Flow Characteristics Around Staggered D-Type Cylinders Near a Flat Wall: A 2D Numerical CFD Investigation

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Abstract: This study presents a 2-D numerical investigation of fluid flow characteristics around staggered D-type cylinders (θ_s =36°) placed near a flat wall at a high Reynolds number (5.3×10^4). Using ANSYS Fluent with the k–ω SST turbulence model, the effects of spacing ratio (L/D), stagger angle (α), and gap ratio (G/D) were systematically examined. The results demonstrate that the upstream cylinder governs the global pressure distribution and wake dynamics, while the downstream cylinder experiences significant shielding effects that reduce aerodynamic loading. At short spacing (L/D = 1.5), strong wake interference and irregular vortex shedding dominate, leading to highly unstable flow. Conversely, for L/D ≥ 3, independent and more stable wake structures emerge behind each cylinder. The gap ratio (G/D) further modulates base pressure and flow separation, with smaller gaps intensifying wall–wake interactions. These findings provide new insights into wake interference mechanisms of modified bluff bodies and are directly relevant for engineering applications such as heat exchangers, offshore structures, and drag-reduction devices.

Keywords: D-type cylinder, staggered configuration, CFD, wake dynamics, flow interference

1. Introduction

Flow over bluff-body configurations has been widely investigated due to its fundamental importance in fluid mechanics and its relevance to practical engineering applications such as heat exchangers, tube banks, marine risers, and flow-control devices [1-3]. When two or more cylinders are placed in close proximity, complex wake interactions arise that strongly depend on the relative arrangement, typically classified into side-by-side[4], tandem (longitudinal) [5], and staggered configurations [6]. Each configuration introduces unique flow features including gap-flow switching, wake merging, shear-layer interaction, and vortex synchronization, which significantly alter the global coefficient pressure, force coefficients, vortex-shedding frequency, and flow-induced vibration characteristics [7-9]. Among various bluff-body geometries, the D-shaped (type-D) cylinder, formed by truncating a circular cylinder along a chord, has gained increasing attention as an effective passive flow-modification geometry [10]. Compared to

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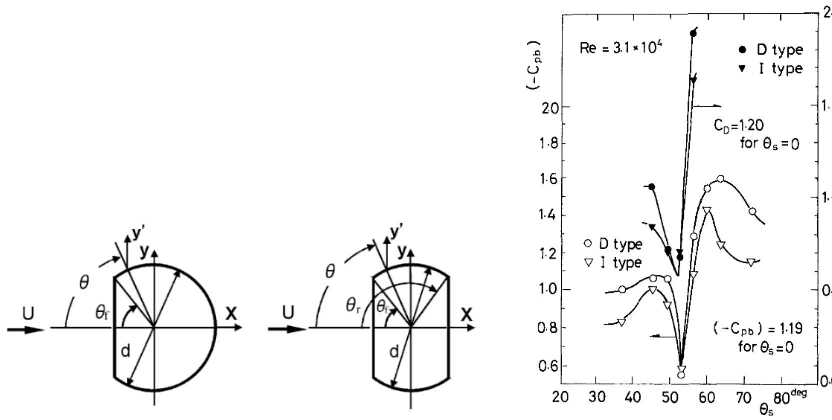
circular cylinders, D-type cylinders exhibit earlier shear-layer separation, altered pressure distribution, and reduced drag coefficients, particularly at cutting angles near (θ_s=53°), which lead to wake contraction and modified vortex-shedding behavior [10, 11]. Similar investigations on modified geometries such as I-type or double-cut sections have also confirmed that leading-edge modification can serve as an efficient drag-reduction strategy [11-13].

Previous studies on single D-type cylinders have clarified their aerodynamic and hydrodynamic characteristics, yet investigations on pairs of D-type cylinders remain limited. In contrast, extensive research on circular-cylinder pairs has demonstrated the strong dependence of wake interactions on spacing ratio and Reynolds number, with multiple wake modes observed for side-by-side, tandem, and staggered arrangements [14, 15]. These findings highlight the crucial role of relative positioning in determining force coefficients and wake stability. Extending such knowledge to D-type geometries is particularly important, since their sharp leading edges fundamentally alter shear-layer development and wake transition mechanisms. Recent contributions by several authors have emphasized the potential applications of D-type and other modified bluff-body sections in drag reduction and flow control. For instance, numerical simulations and wind-tunnel experiments have shown that D-type geometries can reduce mean drag, suppress vortex-induced vibrations, and enhance performance in energy-harvesting systems [16, 17].

However, a comprehensive parametric understanding of paired D-type cylinders in canonical arrangements-side-by-side, tandem, and staggered, particularly in the presence of a near-wall effect-remains absent in the literature. Existing research on flow around cylinders has predominantly focused on circular geometries, both in isolation and in various arrangements (tandem, side-by-side, staggered). Extensive studies have explored vortex shedding, wake interference, and aerodynamic forces for these conventional shapes. While some investigations have ventured into non-circular cylinders, such as squares and ellipses, the literature specifically addressing D-type and I-Type cylinders as shown in figure 1 (a, b), particularly in complex arrangements like staggered configurations near a flat wall, remains sparse. Studies on single D-type cylinders have provided initial insights into their unique flow separation characteristics and pressure recovery compared to full cylinders [11, 18].



(a) D-shape cylinder (b) I-shape cylinder (c) Drag Coeficient of D-type and I-type

Fig 1. Configuration of cylinder (a) D-type (b). I -type (c). Drag Coeeficient (C_D) of D-type and I-type cylinders [11, 18]

However, the introduction of multiple D-type cylinders, especially in a staggered formation, and their proximity to a solid boundary dramatically increases the complexity of the flow. There is a clear knowledge gap regarding the detailed flow characteristics around staggered D-type truncated cylinders near a flat wall. Specifically, the intricate interplay of truncation angle, stagger parameters (transverse spacing and stagger angle), and Reynolds number on phenomena like flow separation, reattachment, pressure distributions, velocity profiles, and vortex structures has not been comprehensively explored. This study aims to bridge this critical gap by providing a detailed numerical investigation into these complex interactions. The novelty of this research lies in investigating, for the first time, the combined effects of spacing ratio, stagger angle, and gap proximity (G/D) on the wake dynamics of paired D-type cylinders (θ_s = 36°). Unlike previous studies that mainly focused on circular and square cylinders, this work extends the analysis to D-type geometries with distinct shear-layer separation mechanisms. A two-step methodology is adopted, beginning with detailed two-dimensional numerical simulations to establish parametric trends, followed by future experimental validation. This approach ensures both efficiency and reliability of the results. By examining variations in transverse spacing (T/D) and stagger angles (α) at high Reynolds numbers, the study provides new insights into interference effects and wake behavior. The outcomes are expected to support design optimization in engineering applications such as heat exchangers and offshore structures, where controlling flow phenomena is essential for performance and structural integrity.

2. Methodology

This study was carried out using numerical simulations with the Fluid Dynamis solver FLUENT 6.2 to investigate the flow interaction around D-type cylinder (36°). The D-type cylinder configuration was arranged in tandem with spacing ratios (L/D=T/D = 1.5, 2, 3, and 4) with stagger configuration (α= 0-45°), and subjected to the influence of a side wall with gap ratios (G/D) = 0, 0.5, and 1, progressively moving away from the flat wall, as illustrated in Figure 1. The computational domain is a rectangular region designed to minimize boundary effects on the flow. The inlet boundary is positioned 10D upstream of the leading cylinder's centre, and the outlet boundary is 20D downstream. The top and bottom boundaries of the domain are located 10D from the centreline of the cylinder arrangement. The flat wall is positioned immediately below the cylinders, with a minimal gap to represent a near-wall condition. These dimensions ensure fully developed flow at the inlet and allow for sufficient wake development before the outlet.

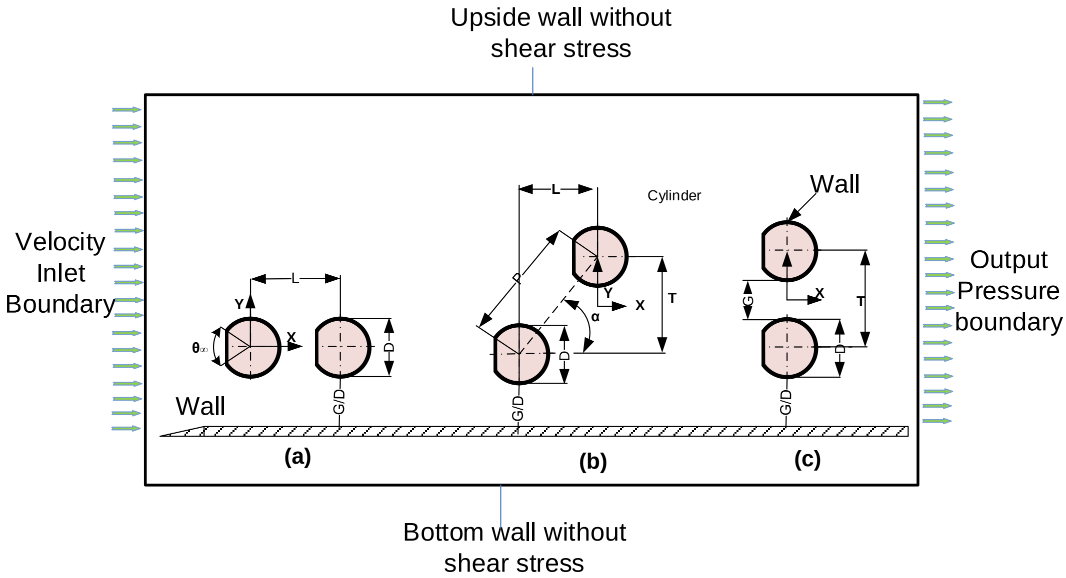


Fig 2. Schematic diagram of 2D simulation

Figure 2 illustrates the computational domain of the numerical simulation for different cylinder arrangements: (a) longitudinal configuration with spacing ratio (L/D), (b) transversal configuration, and (c) staggered configuration with inclination angle (α). Figure 2 presents the meshing process (quadrilateral-map). A uniform velocity inlet is prescribed at the inlet boundary, while an outflow condition is applied at the outlet. The simulations are performed at a Reynolds number (R_{eD}) of 5.3×10^4, based on the cylinder diameter. The numerical analysis employs a 2-D with k–ω SST turbulence model.

2.1. Governing Equations and Turbulence Model:

In this investigation, the fluid flow is modeled as a 2-D, viscous, and incompressible Newtonian fluid with constant thermophysical properties. The governing parameters and flow variables are subsequently formulated in a non-dimensional framework to ensure generality and facilitate comparative analysis[17, 19]

Continuity Equation:

$$\frac{\delta u^*}{\delta x^*} + \frac{\delta v^*}{\delta y^*} = 0 \tag{1}$$

Momentum Equations:

$$\frac{\delta u^*}{\delta t^*} + u^* \frac{\delta u^*}{\delta y^*} + v^* \frac{\delta u^*}{\delta y^*} = -\frac{\delta p^*}{\delta x^*} + \frac{1}{R_e}\left(\frac{\delta^2 u^*}{\delta x^{*2}} + \frac{\delta^2 u^*}{\delta y^{*2}}\right) \tag{2}$$

$$\frac{\delta v^*}{\delta t^*} + u^* \frac{\delta v^*}{\delta x^*} + v^* \frac{\delta v^*}{\delta y^*} = -\frac{\delta p^*}{\delta y^*} + \frac{1}{R_e}\left(\frac{\delta^2 v^*}{\delta x^{*2}} + \frac{\delta^2 v^*}{\delta y^{*2}}\right) \quad (3)$$

To model the Reynolds stresses, the $\boldsymbol{k-\omega}$ SST turbulence model was employed. This model is chosen for its robustness and accuracy in predicting flows with adverse pressure gradients and separation, which are characteristic of flow around bluff bodies. The $k-\omega$ SST model effectively blends the k−ω model (suitable for near-wall regions) and the $k-\epsilon$ model (suitable for free-stream regions) using a blending function, providing accurate predictions across the entire boundary layer.

2.2. Computational Fluid Dynamics (CFD) Setup:

All numerical simulations were conducted using ANSYS Fluent with a pressure-based solver under steady-state formulation to capture the time-averaged flow field. The SIMPLE algorithm was employed for pressure–velocity coupling, while second-order discretization schemes were applied to pressure, momentum, and turbulence variables (k, ω) to enhance accuracy in resolving flow separation and wake structures. The computational domain was subjected to a uniform velocity inlet corresponding to a Reynolds number of 5.3×10^4, a pressure outlet with zero-gauge pressure, and no-slip boundary conditions on both the wall and cylinder surfaces. Turbulence intensity was fixed at 1% with a viscosity ratio of 10. Convergence was assumed when scaled residuals of continuity, momentum, and turbulence equations decreased below 10^{-6}, and when the drag coefficient of the cylinders stabilized. This setup, following established CFD procedures [20]; [21], ensures numerical stability and reliability in predicting aerodynamic responses and wake dynamics of D-type staggered cylinders.

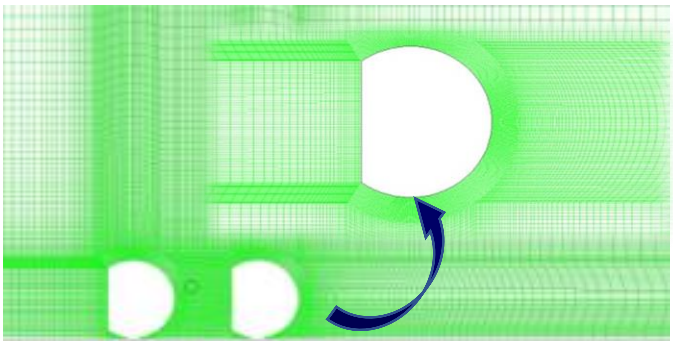


Fig 3. Geometry Mesh used for simulation at tandem position with stagger α=0

To ensure accurate resolution of the flow around the truncated D-type cylinder placed near a flat wall, a structured 2-D quadrilateral mesh was employed with local refinements in three critical regions: the near-wall boundary layer, the cylinder–wall and inter-cylinder gaps, and the wake region downstream. The mesh topology was generated using block-structured mapping around the cylinder surface to minimize skewness. Mesh refinement was introduced in the gap region and extended downstream up to 20D to capture wake dynamics while maintaining orthogonality.

3. Results and Discussion

3.1. Results

Validation of Numerical Approach:

The robustness and accuracy of the numerical approach were primarily established through a thorough mesh independence study, as detailed in section 2. This internal validation confirmed that the chosen mesh density provided results that were independent of further refinement. While direct experimental data for the exact D-type cylinder configurations near a flat wall at the specified Reynolds number are scarce in the literature, further confidence in the methodology was gained by comparing results for a simpler, related case: flow around a single D-type cylinder in an unbounded domain at a similar Reynolds number. Numerical results for the drag coefficient and the overall wake structure were found to be in good agreement with trends and magnitudes reported in existing literature for isolated bluff bodies, thereby supporting the general applicability and reliability of the chosen turbulence model and numerical setup.

Pressure Coefficient (C_p) and Base Pressure (C_{pb}) Distributions:

The pressure coefficient (C_p) distributions along the cylinder surfaces provide crucial insights into the pressure field and aerodynamic forces.

$$C_p = \frac{(p_c - p_\infty)}{1/2 \rho U_\infty^2} \qquad (4)$$

where p_c is the local static pressure, p_∞ is the free-stream static pressure, ρ is the fluid density, and U_∞ is the free-stream velocity.

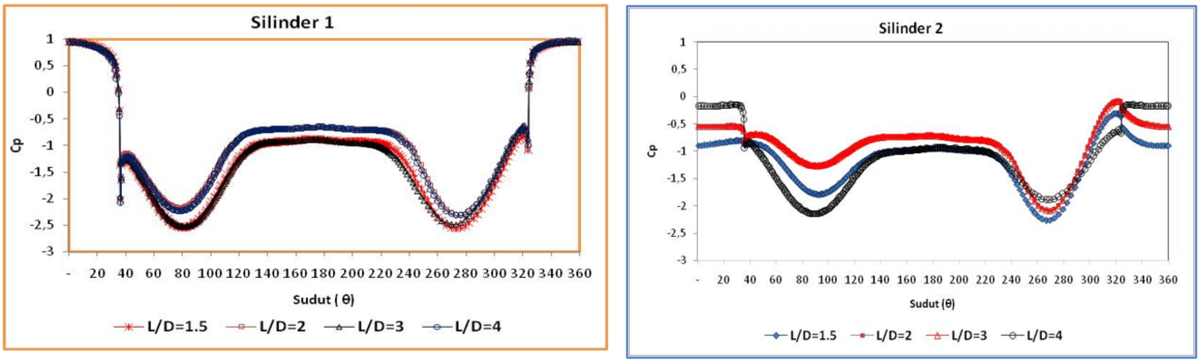


Fig 4. Pressure distribution around D-type cylinder θ_s=36° for Re = 5.3x10^4 with configuration L/D =1.5, 2, 3, and 4, stagger α=0°.

For tandem arrangements, the C_p distributions on the leading (circular) face of both cylinders generally exhibited a similar pattern, with a high positive pressure at the stagnation point as shown in Fig.4. A quantitative comparison between Cylinder 1 and Cylinder 2 further emphasizes the influence of gap ratio (L/D) on flow separation and wake dynamics. Cylinder 1 consistently experiences higher suction peaks with minimum Cp values reaching approximately –2.1 at L/D = 1.5, indicating strong acceleration and a massive adverse pressure gradient along the upper curved surface. In contrast, Cylinder 2 shows significantly reduced suction levels, with minimum C_p values around –1.2 under the same configuration. This reduction demonstrates the shielding effect of Cylinder 1, which weakens the incoming flow energy and alters the separation characteristics on the downstream surface. At larger gap ratios (L/D = 3 and 4), the pressure distribution around Cylinder 1 tends to stabilize, with a gradual recovery toward the base region. The C_p values in the wake zone exhibit smoother profiles, suggesting delayed separation and less turbulent vortex shedding. Conversely, Cylinder 2 at the same gap ratios maintains a more flattened C_p curve, with weaker pressure gradients and earlier but less intense separation. This indicates that although the downstream cylinder is strongly influenced by the wake of Cylinder 1, the overall instability decreases with increasing spacing. The comparative analysis highlights that Cylinder 1 governs the primary flow features through its strong suction and intense separation, while Cylinder 2 experiences attenuated aerodynamic loads due to the shielding effect. Therefore, the aerodynamic behavior of staggered D-type cylinders is highly asymmetric, with the upstream cylinder dictating the overall wake dynamics and the downstream cylinder responding with reduced but more stable pressure variations at larger spacing. These findings provide valuable insight into wake interference mechanisms, particularly in engineering applications involving staggered bluff bodies such as heat exchangers, offshore structures, and bridge pylons.

Flow Pathline Visualization and Wake Dynamics

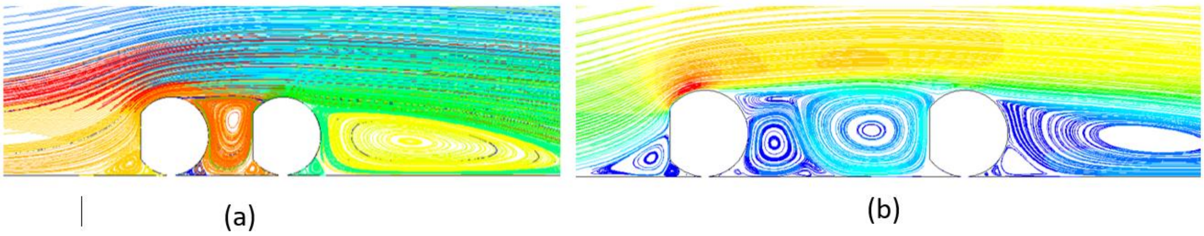
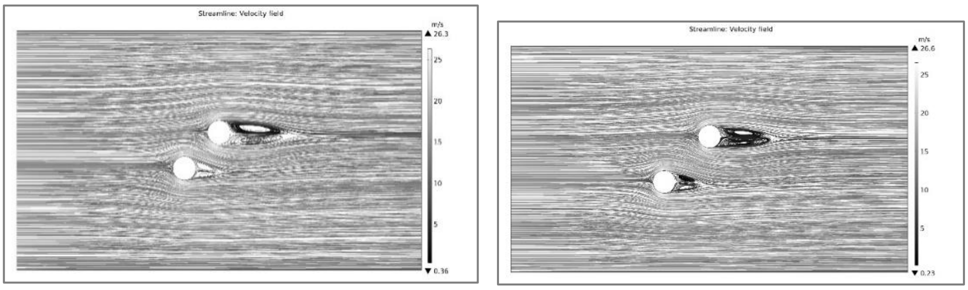


Fig 5. Path line visualization of flow around tandem D-shaped cylinders (θ_s=36°) at different spacing ratios: (a) L/D=1.5 (b) L/D=3; G/D=0, α=0

Figure (5a) illustrates the flow field for tandem D-shaped cylinders with a short longitudinal spacing ratio of L/D=1.5 The path lines indicate strong flow interference between the upstream and downstream cylinders. A large recirculation bubble forms in the gap region, accompanied by pronounced vortex shedding in the near-wake zone. This behavior is consistent with the findings of [22]), who reported that at small spacing ratios, the downstream cylinder is fully submerged within the shear layer separation from the upstream cylinder, leading to enhanced flow instability and turbulence intensity. Similarly, Sumner [23]emphasized that for closely spaced tandem arrangements, the downstream body experiences significant shear-layer impingement, which suppresses periodic vortex shedding and generates irregular wake dynamics. In contrast, Figure (b), corresponding to L/D=3, demonstrates a clear transition toward independent vortex formation behind each cylinder. The separated shear layers from the upstream cylinder reattach before reaching the downstream body, thereby creating a more stable recirculation region between the two cylinders. This observation is in good agreement with [3, 24]), who highlighted that beyond a critical spacing, the downstream cylinder experiences a weakened shear layer interaction and gradually recovers a wake structure similar to that of an isolated cylinder. As a result, the downstream wake exhibits a more coherent Kármán vortex street with reduced unsteadiness compared to the short-spacing case. Overall, the comparison between L/D=1.5, and L/D=3 confirms the critical role of inter-cylinder spacing in determining wake dynamics. At small spacings, the flow interference induces strong wake coupling and highly unsteady forces, while at larger spacings, the cylinders exhibit more independent wake structures. These observations are in strong agreement with prior numerical and experimental investigations [3, 22, 24] reinforcing the importance of spacing ratio in controlling flow-induced vibrations and aerodynamic forces on bluff bodies.



(a) (b)

Fig 6. Path line visualization of flow around staggered D-shaped cylinders (θ_s=36^o) at different spacing ratios:
(a) L/D=1.5; (b) L/D= 2; G/D=1, α=45^o

Figure 6(a) shows the streamline pattern for the case of L/D=1.5; stagger α=45^o and D-shaped cylinders (θ_s=36^o) The flow entering the narrow gap between the cylinders is strongly biased toward the outer side, forming a jet-like stream that impinges on the downstream cylinder. This accelerated gap flow produces a high-momentum reattachment on the downstream cylinder, while compact counter-rotating vortices develop within the gap. As a result, the wake behind the tandem system becomes highly asymmetric, accompanied by intensified shear-layer interaction and enhanced unsteady loading on the downstream cylinder. Figure 6(b) (L/D=2) demonstrates a weaker gap jet, as the increased spacing allows the shear layers to diffuse before reaching the downstream cylinder. This reduces the strength of the gap suction effect, leading to a more organized recirculation bubble and the partial recovery of alternate vortex shedding in the wake. Consequently, the aerodynamic interference diminishes, with the downstream cylinder experiencing forces closer to those of an isolated body. These results are consistent with previous studies on tandem and staggered arrangements, which reported strong gap-flow control at close spacing and progressive re-establishment of independent wakes as the spacing increases [22, 23]

3.2. Discussion

Interference Mechanism and Shielding Effect

The reduction in suction levels on Cylinder 2 demonstrates the shielding effect of Cylinder 1, which weakens the incoming flow energy and alters the separation characteristics on the downstream surface. This effect is critical because Cylinder 1 governs the primary flow features through its strong suction and intense separation, while Cylinder 2 experiences attenuated aerodynamic loads. Therefore, the aerodynamic behavior of staggered D-type cylinders is highly asymmetric, with the upstream cylinder dictating the overall wake dynamics.

The Critical Role of Spacing Ratio (L/D)

The comparison between L/D = 1.5 and L/D = 3 confirms the critical role of inter-cylinder spacing in determining wake dynamics.

- Short Spacing (L/D = 1.5): The strong flow interference means the downstream cylinder is fully submerged within the shear layer separation from the upstream cylinder. This leads to enhanced flow instability and turbulence intensity. The closely spaced arrangement causes the downstream body to experience significant shear-layer impingement, which suppresses periodic vortex shedding and generates irregular wake dynamics.

- Larger Spacing (L/D = 3 and 4): The smoother C_p profiles in the wake zone suggest delayed separation and less turbulent vortex shedding. The transition toward independent vortex formation at L/D $\geq$ 3 is in good agreement with prior work that highlights that beyond a critical spacing, the downstream cylinder gradually recovers a wake structure similar to that of an isolated cylinder. As a result, the downstream wake exhibits a more coherent Kármán vortex street with reduced unsteadiness. These observations reinforce the importance of spacing ratio in controlling flow-induced vibrations and aerodynamic forces.

Gap-Flow Control in Staggered Configurations

In the staggered case (L/D = 1.5, α = 45°), the accelerated gap flow causes a high-momentum reattachment on the downstream cylinder. Consequently, the wake behind the tandem system becomes highly asymmetric, accompanied by intensified shear-layer interaction and enhanced unsteady loading on the downstream cylinder. Increasing the spacing to L/D = 2 weakens the gap jet, which reduces the strength of the gap suction effect and leads to the partial recovery of alternate vortex shedding in the wake. Consequently, the aerodynamic interference diminishes, and the downstream cylinder experiences forces closer to those of an isolated body. These results are consistent with previous studies on staggered arrangements, which reported strong gap-flow control at close spacing and the progressive re-establishment of independent wakes as the spacing increases. These findings provide valuable insight into wake interference mechanisms, particularly in engineering applications involving staggered bluff bodies such as heat exchangers, offshore structures, and bridge pylons.

4. Conclusion

This study numerically investigated flow characteristics around staggered D-type cylinders (θ_s =36°) near a flat wall at Re=5.3×10^4. The results confirm that the upstream cylinder dominates the global pressure distribution and wake dynamics, while the downstream cylinder is strongly influenced by shielding and gap-flow effects. At short spacing (L/D=1.5), a jet-like gap flow induces highly asymmetric wakes, strong recirculation, and irregular vortex shedding. With increased spacing (L/D ≥3), the wake recovers toward a stable Kármán vortex street and aerodynamic forces on the downstream body approach those of an isolated cylinder. The gap ratio (G/D) further modulates wall–wake interaction, with smaller gaps amplifying base-pressure reduction. These findings provide new physical insight into the interference mechanisms of truncated bluff bodies and are directly applicable to engineering systems where drag reduction and vibration suppression are critical.

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