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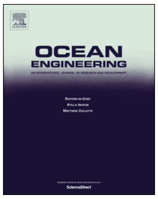

Effect of gap spacings on flow past row of rectangular cylinders with aspect ratio 1.5

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ABSTRACT

Two-dimensional numerical study has been carried out to investigate the effect of gap spacings for flow past five side-by-side rectangular cylinders using the lattice Boltzmann method at a Reynolds number of 150 and aspect ratio defined as AR=length/height=1.5. The gap spacing between the cylinders is varied systematically from $g=0.5$ to 4, so that the sensitivity of the flow and force statistics can be inspected. The gap spacings have strong effect on the hydrodynamic interaction of the cylinders wakes which significantly affects the flow structure. The flow behavior can be grouped into five patterns: (i) symmetric, (ii) flip-flopping, (iii) in-phase and anti-phase modulated deflected, (iv) in-phase modulated non-synchronized and (v) in-phase and anti-phase modulated synchronized. Calculations of mean drag coefficient, Strouhal number and root-mean-square value of drag and lift coefficients are carried out on each cylinder and compared with available literature. Each flow pattern will be studied in terms of wake structure, power spectra analysis of lift coefficients and time analysis of drag and lift coefficients. The average Strouhal number and average drag coefficient show significant variation against gap spacing.

1. Introduction

Flows around bluff bodies have many applications in science and engineering and attracted considerable interest of researchers. Bluff structures, e.g., circular cylinders and rectangular cylinders have been employed in many architectural structures, high-rise buildings, bridges, heat exchangers etc. When flow moves around a cylinder, several phenomena such as separation, separation bubbles and vortex shedding occurs. Researchers have conducted many studies on circular and square cylinders. In case of rectangular cylinders the aspect ratio (AR) plays an important role and in some situations causes local and global instabilities (Sohankar et al., 1997; Nakamura et al., 1996; Nakagawa et al., 1999; Bearman and Trueman, 1972). In addition, the difference in aspect ratio can create strong change in fluid dynamics characteristics. Okajima (1982) analyzed the vortex shedding frequency for flow past a rectangular cylinder with different aspect ratios and Reynolds numbers ($Re=U_\infty h/\nu$, where U_∞ is the uniform inflow velocity, h is the height of the cylinder and ν is the kinematic viscosity). He observed that for $10^4<Re<2\times10^4$ the highest Strouhal number ($St=f_s h/\nu$, where f_s is the vortex shedding frequency) is 0.13. Islam et al. (2012) numerically investigated that the drag coefficient decreases with increase in aspect ratio and the decreasing rate is more in the range of $0.15\le \mathrm{AR}\le 2$. They also studied that the vortex formation region is smaller compared to square cylinder for low aspect ratios. Okajima et al. (1990) analyzed the aspect ratio effect for flow past a rectangular cylinder with Re varying from 500 to 1200 and AR ranging from 0.4 to 8. They observed critical changes in wake patterns at AR=2.8 and 6. While Abdollah et al. (2008) experimentally investigated that the wake flow around a rectangular cylinder decreases as the aspect ratio increases.

The appearance of more than one cylinder in fluid field has also taken much attention in fluid mechanics from many researchers because of its importance in engineering applications (Han et al., 2014; Kang, 2003). When these cylinders are arranged side-by-side to the flow, the wake of the cylinders interacts from each side of the gap between the cylinders with one another. They behave like a single bluff body at very close gap spacings ($g=s/h$, where s is the surface-to-surface distance between the cylinders) (Kang, 2003). At large gap spacings, they behave as independent bluff bodies, with possible synchronization (Kang, 2003; Sanaati and Kato, 2014). In addition, at intermediate gap spacings, complex wake structures and strong interactions between the vortex-street occurs, as a result biased or asymmetric flow pattern exist (Han et al., 2014; Kang, 2003).

One can find the effect of gap spacing and Reynolds numbers for flow past three side-by-side square cylinders (Rahman et al., 2015; Islam et al., 2016a, 2016b, 2016c). Rahman et al. (2015)

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numerically investigated the effect of Reynolds number for flow past three side-by-side square cylinders for different unequal gap spacings (g_1, g_2)=(1.5, 1), (3, 4) and (7, 6). They found that the Reynolds numbers have strong effect on flow at small unequal gap spacing while at intermediate gap spacing the primary vortex shedding frequency is predominant and secondary cylinder interaction frequencies almost diminishes. They observed flip-flopping, in-phase and anti-phase modulation synchronized and in-phase and anti-phase synchronized flow patterns. Further, they examined that the wake between the cylinders strongly depends on Reynolds number as well as on unequal gap spacing. Islam et al. (2016a, 2016b, 2016c) numerically investigated flow past three side-by-side square cylinders using multi-relaxation-time lattice Boltzmann method. They studied the effect of equal and unequal gap spacing on wake structure at $Re=150$. A slight change in equal and unequal gap spacing cause changes in wake structures and fluid forces. They also observed the bistable, asymmetric, in-phase-anti-phase and modulated synchronized flow patterns.

The more detail literature about two and three side-by-side circular and square cylinders is given in introduction section of our recent papers (Rahman et al., 2015; Islam et al., 2016a, 2016b, 2016c). Here, we will discuss only the flow past row of cylinders. Huang et al. (2006) studied the flow patterns of flow past row of rectangular cylinders using FLUENT for $Re=150$. They investigated that for large gap pacing ($g=4$) the vortex street is stable and for moderately gap spacing ($g<2.5$) the vortices behind the cylinders merges and move in a synchronized in-phase pattern. The interaction of flow past row of circular and square cylinders have been analyzed experimentally and numerically by Mizushima and Akinaga (2003), Kumar et al. (2008) and Chatterjee et al. (2010). Mizushima and Akinaga (2003) investigated in-phase and anti-phase vortex shedding at $g=1$ and 3, respectively, for flow past row of square and circular bars. Kumar et al. (2008) studied row of square cylinders numerically, and observed synchronized, quasi-periodic and chaotic flow regimes at small gap spacing while at large gap spacing no significant interaction between the wakes is observed. They investigated that the mean drag coefficient (Cdmean) and St increase rapidly with decrease in g. Chatterjee et al. (2010) observed flip-flopping, in-phase, anti-phase and non-synchronized flow patterns at $Re=150$ and $g=1.2$, 2, 3, and 4 for flow past five side-by-side square cylinders using Finite Volume method (FVM). At small gap spacings they observed the jet effect in terms of secondary frequencies while at large gap spacings the secondary frequencies disappear and the resulting flow is synchronized. Beside side-by-side arrangement the study of flow around bluff bodies in different other arrangements like staggered and inline arrangements are also found in literature. Anagnostopouls and Seitanis (2014) numerically studied cross flow past two staggered rows of cylinders at $Re=200$ using the finite element method at $g=0$–1, where the upstream row contains three and downstream row contains four cylinders. They observed that the drag force exerted on the upstream row is higher than downstream row of cylinders and shedding frequency of upstream row is higher than the downstream row of cylinders. Further studies related to such arrangement can be found in Abbasi et al. (2014), Chatterjee and Biswas (2015), Chatterjee and Gupta (2015) and Islam et al. (2016a, 2016b, 2016c). One other important aspect of flow around bluff bodies is the transfer of heat from the bluff body to fluid or from fluid to fluid body. This phenomenon has also been studied by many researchers (Chatterjee et al., 2009, 2012; Garoosi et al., 2015a, 2015b, 2015c; Sheikholeslami et al., 2015).

Based on above mentioned studies, we decided to focus on aspect ratio 1.5 for this article. Different flow patterns, jet effect, downstream flow characteristics and the existence of primary and secondary frequencies will be analyzed in this work. Alteration of wake structure at different time steps between the gaps and at downstream will also be analyzed. Another main agenda of this study is that the sensitivity of physical parameters will be examined on each side of the cylinder and also the capability of the lattice Boltzmann method.

The paper is organized as follows. After introduction in Section 1 problem description and research methodology is discussed in Section 2. Grid resolution and code validation is discussed in Section 3. In Section 4 we present the results and discussion. Data analysis of physical parameters and empirical relations of mean drag coefficient and Strouhal number are given in Sections 5 and 6, respectively. Finally, some concluding remarks are presented in Section 7.

2. Problem description and research methodology

2.1. Problem description and boundary conditions

The computational domain shown in Fig. 1 is fixed in stream wise direction and varies in transverse direction for different gap spacings. Five rectangular cylinders of height 'h' and length 'ℓ' are arranged side-by-side in a channel of height 'H' and length 'L'. The length of the channel is fixed at 45.5 h and height varies for different gap spacings shown in Table 1. g^* is the distance from the first and fifth cylinders to lower and upper walls, respectively. Five rectangular cylinders c_1, c_2, c_3, c_4 and c_5 present first, second, third, fourth and fifth cylinder, respectively, arranged in the channel from bottom to top. Lu is the upstream distance before the cylinder and Ld is the downstream distance after the cylinder in streamwise direction. x and y are the Cartesian coordinates in the streamwise and transverse directions, respectively. s is the surface-to-surface distance between the cylinders and g is the gap spacing.

In a channel flow, the uniform inflow velocity ($\mathbf{u}=U_\infty$, $\mathbf{v}=0$) is prescribed at the channel inlet. At the outlet, a convective boundary condition is applied (Breuer et al., 2000). The no-slip boundary conditions are applied at the surfaces of the cylinder (Guo et al., 2000). The periodic boundary conditions are applied at the lower and upper walls of the channel (Sukop and Thorne, 2005). The total fluid force on the square cylinder is calculated using the momentum exchange method (Yu et al., 2003).

2.2. Lattice Boltzmann method

In lattice Boltzmann method the fluid is replaced by small

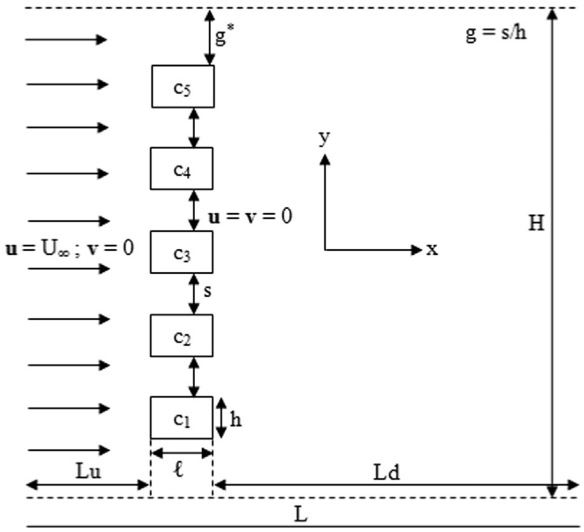

Fig. 1. Computational domain for flow past row of rectangular cylinders.