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Research Article

Numerical investigation of flow over tandem and side-by-side cylinders

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ABSTRACT

In the present paper, two-dimensional unsteady flows over circular cross-section cylinders are analyzed numerically. The effects of placement of the cylinders are investigated for two different arrangements: tandem and side-by-side. Several turbulence models are tested, and it is found that Spalart-Allmaras turbulence model is the best among one- and two-equation turbulence models. The most appropriate time step, which is one of the important parameters in unsteady simulations, is found as 0.002 seconds. After successful validations, the cylinders are positioned as side-by-side and tandem. The effects of the arrangement on flow regime, drag coefficient, lift coefficient and Strouhal number are presented for various distances between the cylinders. It is found that the flow is almost steady without any vortex in the gap when cylinders are in tandem and the gap between them is low. In contrast, the interactions are strong in case of side-by-side arrangement at the lowest gap. When the gap increases, the flow is affected that results in change on the global parameters.

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INTRODUCTION

Study of flow of various fluids over single or multiple bluff bodies finds lots of applications in industry such as heat exchange tubes, cooling systems including cooling towers, various structures including offshore applications, transmission cables, etc. Such problems must be analyzed in detail for not only their complex structures but also for flow-induced vibration and sound. Due the complexity of the flow structures it is observed that the simulation of multiple bluff bodies in line is not an easy work as of only one body such as flow over a single cylinder due to dynamic interaction between the vortices, shear layer and Karman vortex street appears after the bluff bodies as reported by Harichandan and Roy (2010).

Lots of studies performed experimentally, numerically or as a combination of these two techniques have been published so far for different geometric bodies. For example, Saha et al., 2000 carried out an experimental study for flow past a square cylinder at Reynolds number of Re=8700 and Re=17625. It is found that the mean drag coefficient CD=2.13 for Re=8700 and CD=2.2 for Re=17625 while Strouhal (St) numbers were found as St=0.144 and St=0.142 for Re=8700 and Re=17625, respectively. Jester et al., 2003 revealed flow structure around two circular cylinders which were placed as tandem and side-by-side. For tandem arrangement at L/D=1.1 where L is the distance between the cylinders and D is the diameter of the cylinder, it was seen that the shear layers separate from upstream cylinders and reattach to downstream cylinder

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while cylinders act like single body. For $1.1<L/D<3.8$, vortex shedding is seen in the wake of downstream cylinder but not in the gap between cylinders. Finally for $L/D>3.8$ vortex shedding occurrs in the wake region of both cylinders. For side-by-side arrangement, it was stated that when $T/D\leq 1.2$ where T is the vertical distance between side-by-side cylinders, like tandem arrangement, the cylinders behave like a single body. For $1.2<T/D<2$, wide and narrow near wake formations are detected. For $2<T/D\leq 4$, vortex shedding develops in the wake region of cylinders. Aerodynamic characteristics of tandem cylinders were investigated experimentally by Alam et al., 2003 for Re=65.103. It was reported that fluctuating CD and lift coefficient, CL are influenced by gap between cylinders specifically before L/D=3.0 due to the bistable flow regime occurs after L/D=3.0 while it remains steady before L/D=3.0. Carmo et al., 2006 investigated effects of Reynolds number and gap on flow past tandem cylinders. It was observed that for L/D=1.5, the shear layers separate from upstream cylinder and reattach to downstream cylinders and no vortex shedding appears in the gap region between cylinders; on the other hand, for L/D=3.5, asymmetric vortices occur in the gap. Numerical simulations for flow around equal-sized two square cylinders placed in line were performed by Lankadasu et al., 2007. They concentrated on the influence of L/D ratio on flow characteristics. It was revealed that fluctuating CD and CL increase with L/D ratio for both cylinders, but after critical ratio the value of both parameters decrease for upstream cylinder. It was shown that the St number are the same for upstream and downstream cylinders at any L/D and lower than St number of single square cylinder. The effects of gap between tandem cylinders were investigated numerically by Kitagawa et al., 2008. They showed that mean CD decreases with increasing gap for both cylinders when $L/D\leq 3$ and they reach minimum and maximum value at L/D=3.0 and L/D=3.25. Like the mean CD, the Strouhal number also decreases with increasing gap. Yen et al., 2008 performed an experimental study for two tandem square cylinders. For the case of L/D=1.5 flow separates from corners of upstream cylinder and minor symmetrical vortices occur in the gap. Additionally, major symmetrical vortices form wake of downstream cylinder. For L/D=3, same flow configuration appears, however, this time shear layers reattach to downstream cylinder while vortex shedding forms when L/D=5. Liang et al., 2009 carried out a numerical study for flow around tandem multiple circular cylinders. For two cylinders case, they reported that there is no apparent vortex shedding in the gap between cylinders when gap distance (s) are s=2 and s=2.5. For s=3.6, asymmetric vortices were observed in the gap while for s=4 a clear vortex shedding occurs there. Bao et al., 2010 conducted a series of simulation for flow characteristics past side-by-side two cylinders. Based on their numerical studies, Ying et al., 2012 reported that CD and fluctuating CL of a rectangular cylinder reduce with increasing aspect ratio at Re=21400. Lu et al., 2012 analyzed flow characteristics of equal sized two square cylinders that were in-line. A notable change in the mean CD occurs when spacing is s=4.0 and s=4.5. Teixeira et al., 2014 revealed flow characteristics for tandem cylinders. It was stated that the Strouhal numbers of upstream and downstream cylinders are the same and their values are 10% lower than of the single cylinder as CL of downstream cylinder is higher than those of single cylinder whereas, the mean CD of downstream cylinder value is nearly half of CL of single cylinders. Golani et al., 2014 presented the effect of Reynolds number on the mean CD, CL and St number of circular cylinders. It was found that CD decreases with increasing Re number. However, mean CL remains approximately zero for all cases. The effects of Reynolds number and proximity of the bodies on the Newtonian and Non-Newtonian fluids over side-by-side cylinders for $1.2\leq T/D\leq 4.0$ and $0.1\leq Re\leq 100$ was investigated, Panda 2017. It was demonstrated that the Reynolds number, power-law index, and gap ratio significantly affect the streamline as well as the surface pressure and lift coefficients of both the cylinders. Although most of the studies devoted to a pair of cylinders in tandem, Hosseini et al., (2020) reported flow in a multi-cylinder tandem array to reveal the effects of increasing the number of cylinders on the flow field for low Reynolds numbers ($Re<200$). Basically, three flow types were identified based on the behavior of the flow in the gap between the cylinders. A recent study (Shan & Sun, 2021) presented evolution of the flow in the gap and near-wake of tandem cylinders in the alternating in the gap regime. It was shown that under the influence of the gap-flow, a near-wake vortex is generated behind the downstream cylinder that has influence on the length of the recirculation region.

Despite such studies, there are not so much research on tandem and side-by-side cylinders. The few are the numerical studies of Saltara et al., 2001, Zhao & Cheng, 2014 and Vu et al., 2016 where shedding of vortices and oscillatory flow interference between two circular cylinders in tandem and side-by-side arrangements are investigated at low Reynolds numbers such as Re=100−300.

The literature survey reveals that there are plenty of studies on tandem cylinders only or side-by-side cylinders only have been investigated so far but flow over the cylinders in tandem and side-by-side at high Reynolds number(s) are rare. In the present study, both configurations are considered for various gaps between two circular cylinders at relatively large Reynolds number (Re=2×104). The most appropriate mesh number, time step and turbulence model are selected based on some comparisons with the experimental data found in relevant literature. The main findings can be used for prospective analyses on flow over multiple bluff bodies located in various configurations.

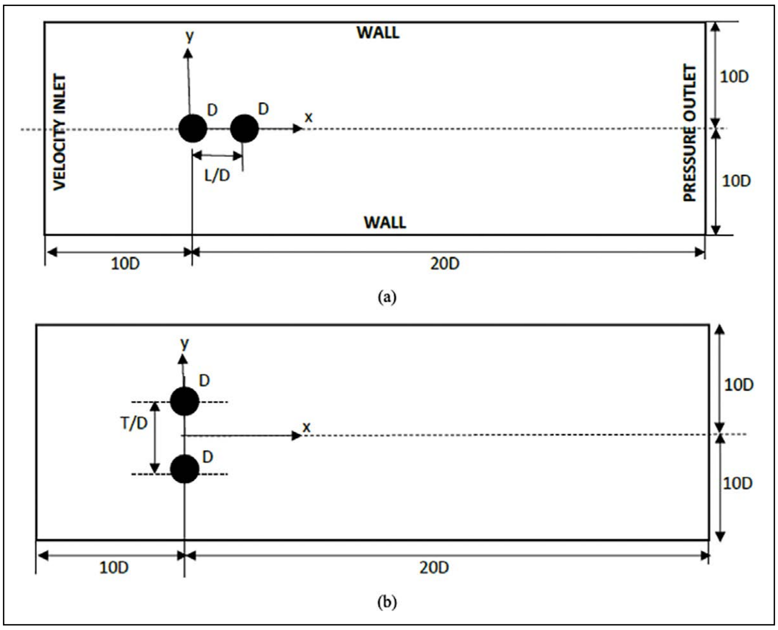

Figure 1. Computational domain for (a) tandem cylinders and (b) side-by-side cylinders (not to scale).

COMPUTATIONAL DETAILS

Computational Domain

A two-dimensional computational domain with the sizes of $-10<x/D<20$ and $-10<y/D<10$ is used for simulation of flow over single, tandem and side-by-side cylinders (Fig. 1). It is noteworthy that a computational domain with only one cylinder was also generated but this one was used for validation only. The Cartesian coordinate system is located 10D away from the inlet of the domain. At the inlet, streamwise and normal velocity components are applied as u=1 m/s and v=0, respectively, while at the outlet, $\partial u/\partial x=\partial v/\partial y=0$ and p=0 were applied. No slip boundary condition was imposed on upper and lower walls of the domain and the cylinders.

Meshing Process

The computational domain was divided into several small control surfaces called meshes. As shown in Figure 2 structured mesh elements were preferred to control the sharp velocity and pressure gradients near the surfaces of the cylinders. A special interest was given to the boundary layer to ensure that the non-dimensional distance between the cylinder surface and the first point of the grid is unity. The quad mesh type was used for two cylinders that were arranged as tandem and side-by-side. Some refinement mesh boxes were also used for each cylinder to control the sharp velocity and pressure gradients near the surfaces of the bodies.

Initially, 24492 mesh elements called Mesh 2 were generated. To ensure that the results are mesh independent the two more meshes called Mesh 1 with 14442 elements and Mesh

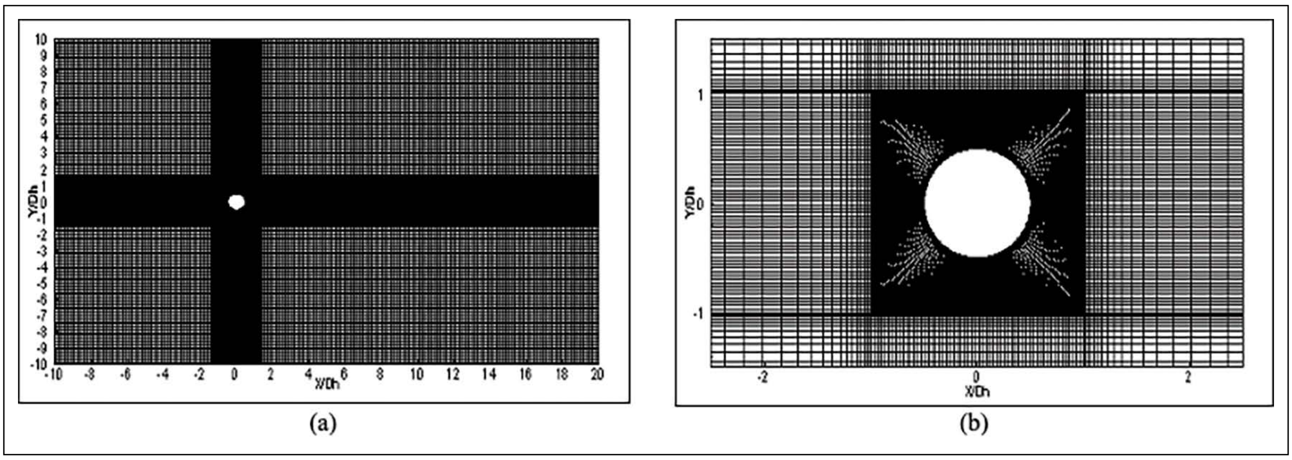

Figure 2. Mesh structure generated in the (a) domain and (b) around each cylinder.

Table 1. Mesh independence study, Re=2×10[4]

Mesh title	Number of mesh elements	Drag coefficient, CD
Mesh 1	14442	1.27
Mesh 2	24492	1.25
Mesh 3	55932	1.25

3 with 55932 elements were generated as well. The simulations were performed with each meshes and the results are present in Table 1 in terms of the change in the average drag coefficient (C_D). It is clear that after Mesh 2 the average drag coefficient does not change any more and implies that Mesh 2 with 24492 mesh elements is enough to conduct the following simulations.

Governing Equations

The continuity equation (Eq.1) and two components of momentum equation (Eq.2 and Eq.3) are the governing equations for two-dimensional, incompressible, isothermal, and Newtonian fluid flow over the tandem and side-by-side cylinders.

$$\nabla.\vec{V} = 0 \tag{1}$$

$$\rho\frac{D\vec{V}}{Dt} = -\nabla P + \rho.\vec{g} + \mu\nabla^2\vec{V} \tag{2}$$

where p, $\vec{V}$, t, P, $\vec{g}$ and μ represent density, velocity, time, pressure, gravitational acceleration and dynamic viscosity. One of the important parameters in the present study is the Reynolds (Re) number, Eq. (3).

$$Re = \frac{\rho.u_\infty.D}{\mu} \tag{3}$$

where u_∞ stands for free stream velocity. The paper reveals the influence of the configuration and space between the cylinder on drag coefficient (Eq.4), lift coefficient (Eq.5), and Strouhal number (Eq.6) since these coefficients provide important information about flow characteristic.

$$C_D = \frac{F_D}{\frac{1}{2}.\rho.u_\infty^2.D} \tag{4}$$

$$C_L = \frac{F_L}{\frac{1}{2}.\rho.u_\infty^2.D} \tag{5}$$

$$St = \frac{f.D}{u_\infty} \tag{6}$$

where, F_D and F_L are the force components in the stream wise and transverse directions respectively, f is vortex shedding frequency which is determined from fluctuating lift force.

Validation

Simulations were performed for Re=2×10[4]. It is proposed that the flow over cylinders is laminar for 40<Re<150, transitional for 150<Re<300 and fully turbulent for 300<Re<2×10[5], (Zdravkovich, 1997). Since the flow Reynolds number is Re=2×10[4] it is obvious that turbulence models must be used to closure the equations. To find out the most appropriate turbulence model for turbulent flow past cylinders a one-equation and four two-equation turbulence models were tested. These turbulence models are Spalart-Almaras (S-A), Standard k-ε (SKE) and Realizable k-ε (RKE) and Standard k-ω (SKO) and SST k-ω (SSTKO). The performance of these turbulence models is presented in Table 2 by comparing the change in drag coefficient with the data of Talay, 1975. It is seen that both SKO and SKE are unfavorable while the C_D obtained with their derivatives such as SSTKO and RKE are closer to the data of Talay, 1975. In comparison with the results obtained by S-A these two-equation turbulence models may also be eliminated since there is only 4.2% difference between the reported C_D of Talay, 1975 and the one found by S-A. These results are not surprising since such problems are commonly analyzed by S-A turbulence model due to its less simulation time and robustness in problems related to the aerodynamics, (Bayraktar et al., 2014).

In unsteady flow simulations results also depend on the time interval, Δt as well. The present simulations were run for three different time intervals: Δt=0.0010[seconds (s)], 0.0015[s] and 0.0020s. The drag coefficient obtained for each time interval is presented in Table 3. It should be noted that Δt is defined as the ratio of the diameter of the cylinder to the free-stream velocity, Δt=D/u_∞. Unlike the expectations, it is seen that the minimum time interval does not cause a close drag coefficient to the experimental data. On the contrary, as time interval reduces drag coefficient found by the present study deviates from the experimentally found drag coefficient reported by Talay (1975) that shows that there is an inverse proportion between the C_D and Δt. As Table 3 suggests the Δt=0.0020[s] was adopted in the study since the closest CD is obtained at this time interval.

Table 2. Assessment of the appropriate turbulence model

Turbulence model	C_D (present)	C_D (Talay, 1975)	Difference (%)
Spalart Allmaras (S-A)	1.250	1.2	4.2
Realizable k-ε (RKE)	0.965	1.2	19.6
Standard k-ε (SKE)	0.835	1.2	30.4
Shear Stress Transport k-ω (SSTKO)	1.415	1.2	18.0
Standard k-ω (SKO)	0.724	1.2	39.6

Table 3. Assessment of the appropriate time interval, Re=2×10^4

Time interval, Δt (s)	C_D (present)	C_D (Talay, 1975)	Difference (%)
0.0010	1.265	1.2	5.4
0.0015	1.250	1.2	4.2
0.0020	1.246	1.2	3.8

Once the main parameters important to conduct robust simulations are determined, the effects of location of cylinders as tandem and side-by-side are presented in terms of some global properties such as the mean drag coefficient, mean lift coefficient and Strouhal number.

RESULTS AND DISCUSSION

In this section, characteristics of flow past tandem and side-by-side cylinders are presented for Re=2×10^4. The distance (gap) between upstream (cylinder 1) and downstream cylinder (cylinder 2) was changed with 1D increments as to be 1.5<L/D<6.0. Figure 3 and Figure 4 present how flow patterns change with the gaps between the tandem and side-by-side cylinders, respectively. Both figures reveal that the gap between cylinders, not matter how they configurated as tandem or side-by-side, has great impact on flow patterns around the cylinders. It can be assessed that the flow behaves as steady for L/D<3.0. It should be noted that, although the flow around cylinders is resolved by unsteady Reynolds-Averaged Navier-Stokes equations, the flow-field especially between the closely spaced cylinders (L/D<3.0) seems do not change with time and that is why it is called as steady flow for such special region of flows.

When the cylinders are very close to each other, the wake mode of upstream cylinder is symmetrical, and the flow interference is mainly controlled by proximity effects. The flow behind the upstream cylinder is almost steady for L/D=1.5 where flow pasts symmetrically upper and lower side of upstream cylinder and no vortex shedding is observed in the gap while two symmetric recirculation zones are observed. With increasing the gap to L/D=2.0 the flow remains steady, whereas the centers of symmetric recirculation zones in gap region move toward inside slightly due to the increasing driven effect from the free stream flow.

The flow patterns for side-by-side cylinders seem different from the patterns over the tandem cylinders (Fig. 4). In side-by-side case, no circulation region is observed between the cylinders whereas two independent circular regions form behind each cylinder.

For T/D=1.5 the flow behind two cylinders forms a flow pattern like the one developed behind a single cylinder due to small gap. However, as cylinders move apart in opposite directions, two symmetrical flow patterns occur behind each cylinder. the further increment in the gap causes independently developed flow regions behind each cylinder and it seems that the cylinders do not affect their flow pattern

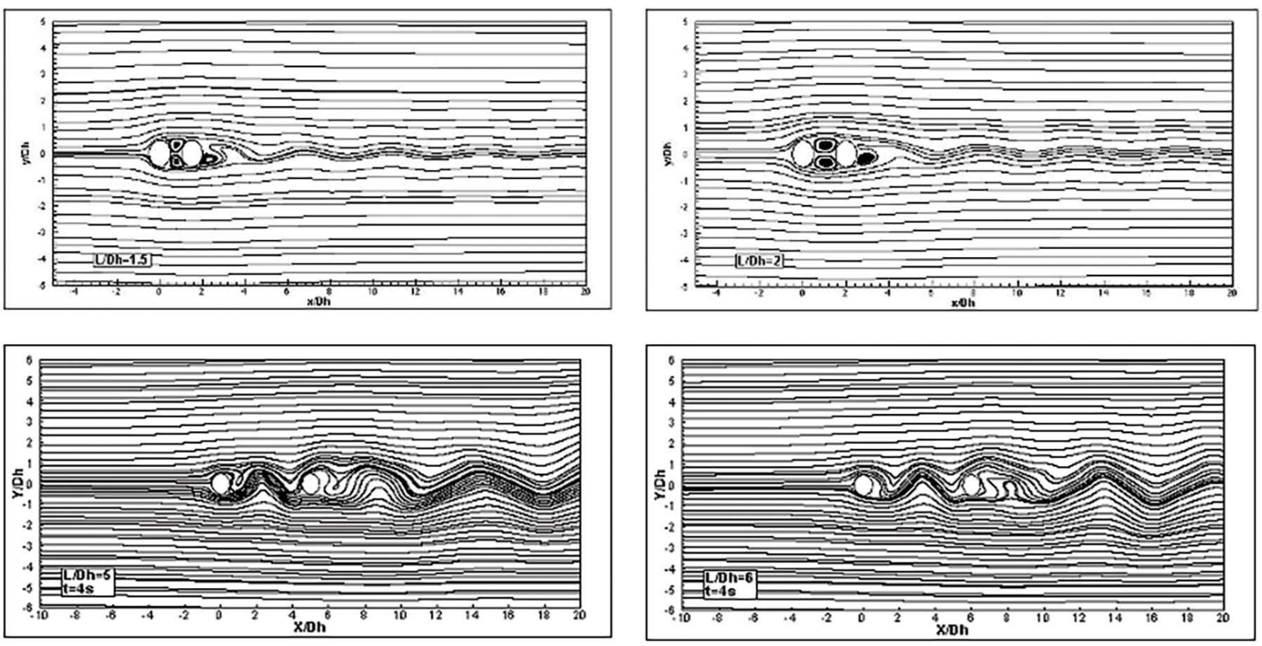

Figure 3. Variation of flow patterns with increasing distance between tandem cylinders.

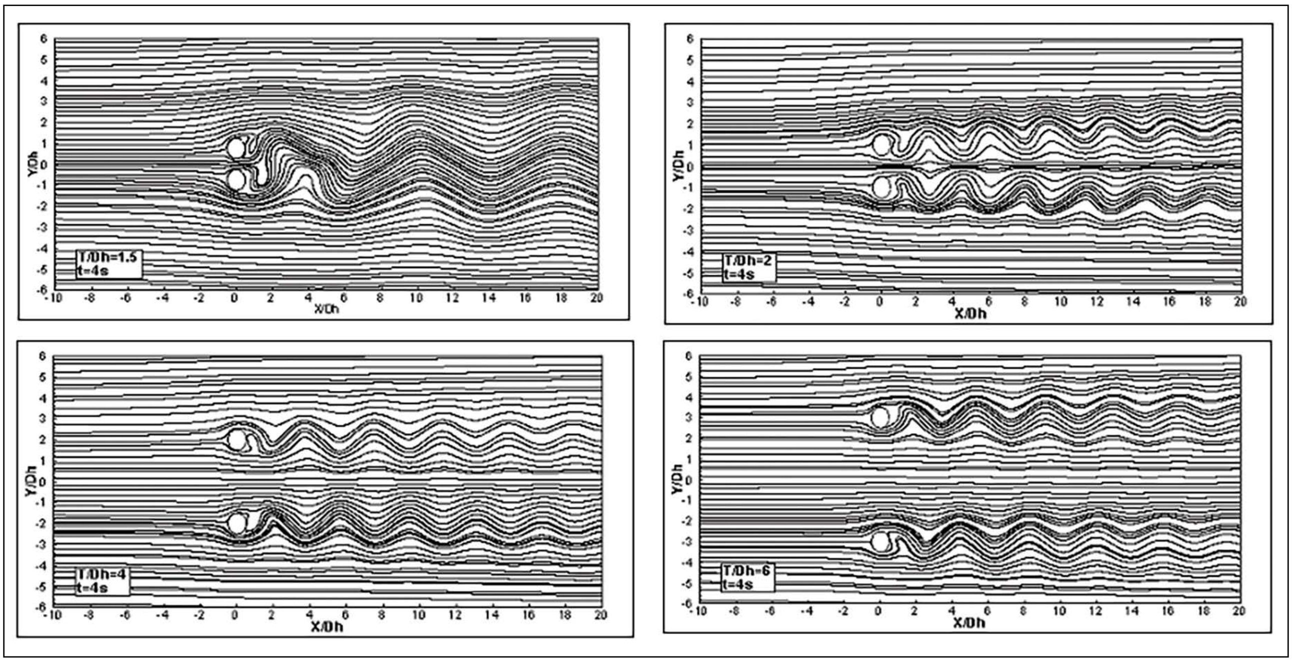

Figure 4. Variation of flow patterns with increasing distance between side-by-side cylinders.

anymore. Figure 5 and Figure 6 show vorticity contours in the computational domain for tandem and side-by-side cylinders, respectively. At the small gaps the shear layers are suppressed by the cylinders and the vortices are alternately shed from the upstream cylinder. At L/D=4.0, the vortex shedding keeps its existence behind the upstream cylinder, but vortices start to shedding simultaneously from opposite sides of the downstream cylinder and two row vortex street is observed. At L/D=5.0 and L/D=6.0, vortex shedding from the upstream cylinder approaches the downstream cylinder and causes the flow became highly unsteady in behind of downstream cylinder.

When the side-by-side cylinders are very close to each other (T/D=1.5), interactions between cylinders are very strong, the vortexes behind top and bottom cylinder merge and behave like a flow behind a single cylinder.

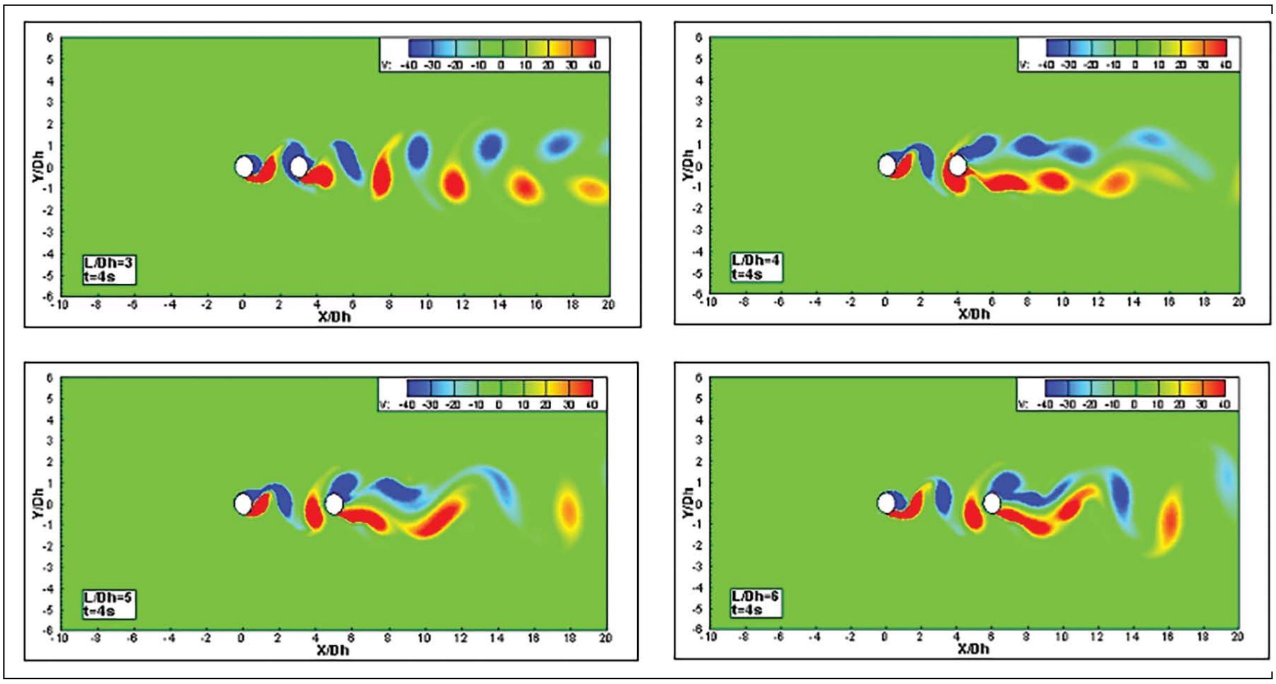

Figure 5. Variation of vorticity with increasing distance between tandem cylinders.

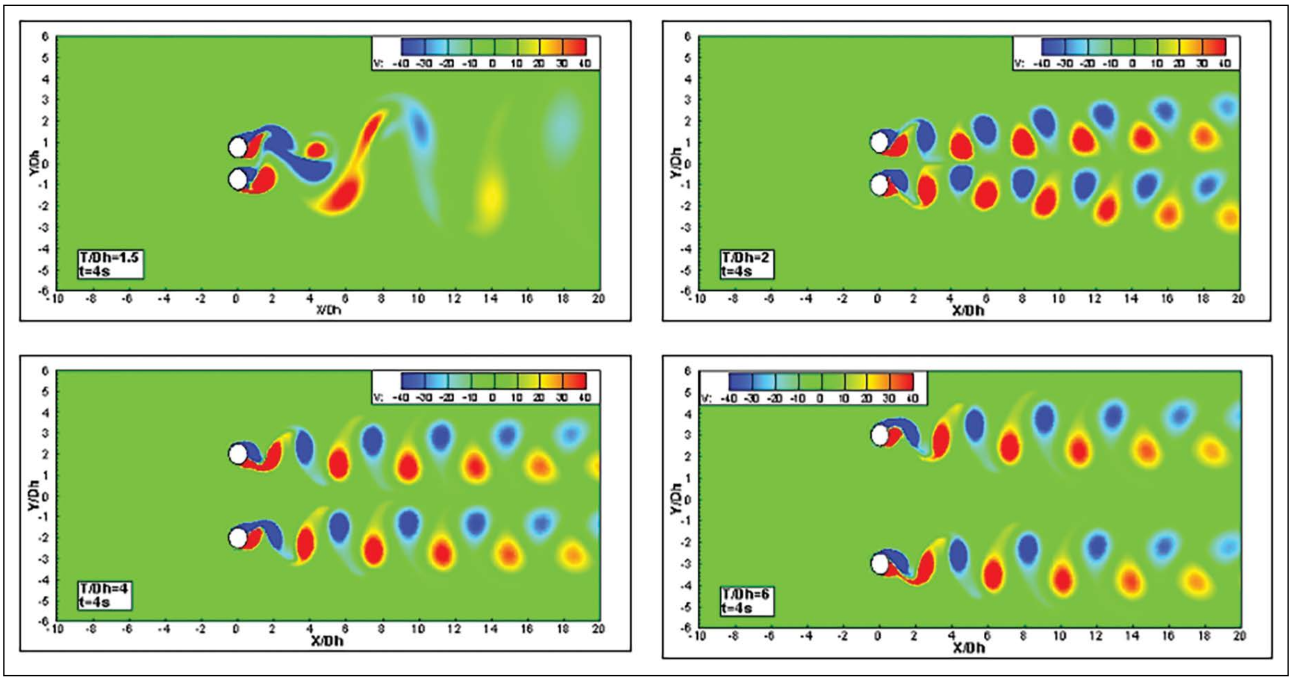

Figure 6. Variation of vorticity with increasing distance between side-by-side cylinders.

With increasing gap, interactions weaken, and vortices are shed alternatively from the top and bottom cylinders for 2.0≤T/D≤6.0.

The variation in drag coefficient with time is presented in Figure 7 for both configurations. As clearly seen the drag coefficients fluctuate around a mean value, hence their mean are presented in Figure.

It can be seen in Figure 8 that the drag coefficient for upstream cylinder (cylinder 1) increases gradually with increasing gap for 1.5≤L/D<3.0. At L/D=1.5, interference between cylinders is very strong and thus the drag of the upstream cylinder (CD)1 takes its minimum value, but the interference between cylinders reduces gradually and at L/D=3.0 the (CD)1 reaches a maximum. At this point, it can

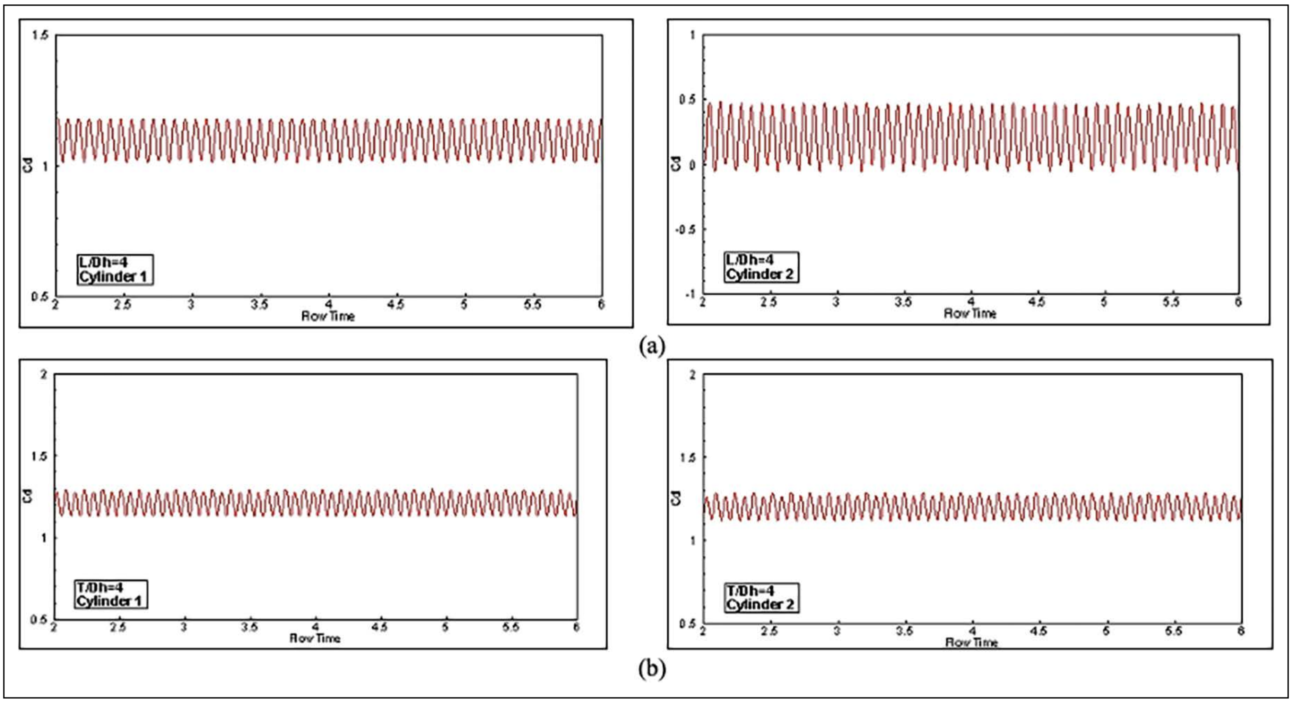

Figure 7. Variation of drag coefficients with flow time for (a) tandem and (b) side-by-side cylinders for L/H=4.0.

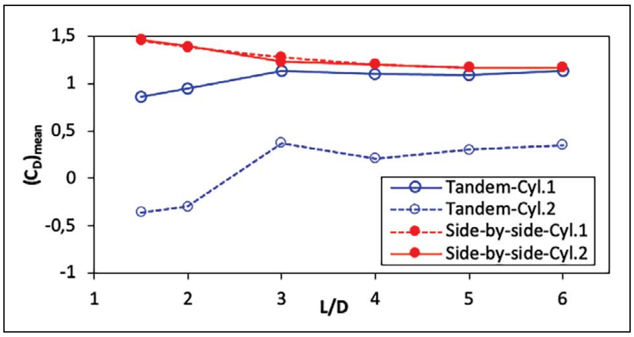

Figure 8. Variation in the mean drag coefficients with gaps between tandem and side-by-side cylinders.

be said that the interference between cylinders is negligible at L/D=3.0. For 3.0≤L/D<5.0, the (CD)1 reduces, but at L/D=6.0, it approaches again the value which is very close to single cylinder case. The (CD)2 has negative value until L/D=3.0 due to interference between cylinders. At L/D=3.0, the (CD)2 reverses to positive region and jumps suddenly to its maximum value due to less interference between cylinders. At 3.0≤L/D<4.0, the (CD)2 drops, but at 4.0≤L/D<6.0, it increases gradually with increasing gap. As shown, maximum mean drag coefficient for both side-by-side cylinders are almost the same at T/D=1.5 due to biased flow regime around cylinders. The preliminary simulations reveal that the variation of drag coefficients with time for both cylinders are irregular at T/D=1.5 because, at this gap, interaction between cylinders is very strong and flow regime drastically unsteady. For 2.0≤T/D≤6.0, the drag coefficients for both cylinders reduce with increasing gap and reach a value that is close to the single cylinder case at T/D=6.0. For these points, the drag coefficients are fully periodic and single row vortex street occurs behind both cylinders.

Lift coefficient variation with time at L/D=T/D=4.0 is shown Figure 9 for tandem and side-by-side cylinders, respectively. In the case the tandem cylinders, the amplitude of the lift coefficient of the upstream cylinder (cylinder 1) is higher than that of the downstream cylinder (cylinder2) since shedding vortices behind the second cylinder has more spaces to develop. When it comes to side-by-side cylinders, the lift coefficient changes between the same extremes since each of them behave like a single cylinder.

The change in the mean squared lift coefficient is presented in Figure 10. For the tandem cylinders, the CL of the upstream cylinder (cylinder 1) has minimum value at L/D=1.5 and then it increases gradually between 1.5<L/D<L/D=2.0, but a sudden jump occurs at the critical gap (L/D=3.0). It is observed that, the CL for upstream cylinder decreases between 3.0<L/D<L/D=5.0 and then it increases gradually again between 5.0<L/D<6.0. For the side-by-side cylinders, the value of CL of both cylinders are nearly the same. Furthermore, the CL of both cylinders with flow time are not periodic at T/D=1.5 due to bistable flow trend in behind of cylinders. After this point, the variations of CL begin to be periodic. For 1.5≤T/D<2.0, sudden jump is observed in CL for both cylinders and it reaches their maximum value at T/D=2.0. Then, the lift coefficients for both cylinders are gradually decreases until T/D=5.0 but, between T/D=5.0 and T/D=6.0, there is no notable change.

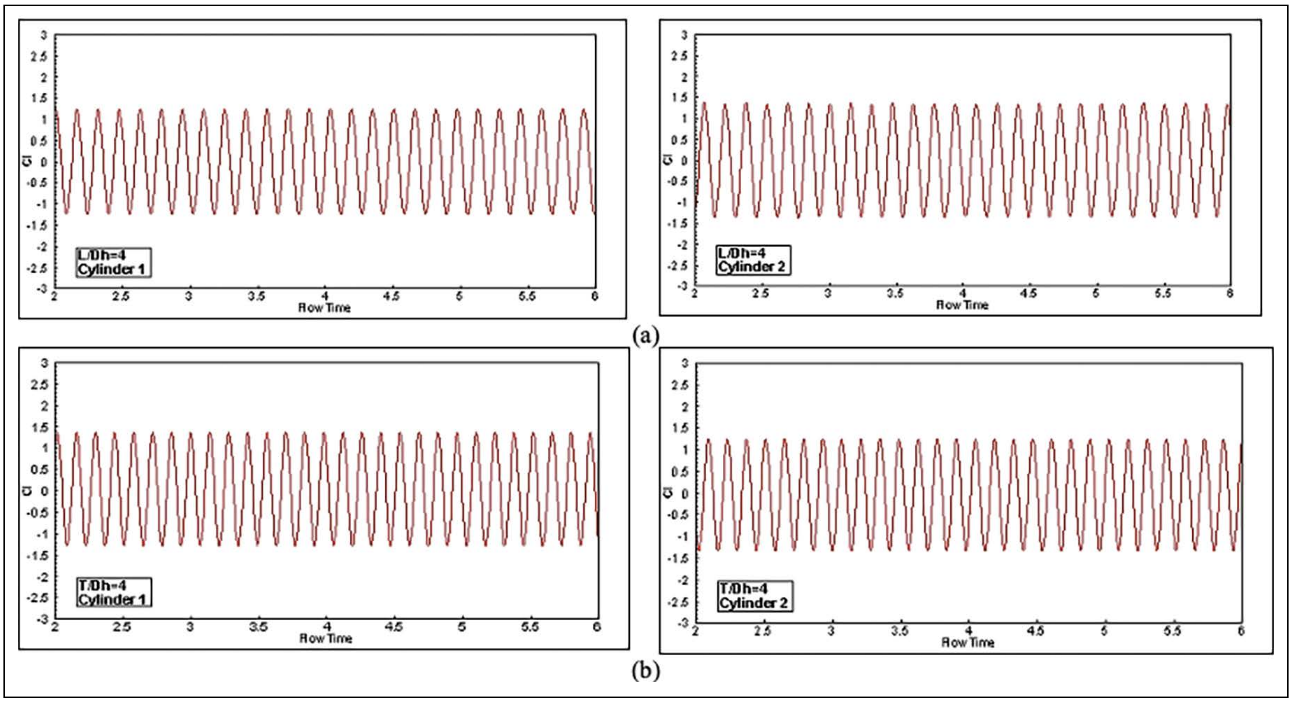

Figure 9. Variation of lift coefficients with flow time for (a) tandem and (b) side-by-side.

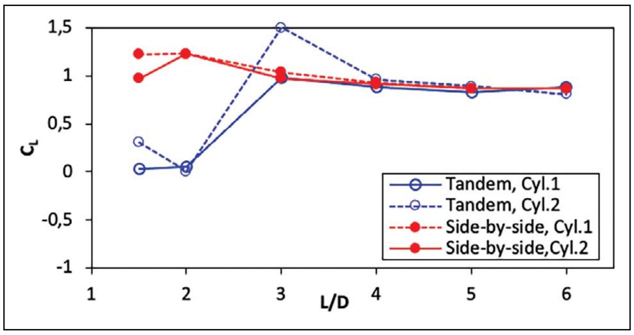

Figure 10. Variation in the mean lift coefficients with gaps between tandem and side-by-side cylinders.

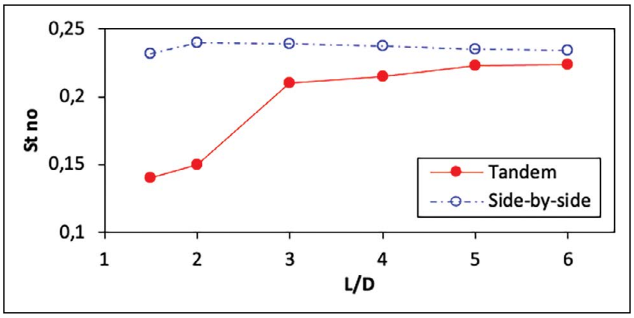

Figure 11. Variation in the Strouhal (St) number with gaps between tandem and side-by-side cylinders.

In the present study, the Strouhal (St) number is also derived by utilizing the time series of the lifts coefficients that are presented before. Fast Fourier Transform was used to get the dominant flow frequency.

Strouhal number variations with gaps between cylinders are presented in Figure 11. It is seen that in vortex attachment phase (2.0≤L/D<3.0) the Strouhal number increases gradually when the cylinders are in tandem, but at critical gap (L/D=3.0), it has sudden jump and reaches value which is very close to single cylinder case. In vortex shedding regime (3.0≤L/D<6.0), it keeps increasing, but no any notable change is observed. For the side-by-side cylinders, in biased flow regime (T/D=1.5) the St number has minimum value, after that, it increases and has maximum value at T/D=2.0. For 3.0≤T/D≤6.0, it decreases gradually.

CONCLUSIONS

In present study, the effects of distance between cylinders on flow characteristics for tandem and side-by-side two circular cylinders are investigated numerically at Reynolds number of 2×10^4. Initially, the mesh independence, turbulence model and time step tests are conducted for single circular cylinder to validate simulation and serve as a base for further simulations. The results of simulation for single circular cylinder agree well with the experimental data available in literature. Afterwards, simulations for tandem and side-by-side cylinders are carried out for different gaps between cylinders. The main findings are summarized below:

i. The gap between cylinders has crucial impact on flow patterns. For tandem arrangement case, when cylinders are very close to each other, the flow regime is steady in gap area and no vortex shedding occurs. After the critical gap (L/D=3.0), a vortex shedding forms in the gap while double row vortex streets are observed behind the second cylinder as the gap increases. For side-by-side arrangement, at T/D=1.5, the interactions between cylinders are very strong and flow regime is bistable. After that the interactions decreases gradually and single row vortex streets starts to appear.

ii. For tandem arrangement case, drag coefficient of upstream cylinder is minimum due to interaction between cylinders at L/D=1.5 and then it increases gradually and reaches a maximum that is very close to single cylinder case at the critical gap (L/D=3.0). On the other hand, drag coefficient of downstream cylinder has negative value before critical distance which means that the downstream cylinder is pushed to upstream cylinder by flow. For side-by-side arrangement case, drag coefficient of both cylinders are almost the same and they have their maximum value at T/D=1.5. A small difference is identified at T/D=3.0. Then, drag coefficient decreases gradually and become closer to drag coefficient of the single cylinder.

iii. When the cylinders are in tandem the mean value of lift coefficients for downstream cylinder are higher than that of the upstream cylinder between L/D=1.5 and L/D=5.0 but this situation reverses at L/D=6.0. A sudden jump in CL of each cylinder occurs between L/D=2.0 and L/D=3.0. For side-by-side arrangement, the CL of both cylinders are nearly the same but a sudden jump between T/D=1.5 and T/Dh=2.0 are observed before it reaches to a maximum at T/D=2.0. Later, it decreases gradually, and no change is observed between T/D=5.0 and T/D=6.0.

iv. The Strouhal number of the tandem cylinders increases gradually until L/D=3.0 then, a notable change is observed. For side-by-side arrangement, the Strouhal number increases between T/D=1.5 and T/D=2.0 later it decreases gradually.

AUTHORSHIP CONTRIBUTIONS

Concept: Bayraktar, S., Design: Mentese, A., Supervision: Bayraktar, S., Data: Mentese, A., Analysis: Mentese, A., Literature search: Mentese, A., Writing: Mentese, A., Bayraktar, S., Critical revision: Bayraktar, S.

DATA AVAILABILITY STATEMENT

The published publication includes all graphics and data collected or developed during the study.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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