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SIMULATION OF VORTEX SHEDDING BEHIND SQUARE AND CIRCULAR CYLINDERS

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ABSTRACT

Many studies have been conducted on downstream flows behind two-dimensional cylindrical sections for low Reynolds numbers. The vortex shedding phenomenon occurs in fluid flows over buildings, trailer trucks, bridge piers, heat exchangers, pipelines in the sea, etc. This phenomenon, which is due to the flow instability in the wake region results in a periodic oscillation of drag and lift forces. In experimental studies, visualization techniques such as hot wire and Laser Doppler Velocimetry (LDV) are usually employed. By performing extensive measurements and using the concept of curve fitting, correlations have been obtained for Strouhal number variation with Reynolds number. In addition to experimental works, some analytical studies on complex wake structures of forced and freely oscillating cylinders have been undertaken. Recently, numerical models have been introduced in order to simulate this phenomenon. Khalak and Williamson made several Direct Numerical Simulation (DNS) studies on freely oscillating cylinders for Re up to 350. Low Reynolds flows (up to 800) over square and circular cylinders are simulated based on a numerical method where transient 2D Navier-Stokes equations are solved. In simulations, the fluid was assumed water with properties at 25°C. The model predictions for pressure fluctuations and the variation of Strouhal number (St) with Reynolds (Re) were compared with those obtained from experiments and correlations. In this numerical model we also compared drag force (CD) against Reynolds (Re). Under sharp rising distribution and horizontal asymptotic regime which are two major parts of St-Re variations, the model results agree well with measurements. Both simulations and experiments reveal that the St-Re variations do not depend on the shape of the cylinder. The model results agreed well with measurements.

KEYWORDS: vortex shedding, laminar flow, simulations, Navier-Stokes equations

INTRODUCTION

Two-dimensional square cylinders at low Reynolds number have attracted considerable interest and have been extensively studied for numerous applications such as in buildings, trailer trucks, bridge piers, monuments, and heat exchangers.

The cross-flow-induced vibration might cause reduction of equipment life and might even lead to occurrence of severe accidents. An insight into the complicated process of vortex structure formation and shedding will lead to a better understanding of wake processes as mixing and transition to turbulence, which is of interest from a more practical point of view. For example, in heat transfer units or during electronic equipment cooling wakes are created behind the heated components.

These wakes will have an influence on performance of downstream components. Especially for the non-adiabatic cases, heat influence the vortex-shedding process can have a strong effect on wake behavior.

The induced heat, for instance from dissipating electronic components, will give rise to buoyant flow. Therefore, vortices generation as well as the formation of a coherent vortex structure will differ from the adiabatic situation. Wake characteristics are expected to change, occasionally leading to an early transition to turbulence Kieft, [8]. Flow asymmetries around an otherwise symmetric bluff body (such as a shear flow impinging on a circular cylinder or a flow around a rotating circular cylinder) or a flow around asymmetric bluff bodies, such as bridge decks, are also known to affect, or even suppress, periodic vortex shedding. Bailey [10] studied the flow around a square cylinder near a wall and found that suppression of a periodic vortex street occurred once the cylinder was sufficiently close to the wall.

They speculated that the suppression was not due to the cancellation of vorticity in the separated shear layer closest to the wall by wall vorticity (which is of opposite sign) but rather to the reattachment of the shear layer to the cylinder surface so that its strength was significantly different from the other separated shear layer. In other words, an alternating, periodic (or Karman) vortex street did not result since the two shear layers were too different to couple.

Bailey [10] also showed the same result theoretically. The formation of a vortex street is considered to be the result of the coupling of instabilities between two separated shear layers, or vortex sheets, which have rolled up. An excellent example of this can be seen in experimental work of Huang and Keffer[11] who studied the wake of a porous mesh strip, however, this idea has existed for some time and has led to the discrete vortex method (e.g., Abernathy and Kronauer, [12]).

In von Karman's famous stability analysis ,where he assumed each separated shear layer can be modeled as an infinite row of co-rotating vortices and that the two rows of opposite signed vorticity are of equal strength, only a single stable arrangement can be found with staggered, opposing rows of vortices with a spacing ratio, $b/a = 0.281$, where b is the vertical spacing and a is the streamwise spacing. While the problems with the result is well known, most notably the spacing ratio of 0.281 is not observed in practice, von Karman's approach still shows to be useful, Aref, [1]. Since the spacing ratio of 0.281 is not observed in practice for equal circulations, we would not expect to see the same value for unequal circulations. Rather, the implication is that b/a should remain constant for variable vortex strengths. [10].

Analysis of the experimental data has confirmed this hypothesis. However, the flow near the wall always raises doubts about data interpretation as a result of the presence of wall vorticity. Nevertheless, this result suggests a practical method for vortex control shedding, where asymmetry in the flow field can be deliberately induced by the bluff body geometry.

Previous studies have determined that unsteady effects appear when the flow moves around a cylinder. These unsteady phenomena have been identified in forms of separation, reattachment bubble, shear-layer instability, or vortex shedding. Some experimental and numerical studies have been conducted on linear shear flow around a circular cylinder.

Experimental studies include those of Adachi and Kato [13], Lin J-C, Towfighi J, Rockwell[15] and Sumner and Akosile [14]. However, due to the difficulty of generating shear flow, these studies were restricted to cases with large shear parameters but low Reynolds numbers, or at sub critical Reynolds numbers with small shear parameters.

Few studies have been conducted at high Reynolds numbers with large shear parameters (Hayashi and Yoshino's study is an exception), in which they considered only one kind of shear parameter. There was a very significant disagreement among results of these studies, even on basic parameters associated with vortex shedding behavior, e.g. Strouhal number, drag force and lift force.

There have been fewer numerical studies than experimental studies, and the numerical studies were restricted to two-dimensional simulations, with low Reynolds number flows of Re 200 . Lee [17]. However Lee drew opposite conclusions about variation of drag with shear parameters. This phenomenon (vortex shedding), which is due to the flow instability in wake region, results in a periodic oscillation of drags and lift forces. This, in turn, may cause structural vibrations, acoustic noise and resonance.

In experimental studies, visualization techniques such as hot wire and Laser Doppler Velocimetry (LDV) are usually employed.

When fluid flows around a bluff body, vortices are alternatively shed and a well known Karman vortex street is formed in the wake of the cylinder.

The oscillating wake rolls up into two staggered rows of vortices with opposite senses of rotation. The frequency of vortices pairs is a function of velocity, cylinder diameter and Reynolds number. By performing extensive measurements and using the concept of curve fitting, correlations have been obtained for Strouhal number variation with Reynolds. Strouhal number is defined as Eq. 1.

The vortex shedding frequencies and flow configurations are major issues to be considered for the design of structures. The flow in a near-wake region behind the cylinder, incorporating the vortex formation region, plays an important role in determining the steady and unsteady forces acting on the body. Periodic vortex shedding patterns and fluctuating velocity fields behind the bluff bodies can cause structural damage as a result of periodic surface loading, acoustic noise and drag forces.

Most work has been done on the flow over a circular cylinder (CC) rather than a square cylinder (SC). Even though their near wake flow structures are expected to be topologically similar to each other, the reasons for flow separation on cylinder surfaces are totally different.

Flow separation occurs due to an adverse pressure gradient in the downstream direction for the CC and the separation points on the CC surface move back and forth depending on the Reynolds number. However, locations of separation points are fixed at upstream corners of the SC due to sudden geometrical changes.

A numerical investigation of the relation between changes in flow pattern and pressure, hence force characteristics of cylinders in an in-line square configuration, at Re 100, 200and up to 800 could enhance the understanding on the relation between vortex shedding and fluctuating pressure behaviors around the cylinder.

Beside experimental work, some analytical studies on complex wake structures of forced and freely oscillating cylinders have been conducted.

Recently, numerical models have been introduced for simulating this phenomenon. Khalak and Williamson based several Direct Numerical Simulation (DNS) studies on freely oscillating cylinders for Re up to 350 [1]. Vortex-induced in-line and cross-flow oscillations for a cylinder are simulated with deforming spatial domain/stabilized space–time finite element formulation of the Navier–Stokes equation by means of Mittal and Tezduyar [2], and S.Kang [3].

Zhou and Graham [4] also simulated cylinders in large-amplitude oscillatory plus a mean flow, numerically. In this paper flow oscillation over circular and square cylinders in laminar flow for Re up to 800 is computed based on transient 2D Navier-Stokes equations. Results for the two cylindrical configurations are compared with experiments and related correlations. Pressure and velocity distributions are discussed for both cases. It is shown that St-Re and CD-Re variations are independent of the shape of the cylinder.

NOMENCLATURE

g	gravitational acceleration
V	velocity
n	Time level
p	pressure
t	time
$\Delta\rho$	density difference
Δp	pressure difference
U_∞	free stream flow velocity
μ	Viscosity
ρ	density
τ	viscous stress tensor
ω	shedding frequency
Re	Reynolds number
St	Strouhal number
CD	drag force number
D	characteristic length

NUMERICAL METHOD

Needing an obvious and particular simulation about the vortex shedding phenomenon, the original academic numerical code is selected for this study. This numerical scheme is based on the old famous RIPPLE code and it has been improved for this application.

Strouhal number is defined as

$$St = \omega D / U_\infty \tag{1}$$

where ω is the shedding frequency, D the characteristic length and U_∞ free stream flow velocity.

$$\vec{\nabla}.\vec{V} = 0 \tag{2}$$

$$\frac{\partial \vec{V}}{\partial t} + \vec{\nabla}.(\vec{V}\vec{V}) = -\frac{1}{\rho}\vec{\nabla}P + \frac{1}{\rho}\vec{\nabla}.\vec{\tau} + \frac{1}{\rho}\vec{F}_b + \vec{g} \tag{3}$$

where $\vec{V}$ is the velocity vector, P indicates pressure, F_b is the body force acting on fluid, $\vec{g}$ is the acceleration due to gravity and τ represents Newtonian viscous stress tensor.

Two-step time projection method is employed to solve the momentum equation. First, an intermediate velocity is calculated based on terms related to advection, viscosity and body forces:

$$\frac{\tilde{\vec{V}} - \vec{V}^n}{\delta t} = -\vec{\nabla}(\vec{V}\vec{V})^n + \frac{1}{\rho^n}\vec{\nabla}.\vec{\tau} + \vec{g}^n + \frac{1}{\rho^n}\vec{F}_b^n \qquad (4)$$

In the second step, pressure term is modeled implicitly by

$$\frac{\vec{V}^{n+1} - \tilde{\vec{V}}}{\delta t} = -\frac{1}{\rho}\vec{\nabla}P^{n+1} \qquad (5)$$

Taking the divergence of the equation and using Eq. 2, results in a pressure Poisson equation as:

$$\vec{\nabla}.(\frac{1}{\rho}\vec{\nabla}P^{n+1}) = \frac{\vec{\nabla}.\tilde{\vec{V}}}{\delta t} \qquad (6)$$

An Incomplete Cholesky Conjugate Gradient Decomposition (ICCG) solver is employed for solving Eq. 6. Having calculated the new time level pressures, velocities are updated using Eq. 5. Williamson's experiments [5] showed that St-Re variation is continuous through laminar range [5]. The measured data when curve fitted in term of 1/Re by a linear least-square fit results in [6]:

$$St = 0.2175 - \frac{5.106}{\mathrm{Re}} \qquad (7)$$

More accurate correlations have been introduced by curve-fitting in terms of $1/\sqrt{\mathrm{Re}}$ as [6]:

$$St = 0.2665 - \frac{1.018}{\sqrt{\mathrm{Re}}} \quad for \quad \mathrm{Re} \le 200 \qquad (8)$$

$$St = 0.2334 - \frac{0.3490}{\sqrt{\mathrm{Re}}} \quad for \quad 200 \le \mathrm{Re} \le 1200 \qquad (9)$$

Domain Specification

In simulations, domain of computations was $100\,mm \times 60\,mm$ with a mesh size of 200×120 nodes. The fluid was assumed water with properties at 25°C. The square was 6 mm in each side and the circular cylinder was 12 mm in diameter

RESULTS AND DISCUSSION

The vortex shedding is simulated in a case for which measurements are available in the literature .To validate the model, vortex shedding is simulated in a case for which measurements are available in the literature. Williamson's experiments [5] showed that St-Re variation is continuous through a laminar range [5]. The measured data, when curve fitted in term of 1/Re by a linear least-square fit, results in [6]. Figure 1 compares model predictions for two shapes with results of experiments and correlations. Two different regimes for St-Re variations are observed: a sharp increase for Re below 200 and an asymptotic distribution (approaching 0.21) for Re between 200 and 1200.

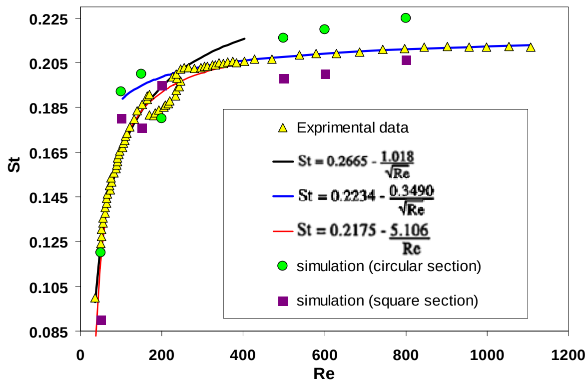

Figure 1. Comparison between model predictions and experimental results [5]. The curve fitted plots based on measurements are also shown in the figure**.**

Several Re numbers were considered in simulations covering a range from 50 to 800. Figure 1 reveals that numerical results agree well with those of experiments for all Re numbers for both cylindrical shapes. The maximum discrepancy between two results is 0.033 for a square shape at Re=50. The figure also shows that the numerical model predicts well the correlations obtained based on experimental values.

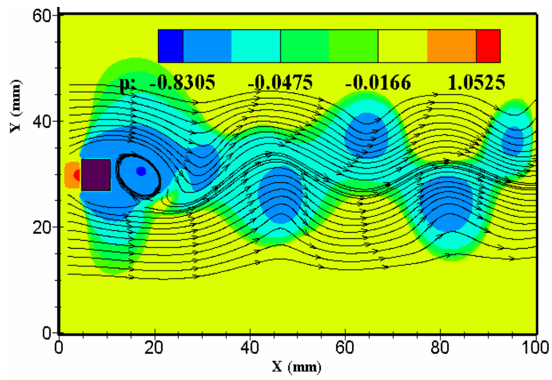

Figure 2. instantaneous Pressure s fluctuations behind a square section for a fluid flow with Re=100.

The wide range of Reynolds number is covered with these simulations and there is compared with available experiments and those of existing correlations. The brief comparison and the accordance between the numerical simulation (for each square and circular cylinder) and experiments in all regimes is also the novelty of this study.

The vortex could be shaped from behind of obstacles alternatively. This pulsating phenomenon is based on the flow characteristics and whenever the Reynolds number increased the flow regimes and the frequency of vortex shedding changed actually. This vortex behavior is made up from very small perturbation in inflow velocity and this may be simulating with artificial perturbation in numerical methods.

However, the reliable numerical code should be detecting the flow regime referred on nature of phenomenon; the data on all figures supports this idea.

Figure 3 displays the pressure distribution around a circular section. Although vortices in this case are closely similar to square cylinder results and both of them predict an experimental behavior.

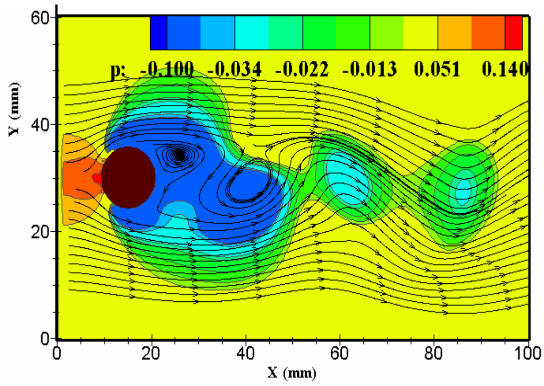

Figure 3. Instantaneous Pressure s fluctuations behind a circular section for a fluid flow with Re=100.

Figure 4 shows vortices generation in corner sides of a square cylinder at Re=500. As we can see vortices numbers are increased in a higher Reynolds number. It is obvious that in square section inception of vortices happened in corner sides Same Reynolds number has been shown in Fig 5 but in the circular section, and as it is expected vortices begin from 80º in laminar flows.

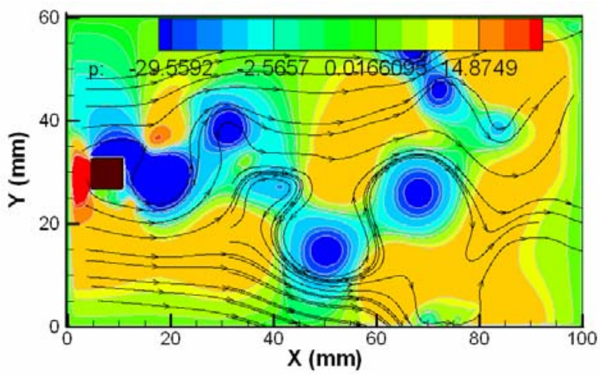

Figure 4. Instantaneous Pressure s fluctuations behind a square section for a fluid flow with Re=500.

Figures 6 and 7 also show pressure distribution in square and cylinder sections at Re=800. We can see in higher Reynolds

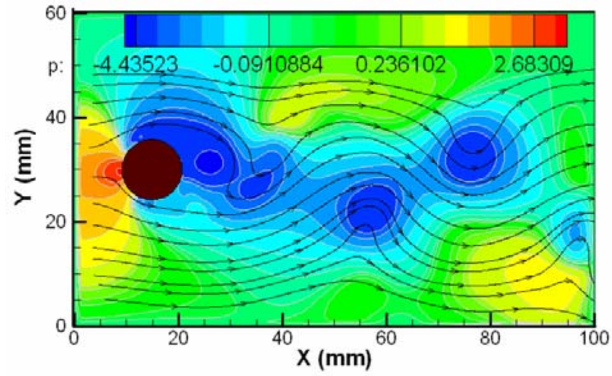

Figure 5. Instantaneous Pressure s fluctuations behind a circular section for a fluid flow with Re=500.

number that vortices generate alternatively above and below a square or circular shape especially in square section. In addition, range of pressure in square section is much more extensive than circular section.

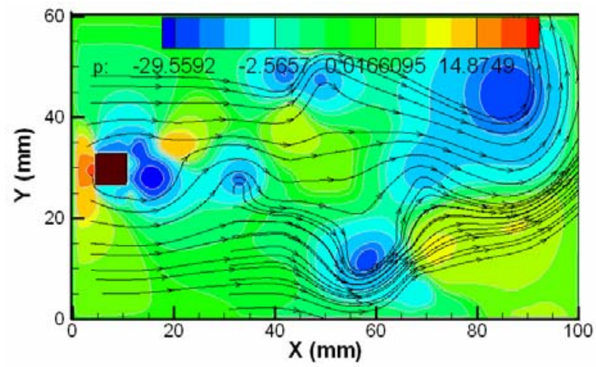

Figure 6. Instantaneous Pressure s fluctuations behind a square section for a fluid flow with Re=800.

The numerical model was validated by comparing Reynolds number dependence of drag coefficient of a circular cylinder at a Reynolds number of Re = 50–800.

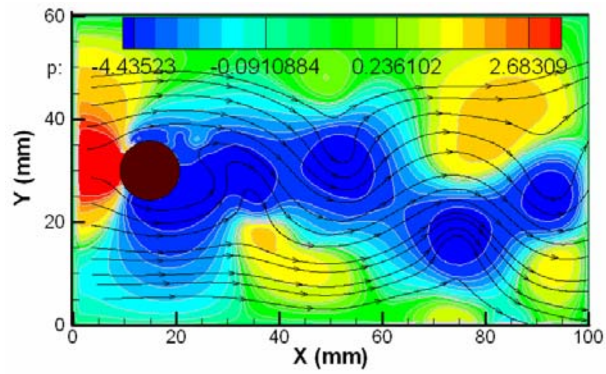

Figure 7. Instantaneous Pressure s fluctuations behind a circular section for a fluid flow with Re=800.

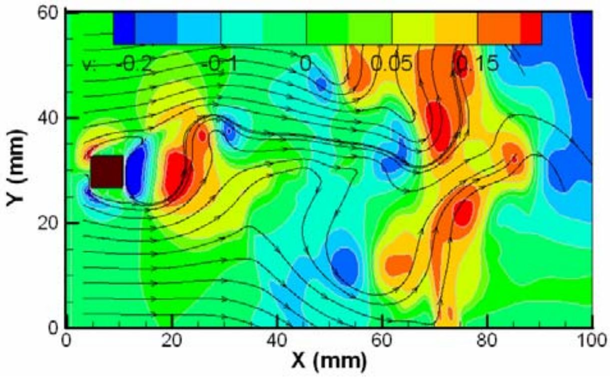

Figure 8. Instantaneous velocity fluctuations behind a square section for a fluid flow with Re=500. Range of velocity is less variable compare to Pressure fluctuations.

Figures 8 and 9 illustrate velocity fluctuations behind square and circular section at Re=500.

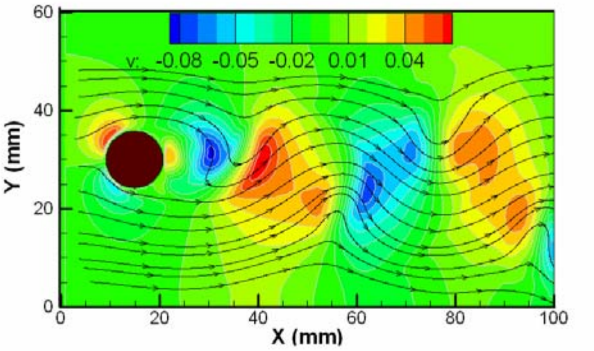

Figure 9. Instantaneous velocity fluctuations behind a circular section for a fluid flow with Re=500.

It is clear that velocity range is much smoother than pressure fluctuations.

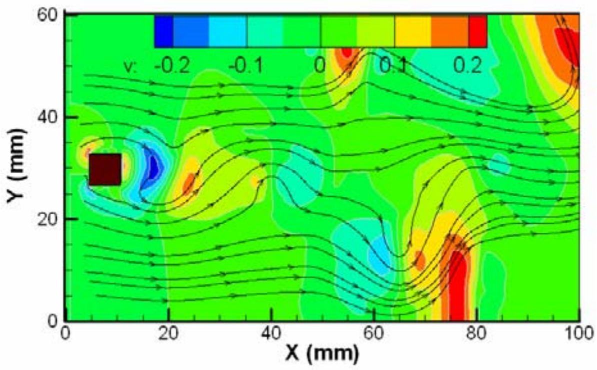

Figure 10. Instantaneous velocity fluctuations behind a square section for a fluid flow with Re=800.

Figures 10 and 11 shows velocity fluctuations at Re=800, it is much smoother than pressure fluctuations at Re=800. however, it is not as smooth as velocity fluctuations at Re=500.

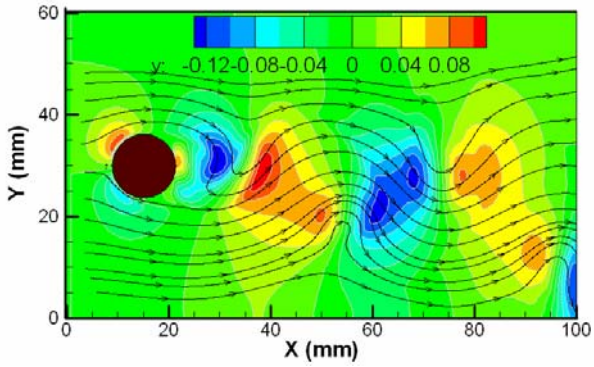

Figure 11. Instantaneous velocity fluctuations behind a circular section for a fluid flow with Re=800. velocity is more smooth compare to square section

Figure 12 compares present results of Strouhal number and drag coefficient with those of Williamson [9] and others. Agreements between tendencies of St–Re and CD–Re are recognized.

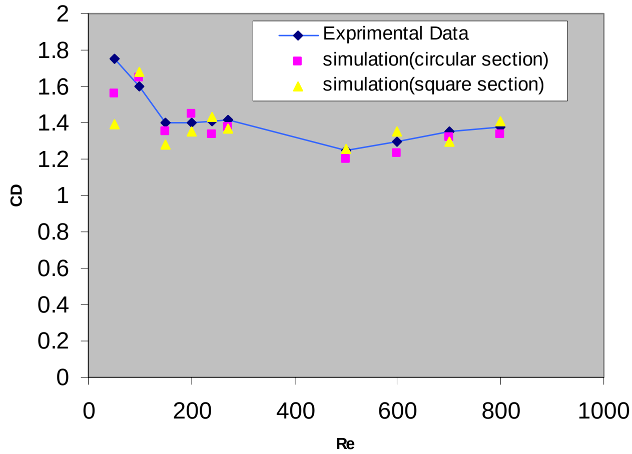

Figure 12. Validation of present simulation—Reynolds number dependence of St and CD. [7]. The maximum discrepancy between the results is 0.38 for square shape at Re=50 but it is more accurate at higher Reynolds number.

The maximum discrepancy for both St–Re and CD-Re between the results is for square shape at Re=50 but it is more accurate at higher Reynolds number.

CONCLUSION

Vortex shedding phenomenon was simulated around two cylindrical sections by a numerical solution of transient 2D

Navier-Stokes equation. Model predictions for pressure fluctuations and the variation of Strouhal number (St) against Reynolds (Re) were compared with those obtained from experiments and related correlations. Model results agreed well with measurements. In this numerical model we also compared drag force (CD) against Reynolds (Re). It is evident that an experimental study and a numerical model are related correlations and these correlations are more accurate in a higher Reynolds number. Most differences in both St–Re and CD–Re happened in Re=50. Both simulations and experiments revealed that St-Re variations do not depend on the shape of the cylinder.

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