Review of Flows Past Arrays of Elliptic and Square Cylinders

Rajesh Kumar and N. K. Singh

Abstract The bodies which create the separation of flow for a certain area of their surface are known as bluff bodies. The bluff bodies can have sharp edges or these can also have a continuous surface. Vortex shedding is important phenomena related to bluff bodies which are present in both laminar and turbulent flows. When more than one cylinder or array of cylinders of the various cross sections is taken, then the results are highly different from the case of flow over one cylinder. Flows past arrays of cylinders of different cross-sectional areas are experienced in numerous engineering relevant. The several cylinders of cross-sectional areas such as of circular, square, ellipse, rectangular, and semi-circular can be organized in side-by-side, tandem or staggered layout. This paper evaluates the prevailing appreciation of the flows past arrays of cylinders with emphasis on the near-wake flow patterns, the transitional wake formation and conduct, Reynolds number influences and aerodynamic force coefficients. A principal attention is on the major numerical and experimental discourse that has noticeably since the last significant review of this issue. In this paper, a vigorous has been made to review the study of the work of various researchers for flows past arrays of elliptic and square cylinders, which will be helpful to perceive the various gaps in the research for conducting further new research work in this field.

Keywords Large eddy simulation · Vortex shedding · Reynolds number

1 Introduction

When the fluid flow is having a very low velocity, then the flow over the body is called an attached flow. If the velocity increases, the flow separates from the body, and shear layers or vortex sheets starts forming. A low-pressure region known as wake is also formed near the cylinder. When the Reynolds number increases

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beyond a certain limit, then these vortex sheets start to oscillate and collapse into small vortices. This phenomenon is given by Theodore von Karman, who discovered this pattern. Flow over arrays of cylinders has many applications in industries that include nuclear rods, offshore structures, heat exchangers, boilers, condensers, construction of bridges, etc. To achieve the analysis of the above-mentioned, one of the foremost processes is the simulation of flow over arrays of cylinders not only for the purpose of heat transfer but also for wake interaction and vortex shedding behind the cylinders. Flows over circular and elliptical cylinders are an important topic of research in marine engineering. Many offshore structures in marine engineering have a cylindrical cross section, such as risers and pipelines. The uses of these pipelines and other structures have increased and will increase further due to demand for oil. It is important to understand the flow around elliptical and circular cylinders to calculate the forces acting on them. Separation occurs over a large part of the surface of a bluff body, which creates a high-pressure drag and a large wake region behind the bluff body. Bluff body wakes involve complex phenomenon, in which three shear layers interact with each other in the same problem: a boundary layer, a free shear layer, and a wake. The wake of a bluff body is quite complex and few patterns can be characterized as periodic, vortex shedding, and a von Karman vortex street. The relationship between the drag coefficient, pressure, and vortex shedding frequency, and the size of the wake region is complex and requires improved insight, for 3-D bluff bodies. This increased physical understanding will help engineers in the prevention of flow-induced vibrations. Despite the fact that two-dimensional and three-dimensional instabilities in wakes have been a subject of interest to engineers and scientists for many years, an understanding of the flow behind a bluff body is a great challenge.

1.1 Cylinders Arrangements

When flow passes over the array of cylinders, then flows interference occurs which is the result of various parameters such as the distance between the adjacent cylinders and the angle of the flow. In the practical observance, staggered arrangement of the cylinders is most common because mostly the flow over the cylinders is not accurately perpendicular to them. In this arrangement, a certain angle is used to create a position of the geometry. The various arrangements of the different cross-sectional cylinders can also be made in alternate rows and columns to find out the various flow characteristic changes occurring due to flow interferences between the cylinders. These arrays of cylinders of various cross sections are used in practical life, such as in the construction of buildings, bridges, and pillars. When a fluid flows across these

Fig. 1 Two square cylinders in cross-flow: **a** tandem configuration; **b** side-by- side configuration; and **c** staggered configuration

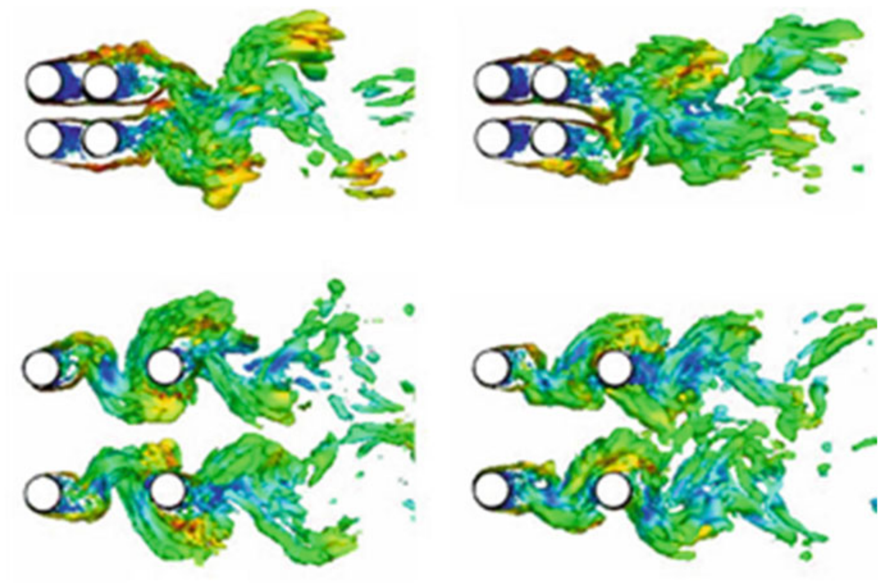

Fig. 2 Vortex formations for four circular cylinders **a** upward deflected *L*/*D* = 1.5, **b** downward deflected *L*/*D* = 1.5, **c** anti-phase *L*/*D* = 3.5, and **d** in-phase *L*/*D* = 3.5 (*L*/*D* is spacing ratio) [1]

cylinders, various characteristics of flowing fluid come into picture which affects these constructions. So, these are necessary to be studied to have better and safer designs for various engineering applications. There are various arrangements of the cylinders, whether they are of circular, elliptical, or square cross sections. These can be arranged in various forms such as in tandem placement, side-by-side placement and staggered placement of cylinders (Figs. 1 and 2).

2 Literature Review

2.1 Review of Flow Past Array of Elliptic Cylinders

Elliptic cylinders are considered as a basic form since it can be altered into a circular and a flat plate by varying the axis ratio. Also, an elliptic cylinder is sometimes preferred over circular cylinders due to its small wake region and drag coefficient values than that of the circular one. There had been a few numerical simulations of flow past elliptic cylinders. Flow over arrays of cylinders is a complicated phenomenon and had been a research topic for many studies of elliptical as well as of circular cylinders. Ota et al. [2] conducted the research on two elliptical cylinders which were tandemly arranged and investigated the heat transfer study. The axis ratio taken was 1:2, the fluid selected for the study was air and the Reynolds number taken was ranging from 15,000 to 80,000 which were based on the major axis length. Castiglia et al. [3] investigated the flow over an array of elliptic cylinders. The modeling of the flow was done by large eddy simulation (LES). The study of the flow over tandem cylinder arrangement of an elliptic cross section was done by using fluid which was non-Newtonian. They used the Smagorinsky model for the 3-D simulation. It was found out that vortex shedding does not start from the first cylinder, free shear layer separates from the surface and attaches to the downstream cylinder and again it gets separated and does not roll up into vortices, but attaches to the surface of the third cylinder. After the third cylinder vortex shedding starts, formed vortices impinge on the next downstream cylinder. As we move downstream, the vortex shedding increases and by the power spectral study it was shown that the peak of vortex shedding increases. They had also shown that in the direction of flow, the turbulence intensity increases because of the presence of the cylinder and due to vorticity transport from the surface of the cylinders.

Ibrahim and Gomaa [4] investigated experimentally and numerically the heat transfer characteristics of flow over arrays of the elliptical cylinder in cross-flow in the turbulent regime. The range of the Reynolds number which was used for the study was ranging from 5600 to 40,000, minor to major axis ratio used for the study were 0.25, 0.33, 0.5, and 1, and angle of attack used for the study was 0 to 150°. In their study, it was found that average Nusselt number for the angle of attack of 90° was higher than the angle of attack of 0° and 30°, also for the angle of attack of 0° and 30° the value of friction was lower than the values of friction at other angles. Lam and Zou [1] had experimentally and numerically studied the flow over circular cylinder arrays at the spacing ratio of 1.5, 2.5, 3.5, and 5.0 in subcritical flow regime from 11,000 to 20,000. The LES was used for the simulation at Reynolds number of 15,000. The bistable flow was found in the study at a spacing ratio of 1.5 and it was confirmed experimentally. At a spacing ratio of 3.5, the flow pattern was different and two phases was found out that was anti-phase vortex shedding and in-phase vortex shedding. The spacing ratio and the Reynolds number affect the vortex formation length. Lin et al. [5] numerically investigated the laminar flow characteristic of flow over the diamond arrangement of cylinder arrays. The simulation was carried out in three dimensions, the Reynolds number used for the study was 200, and the spacing ratio used was ranging from 1.2 to 5. The flow pattern varied from a single bluff body flow behavior to vortex impingement on the cylinder. The transition of the flow occurs at the critical spacing ratio of 3.0 which causes the lift force to increase drastically.

Yu et al. [6] conducted the numerical simulation to find the effect on the drag force of flow over circular arrays of cylinders. A 2-D simulation was carried using (RANS/LES) model. Nejat et al. [7] studied the effect of various numbers, ratios, and the distance between the cylinders on the fluid coefficients. Chatjigeorgion and Mavrakos [8] gave a result of the scattering of waves by the arrangement of the array of elliptic cross-sectional cylinders. Alawadhi [9] conducted the study on the laminar forced convection flow around an elliptic cylinder array in an in-line configuration with some angle of inclination. The angles of inclination used were 0°, 22.5°, 45°, 67.5°, and 90°. The finite element method was used for the solution of the governing equations. The Reynolds number used for the study was ranging from 125 to 1000. Nair and Sengupta [10] numerically investigated the flow past elliptic cylinder using DNS and compared the results for Reynolds number of 3000. In their study, they found that the vortices which were released from the surface were strong and in alignment and depends on the angle of attack taken for the study. Kim et al. [11] corrected Darcy's law non-linearly for the flow over array of elliptic cylinders and found coefficients which are dependent on the outer structure of the body and concluded that little change in the geometry does not affect the flow coefficients. Woods et al. [12] showed the results for the flow over arrays of elliptic cylinders by using the different aspect ratios in the form of a summary. Berbish [13] investigated the change in the flow and heat transfer characteristics over four elliptic cylinders in a staggered configuration in cross-flow. Peng et al. [14] studied the flow behavior for two elliptic cylinders placed in side-by-side configuration and analyzed the effect of various flow parameters on the cylinders. Mittal and Balachander [15] did the direct numerical simulation of the flow over elliptic cylinders and compared the results with the values from the experiments and found satisfactory matched parameter (Fig. 3).

2.2 Review of Flow Past Array of Square Cylinders

Square geometries are observed in various engineering applications and can create complex flow patterns around them. Rodi [16] had made a comparison of large eddy simulation (LES) and Reynolds-averaged Navier–Stokes equation (RANS) for the flow over bluff bodies. The vortex shedding over square cross-sectional cylinders was observed. Agrawal et al. [17] investigated the flow over the side-by-side square cylinders and found the effect of the gap ratio on the incident flow. Burattini and Agrawal [18] showed that a continuous and repeated pattern of the amplitudes occurs when the flow over a set of square cylinders in side-by-side

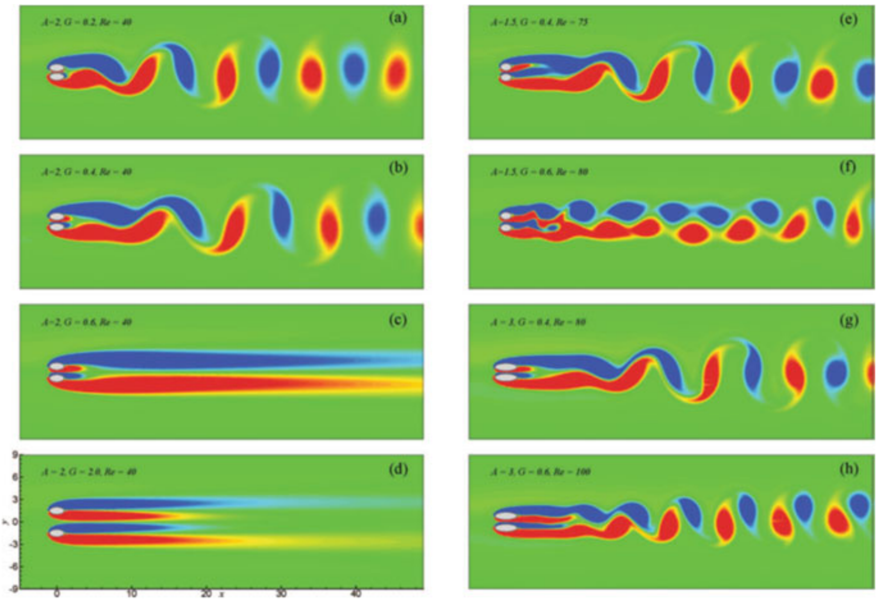

Fig. 3 Illustrating dependence of vorticity contours on the gap ratio (*G*) for two side-by-side placed elliptic cylinders [14]

configuration was made on the surface of the cylinders. A numerical simulation of the 3-D flow over two similar square cylinders arranged in staggered configuration was done.

Niu and Zhu [19] observed the difference in the correlation coefficients for the above-placed and bottom-placed cylinders in the flow stream. Bao et al. [20] did the computations on the six square cylinders placed in the inline arrangement with the help of the finite element technique. Kumar and Vengadesan [21] used the LES technique for the study of flow over long square cylinders of infinite length having side-by-side configuration. The study of various flow characteristics was conducted. Abbasi et al. [22] investigated numerically flow around three inline square cylinders with the help of Lattice Boltzmann method and found that the flow forces can be decreased with the help of different combinations of gap spacing (Fig. 4).

Islam et al. [23] investigated the flow over four square cylinders arranged in a rectangular manner with the help of Lattice Boltzmann Method (LBM) and established that the results are satisfactory with the experimental values. Kim et al. [24] did the study of the flow over two square cylinders arranged in a tandem configuration. Sewatkar et al. [25] investigated both numerical and experimental methods flow over six cylinders of square cross section arranged with in-line configuration and gave the results for lift and drag coefficients. Liu et al. [26] investigated various characteristics of flow by using the subcritical value of Reynolds number for flow over the array of four square cylinders. Various values of

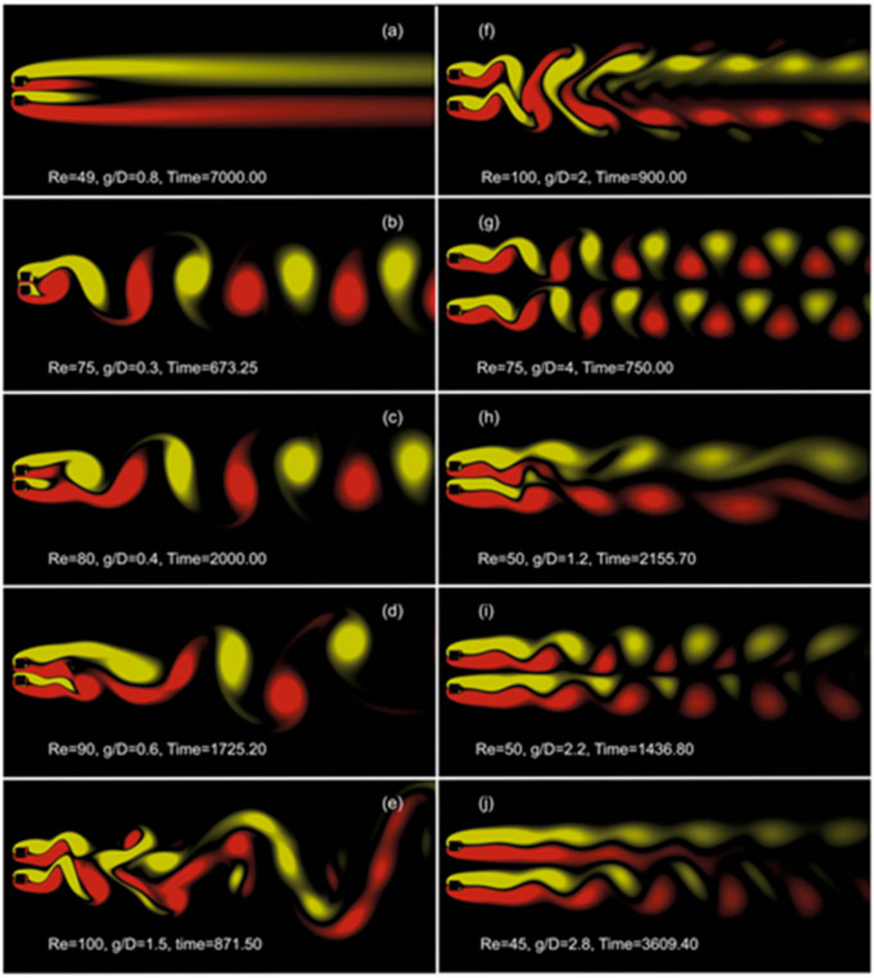

Fig. 4 Formation of different wake patterns for two side-by-side placed square cylinders [18]

gap ratios and the angle of incidence were taken to search for the effect of these different values on flow parameters. Liu and Chen [27] observed the hysteresis in the flow over two square cross-sectional cylinders arranged in tandem configuration and found the effect of hysteresis on the various flow parameters. Chatterjee et al. [28] studied the numerical simulation of flow over a row of square cross-sectional cylinders arranged at various separation ratios. The difference in the frequency at higher and lower ratios of separation was observed. Ehsan et al. [29] did the investigation of the fluid flow over two square cylinders arranged in tandem. It was found that there is a distinction in the separation of leading edge when thin and thick fluids passed over the cylinders. Ma et al. [30] explored wake interactions

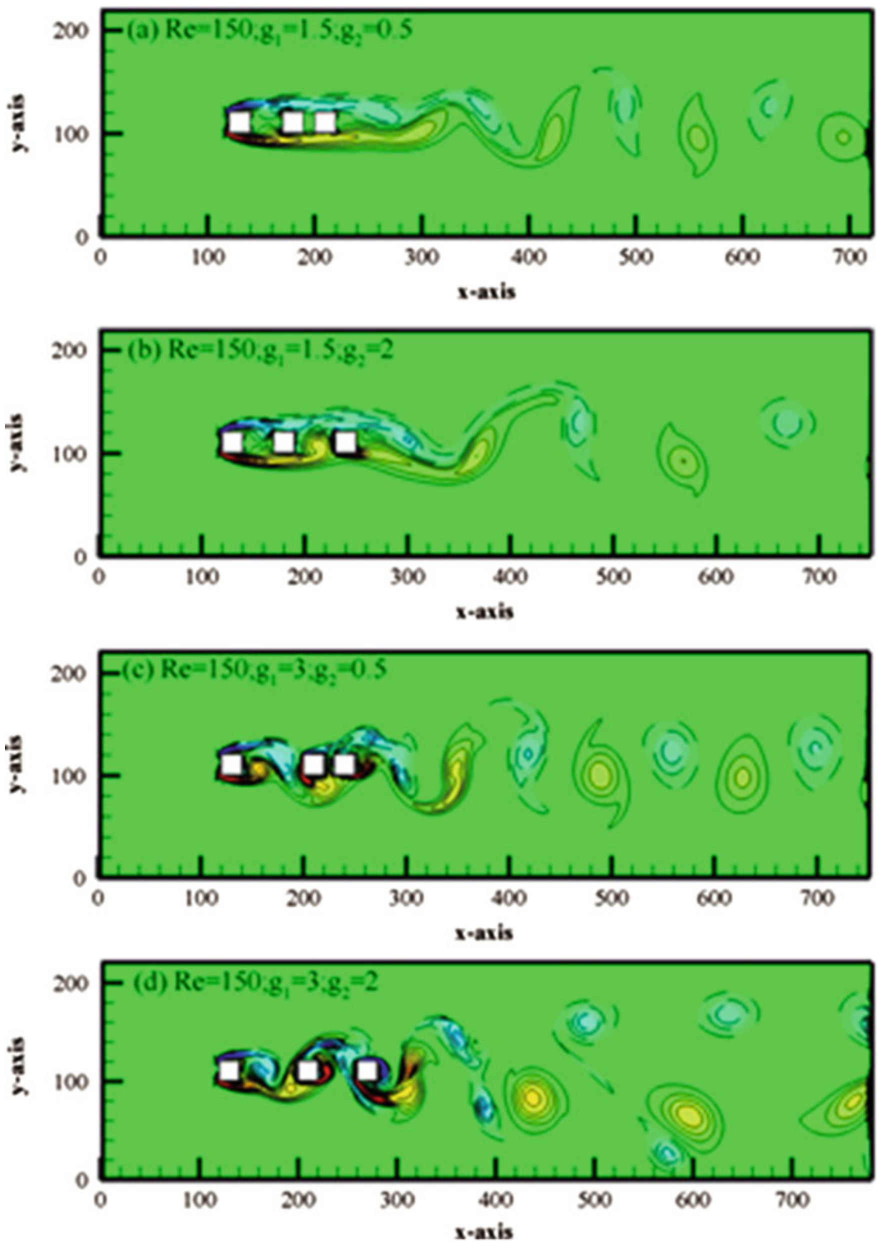

Fig. 5 Vortex formations in three inline square cylinders with different gap spacing [22]

between two square cylinders by using direct numerical simulation (DNS) at small values of the Reynolds number. A certain range of the distance between the cylinders was taken and various sequences of wakes were observed. Islam et al. [31] analyzed 17 square cylinder array with the help of the lattice Boltzmann method (LBM) for 2-D. The changes caused by the different values of the distance between the cylinders and various values of the Reynolds number were noticed. Various graphs using different parameters were also obtained. It was observed that the primary important parameter was Reynolds number and the distance between the cylinders is secondary. Rahman et al. [32] analyzed three square cylinders placed in a side-by-side configuration at various values of the Reynolds number and the disparate distance between the cylinders. They showed that the patterns of wake were different for the disparate distance between the cylinders. Zdravkovich [33] simulated for the steady flow over different arrangements of cylinders. It was found that the vortices produced for an array of cylinders were different from that produced by one cylinder at a particular Reynolds number. Chatterjee and Gupta [34] simulated for the flow past over square cylinders in a staggered configuration. It was observed that when the distance between the cylinders was minor, then the vortex shedding is small and for high values of the distance between the cylinders, vortex shedding is significant (Fig. 5).

3 Conclusion

Research work for flow past array of cylinders had taken place on a large scale, but due to the reason of complex flow situations which occur in practical life, it will be always a motivating field of research for the coming generations. A large number of observations can be made in this area of research. The values of different Reynolds number can be used for the study of various flow parameters. The various arrangements of the array of cylinders can be formed to study the difference in the flow characteristics when the flow passes over the various cross-sectional cylinders. The study of important phenomena such as vortex shedding and wake formation is very beneficial in the design of various useful and desired structures for having a better future of the coming generations. Various researchers investigated array of cylinders with different configuration and of various cross-sectional cylinders. They found different observation by simulation technique using various different methods such as LES, LBM, and RANS and made many conclusions from the results which they got which are very helpful in the technology development and in design industries of the aerodynamic field and ocean engineering. The various fluid flow parameters were studied by the researchers on the arrays of cylinders which are supportive in the design of heat exchangers, which can be designed by the help of study of simulation of fluid passing over the tube bundles of various cross sections. The research in this field is very significant for the future designs of various technical aspects.

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