square cylinders. The mean pressure distributions were measured at various angles of attack with different turbulent intensities and scales. Senthooran *et al.*[6] conducted a computational model to predict the pressure fluctuation around bluff bodies. That model was tested to predict the pressure fluctuation on the low-rise experimental building at Texas Tech. for 60° and 90° wind angle of attack. That model predicted the fluctuation quantities with good accuracy. Mean pressure coefficients obtained from the computational model show very good agreement with the experimental results. Li *et al.*[7] presented in their paper the selected results from the full scale measurements of wind effects on the tallest building in Mainland China during the passage of Typhoon Rananim and 15-hours data of wind speed, wind direction and acceleration responses recorded simultaneously and continuously during the Typhoon were analyzed and discussed in this paper. Grenet and Riccardelli[8] presented in their paper two applications of spectral proper transformation (SPT) analysis to the fluctuating pressure distributions on a square cylinder and a bridge deck box section. Leutheusser[9] presented in his paper the results of static wind loading obtained from wind tunnel tests on scale models of a typical building configuration consisting of four buildings each with different cross-sections. Baines[10] described the effects of velocity distribution on wind loads and flow patterns around buildings. Pressure distributions were measured on models of walls and rectangular block structures in a wind tunnel. Tall buildings with square sections had also been included in his study. The tests were conducted both in an artificially produced velocity gradient used to simulate natural conditions and in a constant velocity field for

Nomenclature

A	Frontal area
B	Bottom downstream cylinder
C_D	Co-efficient of Drag
C_F	Total force co-efficient
C_L	Co-efficient of Lift
C_P	Mean pressure co-efficient
D	Width of cylinder normal to the approach flow
F	Upstream cylinder
F_D	Force due to drag
F_L	Force due to lift
H	Depth of cylinder in the flow direction
L_1	Longitudinal spacing
L_2	Transverse spacing
P	Local static pressure
P_0	Free stream static pressure
T	Top downstream cylinder
U_0	Free stream velocity
α	Angle of attack
γ_w	Specific weight of manometer liquid
ρ	Density of air
ΔP	Difference of ambient and local static pressures

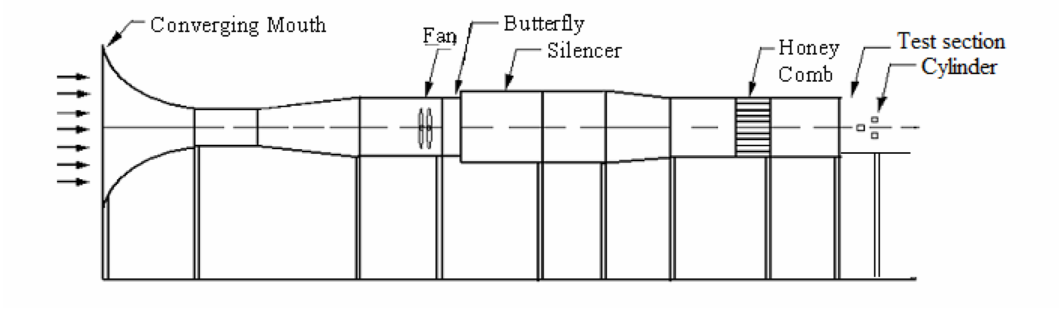
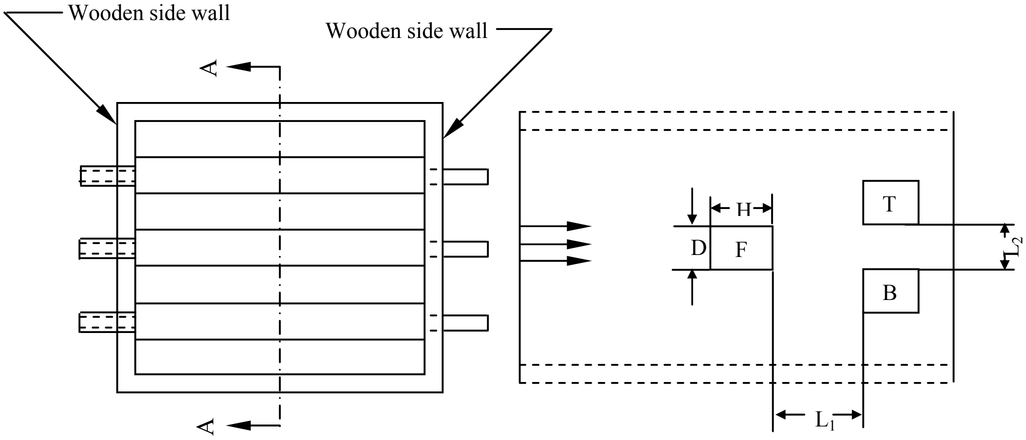


Figure 1: Schematic Diagram of Experimental Setup.



End View of Test Section A-A Section

Figure 2: Tunnel Test Section Showing Position of Cylinders in Staggered Form.

comparison with standard procedures. Mandal[11] performed the study of wind effect on the staggered square cylinder. The test was conducted in an open circuit wind tunnel at Reynolds number of 27,800 based on the side dimension of the square model. The maximum blockage area was 6.96 percent. Three cylinders were arranged in the staggered form (one in upstream and two in downstream flow) varying the longitudinal and transverse spacings and measurements of pressure coefficients were taken for the upstream and downstream cylinders. Experiments were also carried out for drag coefficients, lift coefficients, total force coefficients and moment coefficients. It is 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.

Islam[12] conducted experiments on the wind effect on the rectangular cylinders. The rectangular cylinders had side ratios of H/D = 1.25, 1.5, 1.75 and 2.0, where D is the section width normal to flow direction and H is section depth along the flow direction. The flow had a turbulence intensity of 0.33% and a constant free stream velocity of 18.3 m/s was used for the purpose. Mean pressure distributions around each of the cylinders were measured for different angle of attack. It was found that the drag on the rectangular cylinder with its axis normal to the approaching flow increased with the rise of the value of side ratio up to about 0.6, then decreased with the further increase in the side ratio. It was also observed that the drag on an isolated cylinder was higher in general than that on the same cylinder while it became the part of a group. The rectangular cylinder with the highest side ratio experienced minimum drag for all conditions of spacings.

EXPERIMENTAL SETUP AND PROCEDURE

The schematic diagram of the experimental setup of the present investigation has been shown in Fig. 1. Open circuit subsonic type wind tunnel was used to develop the required flow and the cylinders were positioned at the exit end of the wind tunnel in the downstream side. The tunnel is 5.93 meter long with a test section of 460 x 480 mm cross-section. In order to smoothen the flow a honeycomb is fixed near the end of the wind tunnel. The wind tunnel consists of a bell-shaped converging mouth entry. A digital anemometer is used in each of these tests to measure the wind velocity. The approach flow velocity was maintained at approximately 13.5 m/s. In the tunnel test section, the measured velocity distribution was uniform.

The three cylinders (two square and one rectangular) were made of perspex. The side dimensions of the cylinders in each set were D = 51.08 mm, H = 51.08 mm and 63.85 mm, 4 mm thick and 460 mm long. Perspex plates with the appropriate side dimensions were joined to form the shape of hollow square and rectangular cylinders. One end was closed by inserting a solid wooden block and the other end by inserting another wooden hollow block with 27 mm through hole. In order to mount the cylinders, one end was projected 30 mm long circular portion and the other end was bolted (53 mm long) by wooden block.

To measure the pressure distribution on each square and rectangular cylinder, pressure tappings were made on each side. It was not possible to accommodate all the

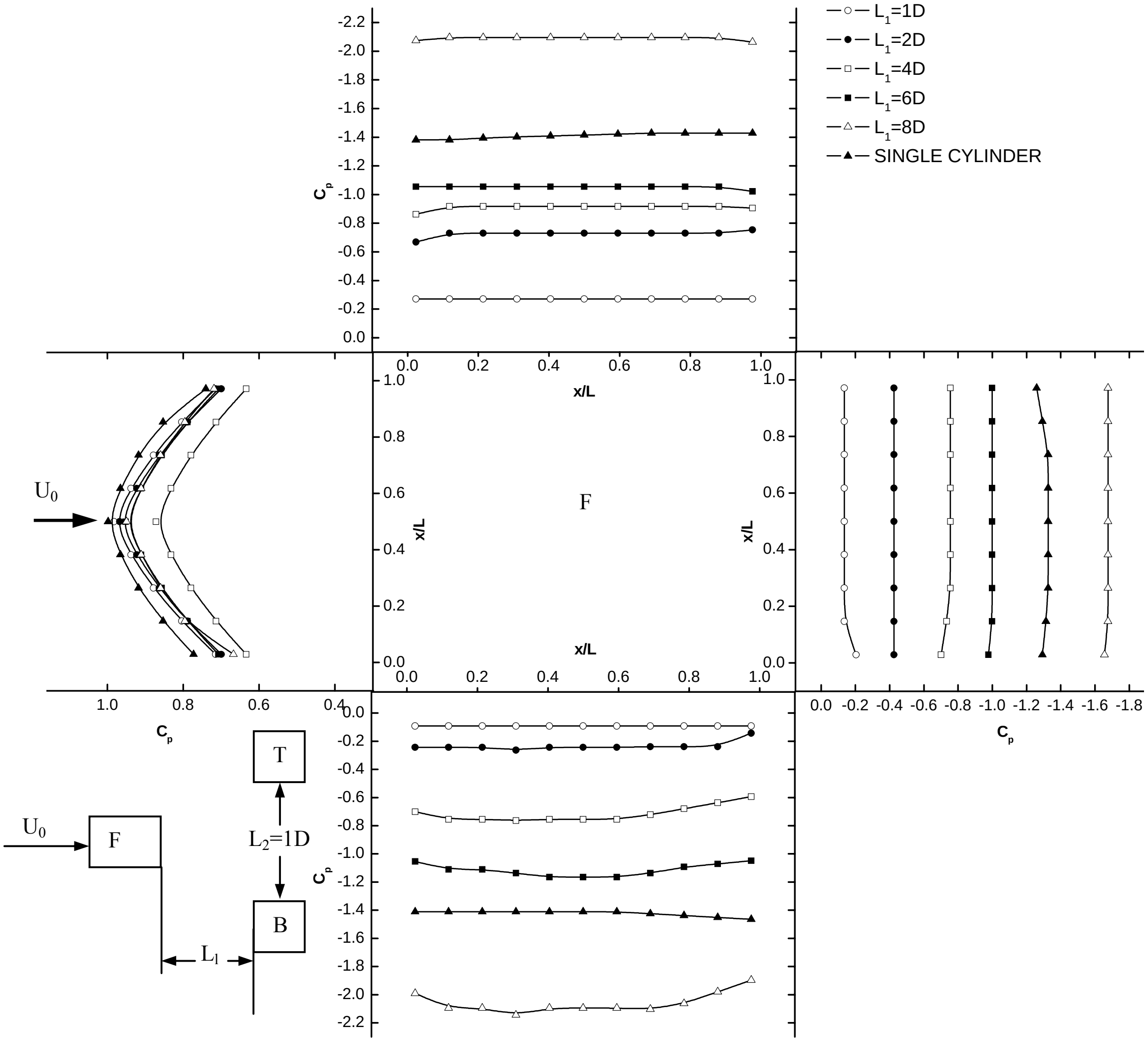


Figure 3: Effect of Longitudinal Spacing (L_1) on C_P on Upstream Rectangular Cylinder (F) for Transverse Spacing (L_2) of 1D.

pressure tappings in a section perpendicular to the axis of the cylinder because of the space limitations. The tappings were placed in an inclined sectional plane within 20 mm from the center of the cylinder. It was assumed that for two-dimensional flow, such tappings would not affect the results. The end tapping points were made at equal distances from the corners and the interspaces between the consecutive tapping points were kept at equal distance. Each tapping was made using 1.71 mm diameter copper tube and the tapping holes were press fitted with 10 mm length copper tubes. The tapping was then connected to the limbs of an inclined multi-manometer using flexible plastic tubes whose diameter was 1.84 mm. Water was used as manometric liquid.

The method in which one rectangular and two square cylinders were placed in staggered form can be seen in Fig. 2. They were positioned in such way that the 51.08 mm side of each of the cylinders was kept normal to the direction of the approaching velocity. One rectangular cylinder labelled as F was placed centrally in the test section and the other two square cylinders were placed symmetrically with respect to tunnel axis in the downstream side of the former. Since the top downstream cylinder (T) and bottom downstream cylinder (B) were symmetrically placed, the pressure distributions were considered on the top cylinder only.

The transverse spacing (L_2) between the surfaces facing each other of the downstream cylinders were set at 1D, where D representing the height of the cylinder. For transverse spacing (L_2), the longitudinal spacings (L_1) were set at 1D, 2D, 4D, 6D and 8D. Mean pressure distributions were measured for the above settings for 5 sets and at zero angle of attack only; keeping the flow characteristics same in each case of the tests. Pressures were measured simultaneously for the upstream and downstream cylinders.

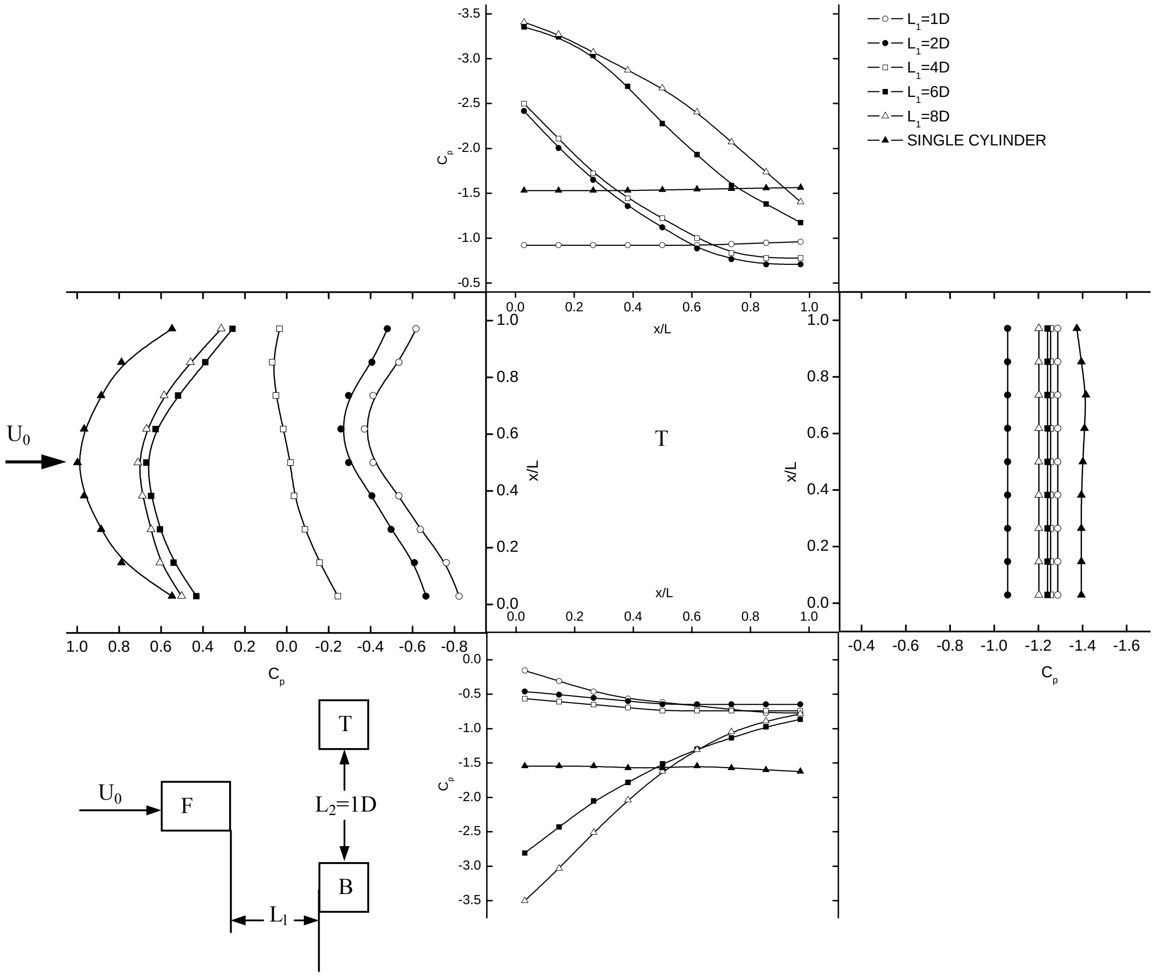


Figure 4: Effect of Longitudinal Spacing (L_l) on C_P for Downstream Square Cylinder (T or B) for Transverse Spacing (L_2) of 1D.

The Reynolds number based on the side dimension was 4.5 × 10^4.

All the data are hereby presented in terms of non-dimensional coefficients. The coefficients of lift, drag and total force were obtained by numerical integration method.

Pressure co-efficient is defined as, $C_P = \dfrac{P - P_0}{1/2\rho U_0^{\,2}}$ (1)

Drag co-efficient is defined as, $C_D = \dfrac{F_D}{1/2\,\rho\,AU_0^{\,2}}$ (2)

Lift co-efficient is defined as, $C_L = \dfrac{F_L}{1/2\,\rho\,AU_0^{\,2}}$ (3)

Total force co-efficient can be defined as,

$$C_F = \sqrt{C_D^{\,2} + C_L^{\,2}} \tag{4}$$

RESULTS AND DISCUSSION

The pressure distribution around the upstream rectangular cylinder for different longitudinal spacing (L_l) with constant transverse spacing i.e. L_2 = 1D is shown in Fig. 3. It is seen in the figure that for all L_l, the pressure distributions on the top and bottom surfaces are symmetrical. It can also be concluded from the same figure that at L_l = 8D, the pressure on the top, bottom and back surface are lower than that of the single cylinder. But at a given location, when the longitudinal spacing (L_l) decreases, pressure coefficient increases (i.e. negative value decrease) up to the spacing L_l = 1D. The pressure distribution on the front surface for different spacing L_l, remains almost same as that of the single cylinder. It is due to the influence produced by the downstream cylinders for which the flow becomes significantly turbulent; the values of fluctuating transverse velocity components increase appreciably thereby high momentum and mass transfer, as the pressure recovery occurs on the surfaces (top, back and bottom) of the upstream cylinder. As the distance increases, this effect is minimized and at large distance (L_l = 8D), it becomes very small.

The pressure distribution around the downstream square cylinder (T or B) with different longitudinal spacing (L_l) keeping transverse spacing constant (L_2=1D) is shown in Fig. 4. It is observed from the figure that, when the longitudinal spacing is low i.e. L_l = 1D, 2D and 4D the pressure distributions on the front surface are negative, but for high longitudinal spacing i.e. L_l= 6D and 8D, the

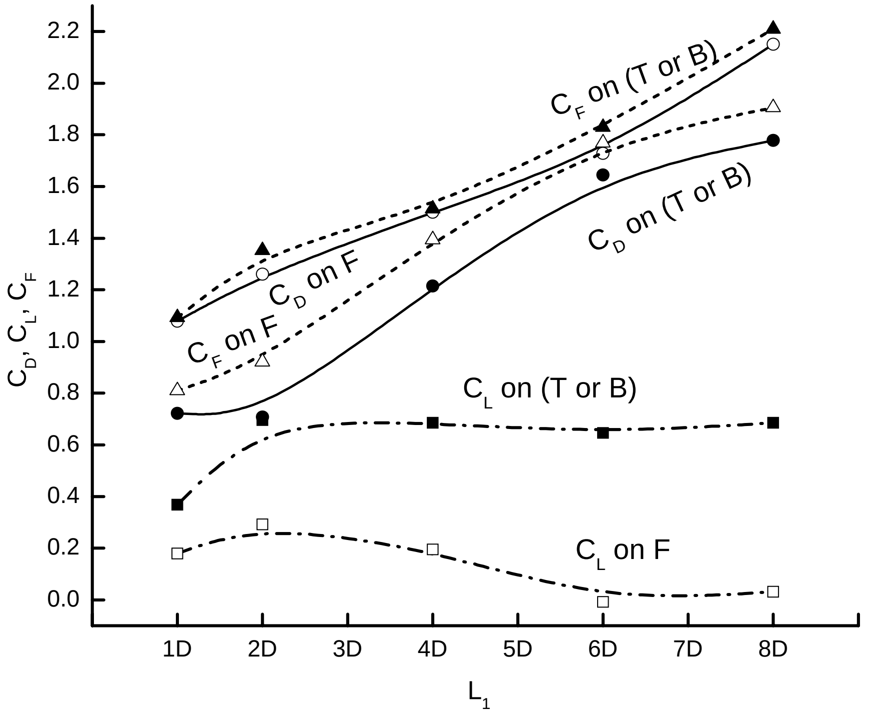


Figure 5: Variation of Drag Coefficients (C_D), Lift Coefficient (C_L) and Total Force Coefficient (C_F) with Longitudinal Spacing (L_l).

pressure distributions become positive and hence, pressure distribution for L_l = 8D is higher than that of the other longitudinal spacings. However, at L_l = 8D, the pressure distribution is lower than that of the single cylinder. There is a wake region ahead of the front surface of the downstream cylinder produced by the upstream rectangular cylinder. When the value of L_l is low, relatively larger wakes take place. The flow on this face never becomes potential, whereas it is potential for the single cylinder. The velocity on the front face of the single cylinder is higher than that of the front face of the downstream cylinder, because the mean velocity in the wake is less than the free stream velocity. For this reason, the pressure distribution on the front face is quite different than those produced on the front face of the single cylinder at $\alpha = 0°$.

On the back surface of this cylinder the pressure distribution curves are almost uniform throughout the surface and do not vary a lot for different longitudinal spacing (L_l). Again, these pressures are higher i.e. less negative, than those of single cylinder on the subsequent surface. This nature of pressure distribution occurred due to high turbulence.

On the top surface, it is noticed that while the upstream rectangular cylinder is close to downstream square cylinder i.e. at L_l = 1D, the pressure distribution is almost uniform throughout the surface and the values are much higher than those for the single cylinder, which is due to the turbulence nature of flow. At longitudinal spacing L_l = 2D and 4D, separation on the front corner and pressure recovery at the rear part of this face is observed. At longitudinal spacing L_l = 6D and 8D, the pressure distribution curves are nearly close together; separation tendency at the front corner and reattaching tendency at the rear part of this face appear. But on the bottom surface, the appearance of pressure curve is quite different. At small longitudinal spacing i.e. at L_l = 1D, pressure recovery is extremely high near the front corner, whereas towards the rear corner again separation tendency is observed. At L_l = 2D and 4D similar distribution occurs with a small variation. At L_l = 6D and 8D, the pressure distribution curves are nearly same having separation near front corner and reattachment near the rear of this face.

Variation of drag coefficient (C_D) on the upstream rectangular cylinder (F) with different longitudinal spacing (L_l) corresponding to keeping transverse spacing constant at L_2 = 1D is shown in Fig. 5. The figure reveals that, as longitudinal spacing increases, the drag coefficients increases up to L_l = 8D. Minimum drag coefficient is observed at L_l = 1D, which is the most favorable position. However, for all values of L_l, the drag developed on the upstream cylinder is always less than that on the single cylinder at angle of attack, $\alpha = 0°$.

The variation of drag coefficient (C_D) on the downstream square cylinder (T or B) with different longitudinal spacing (L_l) keeping transverse spacing constant at L_2 = 1D is shown in Fig. 5. The figure reveals that for transverse spacing L_2 = 1D, the drag is high at large longitudinal spacings (L_l = 4D, 6D and 8D) and low at small longitudinal spacings (L_l = 1D and 2D).

The variation of the lift coefficient (C_L) on upstream rectangular cylinder (F) with different longitudinal spacing (L_l) keeping transverse spacing constant at L_2 =1D is shown in Fig. 5. The figure reveals that for transverse spacing L_2 = 1D at higher range of longitudinal spacing the values of lift coefficient remain almost zero, which is similar to that of the single cylinder at angle of attack, α = 0° i.e. no lift is developed.

The variation of lift coefficient (C_L) on downstream square cylinder (T or B) with different longitudinal spacing (L_1) keeping transverse spacing constant at L_2 = 1D is hereby shown in Fig. 5. The figure reveals that for transverse spacing L_2 = 1D, the value of lift coefficient (C_L) is almost constant at all longitudinal spacings (L_1).

Figure 5 also shows the variation of total force coefficient (C_F) on upstream rectangular cylinder (F) with different longitudinal spacing keeping transverse spacing L_2=1D. It reveals that for transverse spacing (L_2), the total force coefficient for all the longitudinal spacing L_1 =1D to 6D is less than that of the single cylinder at $\alpha = 0°$.

The variation of total force coefficient (C_F) on downstream square cylinder (T or B) with different longitudinal spacing (L_1) keeping transverse spacing constant (L_2 = 1D) is presented in Fig. 5. It may be concluded from the figure that the total force coefficient for all the longitudinal spacing (L_1) is less than that of the single cylinder at $\alpha = 0°$.

CONCLUSIONS

The following conclusions can be drawn from the experimental investigation of flow around square and rectangular cylinders:

(i) The C_P-values on the top, back and bottom surface of upstream cylinder are reduced due to the presence of downstream cylinders.

(ii) The C_P-distributions on the front surface of the downstream cylinders for transverse spacing, L_2 = 1D and longitudinal spacings, L_1 = 1D and 2D are negative.

(iii) The total force coefficient (C_F) of an individual cylinder in the staggered form is always less than that of the single cylinder.

(iv) Even though the net wind load on an individual cylinder in staggered form decreases; however, some portions of the surfaces experiences high local C_P.

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