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BLOCKAGE RATIO INFLUENCE ON FLOW OVER CYLINDERS WITH TANDEM CONFIGURATION $L/D = 1.26$

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Abstract. The present study preliminary explores the influence of the blockage ratio on aerodynamic characteristics and flow pattern of cylinders in tandem with $L/D = 1.26$. The blockage ratio is the relation between the cylinder diameter and the width, D/B , varies from 67% to none. The Reynolds number, based on the inlet velocity and cylinder diameter, is fixed in 1.35×10^4 for all the tested cases. The analyzes are performed with numerical simulations using Reynolds Averaged Navier-Stokes with $k\omega$ - SST (Shear Stress Tensor) turbulence model. The results indicate an increase in the magnitude of the drag and lift coefficient with the increase in the blockage ratio. The drag coefficient on the first cylinder increased with the increase in blockage ratio for all tested cases. The drag coefficient in the second cylinder presents inversion in the acting force with a blockage ratio higher than 26%. The lift coefficient showed significant changes with the increase in the blockage ratio mainly to 67%. The flow patterns present different structures and the occurrence of reattachment of the first cylinder shear layer with the increase in the blockage ratio.

Keywords: Blockage ratio, tandem, forces.

1. INTRODUCTION

The flow over cylinders is observed in many engineering applications such as tube banks, windmills, heat exchanges, electrical wires among others. In some cases, cylinders are in a single configuration, in pairs or array, each configuration present peculiarities, unique mechanisms. Pairs of cylinders in tandem configuration can be often observed in risers, but simplification in tube banks can also represent cylinders in tandem configuration with the close wall (Blevins, 1990; de Paula and Möller, 2013).

The tandem configuration in cylinders is characterized by two cylinders aligned, Figure 1, with one after the other in the flow direction. The distance between cylinders is the pitch ratio that represents the length between the cylinder, L , and diameter, D . The study of tandem configuration always presents the wake interaction, since the second cylinder is immersed in it. The spacing between the cylinders is a determining factor because the spacing allows or not the formation of vortex structures between the cylinders (Zdravkovich, 2002; Sumner et al., 2010)

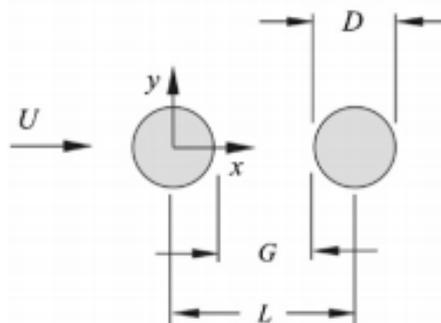


Figure 1. Cylinders in tandem configuration with the usual parameters applied, adapted from Sumner et al. (2010).

The study carried out by Igarashi (1981) presented six distinct patterns in the flow on aligned cylinders, they are related to the spacing and the number of Reynolds. The pattern for spacing $L/D < 2$ shows the shear layer of the first

cylinder does not collapse in the second cylinder, depending on the Reynolds number a reattachment of the first cylinder shear layer can be observed in the second cylinder. Zdravkovich (2002) describes that in this pattern the reattachment is permanent $1.3 > L/D < 1.8$.

Zhou and Alam, 2016, reviewed the studies presented in the literature, with cross-flow over two cylinders. The authors classify the flow regimes and created maps according to each of the variables: spacing between centers, the orientation of the cylinders concerning the flow, Reynolds number, flow structures, Strouhal number, fluid forces, heat transport characteristics, momentum. The forces can vary significantly due to the positioning of the second cylinder.

The blockage ratio is defined as the cylinder diameter and the width of the test section (D/B). In general lines, for $D/B < 0.1$ the blockage effect is small and can be ignored; for D/B between 0.1 and 0.6, the blockage modifies the flow, correction of measured data is necessary. In the cases with $D/B > 0.6$, the blockage radically alters the flow around the cylinder and the corrections are not effective (Zdravkovich, 1997).

The blockage ratio influences the flow and aerodynamic parameters, according to Zdravkovich, 1997 and Barlow et al. (1999), there are two types of blockage: the solid blockage, that is the relation of areas of the flow in the wind tunnel or equipment and the body immersed in the flow. The solid blockage causes an increase in velocity around the cylinders. Besides the solid blockage, there is the wake blockage that acts with the growth of the boundary layer on the model and results in a velocity increment at the model. The increased velocity outside the wake reduces the pressure in it. The walls in a wind tunnel induce a confining effect on the model.

About the influence of blockage ratio on cylinders vibrating, Prasanth et al. (2006) described that have been few studies for the case when the cylinder is vibrating, and presented a numerical study with the effect of blockage on the vortex-induced vibrations of a cylinder at $Re \leq 150$. Cases with 1% and 5% blockage ratio were tested. Hysteretic behavior of the cylinder response close to the lower and upper limits of the lock-in region was observed for the case with 5% blockage. However, for the case with 1% blockage, the hysteretic behavior is not present.

Vortex-induced vibration of a circular cylinder at a low mass ratio of 1.5 between two lateral walls was investigated numerically by Zhao et al. (2012). The study was carried out increasing the distance of the wall. The authors state that the effects of the two walls on the VIV are clear as the width decrease of 6 diameters and negligibly for width values higher than 10 diameters. The VIV amplitudes in both directions increase with the increase of the distance of the walls in the lock-in regime.

A numerical and experimental study with an increase of blockage ratio from 15% to 30% in a square cylinder is presented in Sharify et al (2013). The increase of the blockage ratio increased the interaction between the wake and the vortices formed on the channel walls, which became crucial at the higher blockages. However, the increase in the blockage ratio reduced the size of the vortices, while drag and shedding frequency increased.

Möller et al. (2015) presented features of the flow on Cylinders considering the Blockage Ratio. The results showed that the shedding frequency is not constant over time. A comparison with a prism indicated distinct behaviors in both cases. A correlation for Strouhal number as blockage ratio function was presented.

Neumeister et al. (2020) presented an experimental study with cylinders in tandem assembled in 67% blockage ratio with one or both cylinders free to vibrate, for tested cases with the high blockage a sudden increase was observed in the amplitude of vibration and was associated to the blockage ratio and relation of both cylinders frequencies. For blockage ratios of 13% and 26%, the sudden increase was not observed.

To better understand the influence of the blockage ratio on the flow structures for the tandem configuration, the present work is conduct. Where the influence of the blockage ratio from none to 67% is evaluated with cylinders in tandem with $L/D = 1.26$. The use of blockage ratio up to 67% is due to the assembly in tube banks with the space ratio indicated.

2. METHODOLOGY

The domain used in the analysis presents two cylinders with 25mm in tandem configuration with the distance between cylinders of 31.5mm resulting $L/D = 1.26$, the domain height is 20mm, the width change from 37mm to 193mm, according to the blockage ratio 67% to none blockage. The domain dimensions are presented in Figure 2 a).

The three-dimensional mesh was generated with tetrahedra volumes and prismatic layers in the surfaces of the cylinders, the regions around the cylinders were refined applying a density as shown in Figure 2 b) and c). The volumes sizes in each region were fixed in the setup, resulting in meshes with equivalent characteristics independent of the width. The meshes information are presented in Table 1 and the mesh for Case 5 can be observed in Figure 2 b).

Boundary conditions are velocity prescribed of 8 m/s on the inlet, pressure atmospheric on the outlet, the cylinders present no-slip wall condition, as represented in Figure 2 d). The side walls present no-slip wall condition for the cases with 13% to 67% of blockage ratio, for the case with none blockage ratio, is considered a slip wall. The top and bottom planes are considered symmetry.

The tested Cases are presented in Table 1, where some characteristics are described. The numerical analysis was conducted with Unsteady Reynolds Averaged Navier-Stokes (URANS) and Turbulence Model $k\omega - SST$ (Shear Stress Tensor), Wilcox (1994), using the model constants recommended in the Software Ansys Fluent 19 (Ansys Fluent, 2018). The interpolation method applied was second-order upwind and the residual was limited for 10^{-5} . The time step

adopted was 0.005s, with at least a simulation of 0.5s. The Reynolds Number was based on the diameter of one cylinder and the inlet velocity, the Reynolds number is also presented considering the velocity in the restricted area around the cylinders.

Table 1. Tandem simulated Cases with mesh and flow information.

Cases	Blockage ratio [%]	Width [mm]	Mesh Size [Volumes]	Y+ Maximum in the cylinders	Inlet Velocity [m/s]	Re based on inlet velocity	U_R - Velocity in the restricted area [m/s]	Re based on U_R
Case 1	0	Slip Wall	2,587,006	0.6	8	1.35×10^4	8	1.35×10^4
Case 2	13	193	2,587,006	0.6	8	1.35×10^4	9.2	1.55×10^4
Case 3	26	96	2,556,805	0.7	8	1.35×10^4	10.8	1.82×10^4
Case 4	52	48	1,775,468	0.4	8	1.35×10^4	16.7	2.82×10^4
Case 5	67	37	1,553,559	0.6	8	1.35×10^4	24.67	4.16×10^4

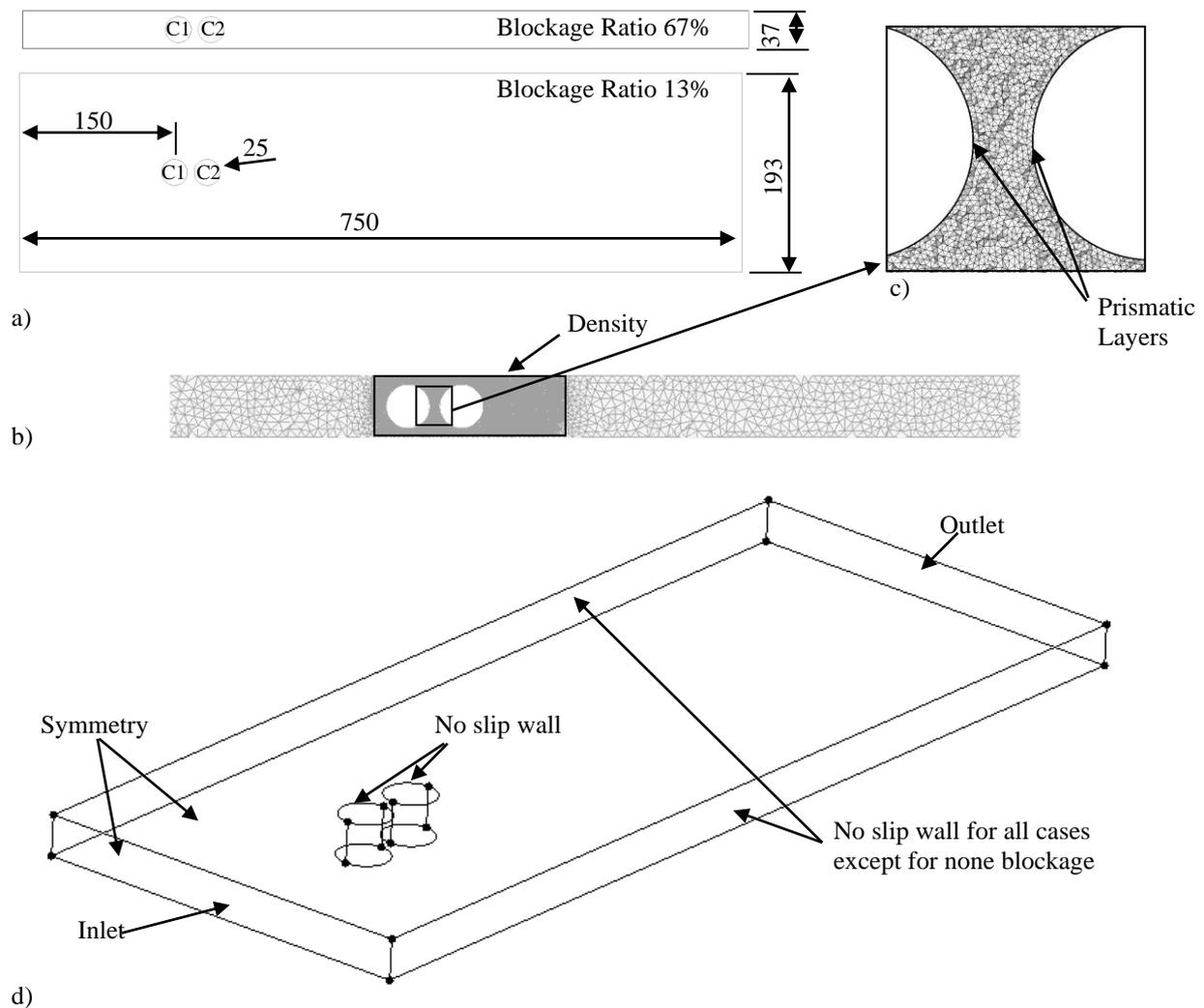


Figure 2. a) Domains size, b) mesh for the case of blockage ratio 67%, c) detail of prismatic layers around the cylinders and d) boundary layers.

The mesh quality was analyzed applying the GCI method (Grid Convergence Index) proposed by Roache (1994) and detailed in Roache (1997). The GCI indicates an error range that the solution is from the asymptotic value. The GCI

is calculated for the mesh combinations, coarse-medium and medium-refined, the difference between the values of GCI indicates the distance from the asymptotic range. For the GCI analysis, three meshes were applied and the mesh ratios were calculated, considering the volume numbers of 7.522 thousand volumes, 1.553 thousand, 0.545 thousand. The variable evaluated was the drag force over the cylinders. The convergence order value results in 5.8 and the relation between the GCIs from the finer mesh and coarser mesh generates a relation between GCIs of 0.978, indicating that the mesh is in the asymptotic region. The comparison with results from the literature were used to validate the responses for cases with low blockage ratio.

3. RESULTS

This preliminary numerical analysis tested five cases, where the blockage ratio was changed for the same flow conditions and geometric parameter, the results obtained in the analysis for No blockage, Case 01, and 13% blockage, Case 02, were compared to some results from the literature to validate the response. Table 2 presents the response of experimental analysis from Alam et al. 2003, Moriya et al. (2002) Alam and Zhou (2016), the results obtained in the present analysis are lower than Alam et al. 2003, Moriya et al. (2002), but in the range expressed by Alam and Zhou (2016). Dehkordi et al. (2011) and Moriya et al. (2002) presented studies for L/D = 2. The responses for Case 01 and Case 02 presented agreement with the response in the literature.

Table 2. Comparison between the present study and the literature

Case	Type	L/D	CD1mean	CD2mean
Case 1	Numerical	1.26	0.964	-0.214
Case 2	Numerical	1.26	0.973	-0.196
Alam et al. 2003	Experimental	1.2	1.1	-0.4
Alam and Zhou (2016)	Experimental	1.26	0.84 – 1.04	-0.2
Dehkordi et al. (2011)	Numerical	2	0.95	-
Moriya et al. (2002)	Experimental	2	1.05	-

The drag and lift coefficients obtained from each of the five tested cases, Table 1, are presented in Table 3, wherein cylinder 1 the drag coefficient increases with the increase in the blockage ratio. The drag force on cylinder 2 changes the direction of the force opposite the flow direction, in Case 01 and Case 02, to the force acting in the same direction as the flow for additional cases. The lift coefficient oscillates in both cylinders but a significant magnitude is observed in Case 5. To observe the differences in drag coefficients they are plotted in Figure 3 and the lift coefficients are plotted in Figure 4.

Table 3. Drag and lift coefficient for the tested Cases

Blockage	CD 1	CD 2	CL1	CL2
Case 1	0.964	-0.214	-0.00087	0.0022
Case 2	0.973	-0.196	-0.0011	0.00235
Case 3	1.161	0.047	0.00067	-0.00102
Case 4	4.039	3.852	0.00152	-0.0079
Case 5	7.042	2.819	-0.00562	0.01014

Figure 3 shows the drag coefficient, for Case 1 and Case 2, the response is equivalent in the first cylinder with the drag force component in the flow direction, while cylinder 2 has the drag force opposite the flow direction, due to the negative pressure region behind the first cylinder. In Case 3, the blocking rate increases to 26%, an increase in the drag coefficient of the first cylinder is observed, while for the second cylinder there is a reduction in the magnitude of the coefficient and the inversion of direction is also observed. In Case 4, the magnitudes of the drag forces are similar for both cylinders. In Case 5, the drag coefficient on the first cylinder increases, but on the second cylinder it decreases.

The influence of the blockage ratio in the lift forces is presented in Figure 4, where Case 1 and Case 2 presented an equivalent response. Case 3 showed the same tendency as Case 1 and Case 2, but with a reduction in the magnitude.

Case 4 and Case 5 presented an increase in the magnitudes and an inversion of signals, in this case, the signal is not relevant, due to the change in pressure field around the cylinders. The main increase in the magnitude is relevant.

The increase in the forces due to the blockage ratio was presented for a square cylinder by Sharify et al. (2013), where the authors observed an increase of 34% in the drag force coefficient with the increase from 15% to 30% blockage ratio.

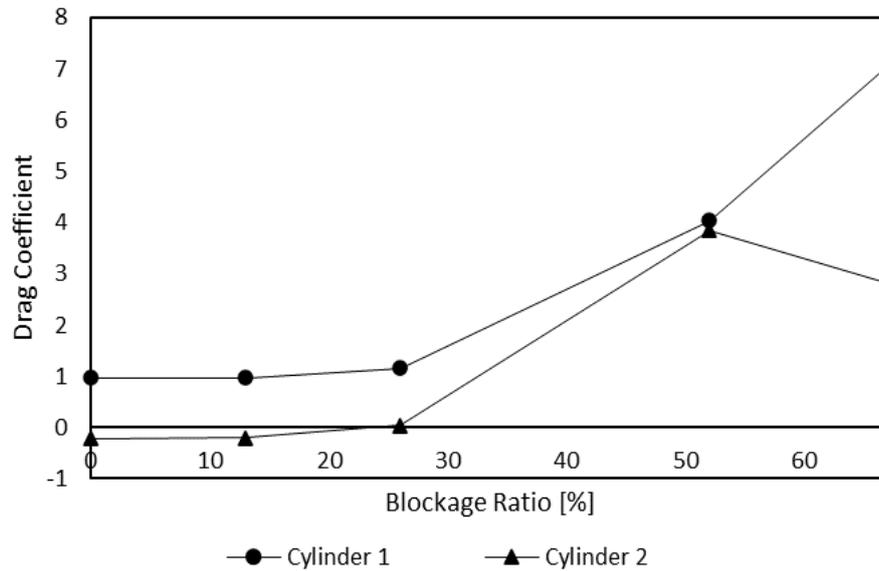


Figure 3. Drag coefficient response with the increase in the blockage ratio.

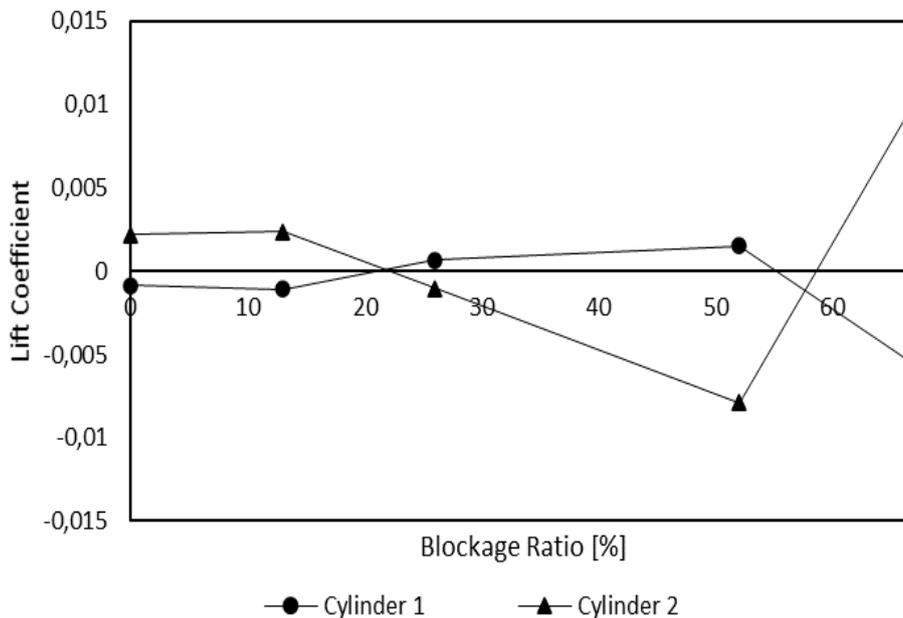


Figure 4. Lift coefficient response with the increase in the blockage ratio.

In Figure 5, the flow pattern observed over the cylinders for Case 2 to Case 5 are presented. The Case 2, with a 13% of blockage ratio, show streamlines with a region of acceleration around the cylinders a vortex formation between the cylinders a wake behind the second cylinder with indication of the first cylinder shear layer reattachment in the right extremity of cylinder 2. Case 3, blockage ratio of 26%, presents a wake shorter than Case 02 and the shear layer reattachment happens in both sides of the second cylinder. Case 4 with a blockage ratio of 52% shows the interaction of the vortices with the walls, directing the wake. Case 5 shows the most significant change with jet flows in both sides of

the cylinders and symmetric vortexes formation behind the second cylinder. The flow patterns change significantly with the increase in the blockage ratio but the analysis of the flow regime needs to be explored. The inlet velocity condition is the same for the tested cases, but the blockage ratio increases the velocity on the cylinders, with an increase in up to three times in the velocity as indicated in Table 2. The influence of this increase in velocity was not explored in the present analysis.

The results from Sharify et al. (2013) showed that the size of the vortex in the wake decreased and the Strouhal number increased as the blockage ratio increased from 0.15 to 0.30. Möller et al. (2015) showed that the Strouhal number for a single-cylinder increased with the increase of the blockage ratio from 0.05 to 0.31. The increase in the blockage ratio increases the vortex shedding frequency and this characteristic can be associated with the increase in the velocity around the cylinders. Zhao et al. (2012) presented an analysis of the flow-induced vibration of a cylinder in different blockage ratio and showed higher amplitudes of vibration with the increase of the blockage.

Zdravkovich (2002) described the complexity of the blockage mechanisms relating to the strength, visibility of the eddies with the increase of blockage ratio, in high blockage, over 0.25, the eddies appear compressed between the walls. The author also describes the regimes for close wall proximity and some characteristics in Case 5, 67% blockage, are related to the narrow gap regime due to jet-like flow in both sides of the cylinders.

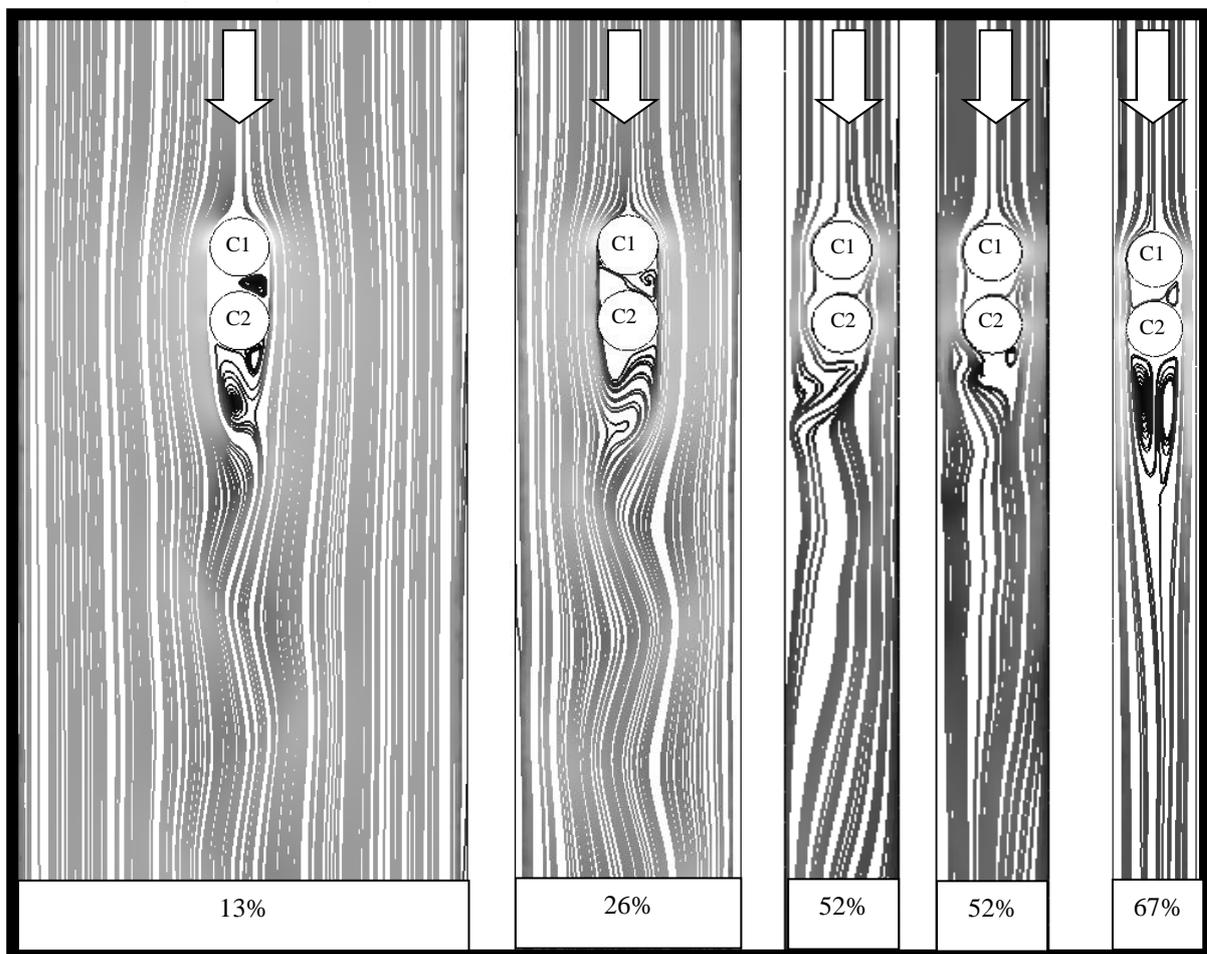


Figure 5. Flow over cylinders in tandem for blockage ratio 13%, 26%, 52% and 67%.

4. CONCLUSIONS

Numerical simulations were applied to investigate the influence of the blockage ratio on forces and flow patterns for two cylinders in tandem configuration with $L/D = 1.26$. The study was a preliminary approach to investigate the flow mechanisms associated with the increase of the blockage ratio from no blockage to 67%.

The forces coefficient results showed agreement with literature for low blockage ratios, Case 01 and Case 02. The increase in the blockage ratio indicates a significant influence on the forces and flow patterns. Case 03 indicates a reduction in the wake size. Case 04 presents the interaction of the wake with the wall and Case 5 presented a jet-like flow characteristic of close wall flows.

The results for tandem cylinders indicate the increase in the lift coefficient on the second cylinder with the increase in blockage ratio, this result agrees with the literature, Neumeister et al. (2020), that showed an increase in the amplitude for experimental analysis with increase in the blockage ratio. Additional investigations are necessary to describe patterns ranges using more cases with intermediate blockage ratios.

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