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Numerical analysis of fluid forces and heat transfer characteristics around tandem rounded corners square cylinders

BiswajitDatta[1]*,Prasenjit Dey[2],Ajoy Kumar Das[3]and Dipak Debbarma[4]
[1,4] *Tripura Institute Of Technology, Agartala, India.*
[2] *Indian Institute of Technology Bombay, Mumbai, India.*
[3] *National Institute of Technology, Agartala, India.*
**corresponding author; Biswajit Datta*

ABSTRACT
A numerical investigation is performed to study the effect of rounding corners on flow and heat transfer characteristics around tandem square cylinders. Two isothermal square cylinders with rounded corners are considered in tandem arrangement in two dimensional unsteady incompressible laminar flow regime. The flow configurations over two equal square cylinders in tandem arrangement are carried out on a finite volume code based commercial software ANSYS FLUENT. The rounded corners have a corner radius of d/4, d is projected width of the square cylinder. The Reynolds number (Re) of the flow is kept constant at 100. In the present computation, the spacing between the two cylinders are kept as 4d, 5d, 6d, 7d, 8d, 9d and 10d. Numerical results are presented in form of streamlines, vorticity contours, isotherm patterns, drag coefficients, Nusselt number and RMS lift. About 19.29 % enhancement in heat transfer is observed.
Keywords—Heat transfer; Numerical simulation; Tandem arrangement; Rounded corners; Square Cylinder.

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I. INTRODUCTION

Different cross section of cylinders e.g. circular and square have many applications in engineering such as heat exchanger tubes, high-rise buildings, electronics cooling , wind turbine farms, chimney stacks, cooling tower, offshore structure etc. When fluid flows over these cylinders, separation occurs from both sides of the cylinder and instability is produced in the flow field that cause periodic shedding of vortices from the cylinder. The flow interaction about groups of cylinders is becoming an increasingly popular field of many studies. The interference of flow is responsible for several changes in the characteristics of the flow around pairs of cylinders which can provide a better understanding of the vortex shedding and aerodynamic forces, in cases involving more complex arrangements. Some examples including; group of electrical transmission lines, tall buildings and skyscrapers in a city, cooling towers, chimneys, pipelines, cables and bundles of tubes in heat exchangers. These flows usually include some complex events such as separation flow, wake region, shear flow and eddy shedding. Cylindrical geometries like Square often appear in many structures and industrial applications. Although these structures are very simple, the flow pattern around them is not. The bluff body like square cylinder can forms a large separated region and a massive unsteady wake downstream. Separated wake and its patterns are nearly impossible to predict analytically and hence must be solved either through experimental and numerical methods. N Mahiret al [1] investigated numerically unsteady laminar convective heat transfer from two isothermal cylinders of tandem arrangement for the Re of 100 and 200. The flow parameters such as the Strouhal numbers, lift and drag coefficients are obtained. Sharma and Eswaran [2] studied the flow structure and heat transfer characteristics for an isolated sharp corners square cylinder. A drastic change in the flow and heat transfer characteristics of the cylinder can occur if sharp corners of the square cylinder are changed with the rounded corners. S. K. Singh [3] performed at Re = 100 the effect of rounding corners on flow and heat transfer characteristics around a square cylinder. Heat transfer enhancement and drag co-efficient reduction is observed due to rounded corners of the square cylinder. R. A. Kumar et al [4] investigated using the particle image velocimetry (PIV) technique, the near wake characteristics of transversely oscillating square-section cylinders with different corner radii. For both under stationary and oscillating conditions corner radius was significant influence on characteristics of the flow around the bodies. P. Dey et al [5] have done a numerical investigation of Drag and lift reduction of two dimensional unsteady flow over a triangular extended solid (thorn) attached with square cylinder. Using thorn they observed an enormous fall in drag and lift. F. Nikfarjam et al [6] investigated numerically the low-Reynolds numbers free-stream flow of power-law fluids and forced convection heat transfer around a square cylinder and two square cylinders in a tandem arrangement. In the tandem case, the spacing between the cylinders is four widths of each cylinder side and Re= 40, 100, 160 and Pr= 0.7.Vikram C. K et al [7] investigated numerically two dimensional unsteady flow past two square cylinders with in-line arrangements in a free stream. The main aim of the study is to systematically investigate the influences on size of the eddy, monitored velocity, frequency of vortex shedding, pressure coefficient and lift coefficient by varying pitch to perimeter Ratio of two square cylinders. P. Dey et al [8] investigated numerically on unsteady two-dimensional laminar forced convection heat transfer around a square cylinder with rounded corner edge for Pr = 0.01–1,000 and non-dimensional corner radius, r=0.50–0.71 at Re = 100. Huy Cong Vu et al[9] studied numerically to compare the characteristics of flows past two cylinders in tandem versus side-by-side arrangements and performed at various Re and with different distances between the two cylinders. Drag force, vortex shedding, and pressure distributions were investigated. Guo Sheng He et al [10]performed experimentally an analysis on flow around square cylinders with cut-corners at the front edges using particle image velocimetry. T. Tamura et al [11] studied the effect of corner shape on aerodynamic characteristics of the square cylinder. Vikram C. K. et al [12]investigated numerically flow past circular and square body for Re 100 and 200 by using commercial CFD code fluent with two dimensional analysis. S.C. Yen et al [13] studied experimentally the effects of the Reynolds number, spacing ratio and rotation angle of the downstream cylinder on flow characteristic modes, drag coefficients and vortex shedding properties of two identical square cylinders were installed in tandem in a vertical water tank. A. Sohankar [14] investigated numerically two-dimensional and three-dimensional unsteady flow over two square cylinders arranged in a tandem arrangement. Okajima[15]investigated experimentally on the vortex-shedding frequencies of various rectangular cylinders conducted in a wind tunnel and in a water tank. The results show how Strouhal number varies with a width-to-height ratio of the cylinders in the range of Reynolds number between 70and 2x 10^4**.** C. Norberg[16] performed an experimental investigation of the flow around and pressure forces on fixed(non vibrating) rectangular cylinders at angles of attack 0^0 to 90^0. Pressure forces and moments for cylinders with side ratios from 1-3 were estimated. Wake frequencies and associated Strouhal numbers were determined from hot wire measurements in the near wake regions. Sharma and Eswaran[17] investigated the flow and heat transfer characteristics from a square cylinder in the steady and unsteady flow regimes up to Re = 160 for the isothermal and constant heat flux boundary conditions.

II. GOVERNING EQUATIONS AND NUMERICAL DETAILS

2.1 Geometrical configuration

The schematically representation of the present problem is shown in Figure 1. The behaviour of the forced convection around tandem square cylinders with rounded corner edges placed in a channel at the symmetric horizontal line. The cylinder has a projected width, 'd' and a corner radius 'r'. Two isothermal square cylinders with constant wall temperature, 'T_w' is held stationary in a channel in tandem arrangement subjected to free stream temperature T∞ and upstream unsteady laminar flow of x-velocity, u=U∞ (free stream velocity) .

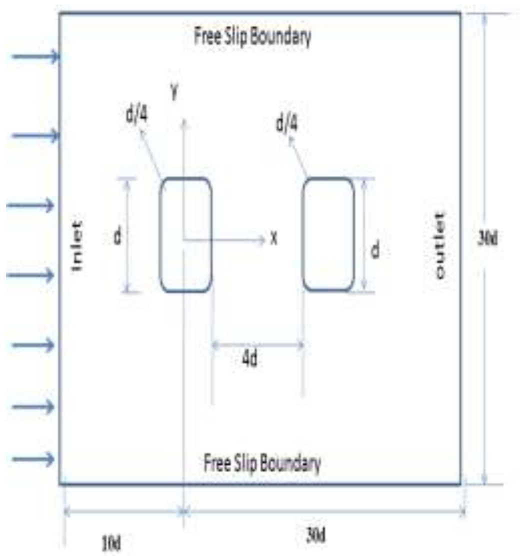


Fig.1: Schematic diagram of physical model and computational domain for rounded corners tandem square cylinder.

2.2 Governing equations

The fluid flow is assumed two dimensional, unsteady, laminar, incompressible and heat transfer with constant thermo-physical properties and negligible dissipation effect. The Non-dimensional governing equations can be expressed in the following forms:

Continuity

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

Momentum

$$\frac{\partial u}{\partial t}+\frac{\partial uu}{\partial x}+\frac{\partial vu}{\partial y}=-\frac{\partial p}{\partial x}+\frac{1}{Re}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)$$

$$\frac{\partial v}{\partial t}+\frac{\partial uv}{\partial x}+\frac{\partial vv}{\partial y}=-\frac{\partial p}{\partial y}+\frac{1}{Re}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)$$

Energy

$$\frac{\partial \theta}{\partial t}+\frac{\partial (u\theta)}{\partial x}+\frac{\partial (v\theta)}{\partial y}=\frac{1}{Re\,Pr}\left(\frac{\partial^2 \theta}{\partial x^2}+\frac{\partial^2 \theta}{\partial y^2}\right)$$

Where u, v are the dimensionless velocity components along x and y directions of a Cartesian coordinate system respectively, p is the dimensionless pressure, Re (= ρU∞d/μ), is the Reynolds number based on the cylinder dimension "d", θ is the dimensionless temperature, Pr (= μCp/k), is the Prandtl number and t is the dimensionless time. The fluid properties are described by the density ρ, dynamic viscosity μ, thermal conductivity k and specific heat capacity Cp. The dimensionless variables are defined as:

$$u=\frac{\bar{u}}{U_\infty}, v=\frac{\bar{v}}{U_\infty}, x=\frac{\bar{x}}{d}, y=\frac{\bar{y}}{d},$$

$$p=\frac{p}{\rho U^2{}_\infty}, \quad \theta=\frac{T-T_\infty}{T_W-T_\infty}, t=\frac{U_\infty t}{d}$$

Where, $\bar{u}$ and $\bar{v}$ are the velocity components in the $\bar{x}$ and $\bar{y}$ directions respectively, T is the temperature. Following boundary conditions are used:

At the inlet: U = 1, V = 0 and θ = 0,

At the outlet:

$$\frac{\partial U}{\partial Y}=\frac{\partial V}{\partial Y}=\frac{\partial \theta}{\partial Y}=0$$

At the left and right boundaries, U = 1, V = 0 and θ = 0 i.e. free slip boundary conditions. At the cylinder surface, U = V = 0 and θ = 1 i.e. no slip condition. The flow is assumed to start from the rest.

2.3 Numerical methodology

The grid for the computational domain has been generated in ANSYS. Figure 2 shows the grid structure of the computational domain used in the present numerical study which is generated by ANSYS with refinement mesh. The non-uniform grid structure for the whole computational domain is assigned for present calculation (refer to Figure 2).The grids for rounded corners tandem square cylinders for each spacing were made having total number of 1,20,149 mixed cells. In the present investigation, the numerical simulation is performed by using the finite volume method (FVM) based commercial software ANSYS FLUENT. It is used to solve the governing equations using the control volume based technique to accumulate all the variables at the same control volume. The laminar viscous model is selected to account for the low Reynolds number flow consideration. The solver used in the present work is pressure-based implicit method. Semi-Implicit Method for Pressure-Linked Equation (SIMPLE) is selected for the pressure-velocity coupling scheme. The dimensionless time step is set to 0.01.

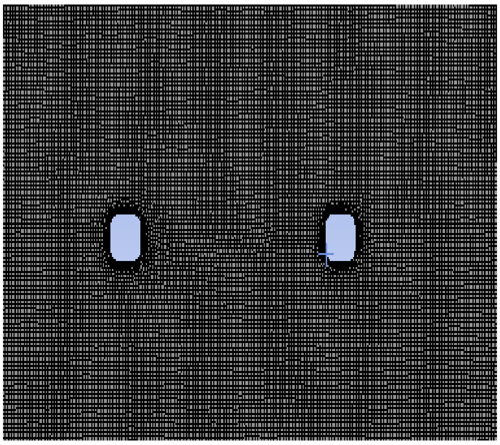


Fig: 2 Mesh Distribution of the computational domain

III. VALIDATION STUDY

3.1. Flow around a single sharp corner square cylinder

Here, the unsteady flow over a single sharp corner square cylinder at Reynolds number of 100 is simulated to serve as a reference for further investigation of tandem square cylinders.

A computational domain of 30d x 40d is used for simulation and the inlet boundary is located 10d upstream from the center of the cylinder and the outlet boundary 30d downstream, the upper and lower boundaries are located 15d away from the horizontal centreline of the computation domain. At the inlet boundary, the stream wise and transverse velocities are set to 1 and 0: u = 1, v = 0, respectively, while at the exit, an outlet boundary is prescribed as $\frac{\partial u}{\partial x}=0$, $\frac{\partial v}{\partial x}=0$, p=0. A slip boundary condition is imposed on the lateral boundaries: $\frac{\partial u}{\partial y}=0$ and v = 0. No-slip conditions are applied for cylinder surface: u = 0, v = 0.

Computational results of some global parameters, including mean drag coefficient, root mean square (r.m.s.) value of lift coefficient, Nusselt number and Strouhal number are compared and found excellent agreement with both the experimental and numerical data in existing literatures(see Table 1).

Table 1: Comparison of global parameters with the values from literatures at Re = 100.

Source	**Drag coefficient (C_d)**	**Lift coefficient (C_{lrms})**	**Strouhal number (St)**	**Nusselt number (Nu)**
Okajima [15] exp.	---------	--------	0.141	---------
Norberg [16] exp.	-----------	--------	0.143	--------
Sharma and Eswaran[17]	1.494	0.192	0.149	4.040
Present work	1.501	0.188	0.146	4.019

3.2. Flow around a single square cylinder with rounded edges

Here, the two dimensional unsteady flow over a single square cylinder with rounded edge (d/4) at Reynolds number of 100 is simulated to serve as a reference for further investigation of tandem square cylinders (see Table 2).

Table-2: Comparison of the Results for Rounded edge square cylinder with literature.

SL. NO	**Reference**	**Nusselt number**	**Drag coefficient (C_d)**	**Lift coefficient (C_{lrms})**
1	S. K. Singh(3)	4.6868	1.3699	0.178
2	**Present work**	4.6745	1.3805	0.157

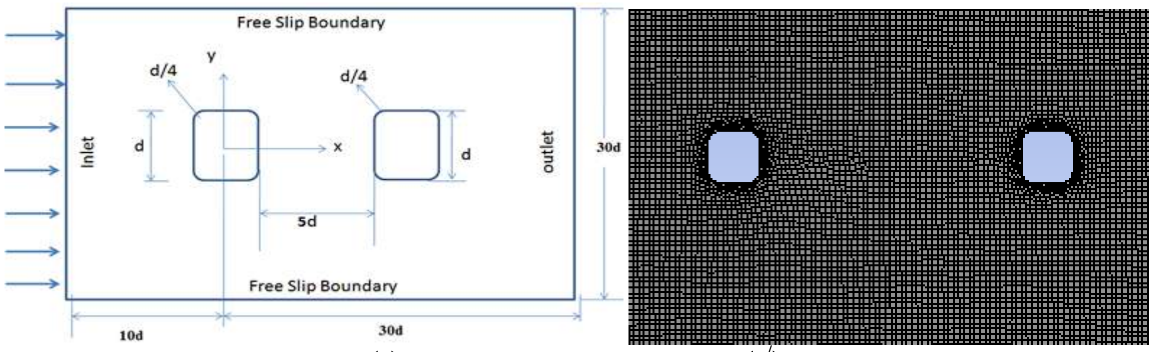
IV. RESULTS AND DISCUSSION

After the validation study, attention is now focused on the problem of flow around tandem square cylinder with rounded edges. The cylinders are of same projected width d and with rounded edge d/4. Table 3 shows different cases with gap between two cylinders.

Table: 3 Different cases with spacing between tandem cylinders.

Different cases	**Distance between cylinders**
Case-1	4d
Case-2	5d
Case-3	6d
Case-4	7d
Case-5	8d
Case-6	9d
Case-7	10d

Two Identical Isothermal Square cylinders with rounded corners placed in tandem arrangement and detailed information of the computational domain and boundary conditions for case1 shows on the schematic diagram of physical model in Fig-1. Same for case2, case3, case4, case5, case6 and case7 shown on the schematic diagram of physical model on left side of Fig-3. Mesh distribution of the computational domain for case- 1 shows on Fig-2 and same for case-2, case-3, case-4, case-5, case-6, case-7 shown on the right side of the Fig-3.



(a) (a/)

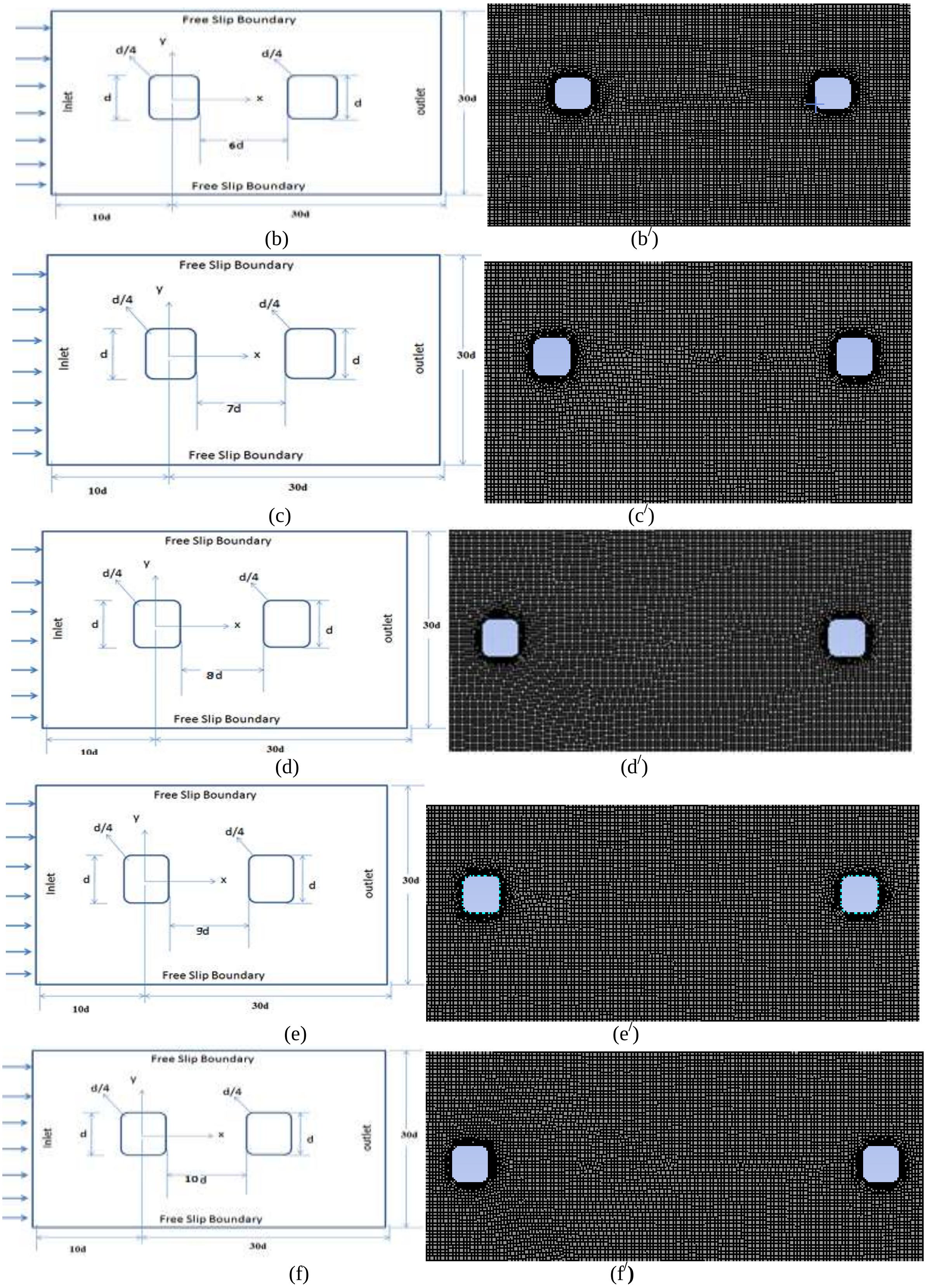


Fig:3 Schematic diagram of physical model and computational domain for tandem square cylinders with rounded corners (left side) (a) 5d, (b) 6d, (c) 7d, (d) 8d,(e) 9d, (f) 10d and mesh distribution of the computational domain (right side) (a$'$) 5d, (b$'$) 6d, (c$'$) 7d,(d$'$) 8d, (e$'$) 9d,(f$'$**)** 10d .

Drag coefficient is defined as ratio of the drag force acting on the cylinder to the dynamic force on projected area of the cylinder. For both the cylinders (upstream and downstream), initially, the drag coefficient sharply decreases from a high value to a minimum value. It then sharply increases and starts oscillating which finally reaches to a constant amplitude of oscillation about a mean value. This shows that the drag force coefficient is also of unsteady periodic nature. Comparing drag co-efficient of upstream and downstream cylinders for all the cases, show that mean value of oscillating drag coefficient becomes lower for downstream cylinder and shape of the curve at bottom becomes little wider. The variation of Drag co-efficient with different spacing between two tandem square cylinders with rounded edges for all the cases shown in Fig:4 and C_d represented in X-component and gap between two cylinders are represented in Y-component. For the downstream cylinder C_d obtained increasing and little variation is observed in upstream cylinder. When the spacing between two cylinders is 10d, the maximum C_d is obtained in upstream cylinder and also maximum C_d for downstream cylinder.

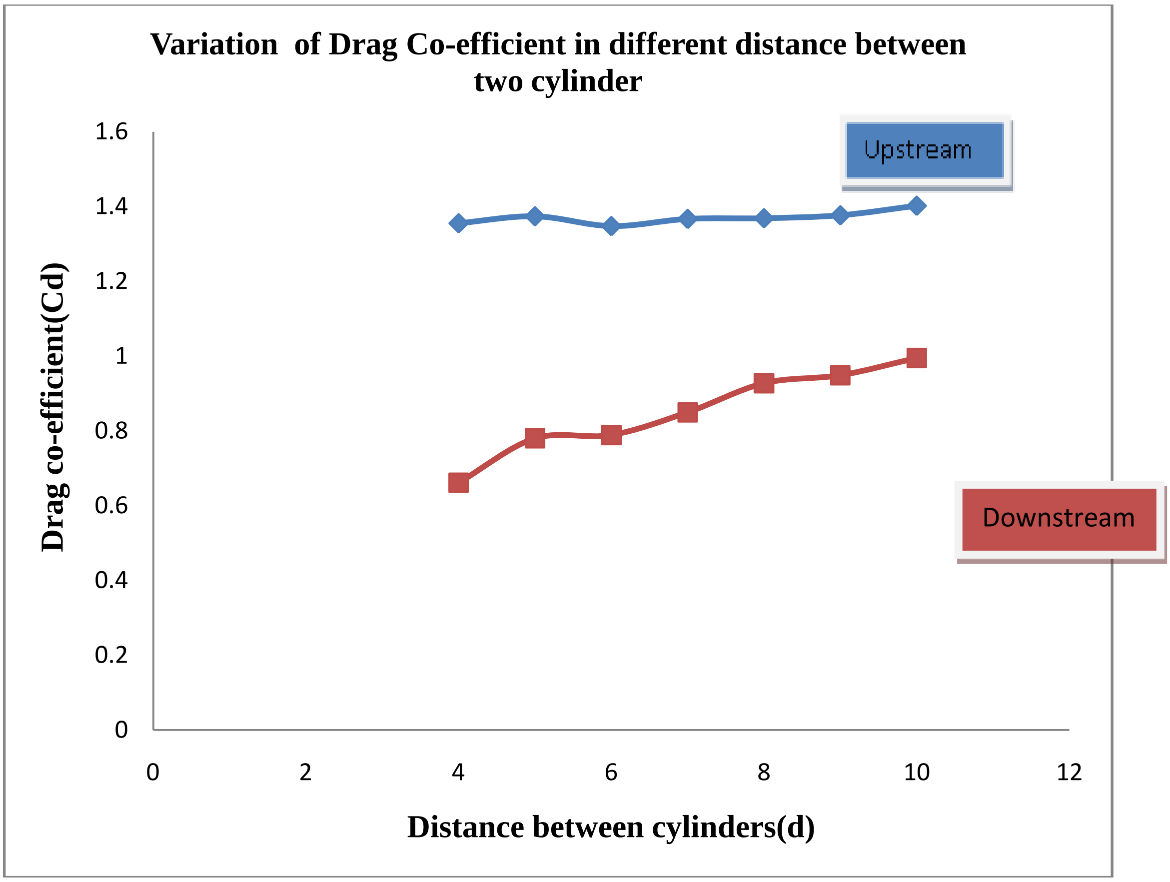


Fig:4 Variation of Drag Co-efficient with different spacing between two cylinders.

Lift coefficient is defined as ratio of the lift force produced around the cylinder to the dynamic force on projected area of the cylinder. It is observed that for upstream cylinder and downstream cylinder, the variation of lift coefficient is a horizontal straight line initially. After some time, lift coefficient starts oscillating due to instability produced in the flow field. The amplitude of oscillating lift coefficient increases with time and finally reaches to a maximum value. The nature of lift coefficient is unsteady periodic due to presence of vortex shedding and pure sine wave oscillating about mean zero value. The r.m.s. value of oscillating lift coefficient (C_{lrms}) is calculated for all the cases. The variation of RMS Lift co-efficient with different spacing between two tandem square cylinders with rounded edges for all the cases shown in Fig:5 and C_{lrms} represented in X-component and gap between two cylinders are represented in Y-component. When the spacing between two cylinders is 4d, the maximum $C_{l\ rms}$ is obtained in Upstream cylinder and when the spacing between is 10 d, maximum $C_{l\ rms}$ is obtained for downstream cylinder among all the cases.

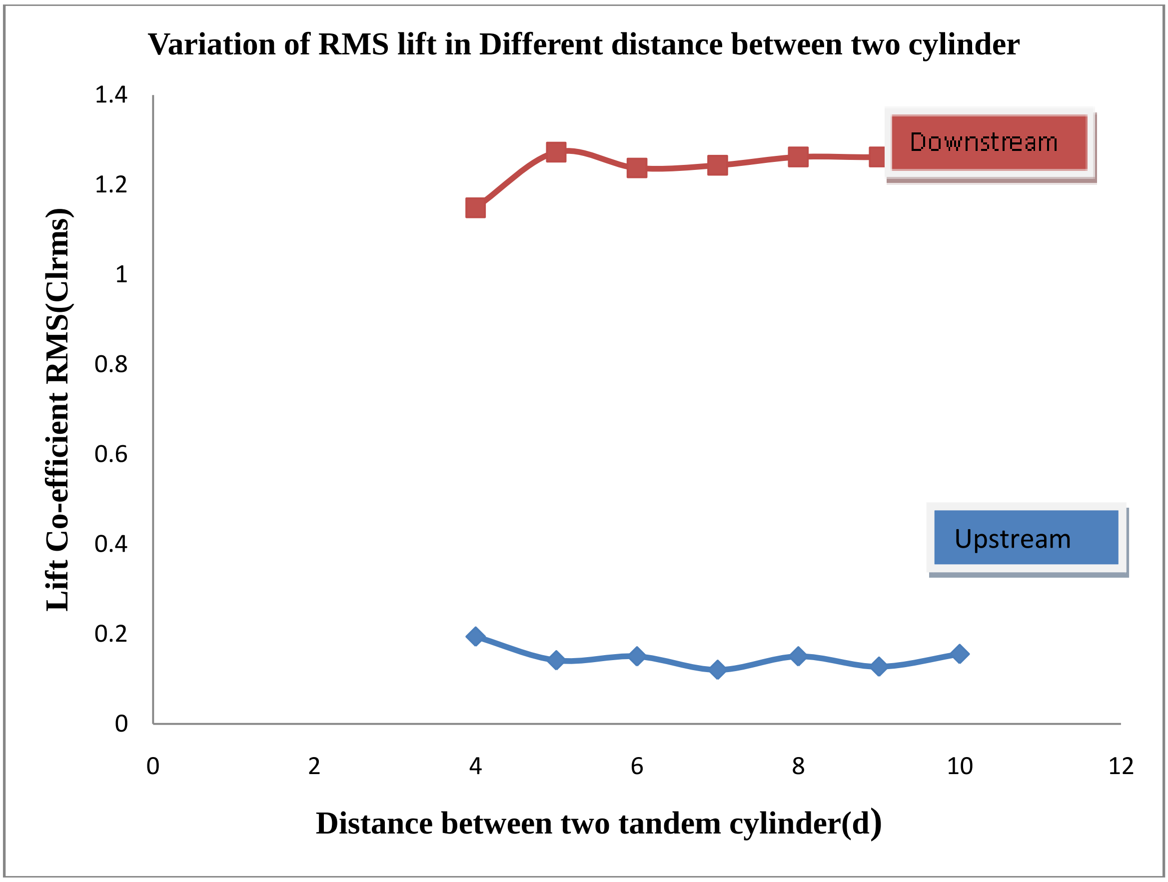
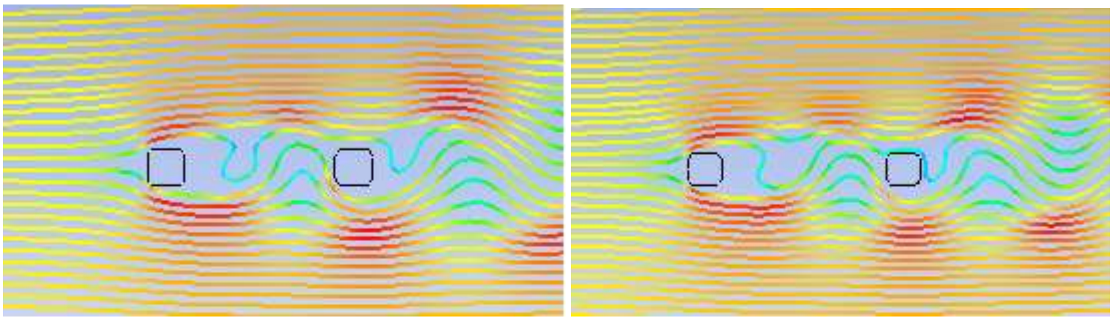


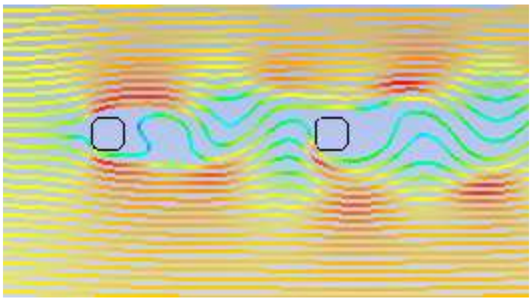
Fig:5 Variation of RMS Lift Co-efficient with different spacing between two cylinders.

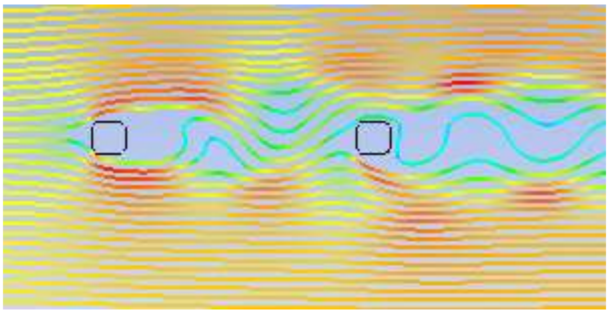
4.1 Streamline contour

Fig-6 shows the instantaneous streamline contour for tandem rounded edge square cylinder in all the cases of spacing between upstream and downstream cylinder. It is noticeably observed from the streamline contour that the separation takes place at the upper and lower surfaces of the upstream and downstream rounded edge square cylinder and for all the cases, streamlines oscillate in the transverse direction at downstream locations and this shows presence of vortex shedding in the flow field. The streamlines touches left rounded corner of the front face and right rounded corner of the front face of both upstream and downstream cylinder for all the cases and this indicates alternate behaviour of vortex shedding process for both the cylinders.



(a) (b)


(c)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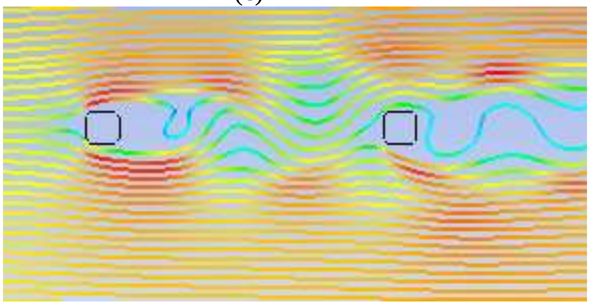
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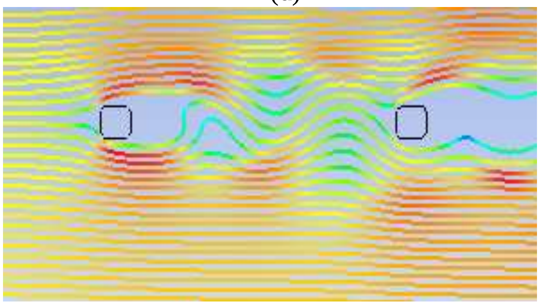
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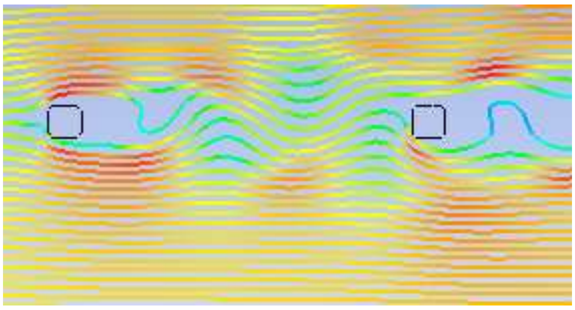
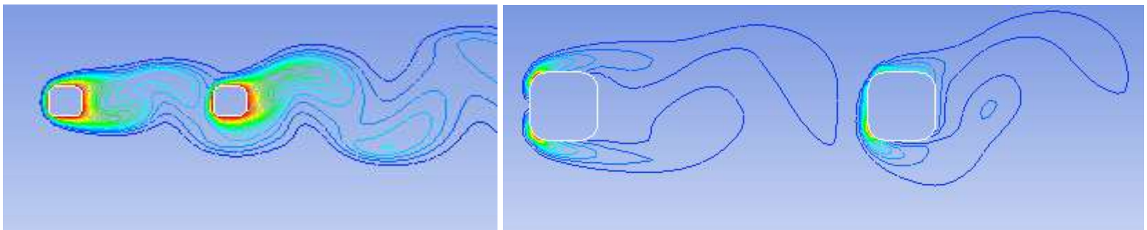

(g)

Fig: 6 Instantaneous streamline contour for tandem rounded edge square cylinder (a) case 1, (b) case2, (c) case 3, (d) case 4, (e) case 5, (f) case 6, (g) case 7.

4.2Isotherm Patterns and Vorticity contour

Fig-7(left side)shows the instantaneous isotherm patterns for tandem rounded edge square cylinder in all the cases of spacing between upstream and downstream cylinder. For both the upstream and downstream cylinders, instantaneous isotherms are also of oscillating nature and observed unsteady periodic nature of the temperature field and existence of vortex shedding. Right side of the Fig.7 shows the instantaneous vorticity contour for tandem rounded edge square cylinder in all the cases of spacing between upstream and downstream cylinder. The asymmetric behaviour of the vorticity is observed for all the cases of upstream and downstream cylinder and the separation of vorticity occurs at the rear curved surfaces and more crowding of vorticity contour is seen around the front half of the cylinder. It is observed that the disengagement length of the one Karmanshed is longer than the other and the flow oscillates further downstream of the cylinder to form vortex street for both of them upstream and downstream cylinder.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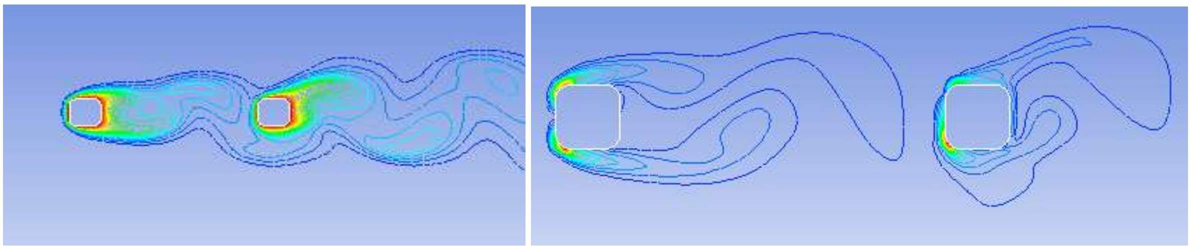

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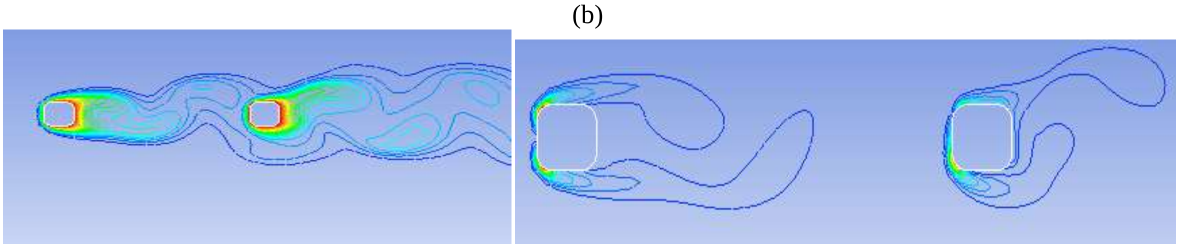

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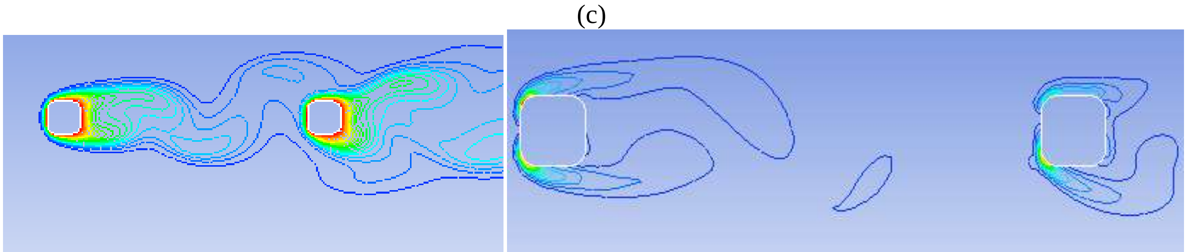

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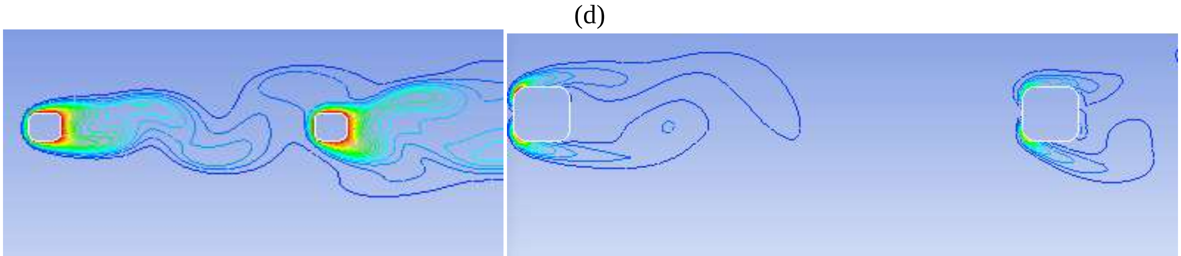

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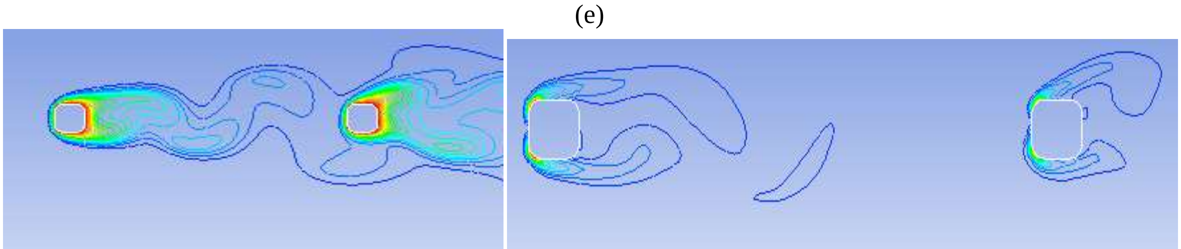

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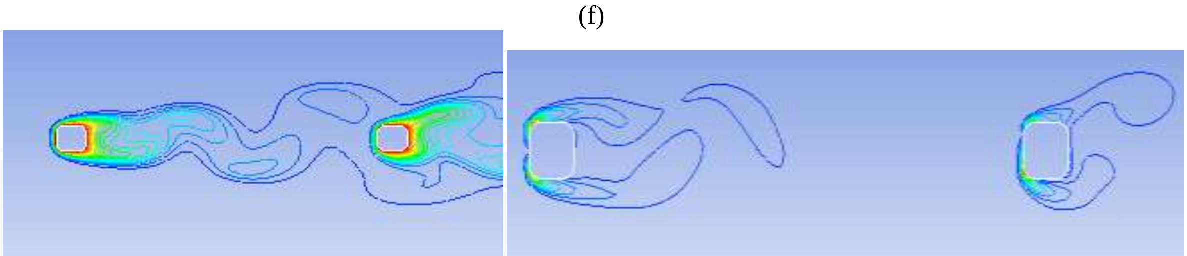

(g)

Fig: 7 Left side Instantaneous Isotherm pattern for tandem rounded edge square cylinder (a) case 1, (b) case2, (c) case 3, (d) case 4, (e) case 5, (f) case 6, (g) case 7 and Right side Instantaneous vorticity contour for tandem rounded edge square cylinder (a) case 1, (b) case2, (c) case 3, (d) case 4, (e) case 5, (f) case 6, (g) case 7.

The variation of Nusselt number with different spacing between two tandem square cylinders with rounded edges for all the cases shown in Fig:8 and Nusselt number represented in X-component and gap between two cylinders are represented in Y-component and small variation is observed for both the curve of upstream and downstream cylinders. When the spacing between two cylinders is 10d, the maximum Nusselt number is obtained in Upstream cylinder (Nu=4.7946) and also maximum for downstream cylinder(Nu=4.2447) among all the cases.

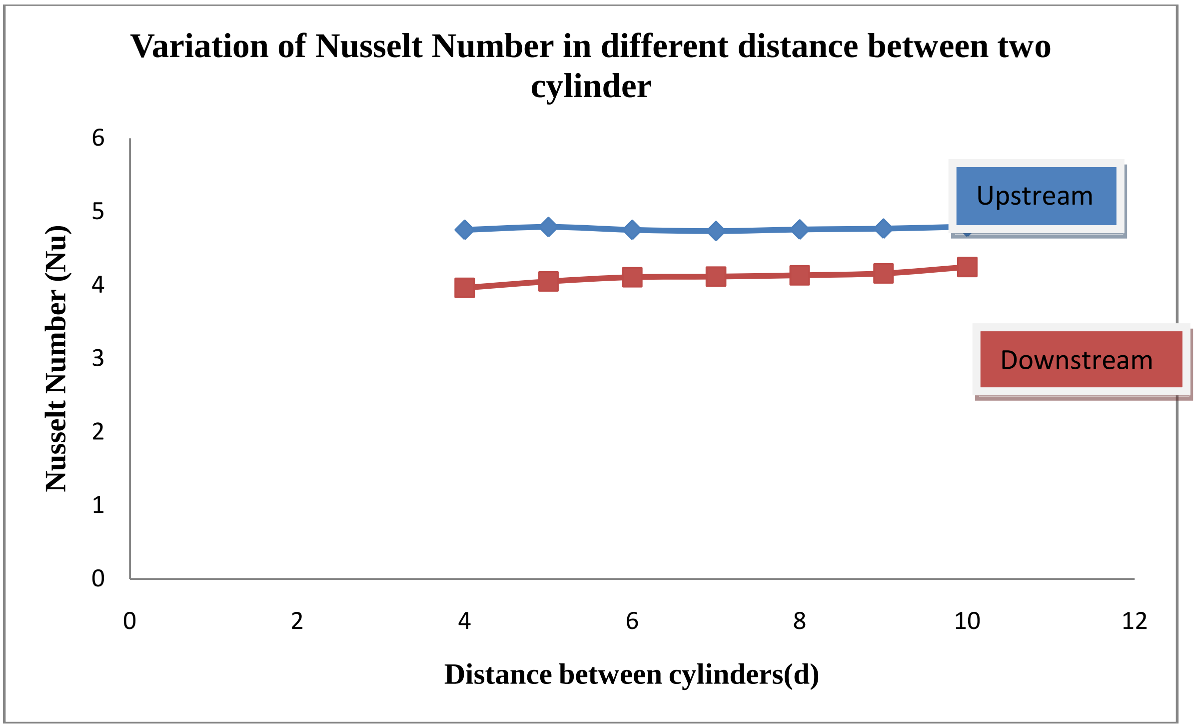

Fig:8 Variation of Nusselt number with different spacing between two cylinders.

Table: 10 shows the comparison of Nusselt number of Upstream rounded edge square cylinder with single rounded edge square cylinder among all the cases and Table :11 shows comparison of Nusselt number of tandem rounded edge square cylinder with single sharp corner square cylinder. It is found that maximum % of heat transfer enhancement of the upstream cylinder obtained when the spacing between tandem square cylinder is 10d.

Table:10 Comparisonof tandem rounded square cylinder with single rounded square cylinder.

Nusselt Number(Nu) of Upstream cylinder		
Distance between cylinders	**% Enhancement**	**% Reduction**
4d	1.66%	----------
5d	2.49 %	-----------
6d	1.66 %	-----------
7d	1.34 %	---------
8d	1.76 %	-------
9d	2.02 %	-------
10d	2.57 %	-------

Table: 11 Comparison of tandem rounded edge square cylinder with single sharp corner square cylinder.

Nusselt Number(Nu) of Upstream cylinder		
Distance between cylinders	**% Enhancement**	**% Reduction**
4d	18.24 %	----------
5d	19.19 %	-----------
6d	18.23 %	-----------
7d	17.84 %	---------
8d	18.35 %	-------
9d	18.65 %	-------
10d	19.29 %	-------

V. CONCLUSION

A numerical study on the heat transfer from heated tandem square cylinders with rounded corner edges in the two dimensional unsteady laminar flow is investigated using ANSYS FLUENT.Two-dimensional numerical simulations are carried out at Re = 100 for sharp corners and rounded corners square cylinders.From the present numerical work, it can beconcluded with the following major findings:

- Streamlines oscillate in the transverse direction at downstream locations for all the cases of upstream and downstream cylinders.
- Unsteady periodic nature of the temperature field and existence of vortex shedding observed for both the upstream and downstream cylinders indifferent spacing between cylinders.
- The asymmetric behaviour of the vorticity is observed of upstream and downstream cylinder in the different cases.
- Maximum 36 % reduction in Lift and 10.23 % reduction in Drag observed due to rounded corners of tandem square cylinder, instead of using single sharp corner square cylinder.
- 23.45 % reduction in lift and 2.41 % reduction in Drag observed due to rounded corners of tandem square cylinder, instead of using single rounded corner square cylinder.
- Instead of using Single rounded edge square cylinder, it is found that using tandem rounded edge square cylinders, Heat transfer enhancement is 2.57 %.
- About 19.29 % enhancement in heat transfer is observed due to rounding corners of the tandem square cylinder, instead of using Single sharp corner square cylinder.

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