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NUMERICAL ANALYSIS OF CROSSFLOW INDUCED VIBRATION IN ONE AND TWO ROWS OF CYLINDERS

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Abstract. *The flow inside a bank of tubes is complex and presents several interaction mechanisms acting at the same time in different positions of the equipment. Simplifying the structures to two cylinders or a few rows can be a way to understand part of the mechanisms and then extrapolate them to a bank of tubes. The flow over a single row in closed space presents wide and narrow wakes, similar to the structure observed in two cylinders side by side, these structures interacting with a second row show a significant change in the incoming flow parameters. The present study aims to show a numerical analysis of the main characteristics of the crossflow in one and two rows of fixed cylinders and to relate the changes in the pressure fields and forces in the cylinders to the expected vibration response. Simulations of rows of cylinders were performed in a domain with a cross-section of 0.193 x 0.05 m and a length of 0.8 m. Five and ten cylinders with an external diameter of 25 mm were applied. The longitudinal and transverse spatial ratio is 1.26 and all cylinders were fixed. The continuity and Navier-Stokes equations were solved using the Large Eddy Simulation with the Smagorinski-Lilly subgrid model with dynamic stress in Ansys Fluent 19. The Reynolds number is 5×10^4, based on the gap flow velocity and the diameter of a single cylinder. The transient analysis is performed with a time step of 1×10^{-5} s and the 10^{-6} convergence criterion is used for all monitored variables. Preliminary results show wake asymmetry after the first and second rows of cylinders. There is an asymmetry between the velocity in the gaps between the cylinders indicating a redistribution of the flow, increasing and decreasing the velocity in the gaps between the cylinders. This velocity and pressure distribution influences the forces along the cylinders showing an increase in forces coefficients at some cylinder positions. The non-homogeneous distribution of velocity in the gaps is an important factor in determining the vibrational response, as the models use this information as an input parameter to determine the instability limits.*
Keywords: *numerical analysis, crossflow, row of cylinders, flow-induced vibration.*

1. INTRODUCTION

The study of tube bundles or tube banks is constantly evolving, and there is still much to explore regarding the various mechanisms and behaviors that occur within the flow and in interaction with the structure. Previous research on crossflow in tube banks has been summarized by Blevins (1990), Zdravkovich (1997, 2002), and Païdoussis et al. (2011), focusing on both fixed and free-to-vibrate structures. These works have identified several lines of inquiry that require further exploration, and additional studies have been conducted in recent years, particularly on in-line tube banks, to shed light on the unknown characteristics. Numerical analysis plays a crucial role in investigating these characteristics, allowing for the examination of individual variables.

Abed and Afgan (2017) conducted a numerical simulation to study the impact of changing the pitch ratio on heat transfer and flow quantities in in-line, square, and non-square configurations of tube banks. They observed that for square pitch ratios, the flow solution gradually transitioned from strong asymmetry to asymmetry, and eventually to perfect symmetry. The narrow pitch ratio of 1.2 produced a strongly asymmetric solution, while the cases with pitch ratios of 1.5 and 1.6 exhibited less pronounced asymmetry. In the larger pitch ratio of 1.75, the flow behavior was mostly symmetric, except for the Nusselt number.

da Silva et al. (2019) conducted a numerical investigation of three-dimensional flow around an in-line tube bank with a subcritical Reynolds number, using the large eddy simulation approach. They studied transversal pitch ratios (p/d) of 1.5 and 3, and longitudinal pitch ratios (l/d) ranging from 2 to 4. Depending on the flow pattern, certain rows experienced greater fluctuations in flow forces. The combined effect of spacing ratios influenced the general behavior and distribution of fluid forces, with the flow regimes playing a significant role.

To simplify the analysis of tube banks, the use of rows of cylinders offers an interesting approach as it allows for the identification of certain phenomena. When examining the flow over a row of cylinders subjected to a uniform flow, it is observed that the resulting interstitial flow is not uniform (Zdravkovich, 2002). Moretti (1993) described the main characteristics of rows, noting that the flow across a row of tubes deflects into new patterns. When the pitch-to-diameter ratio (p/d) is between 1.5 and 2.2, some wakes are wide while others are narrow. The flow complexity leads to the observation of more than two vortex-shedding frequencies behind tube rows when the p/d ratio is small.

Zdravkovich (2002) summarized relevant studies in this area and noted the presence of asymmetric flow characteristics over a cylinder row, which holds for both laminar and turbulent flows. The author summarized studies for various p/d ratios and observed that non-uniform behavior was negligible for p/d ratios greater than 2 but significant in the range of p/d = 1.2 to p/d = 2. The non-uniform behavior can also intermittently change, which is a common characteristic observed in cases with two cylinders, as presented by Alam et al. (2003) for p/d values below 2.2. The flow behind a single row of tubes inherently exhibits non-uniformity, leading to different mean pressures and forces acting on identical tubes. Drag and lift values also vary considerably across different rows, and the magnitude and variation of forces gradually decrease with increasing tube-to-diameter ratio (p/d). The Strouhal number (St) also changes, with narrow wakes corresponding to higher St curves and wide wakes corresponding to St = 0.15 or St = 0.22. The introduction of disturbances in the flow can lead to intermittent metastable states.

de Paula et al. (2012) conducted a study on the crossflow over a row of cylinders, revealing two stable wake patterns that remained unchanged over time. Neumeister et al. (2016) investigated a row of cylinders with a spacing ratio of 1.26, varying the turbulence intensity from 1% to 11%. The results demonstrated that increasing turbulence intensity affected wake dispersion, resulting in reduced downstream wake length due to increased momentum, while the main flow characteristics remained unaffected. In a more recent study, Neumeister et al. (2022) experimentally investigated the influence of the number of rows and the position of a free-to-vibrate monitored cylinder in a tube bank on the critical reduced velocity. The study revealed that the position of the cylinders is significant, depending on the number of downstream rows and whether the cylinder is in the first row. Existing models in the literature consider damping and reduced velocity in the analysis, without additional parameters, focusing on factors related to the arrangement and spacing ratio. It was observed that the critical velocity changes with the number of rows, with a reduction in fluid-elastic instability velocity occurring with an increase in the number of rows when the cylinder is free to vibrate in the second or third row. Olinto et al. (2009) presented a visualization of asymmetric flow inside the tube banks that could be related to the changes in the critical reduced velocity.

Building upon these findings, the present study aims to perform a numerical analysis of the flow over one and two rows of cylinders to analyze the characteristics of the interstitial flow. This analysis aims to contribute to understanding asymmetrical flow behavior and changes in the critical reduced velocity in tube banks.

2. METHODOLOGY

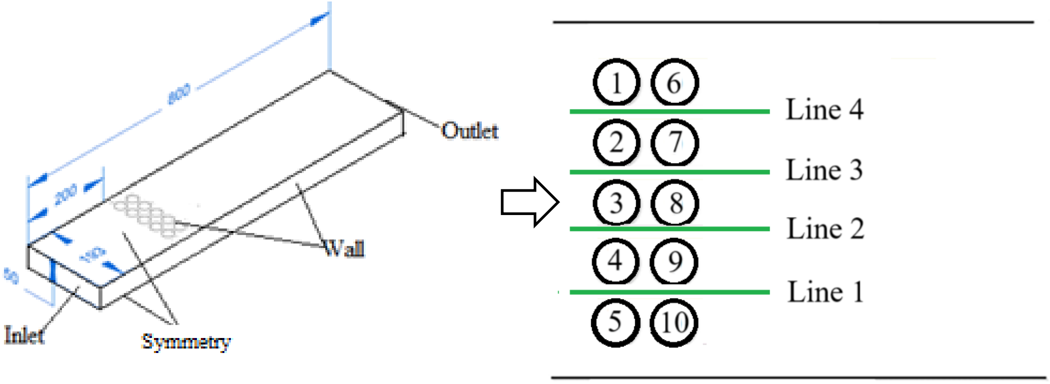
The cases were studied with numerical analysis where fixed cylinders were simulated in the configurations from one row and two rows. The domain presents five cylinders for one row and ten cylinders for two rows. The space ratio longitudinal and transversal is 1.26 and the Reynolds number, based on the gap velocity, simulated for each case is $Re = 5 \times 10^4$.

The named boundary conditions and dimensions adopted are presented in Figure 1 a). The boundary conditions are prescribed velocity inlet, atmospheric pressure in the outlet, wall with the no-slip condition in the sidewalls and cylinders, and symmetry in the top and bottom walls. The analysis with boundary conditions of symmetry in the top and bottom positions was used, due to the studies presented by Iacovides et al. (2014), which reported the assumption of flow periodicity or symmetry in all three directions. The finite volume approach is applied for numerical simulation, with which the domain of interest is divided into elementary volumes that form the mesh, and the conservation equations of the important properties are solved in each one (Maliska, 1995). The discretization of the equations is the transformation of a differential equation into an algebraic relation that connects the values of a variable to the points of a mesh. The values of the variable in the mesh influence immediate neighboring points and with the increase of the number of divisions in discretization the solution tends to be exact, due to the small variation between one point and another. The discretization of the equations for a generic variable is presented in Patankar (1980).

The simulations were executed using ANSYS Fluent (2018) applying Large Eddy Simulation to solve the Navier-Stokes equations with sub-grid-scale model Smagorinski-Lilly and Dynamic stress. The transient analysis is executed with time step 1×10^{-5} s and the convergence criteria 10^{-6} for all monitored variables. A steady solution was used as an initial condition for all simulations. The transient solution was executed for at least 0.5 s.

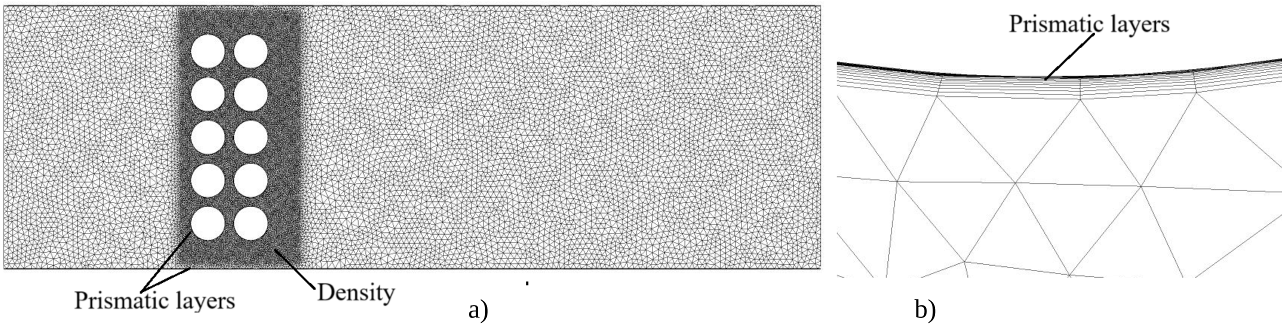
The solution methods were SIMPLE for pressure-velocity coupling. The discretization applied was Least Square Cell Based for gradient, a second order for pressure, and bounded central differencing for momentum, the transient formulation used is bounded second-order implicit. The velocity in the domain is analyzed in lines between cylinders 1 and 10, presented in Figure 1 b).

The mesh is generated using tetrahedral volumes with a region of additional refinement around the cylinders. The face of the cylinders presented prismatic layers. The mesh applied for one-row analysis presented 5,740,445 volumes and the meh used for two rows of cylinders presented 4,815,384 volumes. Details of the mesh with two rows can be found in Figure 2 a). The prismatic layers were used in all wall boundary conditions with fifteen layers in the cylinders as can be observed in Figure 2b). The adopted y+ and time steps are presented in Table 1.



a) b)

Figure 1. a) Numerical domain with boundary conditions and b) top view with monitored lines



a) b)

Figure 2. a) Mesh to view and b) prismatic layers on the cylinders.

2.1 Mesh Quality Criteria

To evaluate the numerical result, two approaches can be chosen, according to Oberkampf and Trucano (2008) one of which is verification and the second is validation. In the verification, it is determined that the model implemented reflects the recommended practices. Thus, verification is not directly linked to the physical results of the analysis. Validation covers physical phenomena and mathematics in comparison. The use of validation and verification comparatives is applied in the present study, using an experimental bench with equivalent characteristics in the validation and a method suggested in the literature for verification.

In most of the works found in the literature, validation is performed by monitoring the variable of interest in numerical and experimental results. The use of a comparative of turbulent kinetic energy solved and modeled is suggested by Celik et al. (2005). The relationship of turbulent kinetic energy-resolved and modeled, 80 - 20, is widespread and for this reason, several authors apply it, such as Afgan et al. (2011) which performed a flow on tubes positioned side by side. When using commercial programs, it is not possible, in some cases, to directly obtain the amount of modeled turbulent kinetic energy, only the one resolved.

Meyer et al. (2008) presented some relations using sub-grid parameter activity and can indicate LES quality. One of the relations was presented by Celik et al. (2005) where the index called LESIQv is defined, which is a dimensionless number between zero and one, that relates the turbulent viscosity to the laminar viscosity. The constants are calibrated in such a way that the index behaves similarly to the ratio of resolved to total turbulent kinetic energy. An index quality greater than 0.8 is considered good LES and higher than 0.95 is considered DNS. The index 0.75 to 0.85 can be considered adequate for most engineering applications that typically occur at high Reynolds numbers; the proposed index is an indicator of good resolution, but not necessarily a good or accurate model.

The mesh quality was analyzed by applying the Kolmogorov microscales estimation for length and time and used to quantify the sub-grid filter and the time step. The evaluation of the dynamic sub-mesh coefficient and y^+ were also monitored. The length scale and time scale are obtained relating the kinematic viscosity and the turbulence dissipation rate as defined by Tennekes and Lumley (1972).

The tested cases LESIQv, length, and time microscale for each simulation are presented in Table 1, including the y^+, Kolmogorov length scale (η), Kolmogorov time scale (τ), filter length in the mesh, and time step.

Table 1. Quantitative comparison for LES application around the cylinders.

Case	LESIQv	Length Scale Kolmogorov [m]	Time Scale Kolmogorov [s]	Mean y^+ y^+ Range	Filter length [m]	Time-Step [s]
Single Row	0.88	$2.75\text{x}10^{-4}$	$4.23\ \text{x}10^{-3}$	1.9 0.1 - 5	$5\ \text{x}10^{-4}$	$1\text{x}10^{-5}$
Two Rows	0.88	$1.41\text{x}10^{-4}$	$1.11\ \text{x}10^{-3}$	0.3 0.05 – 0.7	$7.5\ \text{x}10^{-4}$	$1\text{x}10^{-5}$

In Figure 3, the analysis of the results obtained in the present simulations was compared with the pressure coefficients based on the gap velocity for one row of cylinders. The use of the gap velocity is an approach to counteract the increase in blockage ratio observed with the increase in the number of cylinders. The present data show some agreement for Tube 2, Tube 3, and Tube 4, although they present pressure coefficients closer to the single cylinder than with the small space ratios. The results show that they are within the range of pressure coefficients expected for the tested condition. Due to the intrinsically non-uniform flow behind a row of cylinders, the mean pressure and forces on identical tubes are expected to be different (Zdravkovich, 2002).

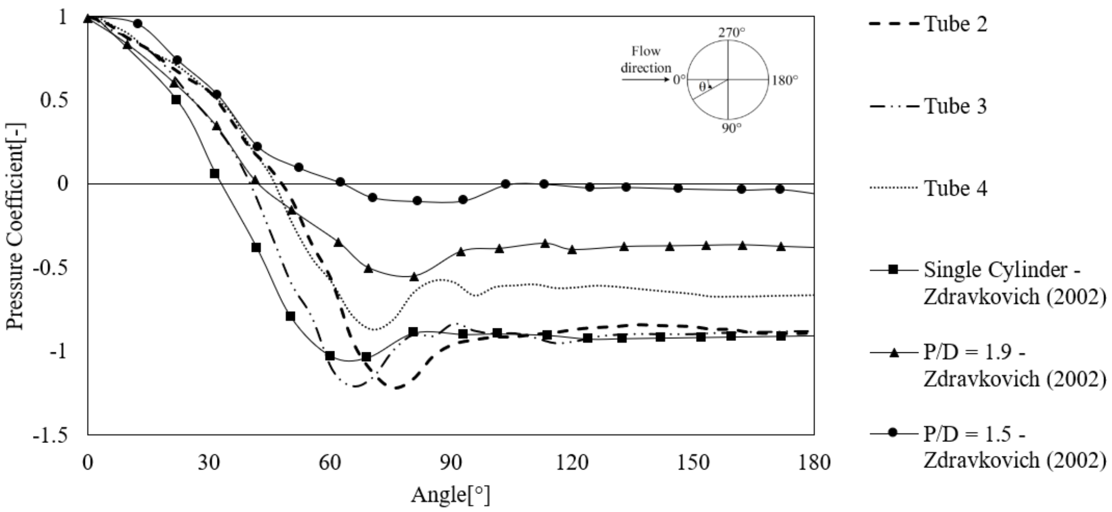


Figure 3. Pressure coefficient based on the gap velocity.

3. RESULTS AND DISCUSSIONS

3.1 Single Row

The analysis for a single row is presented in Figure 4, the characteristics are similar in the planes for most of the cylinders a change in the wake from wide to narrow is observed behind Tube 1. The asymmetric characteristics of a row present many similarities with the studied cases of two cylinders side-by-side, with not-so-common changes in the asymmetric configuration, as described by de Paula et al. (2012). The structures observed in inflow visualizations show qualitative semblance with the results in Figure 4. The changes along the height are plotted for the same time step showing that the wake characteristics change as behind the third cylinder, that the size of the wake and inclination of the gap flow change along the height.

To show these changes in the velocity inside the tube bank, the non-dimensional velocity along lines in the gaps is presented in Figure 5. The results show an equivalent response up to the row of cylinders and after that, the magnitudes of velocity oscillate, in the gap the velocities present equivalent magnitudes but after that, Line 3 and Line 4 maintain higher magnitudes due to the position of the gap flow that is straight, while for Line 1 and Line 2, the wake behind Tube 4 increases the angle and a region of low velocity inside the wake is observed. An analysis of the changes in the wake region velocity was presented by Cheng and Moretti (1988) with a monitored region after the cylinders showing the gap velocities and the wake velocities and the non-uniformity velocity in a single row was reported. The authors measured velocity profiles indicating that at p/d = 1.3, a complex jet instability occurs in which the jets join into groups of more than two jets. The configuration switches from one set of joining to another from time to time. Flow visualizations in the literature support the observation of two pairings leading to the joining of four jets when p/d < 1.5.

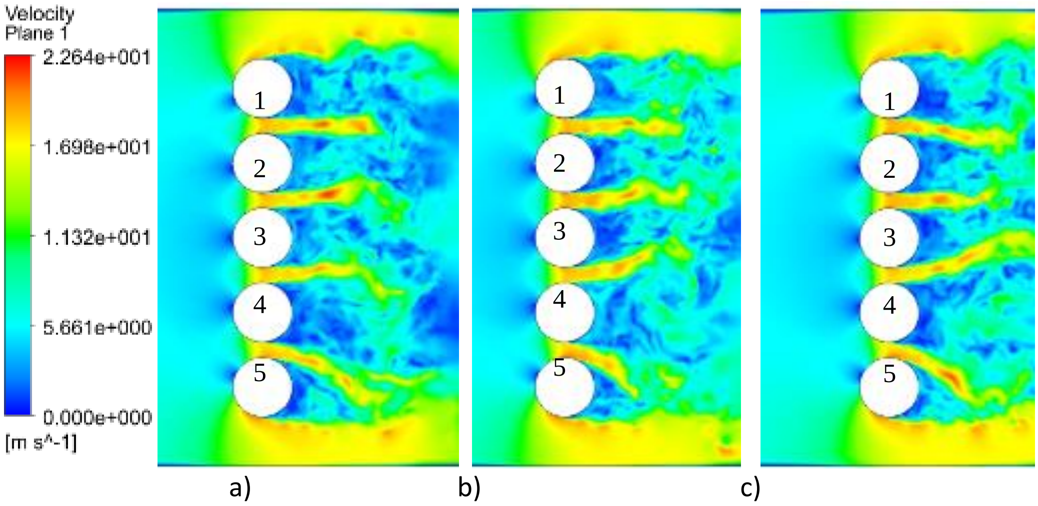


Figure 4. Velocity planes for one row in a) h = 0.002m, b) h = 0.025 m, and c) h=0.04m.

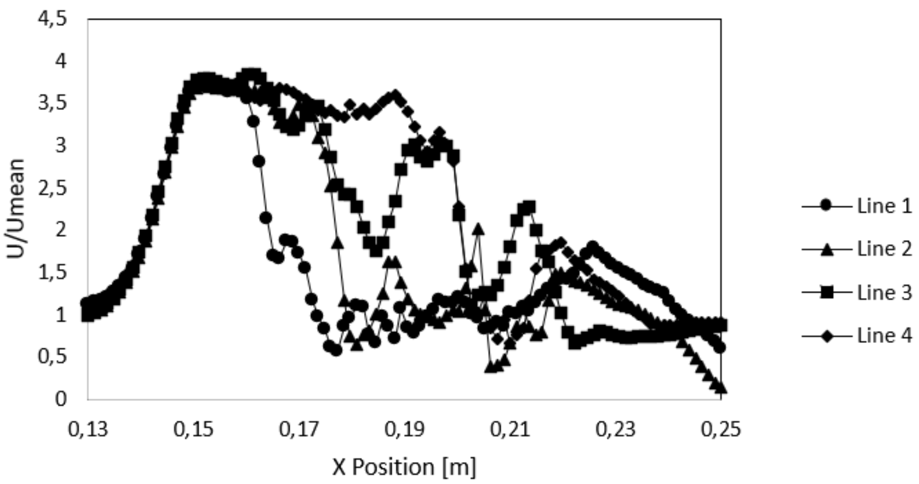


Figure 5. Non-dimensional velocity along lines in a) h = 0.002m, b) h = 0.025 m, and c) h=0.04m.

The biased jets induce a component of the aerodynamic force in the transverse direction with a high influence of the flow velocity and the wake configuration is the force distribution in the cylinders. The analysis in the present case is executed for all the cylinders as can be observed in Table 2 applying the gap velocity to calculate the coefficients. The drag coefficient is lower for Tube 1 and Tube 5 due to the reduction in the velocity over the cylinders on one of the sides, related to the larger gap between the cylinders and the wall. Tube 2 and Tube 3 show a narrow wake at the time of simulation presenting the higher drag coefficient. Tube 4 shows a wide wake and presents a lower drag coefficient with no influence on the extremities. The results agree in tendency with Zdravkovich (2002) who presents results for p/d = 1.2 and p/d = 1.3. The lift coefficient shows lower values in the central tubes due to the asymmetric velocity in the gaps.

Table 2. Drag and Lift Coefficient for all the cylinders in single-row configuration.

Position	Drag Coefficient	Lift Coefficient
Tube 1	0.91	0.43
Tube 2	1.20	0.07
Tube 3	1.21	0.01
Tube 4	1.04	0.00
Tube 5	1.00	0.37
p/d = 1.2(1) - Zdravkovich(2002)	1.13	0.18
p/d = 1.2(2) - Zdravkovich(2002)	1.02	0.16
p/d = 1.3 - Zdravkovich(2002)	0.84	0.01

3.2 Two Rows

The numerical results for fixed tubes with two rows are presented with velocity planes in Figure 6 with a change in height for the same time step. The wake characteristics after the cylinders show expressive changes along the height, behind Tube 8 a narrow wake is observed in Figure 6 a) and the wake is wide in Figures 6 b) and 6 c), this change happens in less than 50 mm in the height of the cylinder. Between the rows, the change in the pattern of the flow is also observed, but there is not a clear interaction between the lines of cylinders inside the tube bank.

The monitored region of gap flow is presented in Figure 7 using the non-dimensional information. In this case, the monitored lines present equivalent velocity up to the first cylinder, between the first and second rows oscillations in velocity are observed. An increase is observed around the second row, but not with the same velocity level as the first row. The asymmetry observed behind the last row and inside the tube bank was also described by Ishigai and Nishikawa (1975) which showed the asymmetry on the wakes behind the single row with a large wake and narrow wake for $p/d < 2.5$. The authors emphasize that the vortex formation region occurs only behind the tubes with narrow wake. For two rows it was observed that for in-line arrangement the vortex formation happens just in the downstream row when the space ratio is lower than 1.5.

The changes in the velocity gap and pattern of wake are reflected in the force over the cylinders, the force over the cylinders is presented in Table 3. The extremity cylinders in the first row show lower drag coefficients, due to the asymmetric flow velocity in the gaps, but this response is not visible in the second row, due to the already disturbed velocity field that arrives on the second row, this is also the reason for the lower drag coefficients in the second row. On the other hand, the already disturbed velocity and the wake formation result in an increase in the lift force over the second row and are also reflected in the first row.

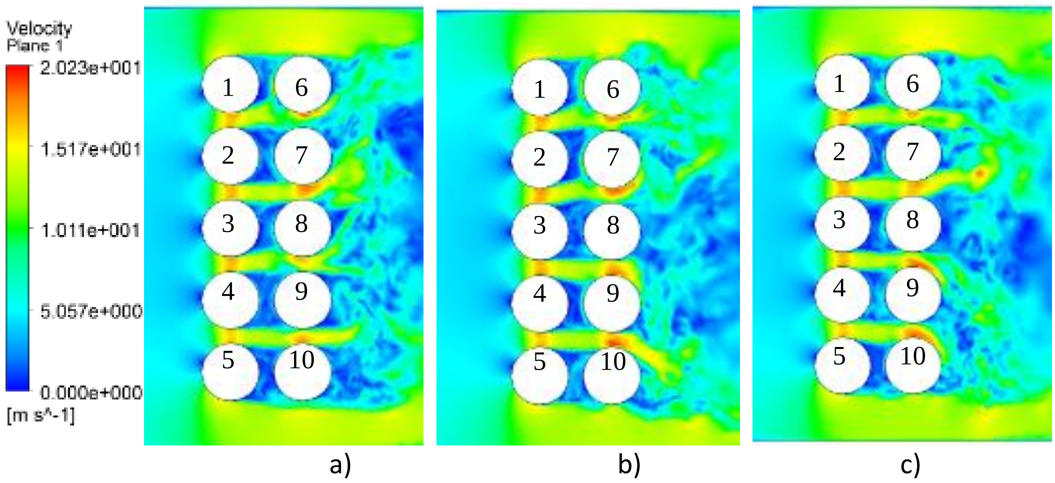


Figure 6. Velocity planes for two rows in a) h = 0.002m, b) h = 0.025 m, and c) h=0.04m.

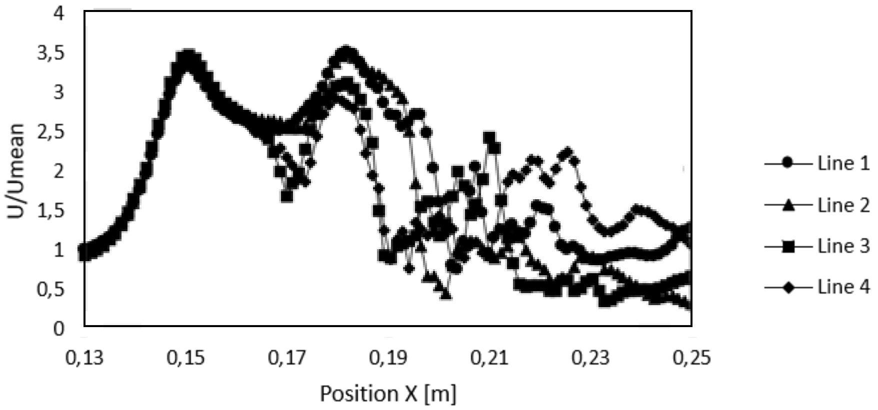


Figure 7. Non-dimensional velocity along lines for two rows in h = 0.025 m.

Table 3. Drag and Lift Coefficient for all the cylinders in two rows configuration.

	Drag Coefficient	Lift Coefficient
Tube 1	0.7	0.24
Tube 2	1.03	0.01
Tube 3	1.06	0.06
Tube 4	1.09	0.10
Tube 5	0.76	0.06
Tube 6	0.45	0.28
Tube 7	0.57	0.33
Tube 8	0.32	0.00
Tube 9	0.67	0.36
Tube 10	0.50	0.16

4. CONCLUSIONS

In this study, we conducted a numerical analysis of flow patterns around one and two rows of stationary cylinders using a large eddy simulation technique. The primary objective was to gain insights into how the spacing between cylinders affects the velocity fields and the resulting forces influencing flow-induced vibrations.

The velocity field data revealed an expected wake asymmetry downstream of the last row of cylinders, this asymmetry was also observed within the shear layer between the two rows of cylinders. This relationship had a notable impact on the flow patterns around the second row of cylinders, leading to an uneven distribution of velocity between the rows and causing fluctuations in velocity within these intervals.

The non-uniform distribution of velocity and pressure exerted a significant influence on the forces acting upon the cylinders. Notably, changes in drag forces were linked to wake patterns and the positioning of the cylinders. The second row of cylinders exhibited higher average lift coefficients, which, in turn, influenced the behavior of the first row of cylinders. This underscores the importance of comprehending the interplay between shear layers and velocity fields within groups of cylinders, particularly in the context of tube banks.

Our findings suggest that an increase in vibration amplitudes occurs when any of the cylinders in the second row are free to vibrate. Nevertheless, it is imperative to emphasize that additional analyses, which consider freedom to vibrate and the presence of additional cylinders, are warranted to provide a more comprehensive understanding of this complex phenomenon.

5. ACKNOWLEDGEMENTS

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