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Effects of Corner Modifications on Flow and Heat Transfer in Square Cylinders

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Abstract: - Fluid flow and heat transfer around a bluff body is an important research area in many engineering fields. Some of the practical examples are heat losses from high-rise buildings, cooling towers, chimneys, power generators, heat exchangers, cooling of electronic systems, flow around nuclear rods etc. In the present investigation flow past a single heated square cylinder with and without corner modifications is being numerically investigated. For sharp-Cornered Square Cylinder, flow separation occurs sharply at the corners, leading to a broad wake and prominent vortex shedding, particularly at higher Reynolds numbers. The pressure distribution shows a sharp drop near the corners, and both lift and drag oscillations intensify with increasing Reynolds number.The oscillations in lift and drag coefficients are larger due to more intense vortex shedding, contributing to high aerodynamic forces.Heat transfer, indicated by the Nusselt number, is less efficient compared to cylinders with corner modifications.In case of Chamfered-Cornered Square Cylinder,Chamfering reduces the bluffness of the cylinder, resulting in smoother flow separation, narrower wakes, and more stable vortex dynamics.Pressure force and oscillations in lift and drag coefficients are moderate compared to the sharp-cornered case.The Nusselt number is more uniform around the cylinder, but still lower than for the rounded corners.But in Rounded-Cornered Square Cylinder,Rounded corners significantly delay flow separation, leading to a narrow wake and reduced vortex shedding intensity.Pressure variations are smoother, and both lift and drag forces are more stable compared to sharp and chamfered corners.Heat transfer is most efficient in the rounded-corner configuration, as reflected by the higher Nusselt number, especially at higher Reynolds numbers.

Keywords*: Strouhal Number, Nusselt number, Vortex shedding, RMS Lift and Mean Drag cofficient*

1. Introduction

Fluid flow and heat transfer around a bluff body is an important research area in many engineering fields. Some of the practical examples are heat losses from high-rise buildings, cooling towers, chimneys, power generators, heat exchangers, cooling of electronic systems, flow around nuclear rods etc. The use of circular bluff bodies was frequently encountered in the earlier research owing to its geometrical simplicity. From an engineering point of view, it is also necessary to study flow around other bluff bodies such as square, rectangular and elliptical so on. A circular bluff body, unlike a square bluff body, does not have a fixed separation point for boundary layer separation when a fluid flows past it. When the flow passes over the bluff body at a certain Reynolds number, wake is produced that is frequently associated with unsteady and periodic vortex shedding. A thorough knowledge of the vortex shedding mechanism is required for better understanding heat transfer in the wakes which is essential for the development of many engineering equipment. Later on attention has been directed towards fluid flow and heat transfer around side-by-side bluff bodies. With the fast advancement of semiconductor technology, the trend of electronic packaging tends to minimize component size with high performance. To achieve this goal, high dense integrated circuits are required. The heat generated by the new devices is always several times that of the earlier ones and this becomes the main defect leading to the failure of the devices. As a result, it is required to dissipate the excess heat generated in the ICs to make it work efficiently. Generally a fan is used to cool the surface of the heated electrical components. The electrical component may be modeled as a square cylinder. But no systematic study is available in the literature that deals with the effect of rounding or chamfering the corners of square cylinder or multiple cylinders. The flow over a three-dimensional bluff object is very different from that of a two-dimensional bluff body and is exceedingly complex, additionally, the computing time required to perform a three-dimensional calculation is considerably greater than the time required for a two-dimensional simulation. Therefore, the present investigation is concerned with the two- dimensional fluid flow and heat transfer for a confined square cylinder with an inline arrangement. Therefore, present investigation is performed in two-dimensional to study the influence of rounding and chamfering the corners of heated square cylinders subjected to a vortex shedding.

2. Geometry and boundary conditions

Figures 1 (a)-(c) illustrate the geometry of a square cylinder, a square cylinder with chamfered corners and a square cylinder with rounded corners. These configurations are examined at Reynolds numbers 100 and 200. In each case, the computational domain extends 6.5 times the square cylinder's dimension (D) upstream and to the top and bottom boundaries, while it extends 30 times D downstream from the cylinder. The boundary conditions applied in the investigation are as follows:

Inlet Boundary: Uniform velocity (U=1, V=0) and uniform temperature (T=300K).

Outlet Boundary: Gauge pressure set to zero.

Cylinder Surface: No-slip boundary condition with a temperature of 400K to represent a heated cylinder.

Lateral Boundaries (Upper and Lower): Symmetry boundary condition.

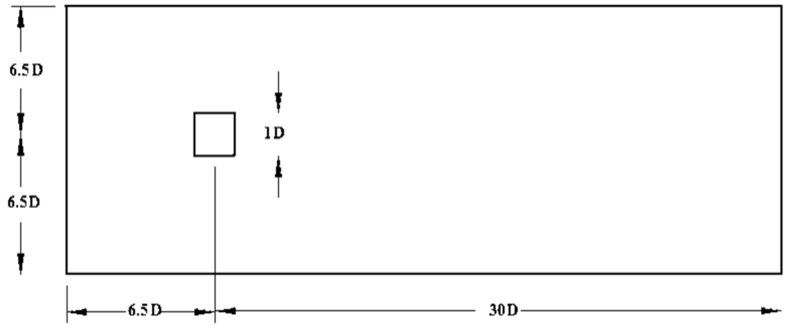

Fig.1(a):Geometry of a square cylinder[not as per the scale]

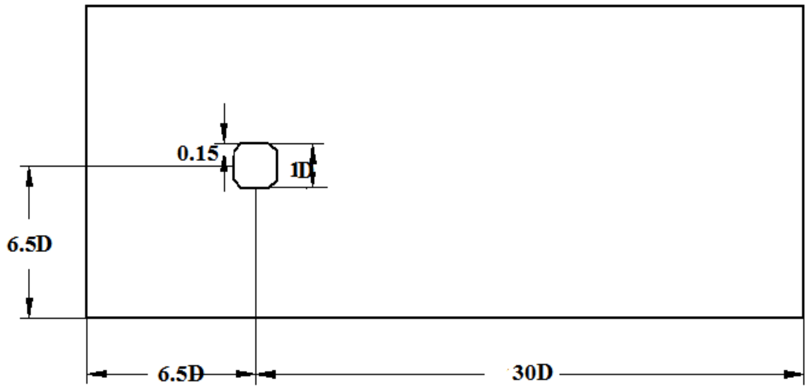

Fig.1(b): Square cylinder with corners chamfered[not as per the scale]

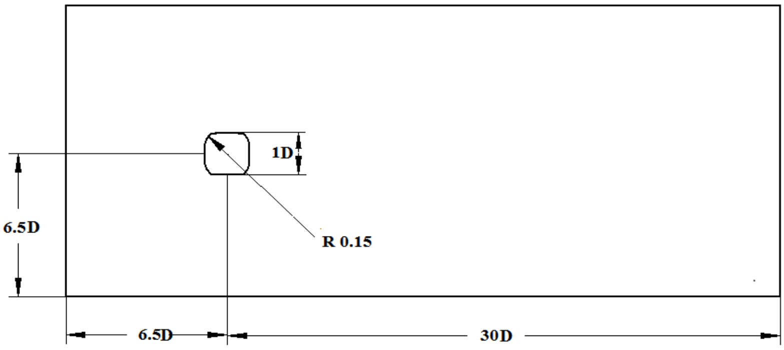

Fig.1(c): Square cylinder with corners rounded [not as per the scale]

3. Result and Discussion

3.1. Streamline plots of fluid flow around a heated square cylinder with and without modified corners

Figs.2 (a)-(f) shows streamline plots of fluid flow around a heated square cylinder with and without modified corners for Reynolds number 100 and 200. The observations made for the flow around a heated square cylinder with different corner modifications (sharp corners, chamfered corners and rounded corners) at Reynolds numbers of 100 and 200 highlight distinct differences in flow behavior. For the sharp cornered square cylinder (No Corner Modification), flow separates sharply from the corners of the front face leading to the formation of alternating eddies in the downstream. A prominent clockwise eddy develops, resulting in faster flow past the top of the cylinder compared to the bottom due to its bluff nature. Vortex formation region is broader and longer with fixed separation points either at the leading or trailing edge, resulting in a wide wake. At Re=200, the clockwise eddy rushes past the top of the cylinder even faster compared to Re=100.In square cylinder with chamfered corners alters the flow separation behavior compared to the sharp cornered square cylinder. The vortex formation region becomes less pronounced due to reduced bluffness resulting in smoother flow patterns and potentially narrower wakes. Separation points differ from those of the sharp cornered cylinder potentially affecting the distribution and intensity of downstream vortices. Streamline plots show a variation in the size and position of vortices compared to the sharp cornered cylinder indicating a different flow behavior. At Re=200, the flow features become more prominent with potentially faster eddy formation and dissipation compared to Re=100. In case of square cylinder with rounded corners further modifies the flow separation characteristics compared to both sharp and chamfered corners. The vortex formation region is expected to be even less prominent than that of the chamfered corners potentially resulting in smoother flow patterns and narrower wakes. Streamline plots depict further differences in vortex size and position compared to both sharp cornered and chamfered cornered cylinders. At Re=200, the flow behavior around the rounded cornered cylinder exhibit enhanced fluid dynamics features with faster eddy formation and dissipation compared to Re=100.

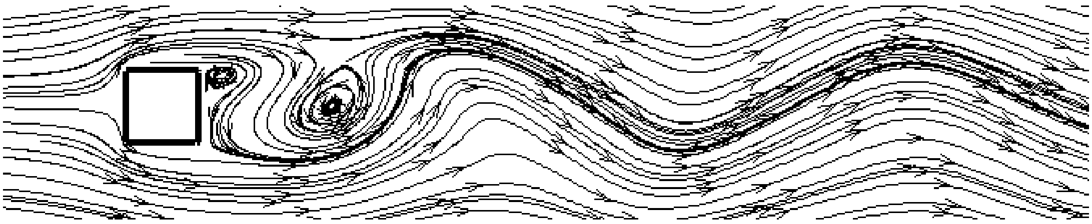

Fig.2 (a): Square cylinder for Re=100.

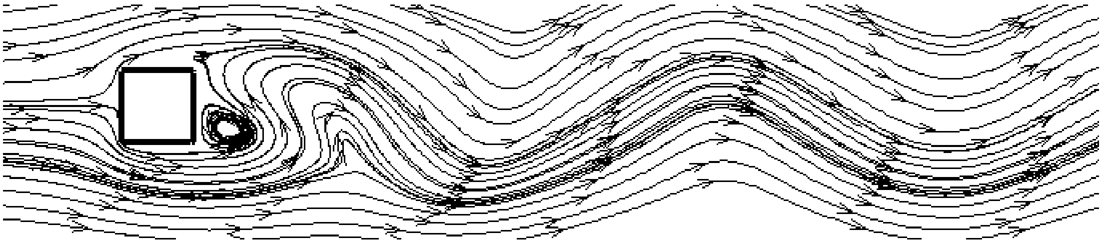

Fig. 2(b): Square cylinder for Re=200.

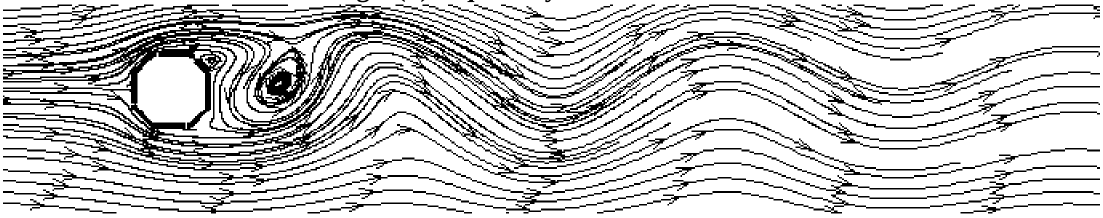

Fig.2(c): Square cylinder with corners chamfered for Re=100.

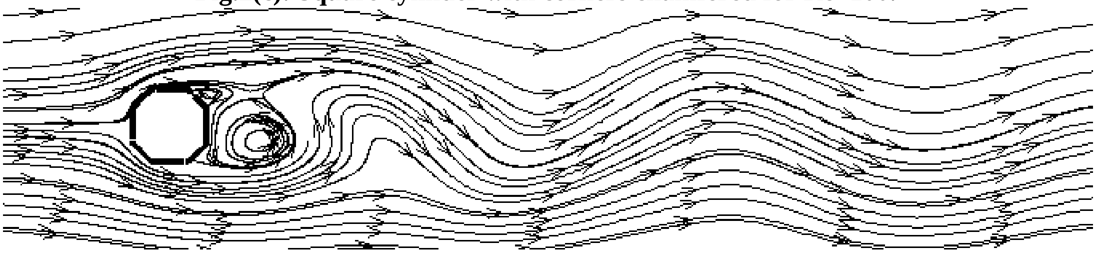

Fig. 2(d): Square cylinder with corners chamfered for Re=200.

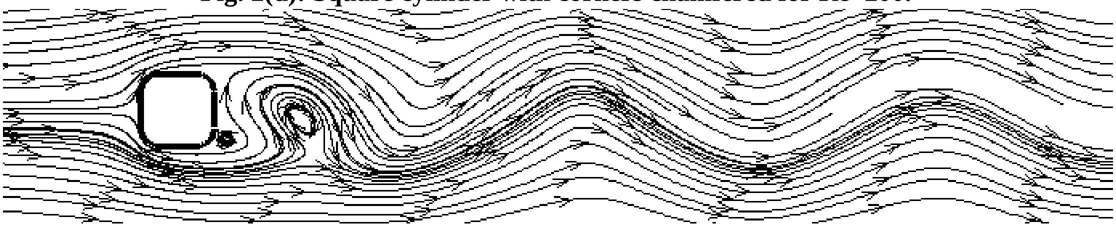

Fig. 2(e): Square cylinder with corners rounded for Re=100.

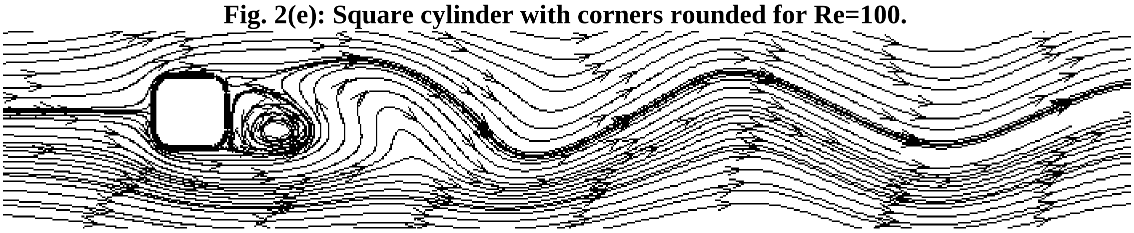

Fig. 2(f): Square cylinder with corners rounded for Re=200.

3.2 Pressure variation around a heated square cylinder with and without corner modifications

Figs.3 (a)-(f) shows pressure variation around a heated square cylinder with and without corner modifications for Re=100 and 200. In the pressure variation plots for square cylinders with different corner modifications (sharp, chamfered, and rounded) at Reynolds numbers (Re) of 100 and 200 reveal significant differences in the pressure forces experienced by each configuration. In sharp cornered square cylinder (No Corner Modification), flow separation around the sharp corners leads to the formation of shedding vortices and recirculation in the wake region, resulting in an unsteady flow field. The stagnation pressure is highest at the main edge of the square cylinder where the flowing fluid's kinetic energy is abruptly stopped. While the pressure force on the frontal side of the cylinder is high the pressure behind the cylinder may be relatively lower due to the presence of shedding vortices. At Re = 200, the pressure force on the leading side of the cylinder increase compared to Re = 100 due to intensified flow dynamics. However, the pressure force behind the cylinder relatively low compared to Re = 100 due to the continued shedding of vortices.For square cylinder with chamfered corners, pressure variation on the frontal side slightly lower compared to the sharp cornered cylinder due to reduced flow separation effects. Behind the cylinder, the pressure force is moderate lying between the extreme values observed for the sharp cornered and rounded cornered cylinders. At Re = 200, the pressure force on the leading side increase compared to Re = 100, similar to the sharp cornered cylinder. However, the pressure force behind the cylinder relatively moderate due to the altered flow separation behavior. In case of square cylinder with rounded corners further modifies the flow separation characteristics, potentially reducing the pressure force on the frontal side compared to the sharp cornered and chamfered cornered cylinders. However, the pressure force behind the cylinder highest among the three configurations due to the smoother flow separation and reduced shedding of vortices. At Re = 200, the pressure force on the leading side increase compared to Re = 100, similar to the other configurations. However, the pressure force behind the cylinder relatively high compared to Re = 100, indicating the influence of the rounded corners on flow dynamics.

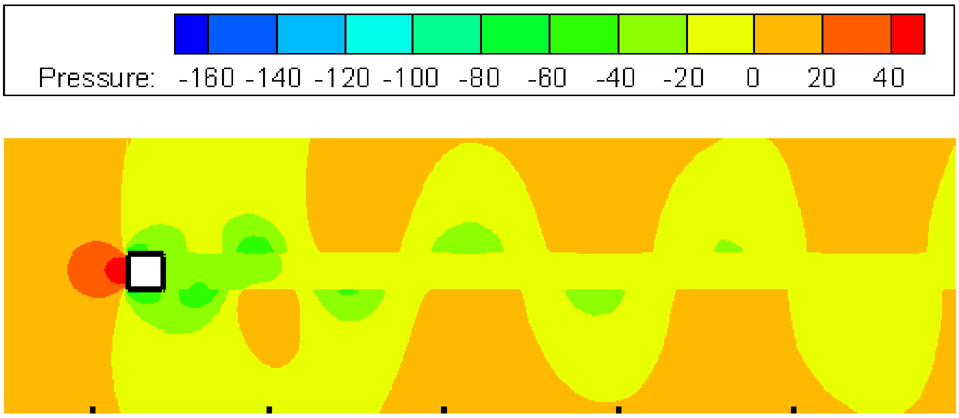

Fig.3 (a): Pressure variation around a square cylinder for Re=100.

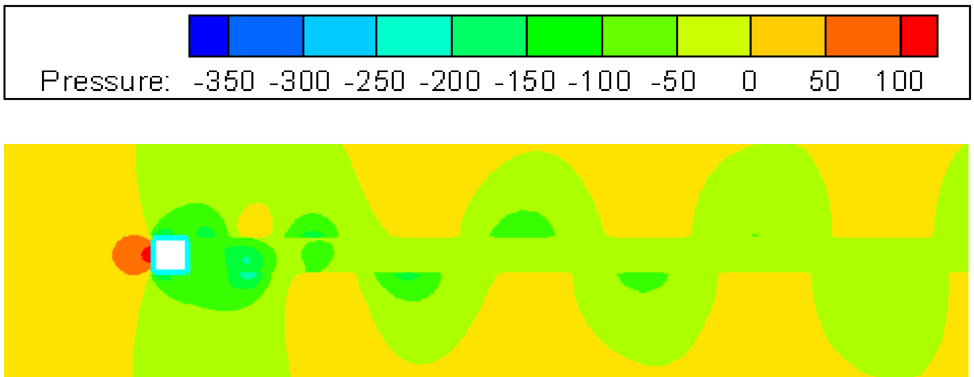

Fig.3 (b): Pressure variation around a square cylinder for Re=200.

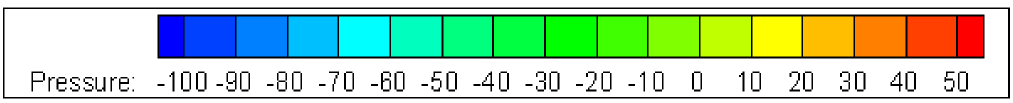

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Fig.3(c): Square cylinder with corners chamfered for Re=100.

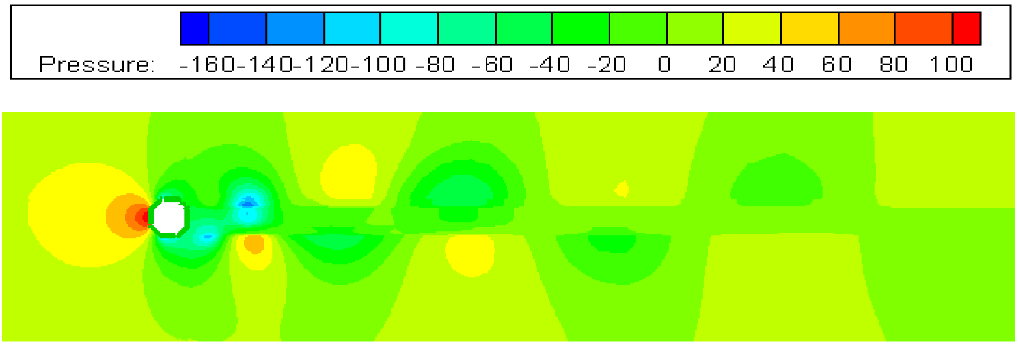


Fig.3 (d): Square cylinder with corners chamfered for Re=200.

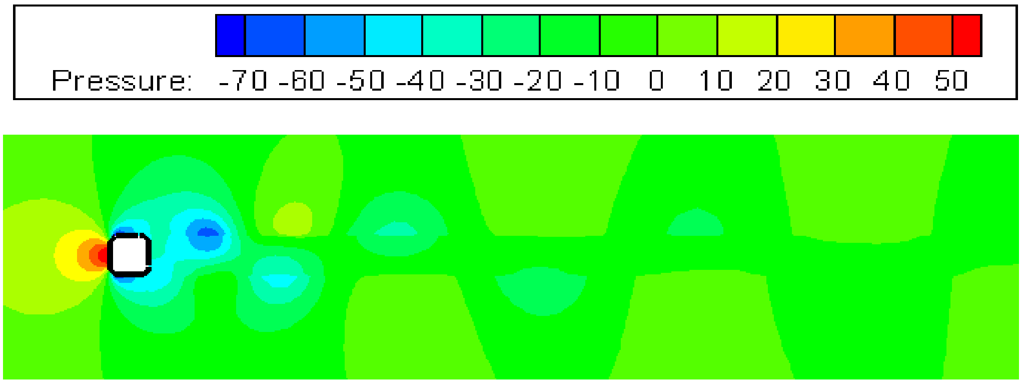


Fig.3 (e): Square cylinder with corners rounded for Re=100.

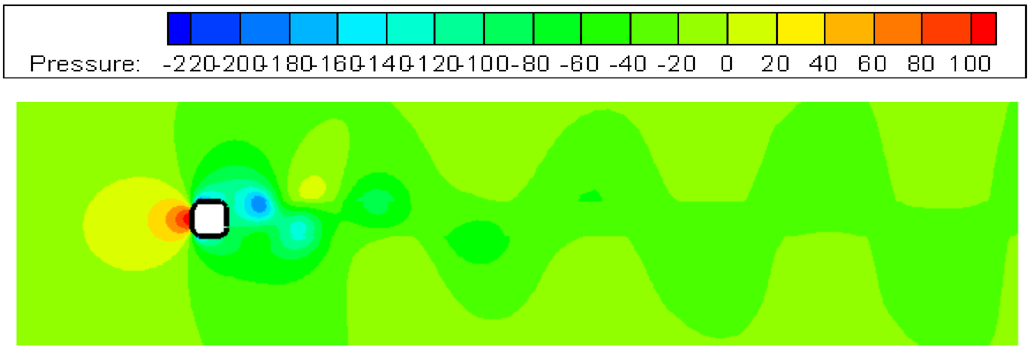


Fig.3 (f): Square cylinder with corners rounded for Re=200.

3.3 Velocity profiles for flow past a heated square cylinder with and without modified corners

Figs.4 (a)-(c) show velocity profiles for flow past a heated square cylinder with and without modified corners for Re=100 and 200. The observations for transverse velocity in the downstream of square cylinders with different corner modifications (sharp, chamfered, and rounded) at Re=100 and 200 highlight notable differences in the time delay to reach vortex shedding and the magnitude of oscillation. In sharp cornered square cylinder (No Corner Modification), the transverse velocity in the downstream of the sharp cornered square cylinder experiences relatively lesser time delay to reach vortex shedding. At Re = 100, the magnitude of oscillation is ±0.71, indicating significant variations in the transverse velocity over time. At Re = 200, the time delay to reach vortex shedding is much lesser compared to Re = 100, with a magnitude of oscillation of ±0.82, indicating intensified flow dynamics. For the flow past square cylinder with chamfered corners, the transverse velocity in the downstream of the chamfered cornered square cylinder requires more time to reach vortex shedding compared to the sharp cornered cylinder. At Re = 100, the magnitude of oscillation is slightly lower at ±0.60 compared to the sharp cornered cylinder. At Re = 200, the time delay to reach vortex shedding is reduced compared to Re = 100, with a magnitude of oscillation of ±0.75, indicating increased flow dynamics. In case of square cylinder with rounded corners, the transverse velocity in the downstream of the rounded cornered square cylinder experiences much more time delay to reach vortex shedding compared to both the sharp and chamfered cornered cylinders. At Re = 100, the magnitude of oscillation is relatively lower at ±0.50 compared to the other configurations. At Re = 200, the time delay to reach vortex shedding is reduced compared to Re = 100, with a magnitude of oscillation of ±0.60, indicating intensified flow dynamics similar to the other configurations.

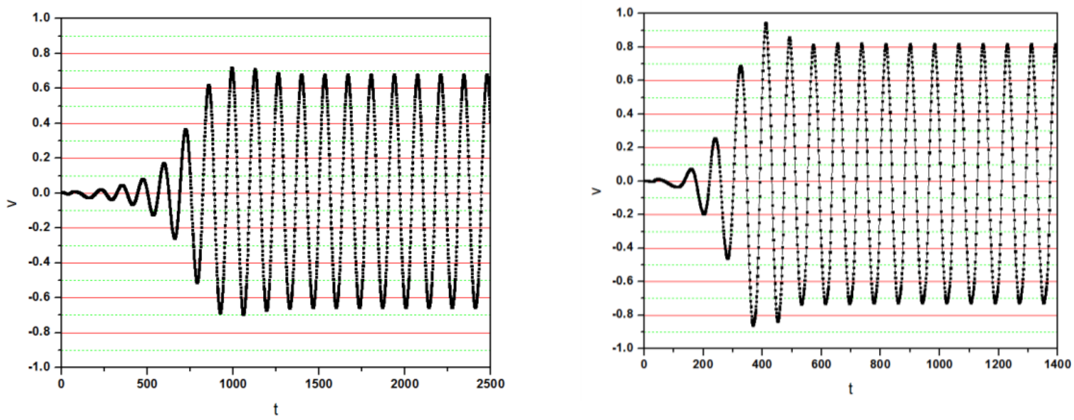


Fig.4 (a): Transverse velocity in the square cylinder downstream for Re=100,200.

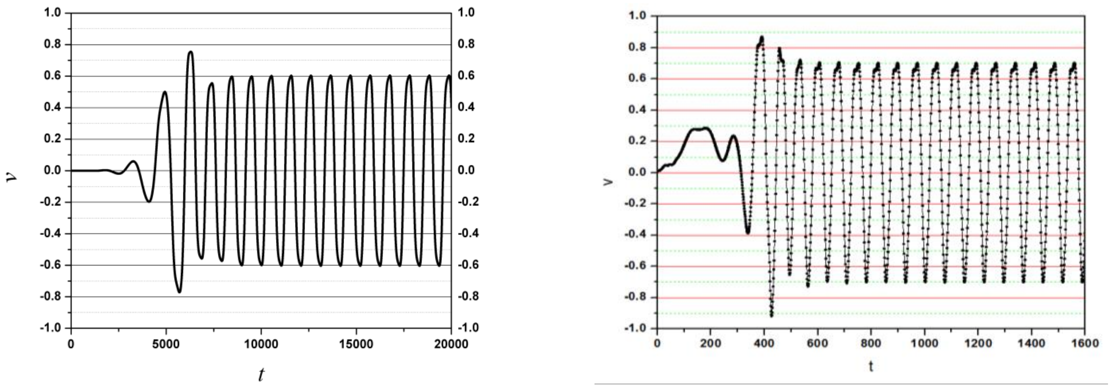


Fig.4 (b): Square cylinder with corners chamfered in downstream for Re=100 & 200.

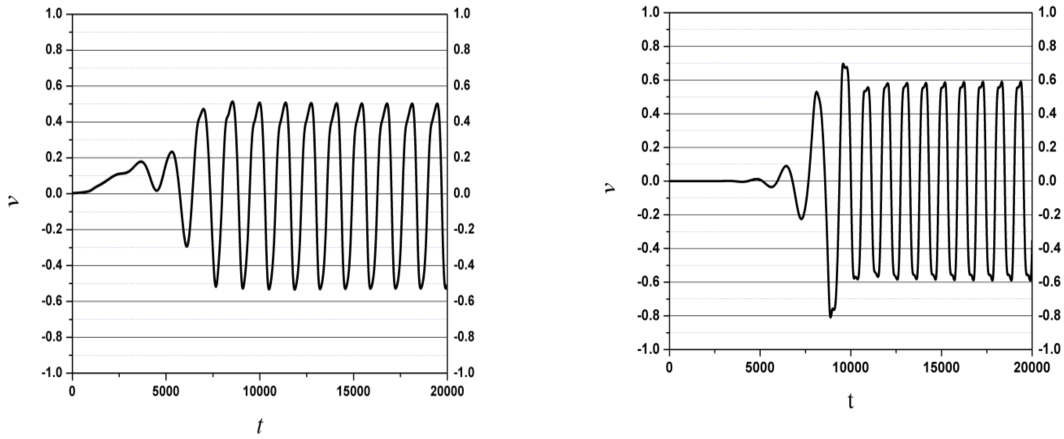
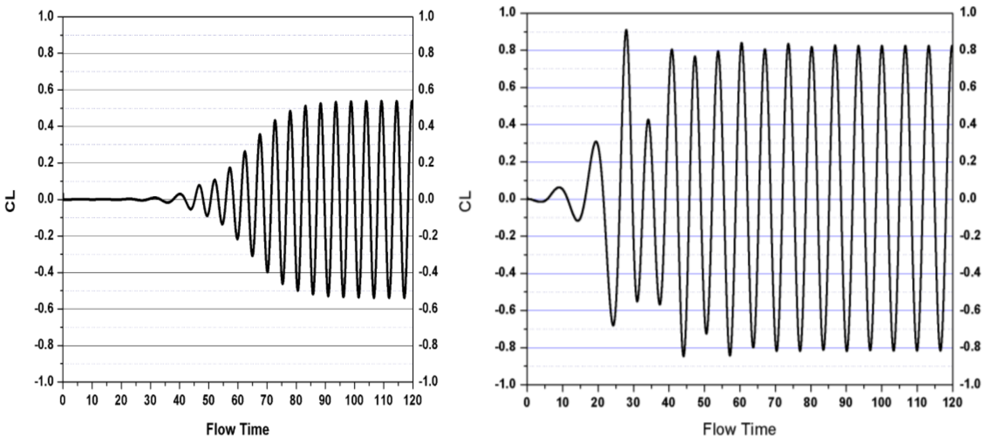


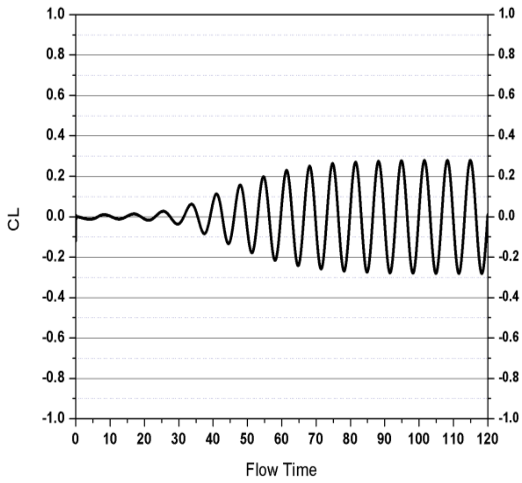
Fig.4(c): Square cylinder with corners rounded in downstream for Re=100 &200.

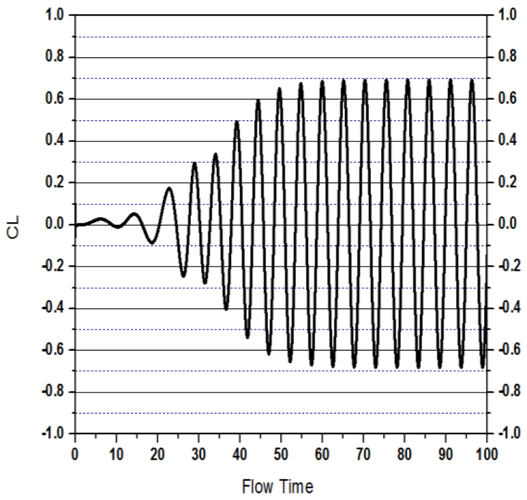
3.4 Lift coefficient plots for the flow past a heated square cylinder with and without modified corners

Figs.5(a)-(c) show lift coefficient plots for the flow past a heated square cylinder with and without corner modifications (sharp, chamfered, and rounded) at Reynolds numbers (Re) of 100 and 200 reveal significant differences in the onset of oscillations and amplitude of oscillations. In sharp cornered square cylinder, oscillation of lift coefficient starts early due to relatively faster vortex shedding. The amplitude of oscillation for Re=100 is ±0.30. At Re=200, oscillations start even earlier compared to Re=100, with a larger amplitude of ±0.82. For the square cylinder with chamfered corners, oscillation of lift coefficient is delayed compared to the sharp cornered cylinder due to the stabilizing effect. The amplitude of oscillation for Re=100 is slightly reduced to ±0.27. At Re=200, oscillations start earlier compared to Re=100, with a larger amplitude of ±0.70. In case of square cylinder with rounded corners, oscillation of lift coefficient is further delayed compared to both sharp and chamfered cornered cylinders due to the stabilizing effect of rounded corners. The amplitude of oscillation for Re=100 is further reduced to ±0.17.At Re=200, oscillations start earlier compared to Re=100, with a larger amplitude of ±0.27.

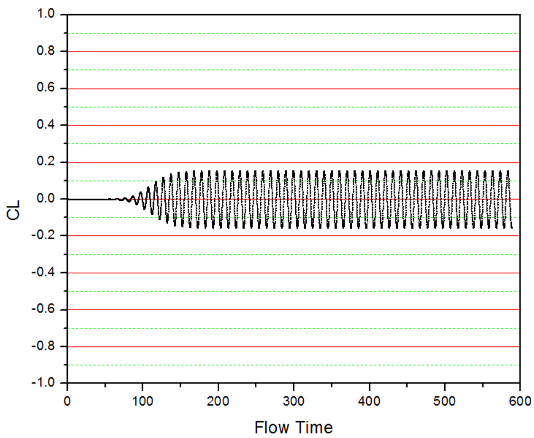


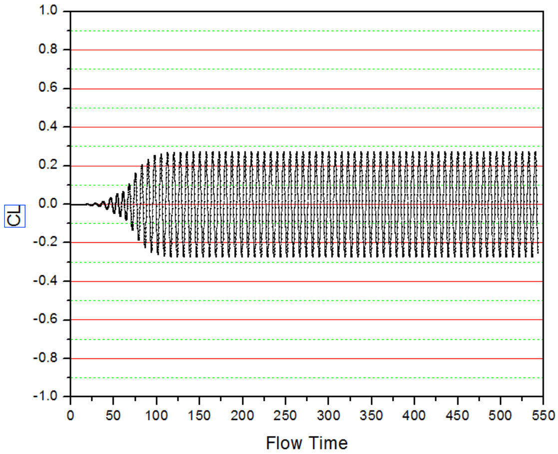
Figs.5 (a): Lift coefficient plot of square cylinder for Re=100 and 200.





Figs.5 (b): For square cylinder with corners chamfered for Re=100 and 200.

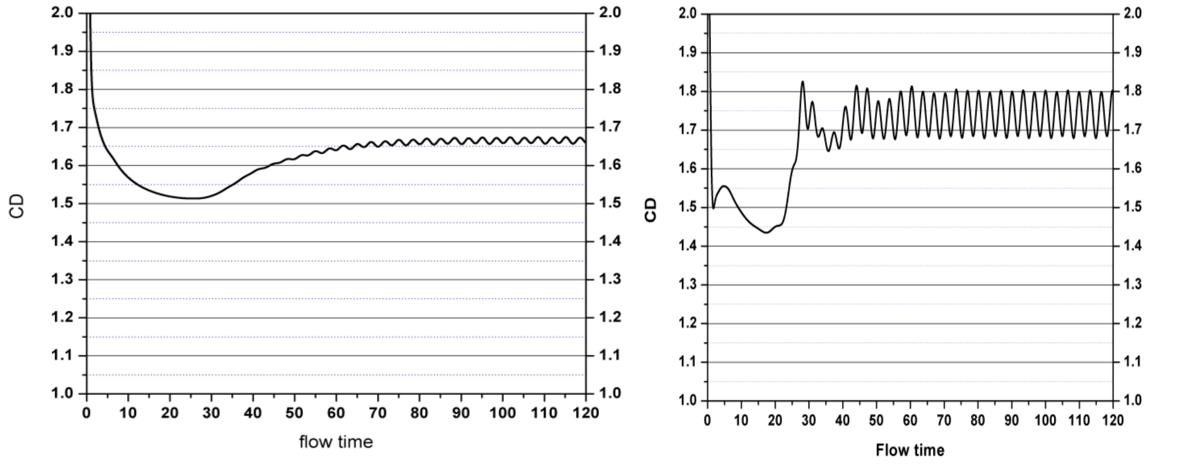




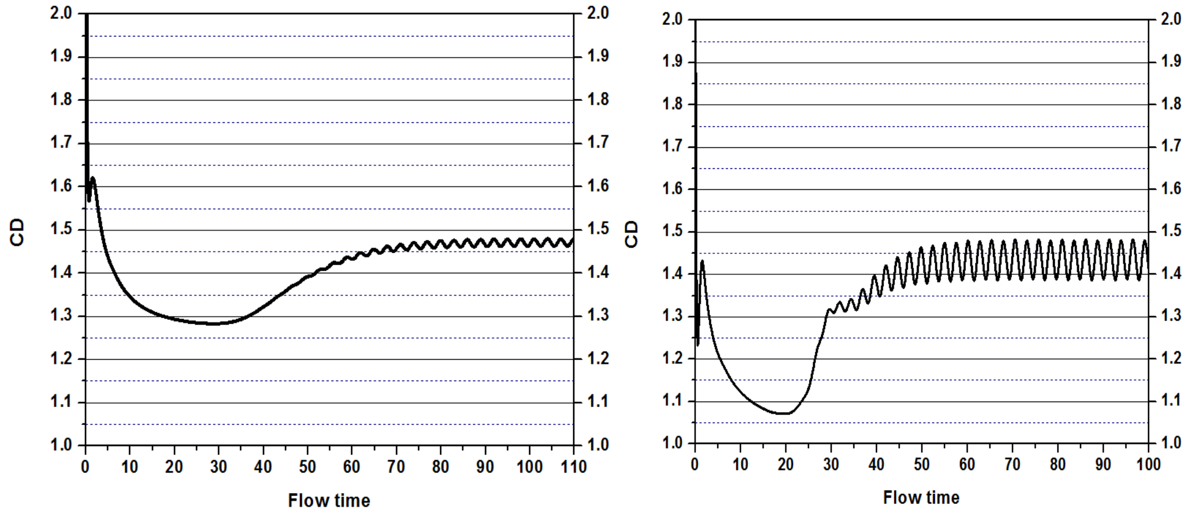
Figs.5 (c): For square cylinder with corner rounded for Re=100 and 200.

3.5 Drag coefficient plots for the flow past a heated square cylinder with and without modified corners

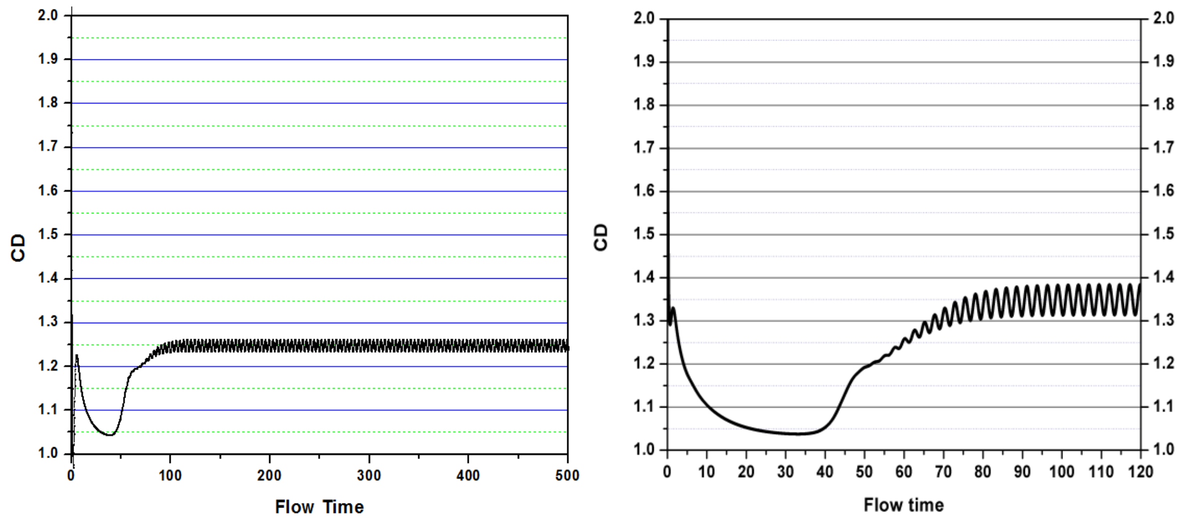
Figs.6 (a)-(c) show the drag coefficient plots for the heated square cylinder with and without corner modifications (sharp, chamfered, and rounded) at Reynolds numbers of 100 and 200 reveal significant differences in the onset of oscillations and amplitude of oscillations. In sharp cornered square cylinder, the drag coefficient initially decreases sharply from a higher value to a minimum then sharply increases and starts oscillating, reaching constant amplitude of oscillation about a mean value. Oscillation of drag coefficient starts early due to relatively faster vortex shedding. The amplitude of oscillation for Re=100 is +1.67. At Re=200, oscillations start even earlier compared to Re=100, with a larger amplitude of +1.80. For the square cylinder with chamfered corners, oscillation of drag coefficient is delayed compared to the sharp cornered cylinder due to the stabilizing effect of chamfered corners. The amplitude of oscillation for Re=100 is slightly reduced to +1.46. At Re=200, oscillations start earlier compared to Re=100, with a larger amplitude of +1.48. In case of square cylinder with rounded corners, oscillation of drag coefficient is further delayed compared to both sharp and chamfered-cornered cylinders due to the stabilizing effect of rounded corners. The amplitude of oscillation for Re=100 is further reduced to +1.25. At Re=200, oscillations start earlier compared to Re=100, with a larger amplitude of +1.36.



Figs.6 (a): Drag coefficient plot of square cylinder for Re=100 and 200.



Figs.6 (b): For square cylinder with corners chamfered for Re=100 and 200.



Figs.6(c): For square cylinder with corner rounded for Re=100 and 200.

3.6 Root Mean Square (RMS) lift coefficient and mean drag coefficient for a heated square cylinder with and without corner modification

In the numerical investigations into the aerodynamic properties of a heated square cylinder with and without corner modifications, the terms root mean square (RMS) lift coefficient and mean drag coefficient refers to the statistical measures of the forces acting on the cylinder. The RMS lift coefficient is a measure of the fluctuating component of the lift force acting on the cylinder. It quantifies the intensity of lift fluctuations around a mean value. In order to obtain the RMS lift coefficient, calculate the lift coefficient at different time intervals during the simulation. Then, compute the root mean square of these values, which involves squaring the deviations from the mean lift coefficient, averaging these squared deviations, and then taking the square root of this average. A high RMS lift coefficient indicates significant fluctuations in lift, which is related to vortex shedding or other instabilities in the flow. A lower RMS value suggests more stable lift forces. Modifications to the cylinder's corners are aimed at reducing these fluctuations and achieving a more stable lift.In case of mean drag coefficient which is the average drag force experienced by the cylinder, normalized by the dynamic pressure and the reference area. It provides an overall measure of the drag that the cylinder experiences over time. The mean drag coefficient is calculated by averaging the drag coefficients obtained from numerical simulations over the duration of the flow investigation. This coefficient is important for understanding the overall resistance to motion due to the drag force. Modifying the cylinder's corners can influence the mean drag coefficient by altering the flow characteristics around the cylinder, potentially reducing drag and improving aerodynamic performance. Tab. 1 shows R.M.S lift coefficient and mean drag coefficient for a heated square cylinder with and without corner modification by numerical investigation. The r.m.s value of lift coefficient and mean drag coefficient for a square cylinder is more compared to the square cylinder of corners rounded whereas, square cylinder with corners chamfered lies in between them.

Tab. 1: Root Mean Square lift coefficient and mean drag coefficient for a heated square cylinder with and without corner modification by numerical investigation.

R.M.S lift and mean drag coefficient	Re=100		Re=200	
	CLrms	CD	CLrms	CD
Square cylinder	0.155	1.704	0.513	1.695
Chamfered corners cylinder	0.151	1.427	0.379	1.360
Rounded corners cylinder	0.107	1.361	0.261	1.253

3.7 Effect of strouhal number in flow past modified and unmodified heated square cylinder

Figs. 7(a)-(c) show the Strouhal number plots of a heated square cylinder, square cylinder with corners chamfered and rounded for Re=100 and 200. The Strouhal number (St) is a dimensionless quantity used to characterize oscillating flow mechanisms, particularly vortex shedding. Strouhal number is influenced by the Reynolds number (Re), the cylinder's geometry, and any modifications to its corners. Understanding these effects is crucial for predicting and controlling flow behavior in various engineering applications. The period of vortex shedding can be analyzed using the temporal history of the lift coefficient and Fast Fourier Transform (FFT). A sharp peak in the power spectra at the vortex shedding frequency indicates an alternating vortex shedding pattern. At Re = 100, the spectral power for the square cylinder with sharp corners is higher compared to the one with rounded corners. The cylinder with chamfered corners lies between these two due to increased oscillation magnitude. At Re = 200, the power spectral density is larger, and the vortex shedding frequency is slightly higher than at Re = 100. The strouhal number for the sharp-cornered cylinder is lower than that for the rounded-cornered cylinder with the chamfered-cornered cylinder lying in between. Tab. 2 shows strouhal number for with and without corner modification for Re=100 & 200, which shows square cylinder with sharp corner is lowest and square cylinder with corners rounded is highest whereas square cylinder with corners chamfered lies in between them for both Re=100 and 200.

Tab. 2: Strouhal number for with and without corner modification for Re=100 &200.

Strouhal number	**Re=100**	**Re=200**
Square cylinder with sharp corner	**0.151**	**0.155**
Square cylinder with corners chamfered	**0.167**	**0.179**
Square cylinder with corners rounded	**0.169**	**0.181**

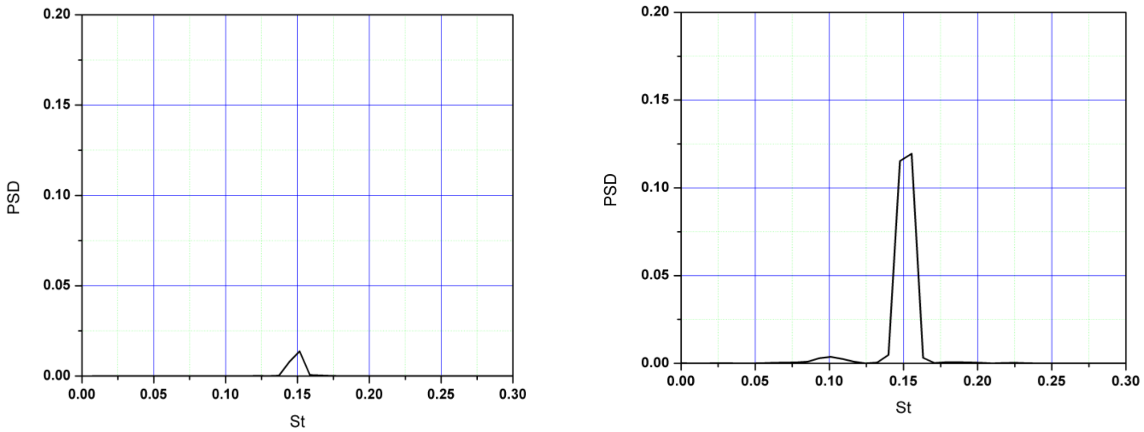


Fig. 7 (a): Strouhal number for square cylinder of Re=100 and 200.

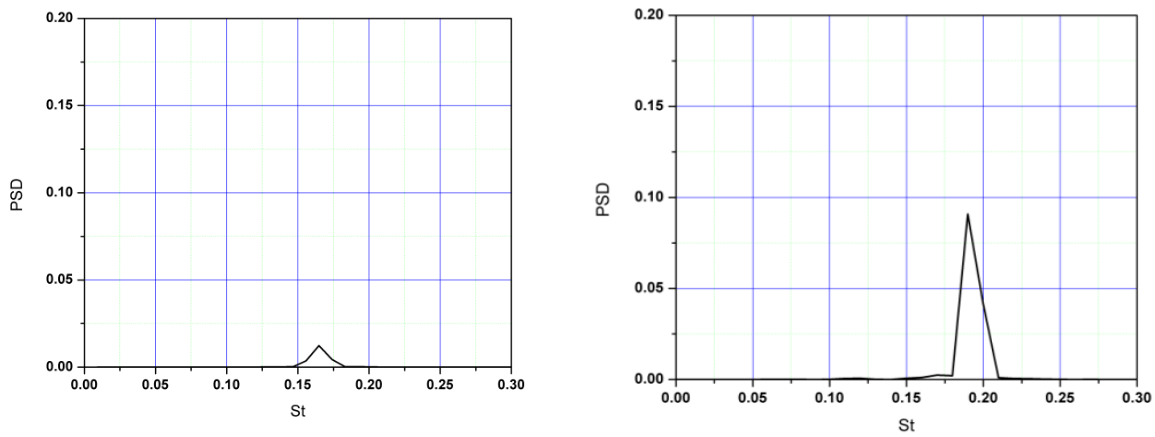


Fig. 7 (b): Square cylinder with corners chamfered for Re=100 and 200.

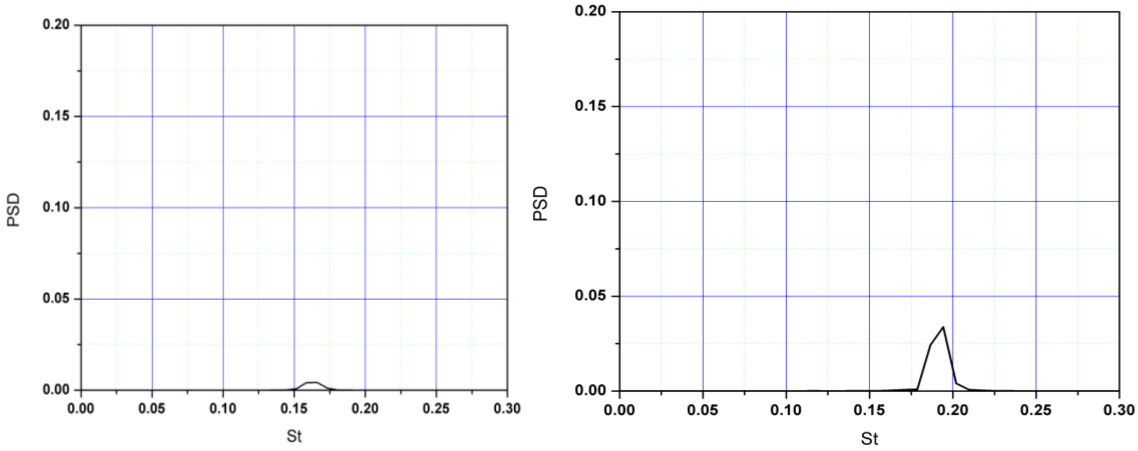
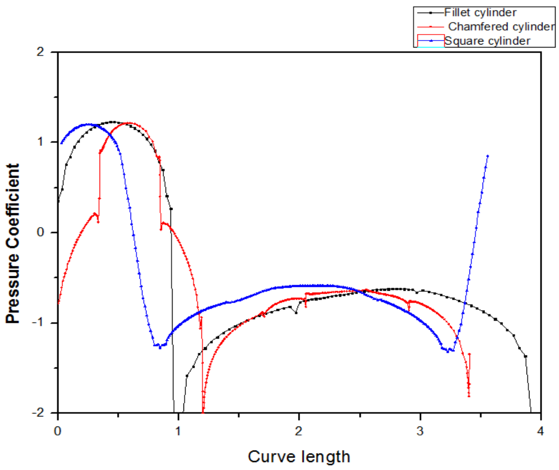


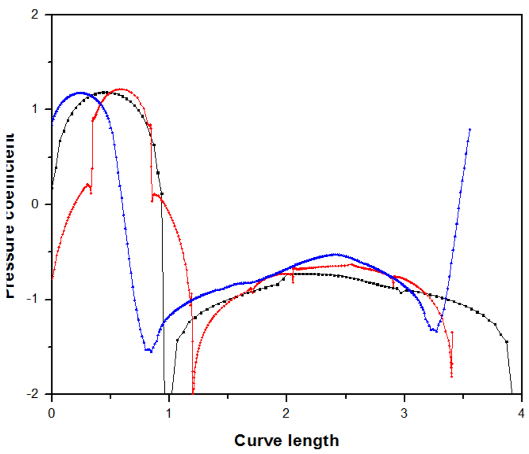
Fig. 7(c): Square cylinder with corners rounded for Re=100 and 200.

3.8 Pressure coefficient distribution around a heated square cylinder with and without corner modifications

Figs. 8 (a) and (b) shows pressure coefficient distribution plots around a heated square cylinder with and without corner modifications for Re=100 and 200. The pressure coefficient is a dimensionless number that describes the relative pressure throughout the flow field around the object. This helps to know whether the force acting on a surface is negative or positive pressure with a change in velocity flow over a surface. A positive pressure coefficient means that there is an increase in pressure on the surface of the body and fluid velocity is slow, and with a negative pressure coefficient, observes a decrease in pressure on the surface and an increase in fluid velocity. The increase in pressure increases drag on the surface and the decrease in pressure reduces drag on the surface. The pressure coefficient distribution around a square cylinder is influenced by the shape of its corners such as sharp, chamfered and rounded also Reynolds number. At Re = 100 and Re = 200, the flow behavior changes, affecting the pressure distribution around the cylinder. In Square cylinder with sharp corners at Re = 100, the flow around the sharp-cornered square cylinder is in the laminar regime. The flow tends to separate from the sharp corners, leading to the formation of a steady and symmetric wake. The pressure coefficient on the upstream face is positive due to flow stagnation. As the flow reaches the sharp corners, separation occurs abruptly, causing a sharp drop in pressure, resulting in high negative pressure coefficient values near the corners. The wake region behind the cylinder is stable and symmetric, with lower pressure on the sides and downstream face. As Re increases to 200, the flow becomes unsteady, and vortex shedding starts to occur. The wake behind the cylinder is more turbulent. The pressure coefficient distribution on the front face remains positive and similar to the Re = 100 case. The negative pressure coefficient values near the sharp corners become more pronounced due to increased separation. The unsteady vortex shedding leads to fluctuating pressure distributions on the sides and downstream face, resulting in a more chaotic pressure field. In case of square cylinder with chamfered corners at Re = 100, the chamfered corners reduce the severity of flow separation. The flow still separates but more gradually compared to sharp corners, leading to a narrower and more stable wake. The front face has a positive pressure coefficient values similar to the sharp-cornered cylinder. As the flow transitions over the chamfered corners, the drop in pressure is less steep, resulting in milder negative pressure coefficient values near the corners. The wake is more symmetric and stable, leading to a smoother pressure recovery on the sides and downstream face. As Re increases to 200, the flow becomes unsteady, but the chamfering still diminishes the severity of vortex shedding compared to the sharp-cornered case. The positive values of pressure coefficient on the front face remains, but the pressure drop near the corners is less extreme than with sharp corners. The sides experience a more gradual decrease in pressure coefficient values, and the wake, although unsteady, is narrower with less turbulent pressure fluctuations compared to the sharp-cornered cylinder. But in case of square cylinder with rounded corners at Re = 100, the rounded corners further delay flow separation, allowing the flow to follow the surface more closely before detaching. The wake is narrow and stable. The positive value of pressure coefficient on the front face remains similar to the other cases. The pressure drop near the corners is gradual, resulting in less negative pressure coefficient values. The sides and downstream face experience a more uniform and smoother pressure recovery, with the least extreme pressure variations among the three cases. As Re increases to 200, the flow becomes unsteady, but the rounded corners help maintain a narrower and more stable wake compared to the other cases. The upstream face still exhibits positive pressure coefficient values. The pressure drop near the corners is the least severe, with a more uniform pressure distribution along the sides. The wake is the narrowest and least turbulent, leading to a more consistent and less chaotic pressure field on the downstream face. By modifying the corner geometry from sharp to chamfered or rounded decreases the intensity of flow separation, leading to a less severe pressure coefficient distribution and reduced aerodynamic drag.



(a)



(b)

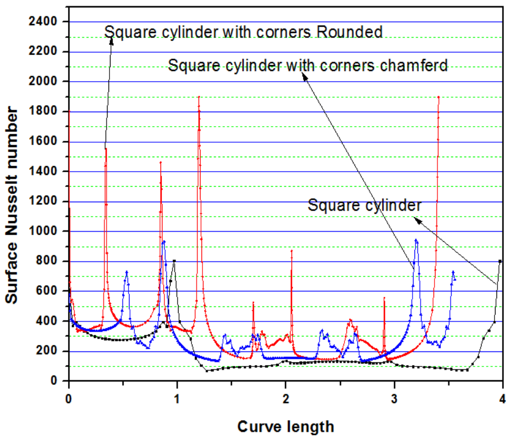
Figs. 8 (a) and (b) shows pressure coefficient distribution plots around a heated square cylinder with and without corner modifications for Re=100 and 200.

3.9 Variation of local Nusselt number on a heated cylinder surfaces with and without corner modifications

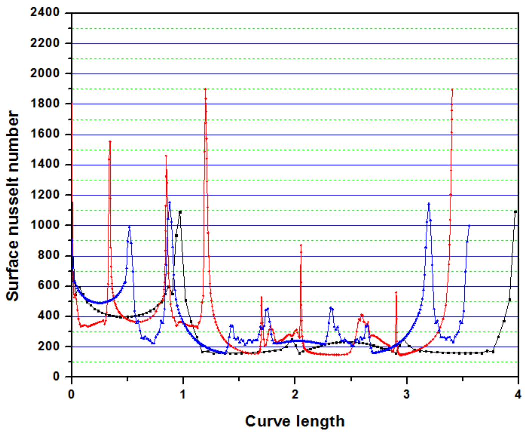
Local Nusselt number (Nu) is used to express heat transfer from the cylinder surface to the fluid. It is given by Nu = hd/k. Where h is the local heat transfer coefficient on the cylinder surface and k is thermal conductivity of the fluid. Figs. 9 (a) and (b) shows distribution of local Nusselt number on the cylinder surface for sharp corners, chamfered corners and rounded corners square cylinders at Re=100 and Re=200. For the flow past heated square cylinder, the local Nusselt number tends to be higher near the leading edges (where the fluid first contacts the surface) due to the high velocity and stagnation effects. However, it decreases rapidly after flow separation, leading to a lower Nusselt number in the wake region. In case of flow past heated square cylinder with corners chamfered, the local Nusselt number tends to be more uniform along the surface of the cylinder due to the smoother flow, but the overall Nusselt number slightly lower compared to a sharp-cornered cylinder because of reduced turbulence and mixing in the boundary layer. But in case of flow past heated square cylinder with corners rounded, the local Nusselt number even more uniform compared to the chamfered case with reduced peaks at the leading edges. The heat transfer become more uniform around the cylinder but with a lower maximum value due to less vigorous mixing in the boundary layer. At Re=100, the influence of corner modifications is more pronounced as the flow tends to remain laminar longer, making the local Nusselt number more sensitive to surface geometry. At higher Re=200, the flow transit to turbulence, reducing the relative impact of corner modifications on the Nusselt number distribution. These variations can significantly influence the design of cooling systems, heat exchangers, and other applications where heat transfer efficiency is critical. Tab.3 shows Nusselt number for a flow around heated square cylinder with and without corner modifications for Re=100 and 200. The Nusselt number for flow around a heated square cylinder with sharp corners found to be lower compared to a square cylinder with rounded corners. A square cylinder with chamfered corners falls between these two cases. When Re is increased from 100 to 200, Nusselt number will increase, it is still likely to be lower compared to the cylinders with modified corners. The Nusselt number for the chamfered cylinder will rise more significantly than in the sharp-cornered case, but it will still remain between the values for sharp and rounded corners. The Nusselt number for the rounded cylinder will see a substantial increase, maintaining its position as the highest among the three geometries.

Tab.3: Nusselt number for a flow around heated square cylinder with and without corner modifications for Re=100 and 200.

	Nusselt number	
Geometry	**Re=100**	**Re=200**
Square cylinder with Sharp corners	**5.71**	**9.64**
Square cylinder with Chamfered corners	**8.38**	**13.67**
Square cylinder with Rounded corners	**10.87**	**15.22**



(a)



(b)

Figs.9 (a) and (b): Distribution of local nusselt number on the cylinder surface for sharp corners, chamfered corners and rounded corners square cylinders at Re=100 and Re=200.

4. Conclusion

Following conclusions are drawn from the present investigations:

For Sharp-Cornered Square Cylinder:

- Flow separation occurs sharply at the corners, leading to a broad wake and prominent vortex shedding, particularly at higher Reynolds numbers (Re = 200). The pressure distribution shows a sharp drop near the corners, and both lift and drag oscillations intensify with increasing Reynolds number.

- The oscillations in lift and drag coefficients are larger due to more intense vortex shedding, contributing to high aerodynamic forces.
- Heat transfer, indicated by the Nusselt number, is less efficient compared to cylinders with corner modifications.

In Chamfered-Cornered Square Cylinder:

- Chamfering reduces the bluffness of the cylinder, resulting in smoother flow separation, narrower wakes, and more stable vortex dynamics.
- Pressure force and oscillations in lift and drag coefficients are moderate compared to the sharp-cornered case.
- The Nusselt number is more uniform around the cylinder, but still lower than for the rounded corners.

In Rounded-Cornered Square Cylinder:

- Rounded corners significantly delay flow separation, leading to a narrow wake and reduced vortex shedding intensity.
- Pressure variations are smoother, and both lift and drag forces are more stable compared to sharp and chamfered corners.
- Heat transfer is most efficient in the rounded-corner configuration, as reflected by the higher Nusselt number, especially at higher Reynolds numbers.

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