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Numerical study on flow and aerodynamic characteristics: Square cylinder and eddy-promoting rectangular cylinder in tandem near wall

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ABSTRACT

Numerically simulated results are presented for shear flow past a square cylinder (of height a) near a wall (at a gap height $0.5a$) in presence of eddy promoting rectangular cylinders (of fixed height a with different widths $b \leqslant a$) to gain a better insight into the dependency of aerodynamic characteristics of both the cylinders on the parameters: spacing distance between the cylinders S $(= D/a\colon\ 0.5 \leqslant S \leqslant 20)$ and aspect ratio r $(= b/a\colon\ 0.1 \leqslant r \leqslant 1.0)$. The value of Reynolds number Re is kept as $Re = 100$ and 200. The governing unsteady Navier–Stokes equations are solved numerically based on the finite volume method on a staggered grid system using QUICK scheme. The resulting equations are then solved by an implicit, time-marching, pressure correction-based SIMPLE algorithm. The influence of numerical parameters on the validated code used in this study is demonstrated here. The strong dependency of vortex shedding (from both the cylinders) on aspect ratio r and spacing distance S are explored and, hence, a region of finite area in the Sr-plane is proposed in order to generate the unsteadiness in the steady flow of the downstream cylinder. *An attempt is made to identify the different flow regimes depending on the flow patterns of the downstream cylinder, associated with the geometrical parameters (S and r).* Owing to the differences in the basic shedding frequency of the square (downstream) cylinder from that of the rectangular cylinder (promoter) of different widths, the major issue of appearing multiple peaks in the spectrum of fluctuating lift coefficient of the downstream cylinder is addressed. The thrust force observed on the downstream cylinder in presence of the thinner promoter at closely spaced arrangement is justified presenting the surface pressure distribution. Finally, the present numerical results at large spacing distances are certified with some previous numerical and experimental findings.

1. Introduction

There have been numerous experimental and numerical studies of unsteady flow past bluff bodies. These studies have several technical applications such as compact heat exchangers, cooling of electronic components, drying of different materials (textiles, veneer, paper and film materials), cooling of glass, plastics and industrial devices, and so on. The objectives of most of the studies have been devoted to examine the unsteady nature of the flow behind the bluff bodies and the effects on heat transfer and flow-induced vibrations. It is known that the high dense ICs may generate high temperature during their operation. Therefore it is required to dissipate the excess heat generated in the ICs to make them work efficiently. As it can be found from the previous literatures (Yang and Fu [49] and Sharma and Eswaran [40]), the heat flux for the case of flow with vortex shedding is higher than that without vortex shedding. An enhancement of heat transfer from heated cylinder/flate tube bank fin due to the interaction of vortices generated by a vortex generator was reported in some of the previous studies (Devarkonda and Humphery [14] and Zhu et al. [50]). An upstream cylinder of rectangular shape can generate the vortices and enhance the heat transfer from a heated square downstream cylinder in tandem arrangement. In the future, a systematic study will be conducted to maximize the heat transfer from the heated square cylinder, beginning with the problem of understanding the fundamental mechanism of unsteady interaction between tandem pair of cylinders without considering the energy equation.

Studies on the problems of wake development and vortex shedding behind a rectangular cylinder in free-stream flows were investigated both numerically and experimentally by Davis and Moore [12] and Franke et al. [17], Patankar and Kelkar [36]. Davis and Moore [12,13] studied the vortex shedding from rectangular/square cylinder numerically in both uniform and channel flows. Flows around rectangular cylinder in unbounded domain were

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extensively studied experimentally and numerically by Okajima et al. [33,34]. Gennaro et al. [15] studied the effect of flow shear on the Strouhal number of cylinder vortex shedding.

When the cylinder is placed in the proximity of a solid wall, the strengths of the upper and lower shear layers separated from the surfaces of the cylinder are not equal and the vortex shedding pattern is distorted. The form of the wake and the vortex shedding behind a cylinder in proximity of a wall were studied by several authors, namely, Bearman and Zdravkovich [4], Bosch and Rodi [10], and Bhattacharyya and Maiti [6–8]. Bhattacharyya and Maiti [6] observed that the vortex shedding frequency was higher for the laminar flow past a square cylinder near a wall with incident inlet shear flow than the unbounded flow. The dependence of flow characteristics of a rectangular cylinder near a wall on the incident velocity and on the gap height has been reported in the previous studies (Maiti [25,26]) under incident inlet shear flow. It has been reported there that the rectangular cylinder with $r = 0.5$ is the optimum size (among all the rectangular cylinders of $r \leqslant 1$) to produce the stronger vortices in the wake irrespective of the position from the wall. It has also been reported there that the vortex shedding from a rectangular cylinder of lower aspect ratio occurs at comparatively lower Reynolds number.

The studies on the several aspects of the unsteady flow past tandem circular cylinders arrangement were performed by Alam et al. [1], Sharman et al. [41], and the flow and heat transfer from other obstacles in tandem arrangements were conducted by Zhu et al. [50], Singha and Sinhamahapatra [42]. The flow over two circular cylinders, with the large diameter cylinder upstream of the smaller one, were experimentally studied by Baxendale and Grant [3] and Sayers and Saban [38] for different cylinder spacings, diameter ratios and stagger angles.

Tatsutani et al. [47] investigated the unsteady flow and heat transfer for a pair of square cylinders (aligned on the centerline of the channel with uniform inlet velocity profile); they reported that Strouhal number *St* is larger for small-large tandem pair than the cylinder pair of the same size. In a similar study, Rosales et al. [37] numerically reported the pronounced differences in the unsteady behavior of cylinders in a fully developed parabolic velocity profile when compared with an initially uniform inlet velocity profile. Mixed convection through a horizontal channel with two isolated protruding blocks on the bottom wall was numerically studied by Wang and Jaluria [48]. They observed that the frequency and amplitude of perturbation are changed by adjusting the geometry of the promoter.

A numerical study of the two- and three-dimensional unsteady flows over two square cylinders arranged in an inline configuration for *Re* ranged in [40, 1000] at $S = 4$ was performed by Sohankar [43]. The effect of the spacing distance, ranged in [0.3, 12], was also studied at selected *Re*. Three major regimes for the flow field are distinguished by Sohankar [43]. Malekzadeh and Sohankar [29] also reported three major regimes in the flow patterns, depending on the values of height and position of a control plate in unbounded region. Etminan et al. [16] numerically studied the unconfined flow characteristics around two square cylinders in both steady and unsteady laminar flow regimes at a fixed $S = 5$. Flow around an inline cylinder array consisting of six square cylinders subjected to unconfined uniform flow at a fixed $Re = 100$ is investigated numerically by Bao et al. [2]. They showed six different flow patterns, which appeared successively with the increase of spacing distance.

For the flow of incompressible fluid past a pair of square cylinders in inline tandem arrangement, Lankadasu and Vengadesan [20] reported the negative drag force on the downstream cylinder at some shear rates. In a similar study (when both the cylinders placed near a wall at a fixed height 0.5 times the cylinder height), Bhattacharyya and Dhinakaran [5] observed that the vortex shedding starts for *Re* beyond 125 for all values of spacing distance, and the wake of the downstream cylinder consisting of a series of negative vortices. Maiti and Bhatt [27] extended the above study considering the upstream cylinder of rectangular shape of different heights and widths. The upstream cylinder was placed towards the wall at gap heights 0.1 and 0.25 times the downstream cylinder height. The suppression of the vortex shedding from the downstream cylinder was reported due to diversion of the downstream cylinder's gap flow depending on size of the upstream cylinder and its position with respect to the downstream cylinder and the wall at a fixed *Re*.

From the above literature discussion, it is plausible that the eddy promoter, placed at the upstream side of an obstacle, can generate the developing boundary layers, swirl, and flow destabilization, and that depends on the shape of the promoter and other parameters such as angles and speed of attack, and the position with respect to the obstacle and wall. From the previous studies (Maiti [25,26]), it can be deduced that the rectangular shape for the promoter would be interesting in generating the vortices (passively) under the incidence of shear flow to dominate the state of the wake of a downstream square cylinder. To the knowledge of the authors, not a single published paper is available in the literature on the shear flow around a square cylinder near a wall in presence of an upstream cylinder of rectangular shape in an inline tandem arrangement. The main objective of this investigation can be divided into three folds: (i) depending of the flow over the upstream/downstream cylinder on the shape (rectangular/square) of the upstream cylinder, (ii) the dependency of the aerodynamic characteristics (namely Strouhal number, time-averaged and root-mean-square (*RMS*) values of the fluctuating forces) of an upstream rectangular cylinder (promoter) of different widths on the presence of a downstream square cylinder, and (iii) the dependency of the aerodynamic characteristics of a square cylinder on the presence and width of an upstream rectangular promoter, under the situation of different spacing distances between the cylinders. An attempt is made to propose a region for the critical spacing distance, for which the unsteadiness can be generated in the steady flow of the downstream cylinder, for different widths of the promoter at a fixed *Re*. The value of critical spacing distance for which the promoter starts to shed the vortices is searched for different sizes of the promoter. The investigation is completed documenting the comparison of the present results with those of some previous experimental and numerical results at higher spacing distances.

2. Problem formulation and numerical method

2.1. Problem formulation

A wall lying along the x^*-axis and a long cylinder of square cross-section of height a is placed parallel to the wall at a height $0.5a$ from the wall, as below this height a suppression of vortex shedding for $Re < 125$ was reported in the previous study (Bhattacharyya and Maiti [6]). Another cylinder of rectangular cross-section of aspect ratio $r = b/a$ with width b and height a is placed in the upstream side of the square cylinder at a distance D and parallel to the wall at the same height ($= 0.5a$) from the wall (see Fig. 1). The upstream flow field is taken as a uniform shear flow $u^* = \frac{U_0 y^*}{a}$ where U_0 is the velocity at height a from the wall. The rationale for this choice of linear velocity profile near the wall has been discussed in the previous study (Maiti [25]). As there is no velocity scale U_0 directly, the prescribed slope λ of the incident velocity profile at the surface multiplied by a, leaving $U_0 = \lambda a$ is taken as the velocity scale based on obstacle height. The height of the cylinder a is considered as the characteristic length scale. It may be noted that there will not be any incidence flow if the velocity gradient λ approaches zero.