Vortex Shredding In Diamond Array Arrangement of A Cylinder

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Abstract- *Flow past four cylinders which are arranged in a diamond and square shape are simulated using ANSYS WORKBENCH. Flow is considered to be unsteady, incompressible and two dimensional and the examined Reynolds number is 5000. Simulations are performed for different gap to diameter ratio (L/D), ranging from 1.5 to 4, and for two incidence angles, α =* 0^0 *and* 45^0*. The flow characteristics, including the flow patterns, force parameters such as the drag and lift coefficients as well as wake oscillation frequencies (Strouhal numbers) were investigated. The force parameters are highly affected by the spacing ratio, three types of flow patterns were observed depending on the spacing ratio at two different angles of incidence. As the gap to diameter ratio varies from 1.5 to 3, more interference effects have been observed and further increasing the gap to diameter ratio, the flow pattern is similar to the flow past a single cylinder, by comparing both the arrangements square arrangement has been less interference effects.*

I. INTRODUCTION

1.1 General

Circular cylinder has an important role in industry because it is a common structure in many industries, it also has various engineering applications. Its practical applications in various engineering areas include heat exchanger tubes, suspension bridges, offshore platforms, boilers, cooling towers and automobile components. These structures are exposed to either water or air flow, so force induced forces are experienced by these structures, which could lead to failure of the structure. It is better to predict the flow behaviour to avoid the damage of these structures. The study of flow past a single cylinder has been simulated by various researchers. Very less work was done in case of flow past an array of cylinders. It is very difficult to find the flow behaviour in case of flow past an array of cylinders because of interference of vortices and wakes.

1.2 Fluid Dynamics

In fluid dynamics we can learn about the fluids which are in motion. fluid mechanics have two parts one is fluid statistics and the other one is fluid dynamics in fluid statics we can learn about the fluids which are in rest. My present study comes under fluid dynamics because it studies about the behaviour of the fluid in motion. Again in fluid dynamics we have two parts one is aerodynamics and the other one is hydrodynamics.

1.3 Flow Classification

Classification of fluid flow is based on the flow speed, properties of fluid in the flow field with time and space, Reynolds number (Re) and Mach number. Based on this fluid flows are classified as uniform and non-uniform flow, compressible and incompressible flow, steady and unsteady flow, laminar flow, transient flow, turbulent flow, subsonic flow, supersonic flow, transonic flow and hypersonic flow.

1.3.1 Uniform and Non-uniform flow

Velocity of the fluid remains constant along the direction of the flow at any given time is referred as uniform flow

Mathematically represented as

$$\left(\frac{\partial V}{\partial S}\right)_{t=constant} = 0$$

Where ∂V is change of velocity

$\partial S$is flow of fluid in the direction S
Velocity of the fluid varies at any given time with the space is termed as Non-uniform flow
Mathematically represented as

$$\left(\frac{\partial V}{\partial S}\right)_{t=constant} \neq 0$$

1.3.2 Incompressible and Compressible flow

If the density of the fluid doesn't vary from one point to another point means density of the fluid remains constant throughout the flow then the flow is said to be incompressible flow

ρ = constant

Density of the fluid varies from one point to another point then the flow is called as compressible flow

ρ ≠ constant

1.3.3 Steady and Unsteady flow

Properties of the fluid does not change with time at a point is said to be steady flow. Here the fluid properties are density, pressure, velocity, etc.

Mathematically it can be represented as

$$\left(\frac{\partial V}{\partial t}\right)_{x_0,y_0,z_0} = 0 \quad , \quad \left(\frac{\partial p}{\partial t}\right)_{x_0,y_0,z_0} = 0 \quad , \quad \left(\frac{\partial \rho}{\partial t}\right)_{x_0,y_0,z_0} = 0$$

1.3.4 Laminar flow, Transient flow and Turbulent flow

In a flow the fluid particles exhibit streamline path and the stream lines are parallel to each other then the flow is called laminar flow. Wakes or eddies are formed behind the solid body in the flow then the flow is termed as turbulent flow. A zigzag flow path is followed by the fluid particles. Cause of turbulent flow is interaction of inertia and viscous term in the momentum equation

Flow classification based on the Reynolds number as follows:

When Reynolds number < 2200 then the flow is called as laminar flow. Reynolds number > 4000 then the flow is said to be turbulent flow. Reynolds number lies between 2200 and 4000 then the flow is called as transient flow.

1.3.5 Sub-sonic flow, Sonic flow and Super-sonic flow

Mach number is a dimensionless number and it is an important parameter for classifying the flow in case of compressible flows. Mach number is defined as the square root of the ratio of inertia force to elastic force or it is defined as the ratio of velocity of fluid or body moving in the fluid to the velocity of sound in the fluid. It can be represented mathematically as

$$M = \frac{V}{C}$$

Here V represents fluid velocity.
C represents velocity of sound in the fluid.

A flow is said to be Sub-sonic if the flow velocity is less than that of the velocity of sound i.e. $M < 1$. When the velocity of the fluid is equal to that of the velocity of the sound i.e. $M = 1$, then the flow is said to be sonic flow. If the flow velocity is more than that of sound velocity then the flow is said to be supersonic flow i.e. $M > 1$.

II. LITERATURE REVIEW

Tang et al.[1] carried out investigations on flow past twin circular cylinders in tandem arrangement placed near a plane wall. A three step finite element method was used for solving two dimensional Navier-stokes equations. Simulations were carried out at a low Reynolds number of 200 for various dimension less ratios of $0.25<G/D<2.0$ and $1<L/D<4.0$, where D is the cylinder diameter, L is the centre-to-centre distance between the two cylinders, and G is the gap between the lowest surface of the twin cylinders and the plane wall. Effect of G/D and L/D on the hydrodynamic force coefficients, Strouhal numbers and vortex shedding modes were observed. From the results three different vortex shedding modes of the near wake were observed. For various combinations of G/D and L/D the hydrodynamic force coefficients and vortex shedding modes are quite different. The vortex shedding is completely suppressed for very small values of G/D this results in the root mean square (RMS) values of drag and lift coefficients of both cylinders and the Strouhal number for the downstream cylinder being almost zero. For the same combination of G/D and L/D the mean drag coefficient of the upstream cylinder is larger than that of the downstream cylinder. It is also found that changes in the vortex shedding modes leads to a significant increase in the RMS values of drag and lift coefficients.

Kumar and Ray[2] carried out simulations by using the recently developed higher order compact scheme for K=0.0,0.1 and for Re=100,200 where Re is the Reynolds number and K is the shear rate based on cylinder side. Flow is assumed to be two dimensional and incompressible shear flow. Flow past a square cylinder is simulated. Investigations were carried out on the effect of shear rate on the vortex shedding phenomenon in terms of stream function and vorticity contours, lift and drag coefficients employed on the cylinder. Based on the results they observed that the vortex shedding phenomenon strongly depends on the Reynolds number as well as on the shear rate. In general average drag coefficient decreases with increase in the shear rate for fixed

Re and for K = 0.0 − 0.1. Strouhal number decreases with increase in k

Investigations were carried out by **Lin Lu et al.[3]** for laminar flow past a circular cylinder having multiple control rods. Effects of Reynolds number, rod to cylinder spacing ratio, rod and cylinder diameter ratio and angle of attack were calculated. Based on lift and drag reduction four different flow regimes have been identified. As the spacing ratio increases at Re=200 the results for the case of six identical control rods show that the lift fluctuations on the main cylinder can be suppressed significantly for various diameter ratios, drag reduction on the main cylinder can also be achieved simultaneously. When compared to the arrangements with less control rods six control rods has been shown better performance in flow control in terms of force reduction at various angle of attack especially.

Valipouret al.[4] simulated two dimensional, steady and laminar flow around and through a porous cylinder numerically, they have taken the range of Reynolds number and Darcy numbers as 1-45 and 10. Finite volume method is used for solving governing equations together with the boundary conditions, the effects of Reynolds numbers and Darcy numbers on pressure coefficient, wake structures and streamlines have been investigated. The results were compared with the solid and porous diamond square cylinders. Based on the results they found that as the Darcy number increases the wake length and pressure coefficient decreases.

Han et al.[5] have done investigations on flow past four cylinders which are arranged as a square shape, Reynolds number was taken as 200. Spectral element method was used to carry out the simulations .flow characteristics of two groups of cases were studied, one with an incidence angle of $\alpha = 0^0$ and other with $\alpha = 45^0$, here the parameter used is spacing ratio L/D which vary from 1.5 to 4. By changing the spacing ratios the flow characteristics including the flow patterns, statistical force parameters such as the drag and lift coefficients as well as wake oscillation frequencies (Strouhal numbers) have been investigated. Three wake flow patterns were observed in each case, these wake flow patterns are more related with the spacing ratio. Force parameters are highly affected by the flow patterns.

Simulations on flow past two tandem circular cylinders of different diameters were done by **Wang et al.[6]** using finite volume method. They kept the diameter of the downstream main cylinder as constant and varied the diameter of the upstream control cylinder. They have taken the input parameters as gap-to-diameter ratio (G/D) and the diameter ratio between the two cylinders (d/D). The gap between the control cylinder and the main cylinder (G) ranged from 0.1Dto 4D. They found that the gap-to-diameter ratio(G/D) and the diameter ratio between the two cylinders(d/D) have considerable effect on the drag and lift coefficients, pressure distributions around the cylinders, vortex shedding frequencies from the two cylinders and flow characteristics.

Yan et al.[7] performed investigations on flow around an inline cylinder array consisting of six square cylinders, they have taken the Reynolds number as 100. A second order characteristic-based split finite element algorithm was used. The numerical method and code were validated for the flow past a single and two tandem square cylinders and the present results were agreeing well with the available literatures. The effect of spacing ratio on flow characteristics was studied by identifying flow patterns, extracting pressure distributions and force statistics such as wake oscillation frequencies. Six different flow patterns were observed. Flow field around the critical spacing range was analysed to find the crucial mechanism behind the observed aerodynamic characteristics.

Square and circular cylinders were placed in a boundary layer flow which was formed over a flat plate, flow over this arrangement has been simulated by **Harichandan and Roy[8]**. Investigations are carried out to identify the behaviour of vertical wake created by this arrangement. Simulations are performed by using finite volume method. They have taken the parameters as Reynolds number, distance of the cylinder from the plane wall and longitudinal gap between two cylinders. To study the effect of these parameters simulations are performed for various gap ratios (g^*). The ratio of the gap (G) and the characteristic cross-stream dimension of the cylinder is known as gap ratio. For square cylinder the characteristic dimension is the length of a side of the cylinder (H) and for circular cylinder diameter of the cylinder was taken as characteristic dimension. An intensive interaction was observed between the vorticity in the boundary layer formed over the plane wall and the vorticity associated with the shear layer from separation points on the cylinder surface due to this complex flow field is observed in the wall gap and cylinder wake. They have made an attempt to analyse these complex flow features through numerical flow visualization tools like vorticity contours and streamlines.

Dehkordiet al.[9] performed simulations on flow around two circular cylinders in tandem arrangement for both laminar and turbulent flows, they have considered flow as 2D unsteady viscous flow. Flow visualization parameters, strouhal numbers, drag and lift coefficients were calculated for different cases based on the Reynolds number and gap spacing. From the results they observed two completely different flow characteristics in laminar and turbulent regimes. Simulations on three dimensional cross flow past a four circular cylinders in diamond arrangement were done by **Zou Lin et al.[10]** at Re=200 and for different spacing ratios where L/D varies from 1.2 to 5, they observed a single bluff body flow pattern at L/D=1.2 and they also observed the critical spacing ratio as L/D=3 where the transition of flow from narrow gap flow pattern to vortex impingement flow pattern, three kinds of flow patterns have been observed based on the spacing ratio and also observed the variation of forces and Strouhal number with L/D, They finally concluded that the spacing ratio has significant effect on flow characteristics, force and pressure characteristics.

Berroneet al.[11] carried out simulations on flow past a rectangular cylinder by using both adaptive finite element and finite volume methods. They have taken a rectangular cylinder with width to height equal to 5. They considered different flow regimes, i.e. the stationary, the periodic and the turbulent flow. 2D computations are performed for different Reynolds numbers in order to consider all these flow regimes. Velocity profiles, strouhal number, drag coefficient and recirculation lengths have compared and found that both the methods are agreeing well with each other and also with the available literature results.

Atal and Roy[12] performed simulations on unconfined flow past a single cylinder, two cylinders and three cylinders. Reynolds numbers have been taken as 100 and 200, simulations were carried out using consistent flux reconstruction method, they compared the present results with the results available in the previous literatures for validation of the code and they found that the results were agreeing well with other literature works. They have taken the input parameter as gap between the cylinders and the reynolds number for both side by side and tandem arrangements. They observed different wake patterns based on the Reynolds number and gap spacing.

Yan Bao et al.[13] numerically investigated flow past a three circular cylinders arranged in equilateral triangle. They have taken Reynolds number as 100 and other parameters are gap spacing and incidence angles. Computations are performed for six gap spacings ‘s’ ranging from 0.5 to 4.0 and for three incidence angles, from the results they observed that at sufficiently small and large s, the range of which is different for different α the flow interference is dominated by proximity and wake effect and in the intermediate range of spacing, the flow pattern is influenced by both of them. The present results were compared with the existing experimental results and that shows a similar variation of mean force with spacing for different Reynolds numbers. They also observed that interference effect in transitions plays an important role with respect to the fluctuating force and strouhal number

Analysis on two and three dimensional flow past a circular cylinder in different laminar flow regimes has been done by **Rajani et al.[14]**. Simulations uses an implicit pressure based finite volume method which is used for time accurate computation of incompressible flow using second order accurate convective flux discretisation schemes. The computation results were validated against measurement data for mean surface pressure, skin friction coefficients, the size and strength of the recirculating wake for the steady flow regime and also for the Strouhal frequency of vortex shedding and the mean and RMS amplitude of the fluctuating aerodynamic coefficients for the unsteady periodic flow regime.

Meneghiniet al.[15] carried out simulations using a fractional step method and the flow is assumed to be two dimensional. The shedding of vortices and flow interference between the cylinders which were arranged in tandem and side by side were investigated numerically here the input parameter is Reynolds number varying from 100 to 200. Finite element method was used for solving the flow. For better description of the boundary layer the mesh was made finer close to the cylinder wall. Vorticity contours of the flow around the cylinders and force time histories have been showed. The present results were also compared with the experimental results of Bear man &Wadcock in 1973 and Williamson in 1985.

III. PROBLEM DESCRIPTION AND PROCEDURE

3.1 Computational Modelling

Computational fluid dynamics is a computer aided engineering tool.it can be designed for analysing the problem involved in heat transfer, fluid motion etc. it gives good result and it has more advantages over experimental approach in terms of reduction of computational time and cost. The computer based soft wares like Auto-Cad, Ansys and Solid works are used for optimisation of numerical models. The differential equations governing the flow are converted to transport equation for the numerical algorithm which is later followed by the software for simulation purpose.

3.2 Numerical Analysis

Methodology:

My present paper contains four cylinders which are arranged at 0^0 angle and 45^0angle. Flow over these four cylinders are simulated using ANSYS WORKBENCH (FLUENT). Air is taken as a fluid. Flow is taken as two dimensional, incompressible and turbulent.

3.3 Problem Specification

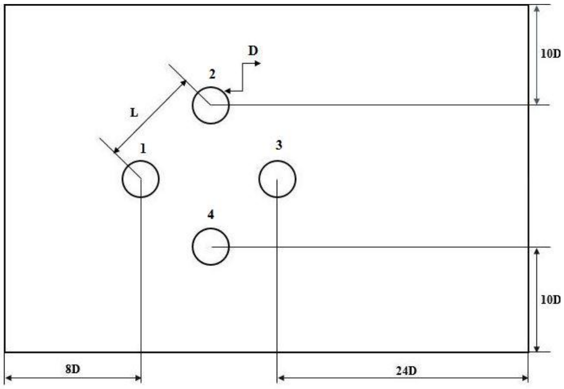


Fig. 3.1 Schematic Diagram of Computational Domain with Four Cylinders in Diamond Arrangement(0^0 angle)

- Cylinder 3 is in downstream of cylinder 1 in tandem, while cylinders 2 and 4 are side by side arranged
- The spacing ratio L varies from 1.5D to 4D in the present simulation
- The inlet boundary is at a distance of 8D from the centre point of the cylinder 1, while the outlet boundary is 24D away from the centre point of the cylinder 3,Each lateral surface is 10D away from the centre point of the cylinders 2 and 4
- Here the spacing ratio L/D varies from 1.5 to 4

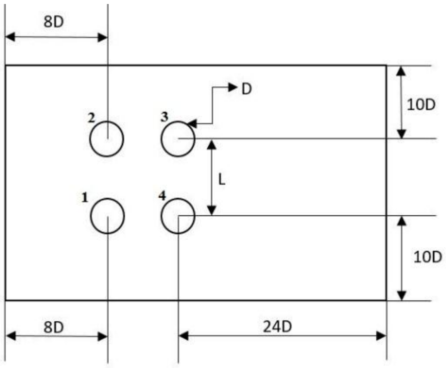


Fig. 3.2 Schematic Diagram of Computational Domain with Four Cylinders in Square Arrangement(45^0 angle)

IV. RESULTS AND DISCUSSION

Flow over a circular cylinder is simulated for different spacing ratios and for two different angles of arrangement those are 0^0 and 45^0. Variation of coefficient of drag with different spacing ratios, variation of lift coefficient with different spacing ratios, variation of Strouhal number for all cylinder with different spacing ratios and for two different incidence angles were plotted in this chapter. Velocity contours, pressure contours and stream lines are also presented at each spacing ratio for two different angles of arrangement.

4.1 Validationfor single cylinder (laminar flow)

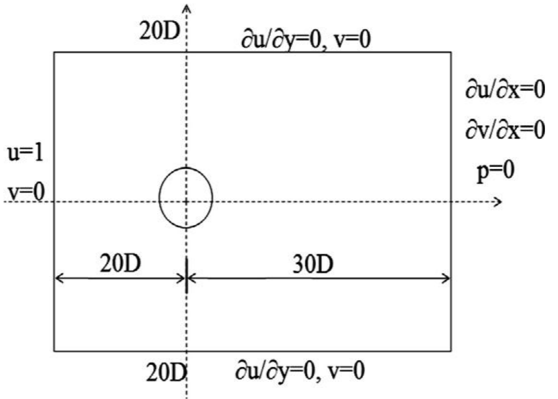


Fig.4.1 Computational domain for single cylinder

- Unsteady, laminar flow past a single cylinder is taken as a reference problem to validate the software.
- Validation is necessary in order to confirm that the results obtained from the simulation are correct.
- Diameter of cylinder is taken as 1m and Reynolds number is taken as 100.

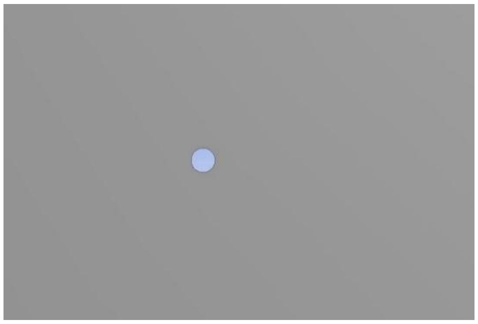


Fig.4.2 Ansys Geometry modelgiven to the computational for single cylinder

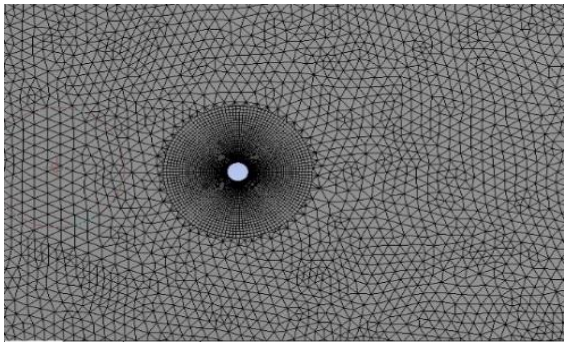
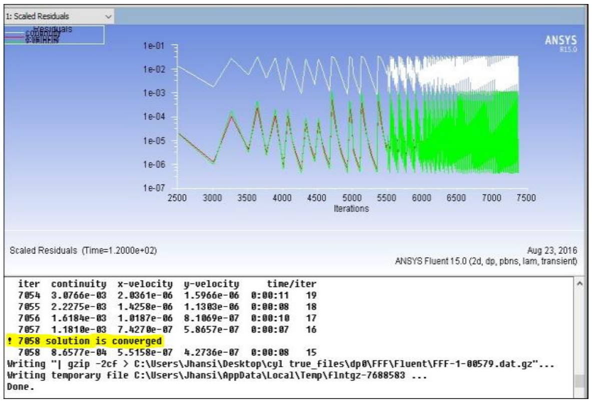


Fig 4.3 Mesh domain

The results for the single cylinder are shown below:



Scaled Residuals (Time=1.2000e+02)

Aug 23, 2016
ANSYS Fluent 15.0 (2d, dp, pbns, lam, transient)

```
  iter  continuity  x-velocity  y-velocity     time/iter
  7054  3.0766e-03  2.0361e-06  1.5966e-06  0:00:11   19
  7055  2.2275e-03  1.4258e-06  1.1303e-06  0:00:08   18
  7056  1.6184e-03  1.0187e-06  8.1069e-07  0:00:10   17
  7057  1.1810e-03  7.4270e-07  5.8657e-07  0:00:07   16
! 7058 solution is converged
  7058  8.6577e-04  5.5158e-07  4.2736e-07  0:00:08   15
Writing "| gzip -2cf > C:\Users\Jhansi\Desktop\cyl true_files\dp0\FFF\Fluent\FFF-1-00579.dat.gz"...
Writing temporary file C:\Users\Jhansi\AppData\Local\Temp\flntgz-7688583 ...
Done.
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Fig. 4.4 Convergence of a solution for single cylinder

Contours and streamlines:

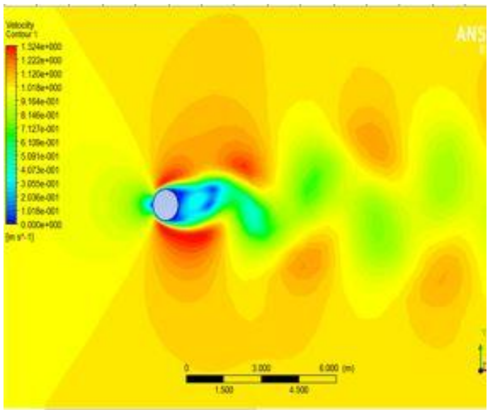

Fig.4.5 Velocity Contours

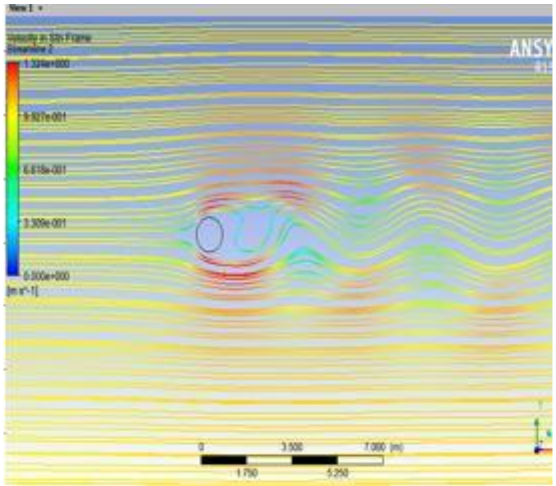

Fig.4.6 Streamlines

4.2 Comparison of results with other literature works

Results of the present work are same as the other literature work results. Validation of software is done

4.3 Results of present work

4.3.1Velocity contours for diamond arrangement(0^0 angle)

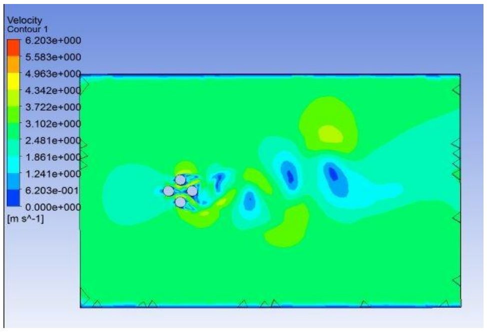

Fig.4.7 Velocity contours for diamond arrangement at L/D=1.5

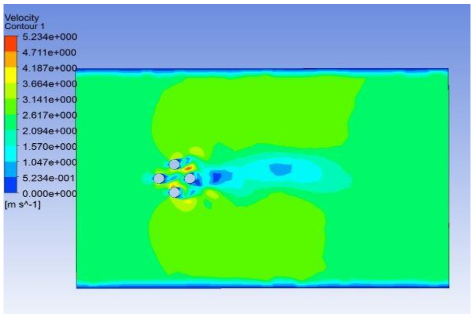

Fig.4.8 Velocity contours for diamond arrangement at L/D=2

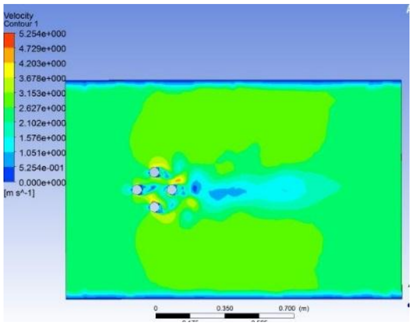

Fig.4.9 Velocity Contours for diamond arrangement at L/D=2.5

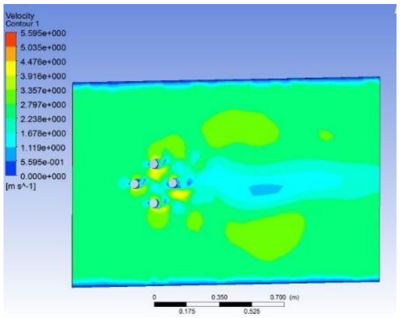

Fig.4.10 Velocity Contours for diamond arrangement at L/D=3

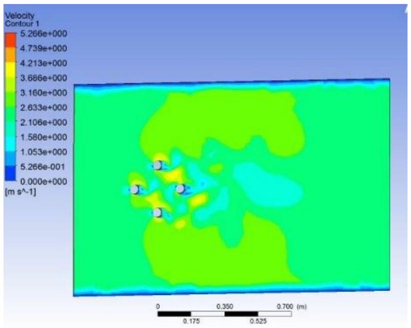

Fig.4.11 Velocity Contours for diamond arrangement at L/D=3.

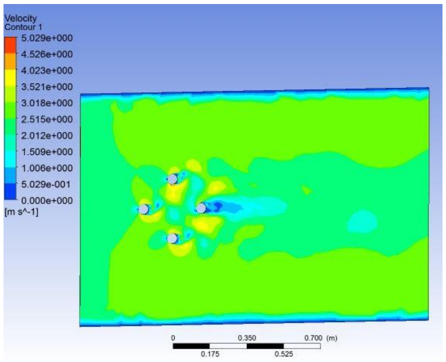

Fig.4.12 Velocity contours for diamond arrangement at L/D=4

4.3.2 Velocity contours for square arrangement (45^0 angle)

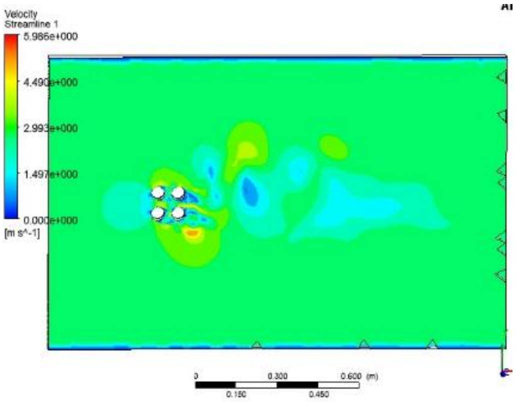

Fig.4.13 Velocity contours for square arrangement at L/D=1.5

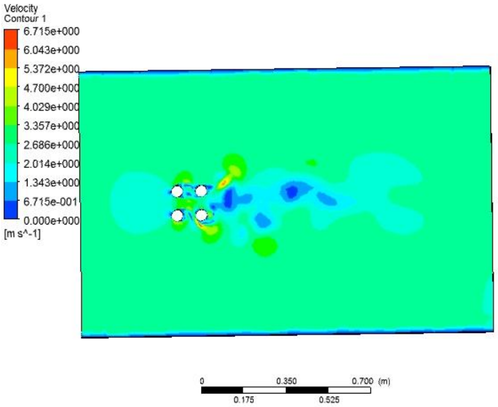

Fig.4.14 Velocity contours for square arrangement at L/D=2

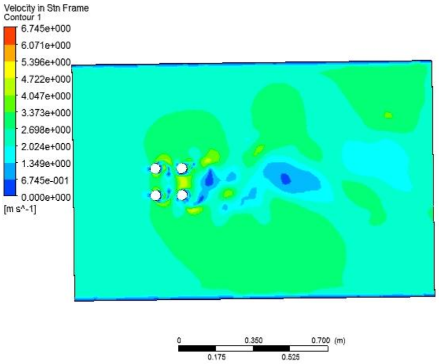

Fig.4.15 Velocity Contours for square arrangement L/D=2.5

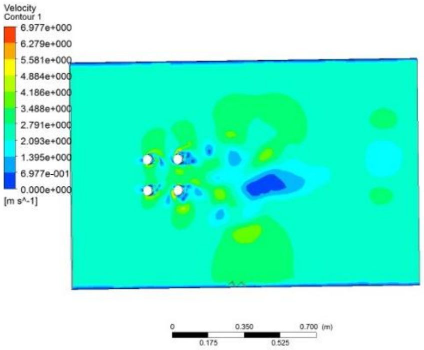

Fig.4.16 Velocity Contours for square arrangement at L/D=3

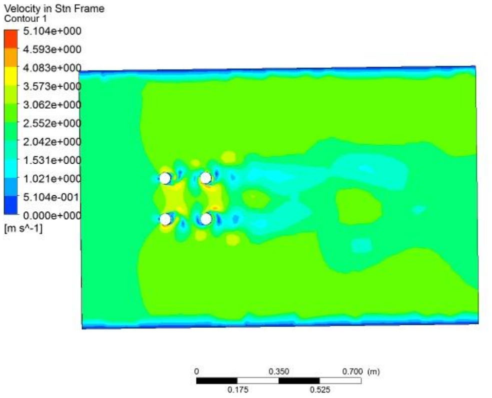

Fig.4.17 Velocity Contours for square arrangement at L/D=3.5

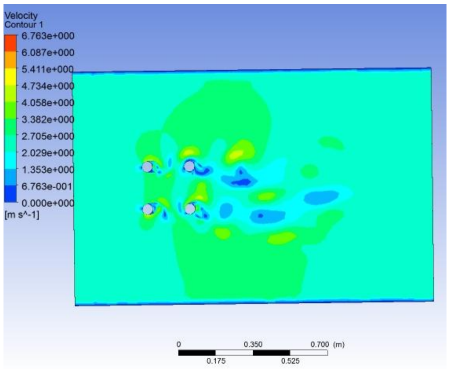

Fig.4.18 Velocity contours for square arrangement at L/D=4

From the velocity contours the following observations were made:

Narrow gap flow i.e. high jet flow takes place at small spacing ratio, formation of vortices were completely eliminated. As the spacing ratio increases from 2.5 to 3 transition of flow takes place from narrow gap flow to vortex impingement flow. Both proximity and wake effects are present at this spacing ratio. So, interference effects are high. With further increasing the spacing ratio interference effects are reduces and vortex impingement flow pattern takes place, vortices are formed from each cylinder like a single cylinder.

4.3.3 Drag coefficient for diamond arrangement (0^0 angle)

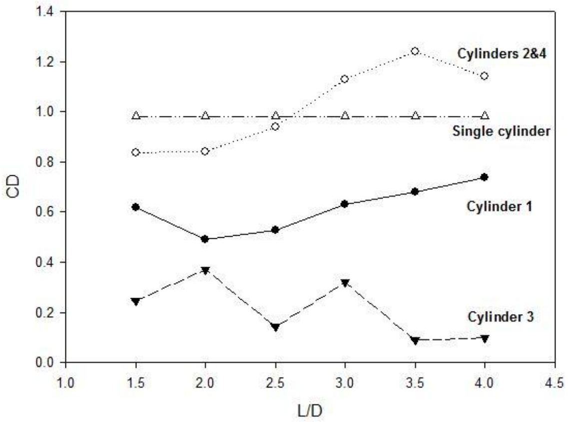

Fig.4.19 Variation of Drag coefficient (C_D) with Spacing ratio (L/D) for Diamond arrangement(0^0 angle)

- C_{D3} is always lower than C_{D1}, C_{D2} & C_{D4} due to the fact that it is located directly downstream of cylinder1
- When L/D = 1.5 cylinder 3 is completely located in the wake of cylinders 1,2 and 4 so, the drag mainly acts on upstream cylinders 1,2 and 4
- Drag on cylinder 2 is always high because it has to overcome the flow separately.
- When L/D increases up to 2, the free shear layers of cylinder1 reattaches on to cylinder 3 and a part of drag is assigned to cylinder 3. Consequently the drag on cylinder 1 decreases
- When L/D increases from 2 to 3, such an abrupt increase in the value of C_{D2} & C_{D4} is due to the transition of flow pattern from gap flow to the vortex impingement flow
- The drag on cylinder3 fluctuates this is due to the effect of impingement of vortices from cylinder1 on cylinder3 this changes the drag on cylinder3

4.3.4 Lift coefficient for diamond arrangement (0^0 angle)

Table 4.3 Values of Lift coefficient for diamond arrangement (0^0 angle) at different spacing ratios

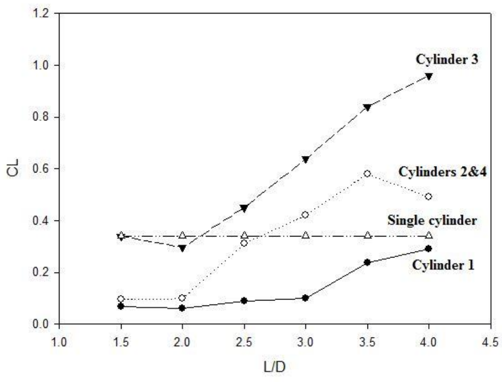

Fig.4.20 Variation of Lift coefficient (C_L) with Spacing ratio(L/D) for Diamond arrangement

- There is a little change of lift coefficient at the ranges of $L/D \leq 2$ this is because at the range of this spacing ratio there is no vortex shedding occurring on cylinders
- At higher than the critical value of 2, the vortex starts to shed which causes an increase in value of C_{L2} &C_{L4}. Similar results also found in case of C_{L1} at L/D=2
- At L/D=3.5, C_{L2} &C_{L4} reaches the maximum value and decreases at high spacing ratio due to the absence of interference effects between wakes of cylinders at high spacing ratio
- C_{L3} increases with increase of L/D this is because of the wake flows from both cylinders 1 and 2 have great impact on the cylinder3

4.3.5 Strouhal number for diamond arrangement (0^0 angle)

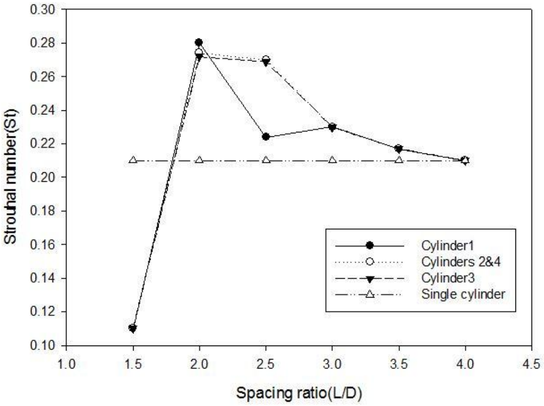

Fig.4.21 Variation of Strouhal number with spacing ratio

- At small spacing ratio Strouhal number for all cylinders is same because the gap flow effects all cylinders at the same time
- Due to interaction of free shear layers at the spacing ratio 2.5 leads to complicated flow frequencies
- Effect of shear layers from cylinder 1 causes the high frequencies for cylinders 2, 3 and 4 at the spacing ratio of 2.5 because at this spacing ratio interference effects are high which leads to these changes in Strouhal number
- As spacing ratio increases further the Strouhal number for all the cylinders reaches the value of the single cylinder due to the shedding of vortices at higher spacing ratio is similar to the flow past a single cylinder

4.3.6 Drag coefficient for square arrangement (45^0 angle)

Due to the symmetrical configuration the results for cylinders 1&2 are same and similarly results for cylinders 3&4 are same due to the symmetrical configuration.

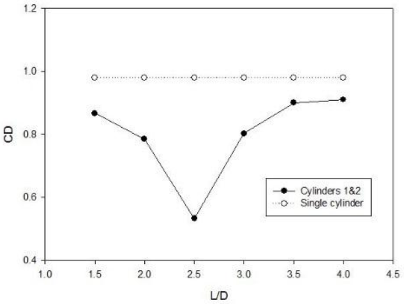

Fig.4.22 Variation of Drag coefficient with different spacing ratios for square arrangement (45^0 angle) and for cylinders 1&2

- Drag on cylinders decreases with spacing ratio from 1.5 to 2.5 because at small spacing ratio high jet flow takes place due to the small gap so, the drag on cylinder is high after that as the spacing increases gap flow increases so, the drag on cylinders again decreases
- At small spacing ratio formation of wakes is completely eliminated due to narrow gap flow so, the entire arrangement behaves like a single cylinder
- The sudden increase in the value of drag coefficient from spacing ratio 2.5 to 3 indicates the transition of flow pattern from narrow gap flow pattern to the vortex impingement flow pattern
- At this gap spacing both proximity and wake effects are presented so, high drag was observed
- With further increasing the gap spacing vortex impingement flow pattern takes place means vortices are formed from the cylinders independently, again the drag on cylinder increases and reaches the value of single cylinder

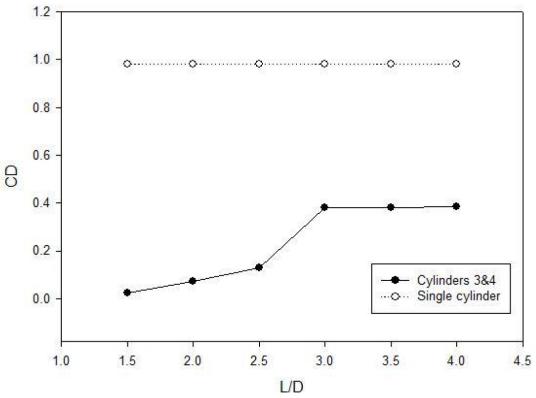

Fig.4.23 Variation of Drag coefficient with Spacing ratio for square arrangement (45^0 angle) and for Cylinders 3&4

- With increase of gap spacing the drag on cylinders 3&4 increases
- Because at small spacing ratio the downstream cylinders are completely submerged in the free shear layers of upstream cylinders so, very less drag is assigned to the cylinders 3 &4 at small spacing ratio
- With further increasing the gap spacing the free shear layers from cylinders 1&2 attaches on to the cylinders 3&4 so, some amount of drag is also assigned to the cylinders 3&4 so, the drag on cylinders 3&4 increases as spacing ratio increases from 1.5 to 2.5
- Sudden increase of drag coefficient with the spacing ratio from 2.5 to 3 indicates the transition of flow from gap flow to the vortex impingement flow
- With further increasing the gap spacing vortex impingent flow takes place means vortices are shed from the cylinders independently.

4.3.7 Lift coefficient for square arrangement (45^0 angle)

Table 4.6 Values of Lift coefficient for square arrangement (45^0 angle) at different spacing ratios

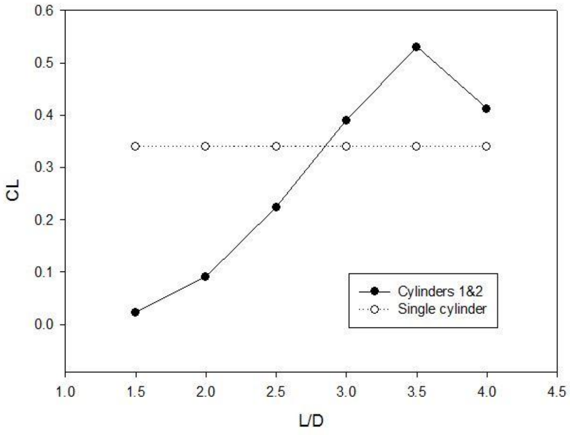

Fig.4.24 Variation of Lift coefficient with spacing ratio for square arrangement(45^0 angle) and for cylinders 1&2

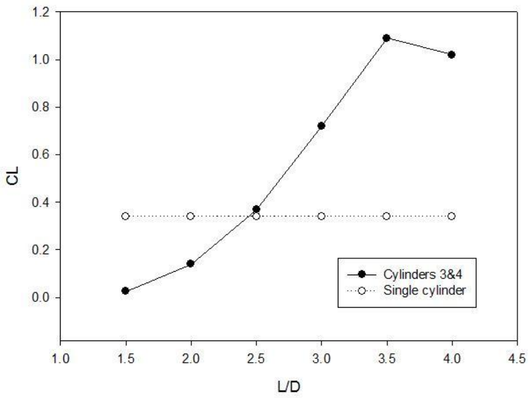

Fig.4.25 Variation of Lift coefficient with spacing ratio for square arrangement and for Cylinders 3&4

- As the spacing ratio increases from 1.5 to 3.5 lift coefficient increases for all the cylinders
- Vortices from the upstream cylinder are fully developed and begin to shed at L/D=3.5 and then move toward and periodically impinge on the downstream cylinders
- Due to this impingement of vortices on downstream cylinders causes large value of lift coefficient on downstream cylinders
- At small spacing ratio no vortices are formed so, lift coefficient is very less, lift coefficient increases with increasing the spacing ratio due to the shedding of vortices
- Lift coefficient again decreases beyond the spacing ratio 3.5, this indicates the absence of interference effects

4.3.8 Strouhal number for square arrangement (45^0 angle)

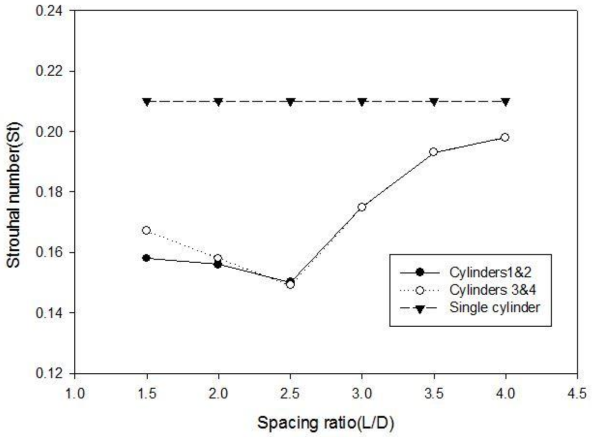

Fig.4.26 Variation of Strouhal number with Spacingratio for square arrangement (45^0 angle)

- At small spacing ratio flow pattern is similar to the flow past a single cylinder i.e the flow past an entire arrangement is similar to the flow past a single cylinder only one vortexshedding array could be observed
- From the spacing ratio L/D=1.5 to 2.5 flow pattern was changed which could be responsible for the reduction of the Strouhal number
- As the spacing ratio increases further Strouhal number also increases due to the formation of vortices and reaches the value of single cylinder because at large spacing ratio interference effects are eliminated, each cylinder behaves like a single cylinder

4.3.9 Diamond arrangement

- In case of diamond arrangement the drag on cylinders 2 and 4 is high because those have to overcome the flow separately.
- The drag on cylinder3 fluctuates this is due to the effect of impingement of vortices from cylinder1 on cylinder3 this changes the drag on cylinder3.
- Drag on cylinders 2&4 is higher than the drag of the single cylinder. At L/D ≥2 lift on cylinders 2, 3 & 4 is higher than the single cylinder.

4.3.10 Square arrangement

- In this case coefficient of drag for all cylinders is less than the coefficient of drag on single cylinder.
- Upstream cylinders have high amount of drag when compared to downstream cylinders because upstream cylinders have to overcome the flow directly
- Downstream cylinders have high amount of lift when compared to the upstream cylinders because of the impingement of vortices from upstream cylinders

4.4 Comparison between two arrangements

- When compared to square arrangement large amount of drag coefficient was observed in diamond arrangement i.e. higher than the single cylinder. But the lift coefficient is high in case of square arrangement however this difference in lift coefficient is very small.
- When compared to square arrangement Strouhal number is high in case of diamond arrangement this is due to the presence of high interference effects
- In case of diamond arrangement interference effects are due to the action of shear layers from cylinder 1 on cylinders 2,3 and 4 which are located directly downstream of cylinder1

4.5 Streamlines for Diamond arrangement(0^0 angle)

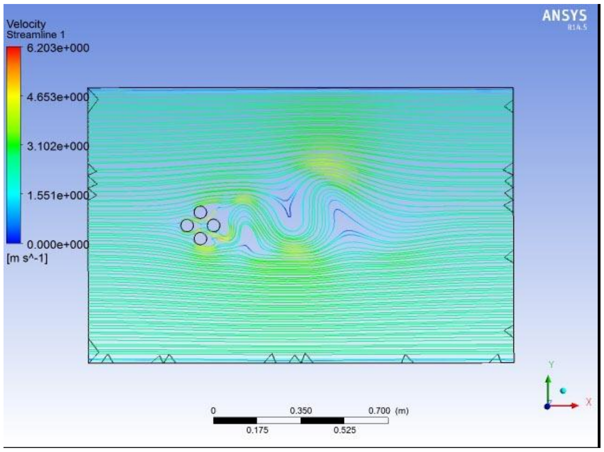

Fig.4.27 Streamlines for diamond arrangement at L/D=1.5

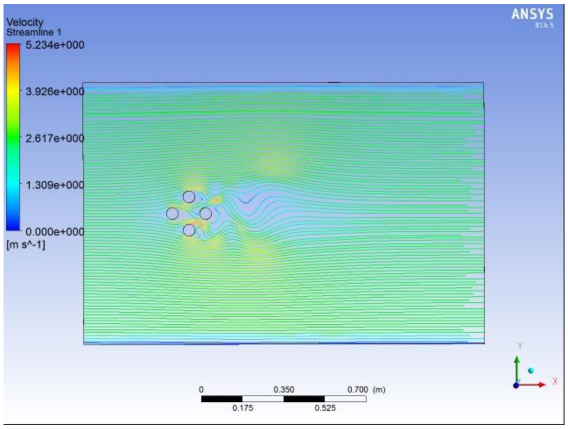

Fig.4.28 Streamlines for diamond arrangement at L/D=2

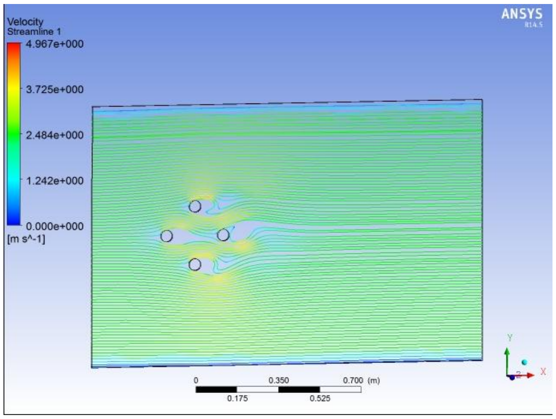

Fig.4.29 Streamlines for diamond arrangement at L/D=3.5

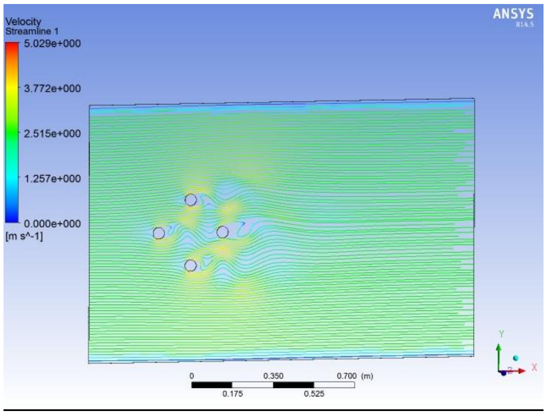

Fig.4.30 Streamlines for diamond arrangemnet at L/D=4

4.6 Streamlines for square arrangement(45^0 angle)

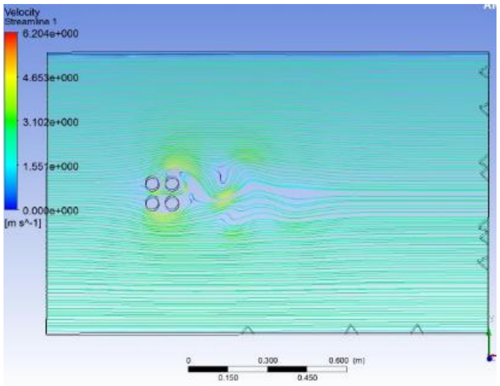

Fig.4.31 Streamlines for square arrangement at L/D=1.5

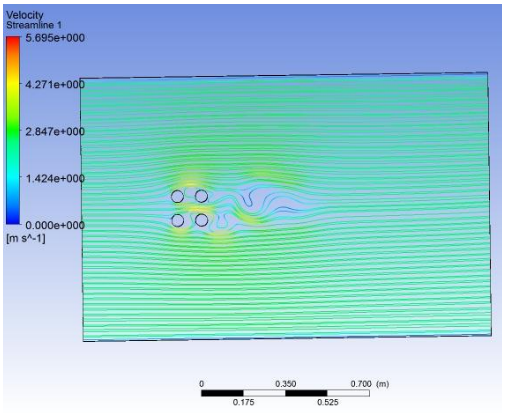

Fig.4.32 Streamlines for square arrangement at L/D=2

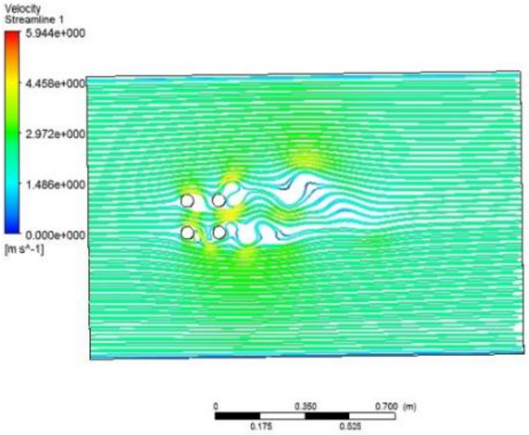

Fig.4.33 Stream lines for square arrangement at L/D=2.5

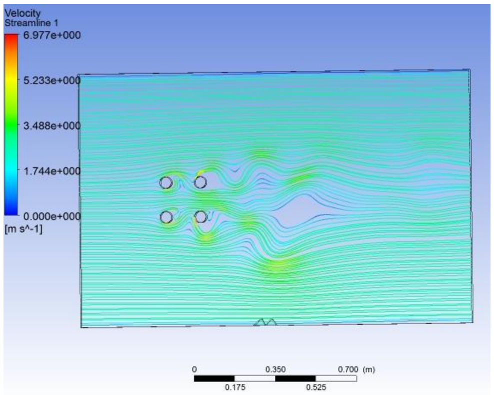

Fig.4.34 Stream lines for square arrangement at L/D =3

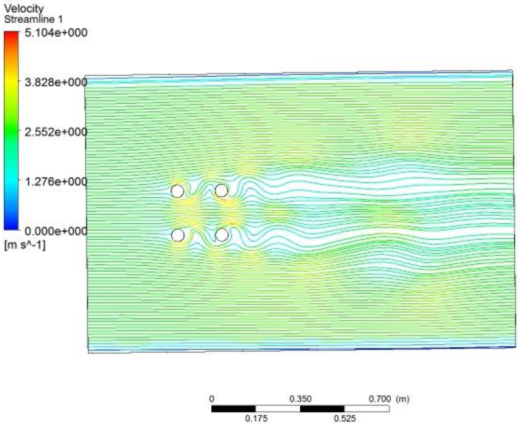

Fig.4.35 Stream lines for square arrangement at L/D=3.5

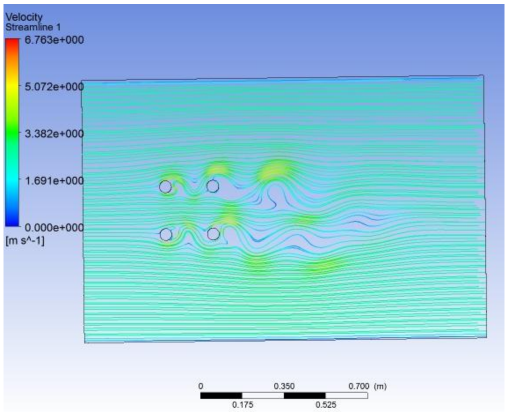

Fig.4.36 Stream lines for square arrangement at L/D=4

V. CONCLUSIONS

- Three types of flow patterns were observed depending up on the spacing ratio.
- At small spacing ratio(L/D=1.5) the overall flow past a four circular cylinders is similar to the flow past a single cylinder because gap flow is completely supressed at small spacing ratio and downstream cylinders are completely submerged in the wakes which were formed behind the upstream cylinders
- At the spacing ratio of 2.5 to 3.5 transition of flow pattern takes place from narrow gap flow to vortex impingement flow, high interactions and very complicated flow was developed.
- With the spacing ratio from 3.5 to 4 vortex impingement flow was developed means vortices were fully developed and shed down from the cylinders
- The drag coefficient and Strouhal number are high in diamond arrangement as compared to square arrangement because of less interference effects in square arrangement

5.2 Scope for future work

- Work can also be done for flow past four circular cylinders arranged at an incidence angles of 30^0 and 60^0
- Simulations are also carried out by varying cross sections (square, triangle and polygons)

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