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Examination of Wake Characteristics for Tandem Circular Cylinders via Computational Fluid Dynamics

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Abstract − Wake characteristics of the cylinders have been numerically investigated for tandem arrangement. The study was done for airflow at a diameter-based Reynolds number of Re = 200 via ANSYS-Fluent 2021 R1. Variations of horizontal distances between two cylinders with the same diameter have been considered in the $1.5 \leq L^* \leq 6$ range. The drag coefficients have been attained, and these results have been presented along with flow characteristics of velocity components, magnitude values for vorticity, and pressure distributions. In front of the upstream cylinder, flow stagnated in all cases. Nonetheless, it has been observed for $L^* \geq 4.5$ in terms of the downstream cylinder. The periodical clusters for cross-stream velocity components have been attained in the wake region. Vortex shedding has been observed in the flow patterns. The unsteady flow structures have been seen. The spacing between the circular cylinders influenced the drag force. Nevertheless, the effect of an upstream cylinder on the downstream one disappeared for $L^* \geq 4.5$ in this study. The drag coefficient of the upstream cylinder is approximately the same concerning the value of a single one in terms of $L^* \geq 4.5$ as a result of the study.

Keywords − *Computational fluid dynamics* (*CFD*), *circular cylinder, drag coefficient, tandem arrangement, wake characteristics*

1. Introduction

Flow around a circular cylinder is encountered in various engineering cases. These examples are bridge piers, chimney stacks, electronic components, energy harvesters, heat exchanger tubes, marine risers, offshore structures, towers, and transmission cables [1-3]. For this reason, multiple bodies are also important for fluid flow problems since the interaction between these bluff bodies considerably affects flow characteristics [4]. In these applications, the circular cylinders are positioned for side-by-side, staggered, or tandem arrangements [5]. Other effective parameters for the present case are the Reynolds number and the distance between them [6]. As considered in various studies, flow dynamics over fixed circular cylinders intensely depend on their spacing [7]. No vortex shedding from the upstream cylinder is observed for the spacing ratio less than the critical one. However, two vortices are seen for higher distance ratios between the cylinders [8]. Vortex formation is also affected by the situations above. As well-known, cylindrical geometries are generally exposed to flow-induced vibration due to the vortex-shedding phenomenon [9]. For instance, various tubes operating in cross-flow, axial-flow, or mixed-flow directions are used in thermal systems, and these forces cause severe vibrations, resulting in irretrievable damage triggered by complex flow structures [10]. Therefore, examining flow characteristics for tandem circular cylinders is very significant. Considering these cases, many studies

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have been conducted in the open literature on the current subject. Papaioannou et al. [11] examined the flow around tandem cylinders at various Reynolds numbers for several distances between them. For higher spacing values than the critical one, the upstream cylinder indicated behavior similar to that of a single cylinder. Kitagawa and Ohta [12] numerically studied the flow characteristics of circular cylinders for tandem arrangement. The effects of the upstream cylinder on the downstream cylinder have been investigated. Carmo et al. [13] considered the wake instabilities of tandem circular cylinders for varying distances between them. Vakil and Green [14] numerically studied the flow around tandem circular cylinders in two-dimensional cases up to a Reynolds number of Re = 40. Wang et al. [15] investigated the effect of wall proximity on circular cylinders with tandem arrangement. In a study by Zhao and Cheng [16], different arrangements have been compared for two circular cylinders. Mahir and Altac [17] evaluated the diameter effect on thermal and flow characteristics of tandem circular cylinders at Re = 100 and Re = 200. Schewe and Jacobs [18] conducted experiments for tandem circular cylinders at several Reynolds number values. Zhu et al. [19] scrutinized the wake structures of multiple circular cylinders at Re = 160. Dubois and Andrianne [20] investigated the aerodynamic flow characteristics of tandem rough cylinders regarding spacing values and flow regimes. Ilkentapar et al. [21] studied the spoiler influence on flow past tandem circular cylinders. Liu et al. [22] presented a study about flow control for tandem circular cylinders at $75 \leq Re \leq 200$. As observed in previous studies, the distance between the circular cylinders is a parameter that affects flow patterns.

Flow around circular cylinders for tandem arrangement has been numerically considered at Re = 200 in the present study. The distance values between the tandem cylinders varied from $L^* = 1.5$ to $L^* = 6$ for $\Delta L^* = 0.5$ as evaluated. The study aims to investigate the effects of more specific distance values chosen in the current range of this study as a distinction because these spacing values have been roughly given for L* values in previous studies. Concerning these parameters of the present study, several flow characteristics have been presented for more specific L* values regarding streamwise and cross-stream velocity components, vorticity magnitude values, pressure distributions, and drag coefficients.

2. Material and Method

The flow domain has been established as two-dimensional, including $-15 \leq x^* = x/D \leq 30$ and $-15 \leq y^* = y/D \leq 15$, and the upstream cylinder has been positioned at $x^* = y^* = 0$, as in Figure 1. The downstream cylinder was placed after the upstream one, with a distance between them. The cylinders have the same diameter as D = 1 cm. Aerodynamic flow characteristics have been considered for $Re = U_\infty D \nu^{-1}$ of 200. Here, the free-stream velocity value (U_∞) and the kinematic viscosity of air (ν) have been considered for the calculation of Reynolds number. The distances between upstream and downstream cylinders have been considered in the $1.5 \leq L^* = L/D \leq 6$ range.

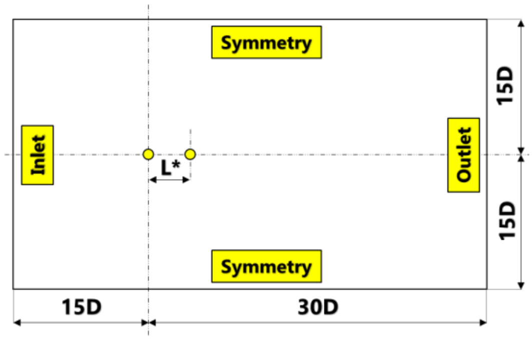

Figure 1. Two-dimensional flow domain for tandem circular cylinders

Regarding numerical methods, continuity, and momentum equations have been considered. Unsteady simulations have been conducted by ANSYS-Fluent 2021 R1 for two-dimensional and incompressible flow. Moreover, body forces have been neglected. The continuity equation has been shown in (2.1), while momentum equations have been presented in (2.2) and (2.3), as also stated by Mahir and Altac [23] and

Goktepeli [24]. In these equations, velocity components have been utilized. Their variations concerning time and coordinates have been considered. Pressure, density, and kinematic viscosity terms have been included. The SIMPLE scheme has been used for pressure-velocity coupling. Gradient, pressure, and momentum have been considered for spatial discretization. The convergence has been attained by 10^{-6} for these equations.

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{2.1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial P}{\partial x}+\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{2.2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial P}{\partial y}+\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \tag{2.3}$$

For the grid structures, element size has been defined. Concerning different element size values, the number of grid elements has been varied. The grid structure is exhibited in Figure 2 as an example. Uniform velocity has been defined for the inlet of the flow domain. On the other hand, a pressure outlet has been used for its exit. Symmetrical boundary conditions have been described for the top and bottom edges of the flow domain. Wall boundary conditions have been applied for the cylinders.

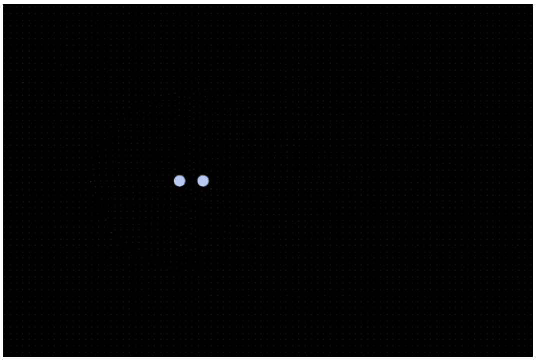

Figure 2. The grid structure

Various grid structures have been tested according to a single circular cylinder's drag coefficient (C_D) at Re = 200. In terms of the grid independence study, the grid numbers 5.4×10^5, 6.7×10^5, 8.4×10^5, and 9.6×10^5 have been contrasted as in Figure 3. The grid element number of 8.4×10^5 has been determined for all analyses in the present study.

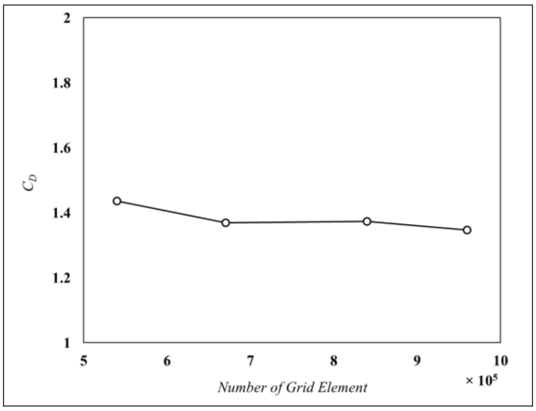

Figure 3. The effect of different grid structures on drag coefficients

The effect of time step on the runs has also been considered by comparing the results of C_D. However, different time step values have not altered the present results, as seen in Figure 4. Thus, the time step size value of Δt = 0.001 s has been utilized.

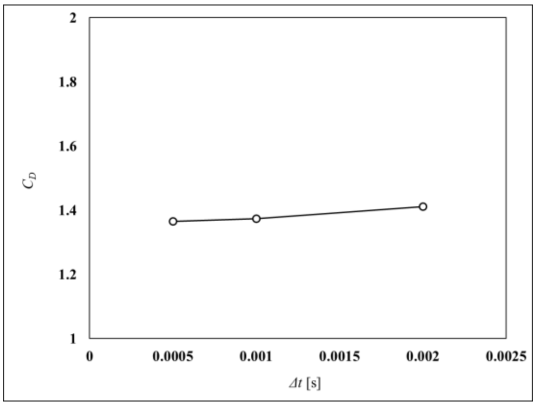

Figure 4. The influence of various time step values on drag coefficients

Concerning the numerical simulation done by 8.4×10^5 grid elements for $\Delta t = 0.001$, the C_D has been compared with the values of open literature at Re = 200 as in Table 1.

Table 1. Drag coefficients of a single circular cylinder for Re = 200

Studies	C_D
Dehkordi et al. [1]	1.33
Mahir and Altac [23]	1.376
Ding et al. [25]	1.348
Singha and Sinhamahapatra [26]	1.337
Koda and Lien [27]	1.376
Present study	1.374

Ding et al. [25] obtained $C_D = 1.348$ at Re = 200. Similarly, at Re = 200, Mahir and Altac [23] presented this value as $C_D = 1.376$ in their study. These values have been attained as $C_D = 1.337$, $C_D = 1.33$, and $C_D = 1.376$ in the studies by Singha and Sinhamahapatra [26], Dehkordi et al. [1] and Koda and Lien [27], respectively, again for Re = 200. The present value of this study is in good agreement with those given previously. Therefore, the validation has been done.

3. Results and Discussion

For Re = 200, the distance effect on the flow characteristics has been considered for two cylinders in a row. The motivation of the study is to examine the effects of more specific distance values because these spacing values have been roughly given for L* values in previous studies. Flow structures of streamwise velocity components, cross-stream velocity components, vorticity magnitude values, and pressure distributions have been presented as the dimensionless results of numerical research. Moreover, drag coefficients have also been indicated for varying L* values.

Streamwise velocity components have been obtained at $-0.14 \leq u^* \leq 1.23$ for $u^* = u\, U_\infty^{-1}$. Concerning the numerical results in Figure 5, flow stagnation has been observed in front of the upstream cylinder for all cases. However, it has been seen for the downstream cylinder in terms of $L^* \geq 4.5$. Flow separation affected the wake characteristics of the cylinders. Furthermore, the spacing between the cylinders also influenced the flow structures of the wake region. For $L^* < 4.5$, the vortex shedding from the cylinders is more prominent. For $L^* < 4.5$, no notable change in the flow patterns has been observed. It is owing to the influence of the flow interaction between the cylinders. On the other hand, for $L^* \geq 4.5$, the effect of the upstream cylinder is limited. Moreover, the downstream cylinder showed a similar behavior to the single cylinder.

Figure 6 shows that cross-stream velocity components have been given as $-0.62 \leq v^* \leq 0.62$ for $v^* = v\, U_\infty^{-1}$. Positive and negative cross-stream velocity components have been observed as a symmetrical distribution. Moreover, the rotational direction is related to the sign of the value. For the wake region, the periodical distributions of the clusters have been seen. The dominant cluster repressed the other one in terms of flow patterns. When the distance between the cylinders is decreased, the clusters are weaker.

Vorticity magnitude values have been attained by $0 \leq \omega^* = \omega\ D\ U_\infty^{-1} \leq 25$, as in Figure 7. Vortex shedding has been obtained concerning the flow patterns. The unsteady flow structures have been observed. For $L^* < 4.5$, the vortex formation of the wake is weaker. Therefore, especially for $L^* < 4.5$, no significant change in the flow patterns has been seen. Because the cylinders affected their flow structures. On the other hand, for $L^* \geq 4.5$, denser vortex shedding has been seen in the wake region.

Pressure distributions have been depicted in Figure 8 for $-0.38 \leq P^* = P\ \rho^{-1}\ U_\infty^{-2} \leq 0.48$ concerning the results. Flow stagnation triggered the peak value for pressure. For this reason, a pressure drop has been obtained. It is more evident in the wake region. The distance between the tandem circular cylinders affected C_D values. However, the upstream cylinder lost its effect on the downstream cylinder by the values of $L^* \geq 4.5$. For this reason, for $L^* < 4.5$, there is no significant change in the flow patterns. This is due to the effect of the flow interaction between the cylinders.

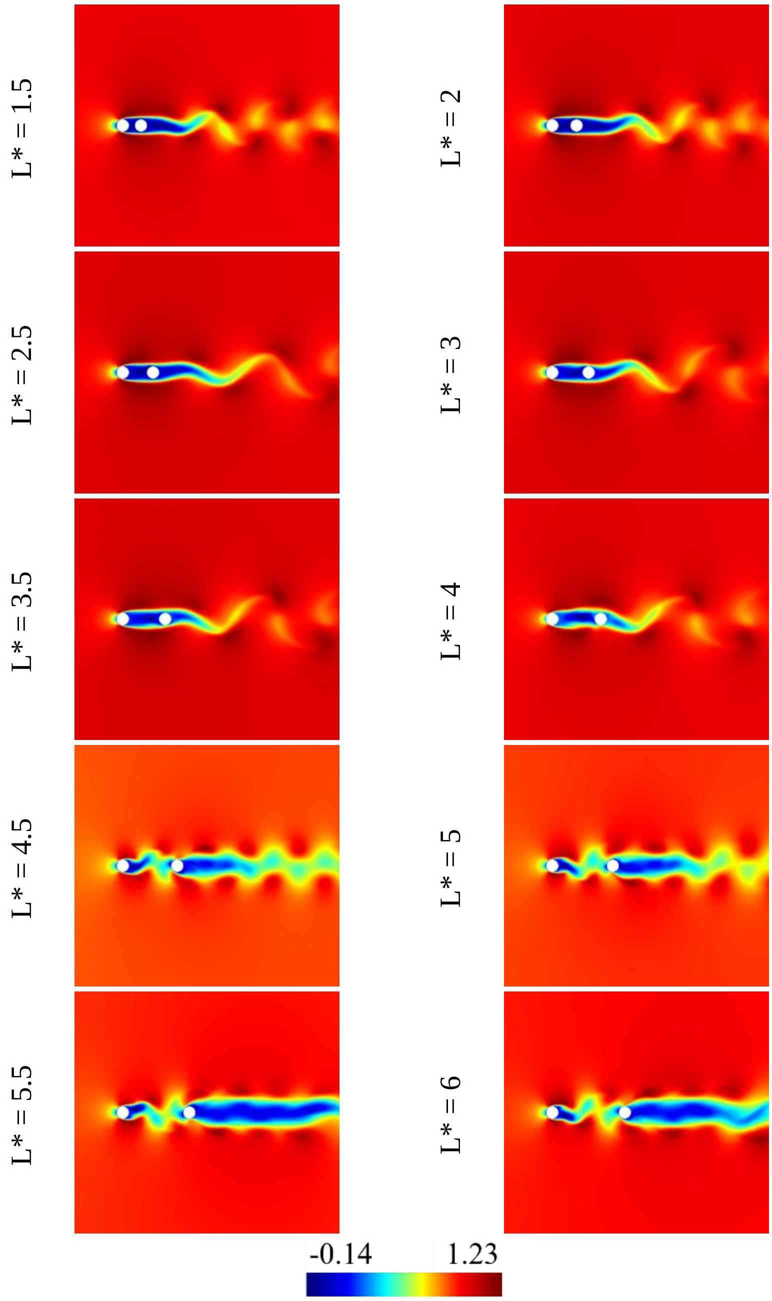

Figure 5. Streamwise velocity components of tandem circular cylinders for L* values

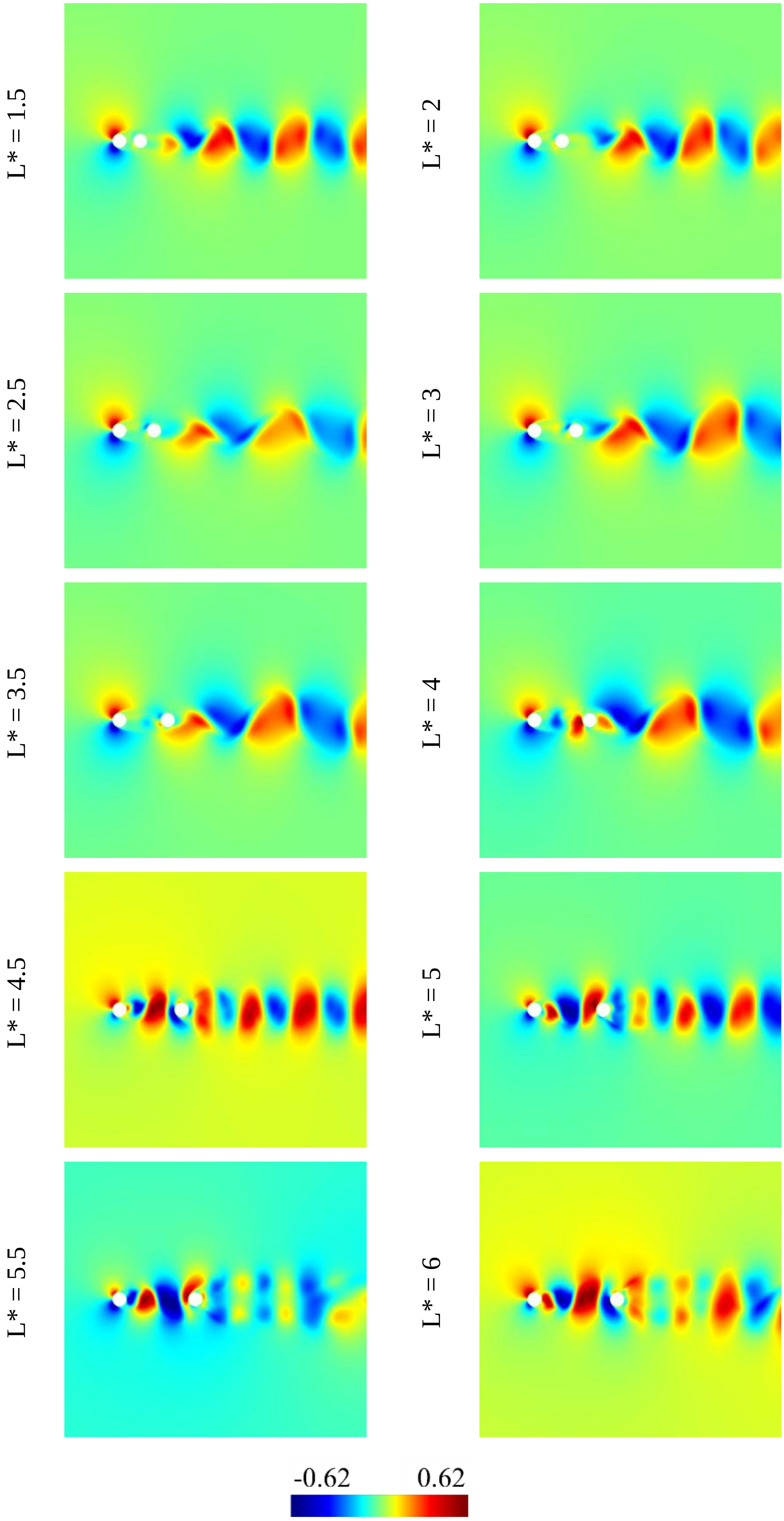

Figure 6. Cross-stream velocity components of tandem circular cylinders for L* values

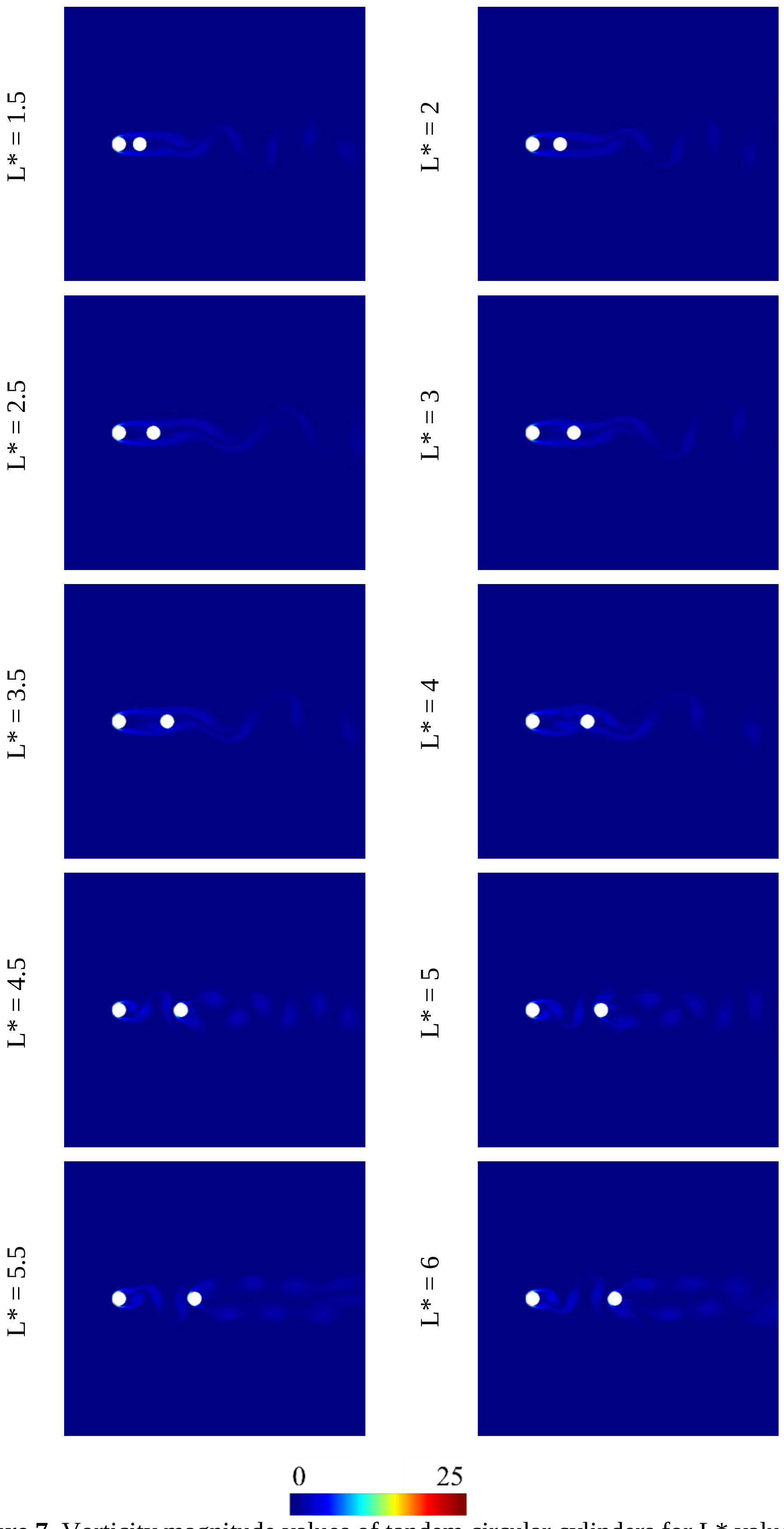

Figure 7. Vorticity magnitude values of tandem circular cylinders for L* values

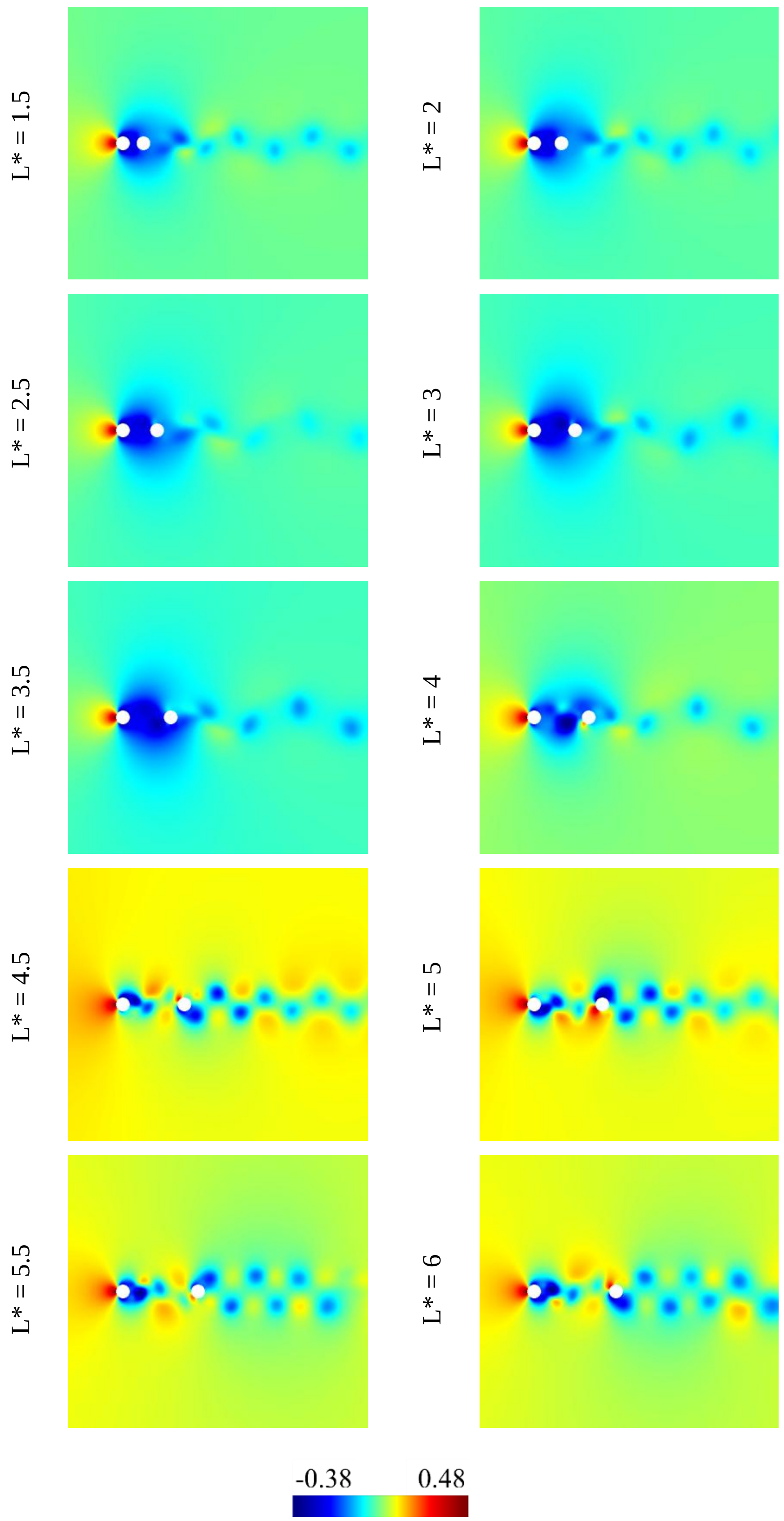

Figure 8. Pressure distributions of tandem circular cylinders for L* values

C_D values for different distances between two cylinders have also been obtained. Concerning these results, the apparent effect of cylinder spacing has been obtained. The numerical results are listed in Table 2, including the drag coefficients of similar studies done at Re = 200. Comparison and validation of the results have been provided by the drag coefficients given for various L* values. For L* ≤ 4, the drag coefficient values of the upstream cylinder are less than the value of the single one. Moreover, the drag coefficient of the downstream cylinder has been reduced when the cylinders are closed. However, for L* ≥ 4.5, the drag coefficient for the upstream cylinder is nearly the same as the value of the single cylinder.

Table 2. Comparison of C_D values for tandem circular cylinders concerning L* values at Re = 200

Studies	L*	$C_{D,1}$	$C_{D,2}$
Koda and Lien [27]	1.5	1.107	-0.201
Present study		1.112	-0.216
Mahir and Altac [23]	2	1.06	-0.21
Present study		1.073	-0.219
Present study	2.5	1.052	-0.204
Mahir and Altac [23]	3	1.051	-0.56
Koda and Lien [27]		1.043	-0.129
Present study		1.039	-0.121
Koda and Lien [27]	3.5	1.023	-0.068
Present study		1.017	-0.091
Mahir and Altac [23]	4	1.34	0.558
Koda and Lien [27]		1.287	0.442
Present study		1.001	0.128
Present study	4.5	1.366	0.389
Mahir and Altac [23]	5	1.327	0.455
Koda and Lien [27]		1.295	0.459
Present study		1.322	0.443
Present study	5.5	1.285	0.259
Present study	6	1.278	0.247

4. Conclusion

Aerodynamics flow characteristics for tandem circular cylinders have been scrutinized at Re = 200 for varying L* values. The drag coefficients have been obtained. These results have been given with streamwise and cross-stream velocity components, magnitude values for vorticity, and pressure distributions. Flow stagnated in front of the first cylinder, as seen in all cases. It is valid for L* ≥ 4.5 regarding the downstream cylinder. The periodical clusters have been provided in the wake for cross-stream velocity values. Vortex shedding and unsteady flow structures have been observed. The spacing between the tandem circular cylinders altered the drag values. On the other hand, the influence of the first cylinder on the second one disappeared for the values of L* ≥ 4.5 in the present study. For L* ≥ 4.5, the drag coefficient of the upstream cylinder is nearly the same concerning the value belonging to the single one. For future studies, different bluff bodies could be considered in various arrangement types. Side-by-side and staggered arrangements for various cylinders are potential cases for experimental and numerical studies. The effects of these formations on flow characteristics should be regarded in forthcoming research.

Author Contribution

The author read and approved the final version of the paper.

Conflict of Interest

The author declares no conflict of interest.

Ethical Review and Approval

No approval from the Board of Ethics is required.

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