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Effect of Plane Boundary Layer on Air Flow Around Two Circular Cylinders in Tandem Arrangement

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***Abstract* - A two-dimensional numerical simulation was carried out using Ansys-fluent for air flow around two circular cylinders placed in tandem arrangement near a plane wall at a constant Reynolds number (Re≈7000) and for horizontal distance ratios (L/D = 1.2, 1.5, 2,3), and for gap ratios (G/D=0.2,0.5,1,2), and the thickness of the boundary layer was relative to the location of the first cylinder (δ/D = 0.95), and the turbulence model (κ-ω SST) was chosen to simulate the flow near the surface of the two cylinders, the diameter of cylinder=0.01m.**

The results showed that there is no shedding of vortices at gap ratios (G/D=0.2) and for all distance ratios (L/D), and vortices shedding from the first cylinder at gap ratios (G/D=0.5,1,2) and for distance ratios. (L/D=2,3), and the second cylinder's drag coefficient has a negative value for the distance ratios (L/D=1.2,1.5) due to the second cylinder being in the low-pressure region of the first cylinder and at vortex shedding from second cylinder only the lift coefficient of second cylinder greater than first cylinder and when vortex shedding from both cylinders the lift coefficient of first cylinder greater than second cylinder.

Nomenclature

L	distance between centers of two cylinders (m)
D	diameter of cylinder (m)
G	distance between surface of cylinder and plane wall (m)
δ	Boundary layer thickness (m)
Re	Reynolds number
C_D	Drag Coefficient
C_L	Lift Coefficient
μ	dynamic viscosity $(\frac{kg}{m.s})$
F_D	Drag force
F_L	Lift force
u	horizontal velocity (m/s)
v	vertical velocity (m/s)
U_∞	free stream velocity (m/s)
ρ	density of air (kg/m^3)
X, Y	cartesian coordinates
p	pressure on surface of cylinder (N/m^2)
A	surface area of cylinder (m^2)

I. INTRODUCTION

The cylinder is one of the widely used geometric shapes in many engineering applications, as the study of flow around the cylinder opens the door to studying more complex shapes, there are many application for flow around cylinder as pipelines, power transmission lines, cables, cooling systems and heat exchangers, and there are many studies in this field where accomplished Baracu, T. & Grigoras, S. [1] (2011) A theoretical study to describe the flow around a circular cylinder to make a comparison between the analytical results using the (ANYSIS Fluent & COMSOL) programs and the previous theoretical and practical results in (2020) HA Son, et al. [2] also completed a theoretical study using (Fluent 19.2 Ansys) drag force on a two-dimensional cylinder immersed in accelerated flowing water and investigated numerically based on the (finite-volume method) where they used the turbulence model (κ- ω SST) due to its high accuracy in treating the viscous region near the cylinder wall, the researchers compared the obtained results with the results of previous research to confirm the validity of the method used in the numerical analysis. Also, study completed (2009) M.C. Ong, et al. [3] A numerical two-dimensional study of the mechanism of flow around a marine tube placed near the seabed and at a high Reynolds number (Re=3.6 x 10^6). The researchers concluded that the suppression or formation of eddy shedding is affected by the three shear layers, where two layers come from the top. And the bottom of the cylinder is a layer that comes from the effect of the sea floor. The researchers noted that the vortex shedding arises when the gap between the cylinder and the sea floor is greater than the critical gap (G/D = 0.1) and the vortex shedding becomes more pronounced as the gap increases, to move the cylinder away from the influence of the sea floor.at (2018) M. Grioni, et al. [4]investigated Numerical two- and three-dimensional study of the flow around a circular cylinder near a flat contiguous layer and at Reynolds numbers (1.89 x10^4, 2.77 x 10^5 Re=8.6 x 10^4) and at two different thicknesses of the contiguous layer /D = 0.1 (1.1) □ (and at gap ratios 0.2, 0.3, 0.4, 0.8, 1.5) G/D = (to show the effect of changing each of the gap, Reynolds number, adjacent layer thickness, and Strouhal number on the coefficients of braking, lift and flow conductance in the wake-up area, The researcher (2013) HX Hu, et al. [5] completed a three-dimensional numerical study of supercritical flow around two identical cylinders in tandem arrangement and at Reynolds numbers (4.2×10^5,5.5×10^5,$7x10^5$ Re=$2.8x10^5$) Where the turbulence model (κ-ω SST) was chosen to obtain the specifications of the flow, the vorticity separation frequencies of the two cylinders and the hydrodynamic forces around the two cylinders, and at the spacing ratios between the two cylinders (L/D = 1.5, 2.5), the results showed that the shedding of the vortices occurs behind each of the cylinders. Front and rear cylinders at a spacing ratio (L/D=2.5).

The researcher (2015) Wang, YT[6] also completed a numerical study of two cylinders of different diameters placed in tandem arrangement, and the two-dimensional (Navier-Stokes) equations were solved by the Finite Element method and for a low Reynolds number (Re=100), based on the fixed diameter of the large rear cylinder, the diameter of the front cylinder relative to the diameter of the rear cylinder ranged (d/D=0.1-1.0), Where the researcher (2017) Li, Z. et al. [7] completed a three-dimensional numerical study of two pipelines placed in tandem near a flat floor and for gap ratios (G/D = 0.1, 0.3, 0.5) and for two inter-space ratios (L/D = 2,5), and at Reynolds number (Re=$1.31x10^4$) to identify the characteristics of the flow around the two cylinders, where the study showed and for the ratios of the interstitial distances (L/D = 2.5) that the value of the braking coefficient decreases (C_D) for the front cylinder as the distance decreases Between the two cylinders and the floor, at a spacing ratio (L/D=2), the brake coefficient of the rear cylinder is a negative value. The researcher (2015) Tang, GQ et al. [8] also performed a numerical simulation of the flow through two circular cylinders close to a wall in tandem arrangement at a low Reynolds number (Re=200), where the two-dimensional (Navier-Stokes equations) were solved using the (finite element method) at relatively low Reynolds number and for different aspect ratios ($2 \geq G/D \geq 0.25$ and $4 \geq L/D \geq 1$), where the effects of (G/D, L/D) ratios on the hydrodynamic force parameters, Strouhal numbers and separation pattern were examined vortex.

II. GOVERNING EQUATIONS AND NUMERICAL METHOD

The two-dimensional Navier-Stoke equations for steady-state incompressible flow have been solved, and the continuity and momentum equations can be written as:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad (1)$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\mu[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}] \qquad (2)$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\mu[\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}] \qquad (3)$$

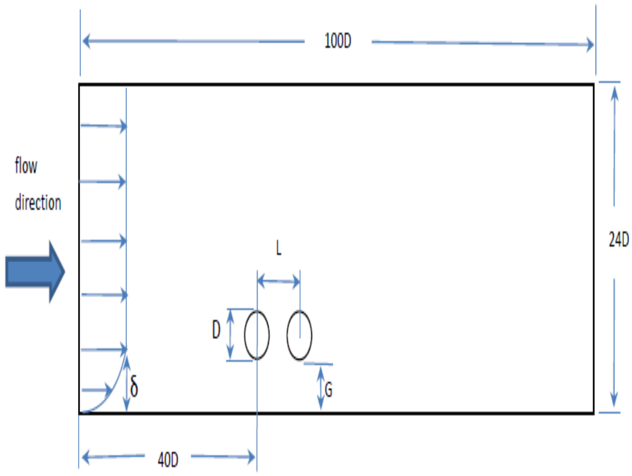

Figure 1: Computational Domain

Where equation (1) refers to the continuity equation and equation (2) and (3) refer to the momentum equations for the X and Y axes, respectively.

Figure (1) shown computational domain for flow around two circular cylinders in tandem arrangement near plane wall with an identical diameter. The computational domain has dimensions (100D) in width and (24D) in high, the first cylinder located at (40D) from front edge of the plane wall to the center of first cylinder, the boundary conditions as follows: (1) at inletvelocity inlet=10 m/s, (2) at outlet pressure outlet=0-gauge pressure (3) there is a no-slip boundary condition on the surface of the cylinder and plane wall (4) wall up symmetry.

The drag and lift coefficients can be defined by the following equations:

$$C_D=\frac{F_D}{0.5\rho U_\infty^2 A} \qquad (4)$$

$$C_L=\frac{F_L}{0.5\rho U_\infty^2 A} \qquad (5)$$

In this study the boundary layer thicknesses (δ) on the plane boundary (ground) can be determined by measuring the velocity profile of the boundary layer at the location of first cylinder, figure (2) shows the velocity profile with boundary layer thickness at first cylinder location($40D$) from edge of plane and ($\frac{\delta}{D}=0.95$).

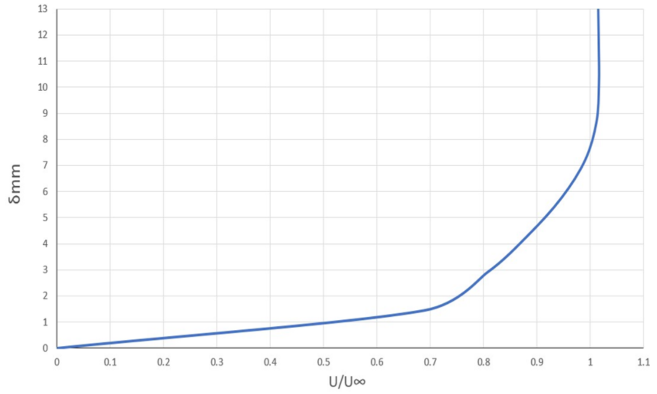

Figure 2: Shows the velocity gradient and the thickness of the boundary layer to the location of the first cylinder

III. VALIDATION CFD

The results were also compared for two cylinders in the free stream with the researcher (Reddy) [9] and others and for the Reynolds number Re=200 and at the ratio of distance (L / D = 1.5) and the results were very close and as shown in the following table (1).

Table 1: Shows a comparison of the results of the present study with (Reddy) at Re=200

	C_{D1}	C_{D2}	C_{L1}	C_{L2}
Reddy	0.0019	-0.0022	-0.1982	1.0910
Present study	-0.0089	-0.0023	-0.21	1.096

IV. RESULTS AND DISCUSSION

1. Vortex shedding

At ratio (G/D=0.2 and L/D=1.2,1.5,2,3) no vortex shedding from first and second cylinders because effect of boundary layer of plane wall,and as shown in velocity contours in the figures (1) (2) (3) (4), at ratio (G/D ≥ 0.5and L/D=1.2,1.5)the shedding of the vortices starts from the second cylinder only as shown in figures (5) (6) (9) (10) (13), at ratio (G/D ≥ 0.5and L/D ≥ 2)the vortex shedding become from first and second cylinder because of the ratio (L/D >LC/D)Critical distance when (L/D=2 and G/D ≥ 0.5)as shown in figures (7) (8) (11) (12) (15) (16), at mode vortex shedding from second cylinder only the vortex narrow and strong but at mode vortex shedding from two cylinder the vortex big and weak.

2. Velocity distribution

At ratio (G/D=0.2 and L/D=1.2,1.5,1,2) wake region behind second cylinder long and narrow, when increase ratio (L/D) the velocity behind second cylinder decrease and the velocity down cylinders its high as the figures (1) (2) (3) (4), at ratio (G/D ≥ 0.5 and L/D=1.2,1.5) wake region behind second cylinder only because vortex shedding from second cylinder only, the velocity up and down cylinders in maximum but at ratio (G/D ≥ 0.5 and L/D ≥ 2) two wake region behind the first and second cylinders big and weak because vortex shedding from both cylinders and the velocity at stagnation points for both cylinders its minimum

3. Drag and Lift Coefficients

From tables (1) (2) (3) (4) showed the drag coefficient of first cylinder greater than drag coefficient second cylinder for all ratio (G/D and L/D) because location the first cylinder in the confrontation of free stream opposite second cylinder it's in wake region to first cylinder,

From table (2) (3) (4) and for ratio (G/D≥0.5and L/D=1.2,1.5) the drag coefficient of the first cylinder has close value because vortex shedding from second cylinder only,

From table (1) (2) (3) (4) and for ratio (L/D=1.2,1.5,2) the drag coefficient of first cylinder increases when (G/D) increase, because far from the effect of boundary layer,

From table (2) (3) (4) and at ratio (L/D=1.2,1.5 and G/D≥0.5) the drag coefficient of second cylinder in negative value, because the second cylinder is in the low-pressure region of the first cylinder,

At ratio (L/D=2, 3 and G/D ≥ 0.5), the drag coefficient of the second cylinder is positive due to the shedding of the vortex from the first cylinder and the second cylinder is far from the effect of the low-pressure region of the first cylinder.

At ratio (G/D ≥ 0.5 and L/D=1.2,1.5) the lift coefficient of second cylinder greater than lift coefficient of first cylinder because vortex shedding from second cylinder and increase in pressure fluctuations behind second cylinder and then increase in lift coefficient and when (G/D) increase the lift coefficient of second cylinder decrease.

At ratio (G/D ≥0.5 and L/D=2,3) the lift coefficient of first cylinder greater than lift coefficient of second cylinder because vortex shedding from first cylinder and increase in pressure fluctuations behind first cylinder and then increase in lift coefficient.

V. CONCLUSIONS

- No vortex shedding at (G/D=0.2) for all ratio of (L/D)
- At ratio (G/D ≥ 0.5 and L/D=1.2,1.5) vortex shedding from second cylinder only
- At ratio (G/D ≥ 0.5 and L/D ≥ 2) the vortex shedding become from first and second cylinder

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- At ratio (G/D=0.2 and L/D=1.2,1.5,1,2) wake region behind second cylinder long and narrow
- at ratio (G/D ≥ 0.5 and L/D=1.2,1.5) wake region behind second cylinder only
- at ratio (G/D ≥ 0.5 and L/D ≥ 2) two wake regions behind the first and second cylinders big and weak
- the drag coefficient of first cylinder greater than drag coefficient second cylinder for all ratio (G/D and L/D)
- for ratio (G/D≥0.5 and L/D=1.2,1.5) the drag coefficient of the first cylinder has close value
- for ratio (L/D= 1.2,1.5,2) the drag coefficient of first cylinder increases when (G/D) increase, because far from the effect of boundary layer,
- at ratio (L/D=1.2,1.5 and G/D≥0.5) the drag coefficient of second cylinder in negative value, because the second cylinder is in the low-pressure region of the first cylinder
- At ratio (L/D=2, 3 and G/D ≥ 0.5), the drag coefficient of the second cylinder is positive
- At ratio (G/D ≥ 0.5 and L/D=1.2,1.5) the lift coefficient of second cylinder greater than lift coefficient of first cylinder
- At ratio (G/D ≥ 0.5 and L/D=2,3) the lift coefficient of first cylinder greater than lift coefficient of second cylinder

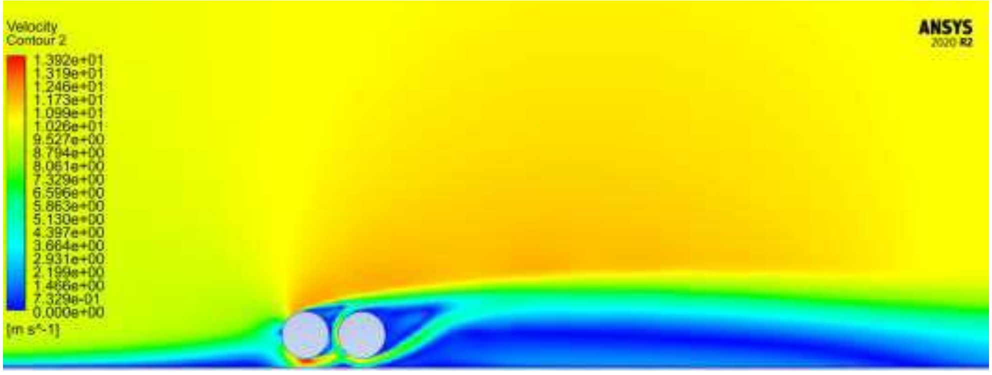

Figure 1: Velocity contour at ratio (G/D=0.2 & L/D=1.2)

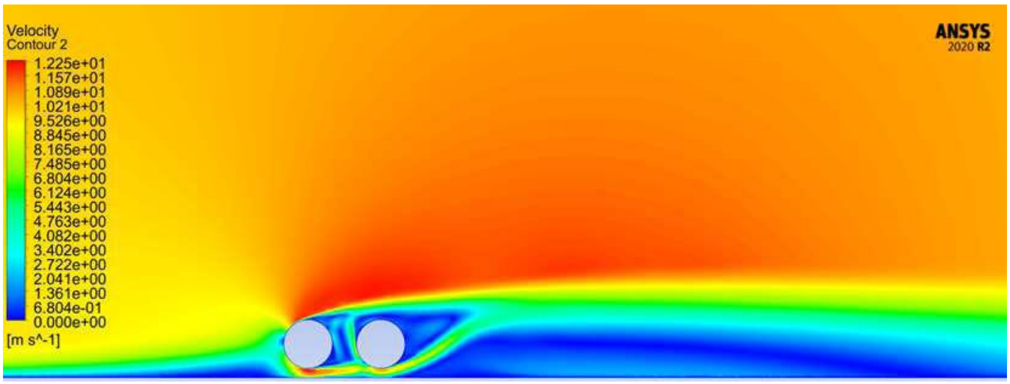

Figure 2: Velocity contour at ratio (G/D=0.2 & L/D=1.5)

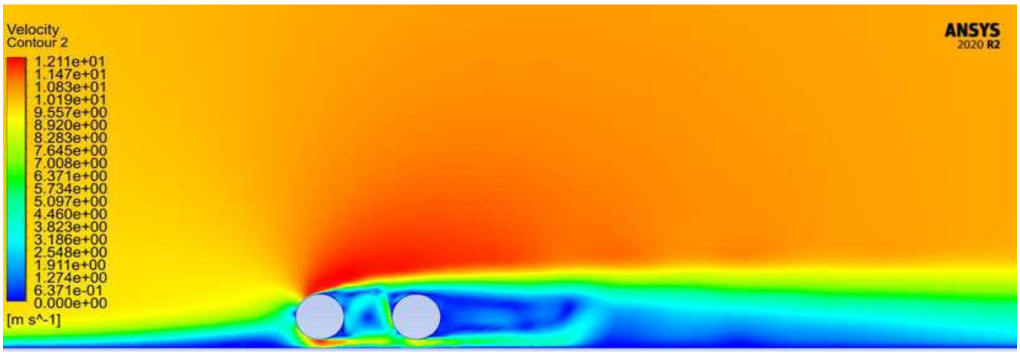

Figure 3: Velocity contour at ratio (G/D=0.2 & L/D=2)

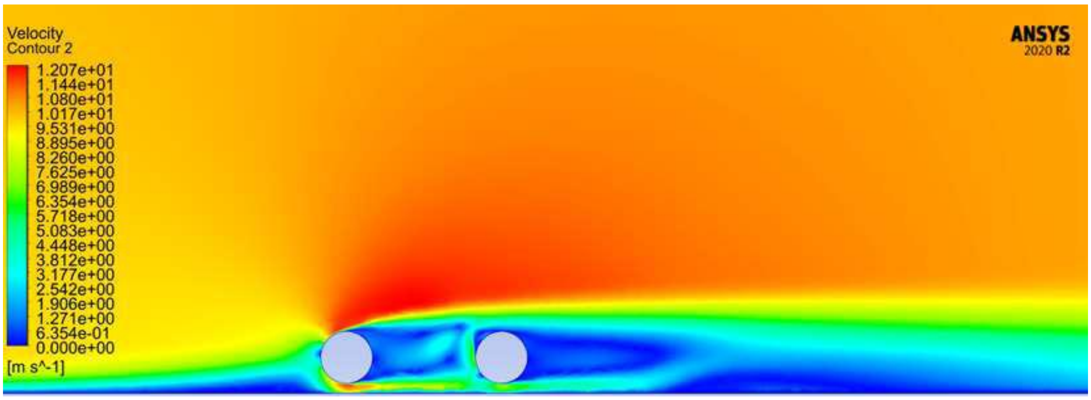

Figure 4: Velocity contour at ratio (G/D=0.2 & L/D=3)

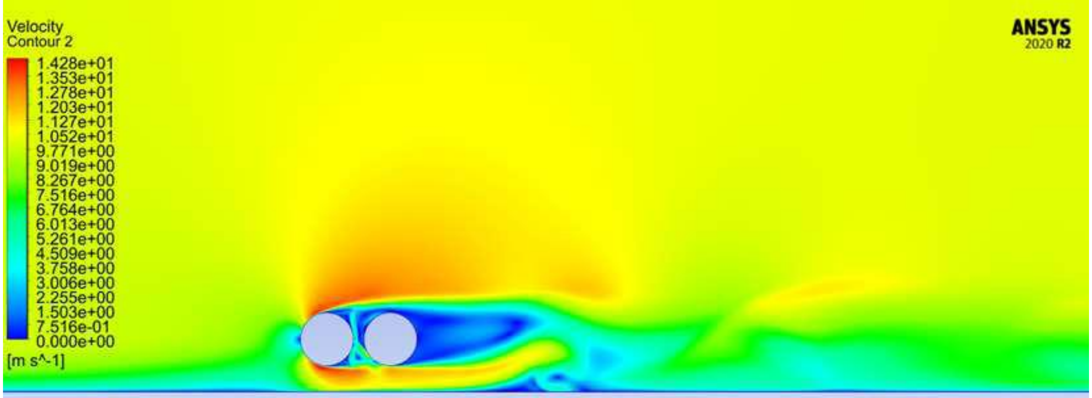

Figure 5: Velocity contour at ratio (G/D=0.5 & L/D=1.2)

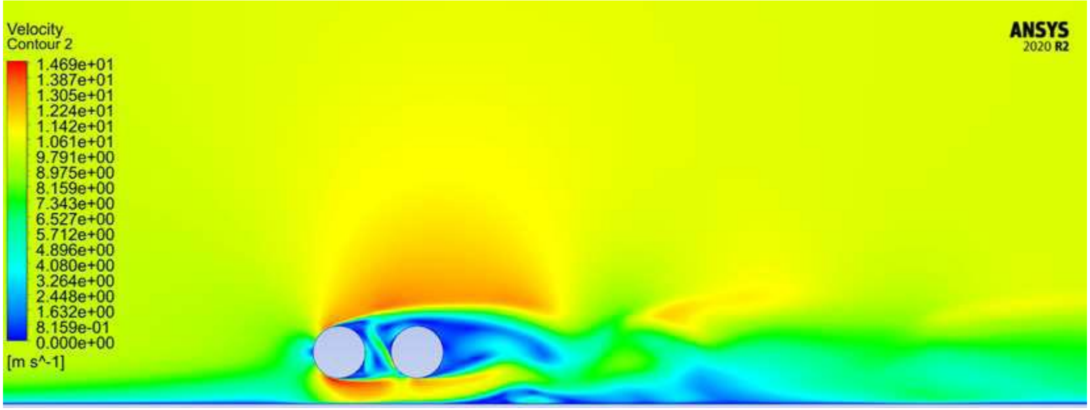

Figure 6: Velocity contour at ratio (G/D=0.5 & L/D=1.5)

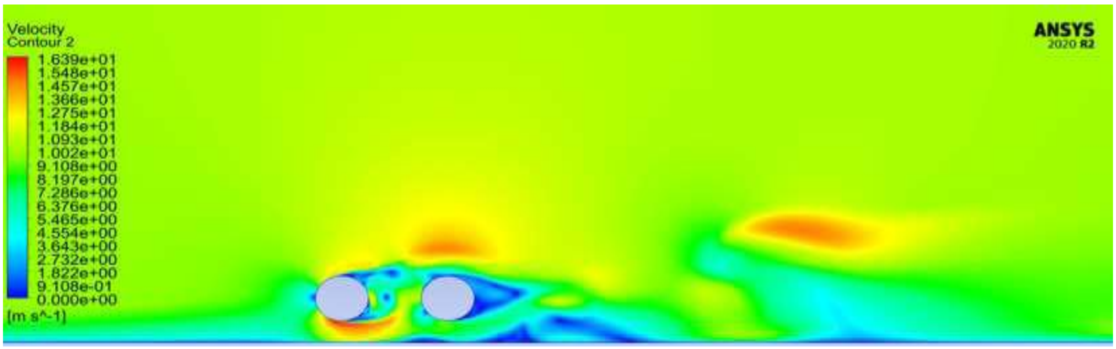

Figure 7: Velocity contour at ratio (G/D=0.5 & L/D=2)

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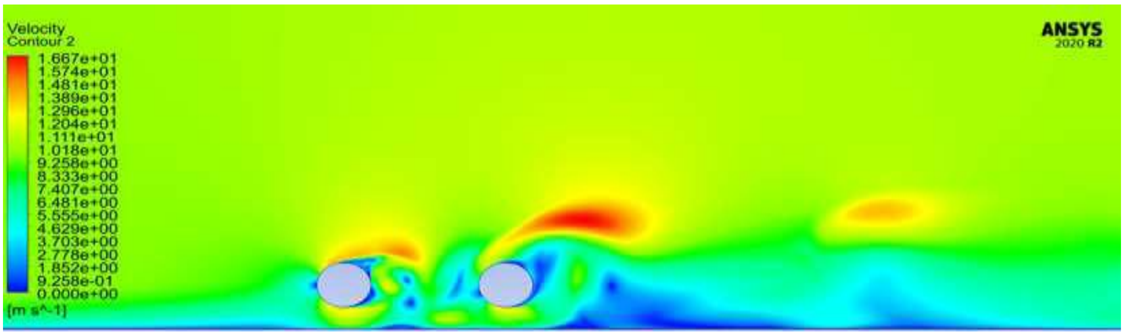

Figure 8: Velocity contour at ratio (G/D=0.5 & L/D=3)

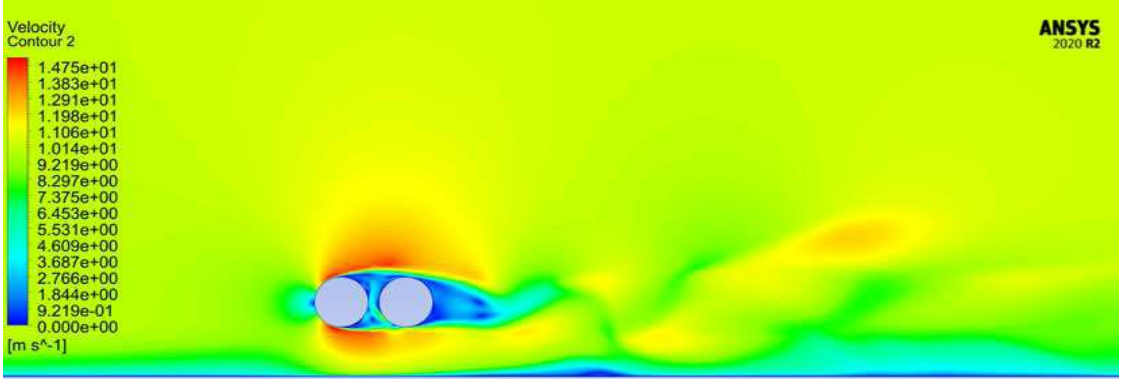

Figure 9: Velocity contour at ratio (G/D=1 & L/D=1.2)

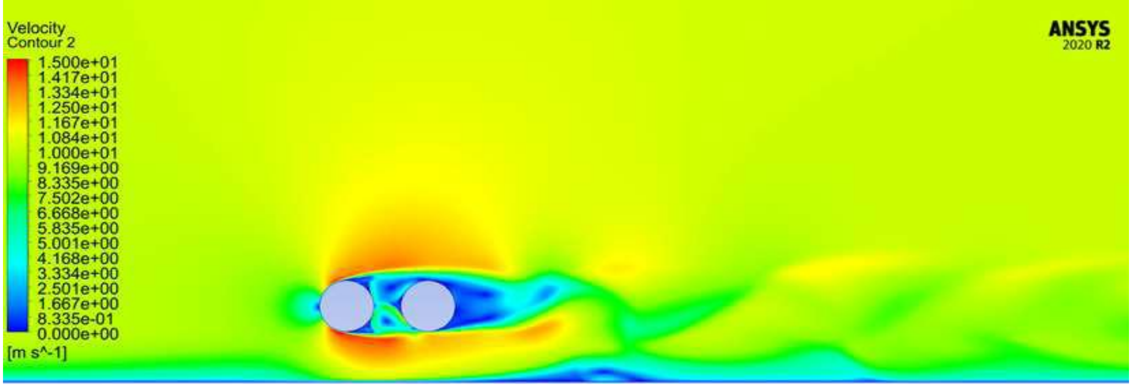

Figure 10: Velocity contour at ratio (G/D=1 & L/D=1.5)

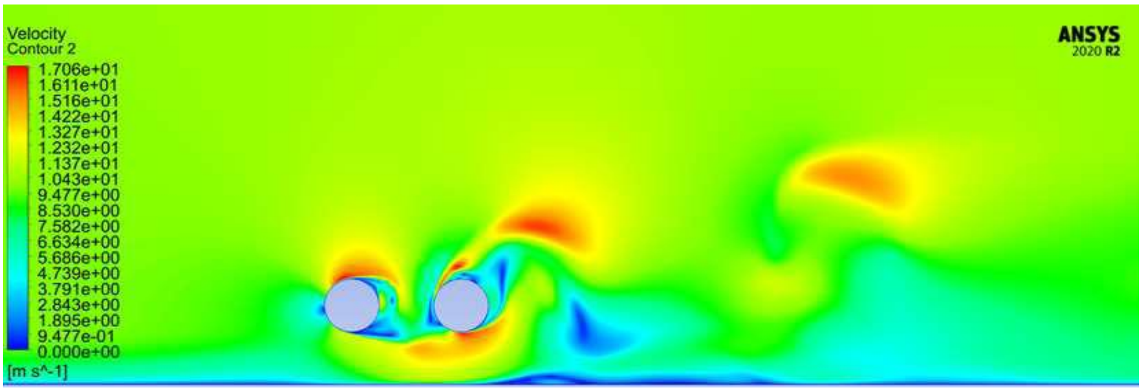

Figure 11: Velocity contour at ratio (G/D=1 & L/D=2)

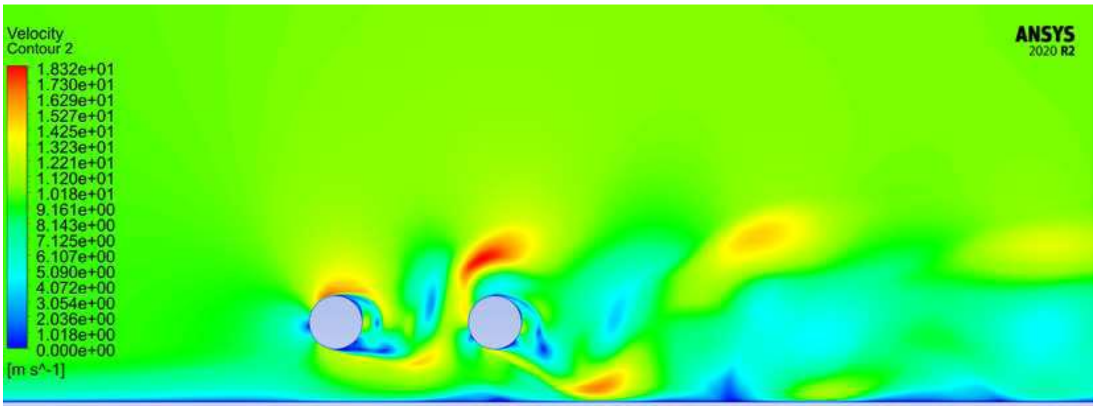

Figure 12: Velocity contour at ratio (G/D=1 & L/D=3)

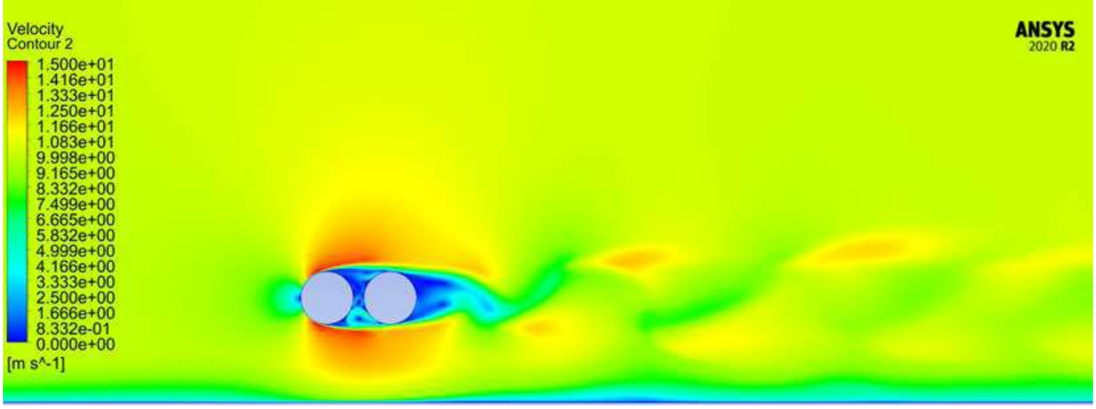

Figure 13: Velocity contour at ratio (G/D=2 & L/D=1.2)

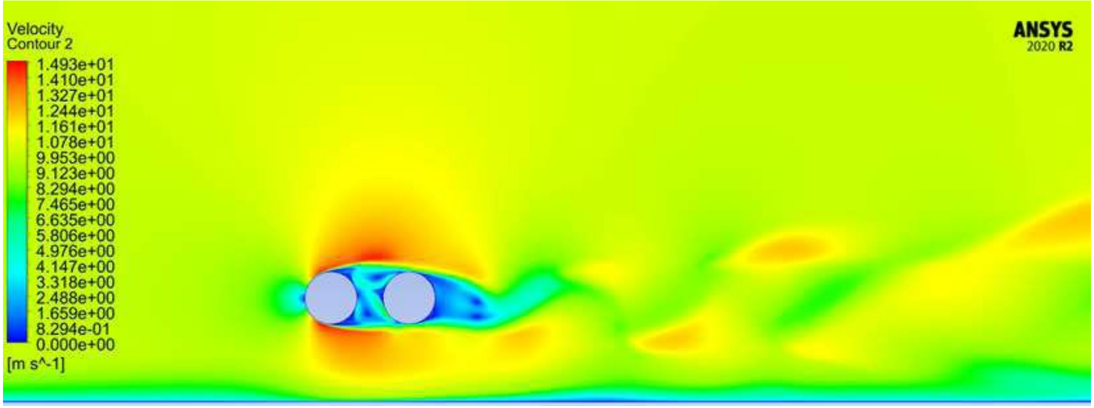

Figure 14: Velocity contour at ratio (G/D=2 & L/D=1.5)

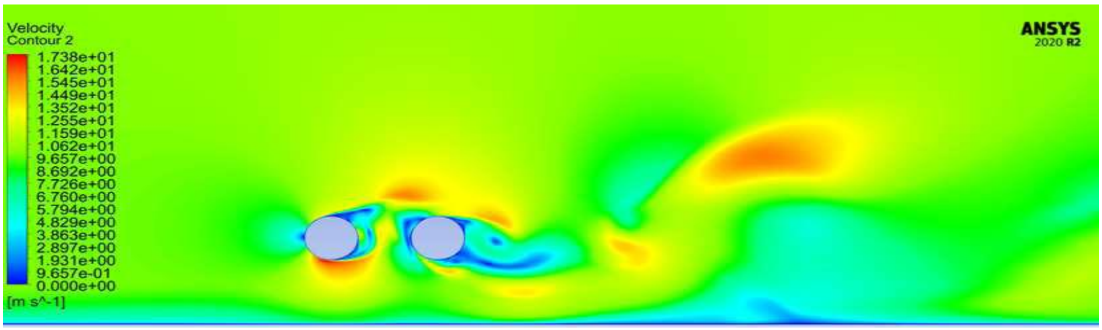

Figure 15: Velocity contour at ratio (G/D=2 & L/D=2)

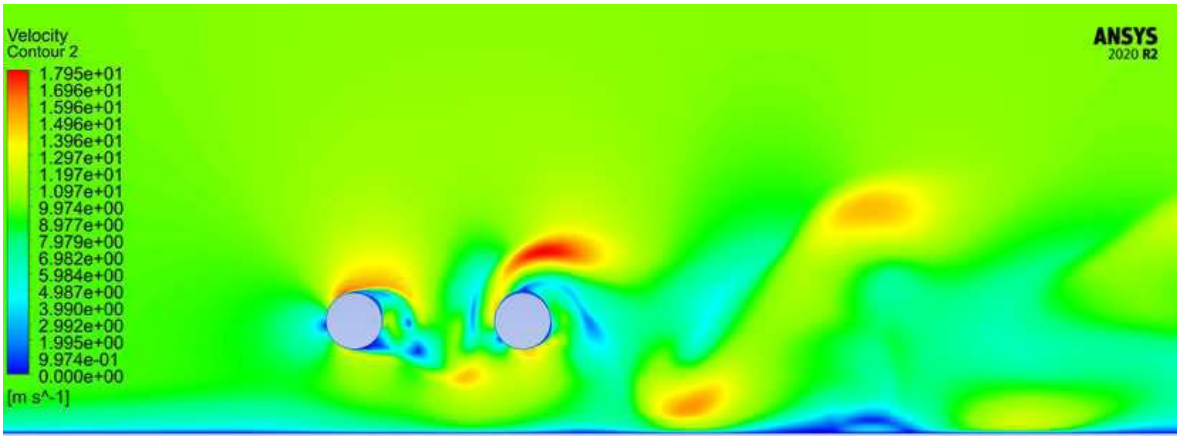

Figure 16: Velocity contour at ratio (G/D=2 & L/D=3)

Table (1) for drag and lift coefficient to first and second cylinder at (G/D=0.2& L/D≥1.2)

G/D=0.2	C_{D1}	C_{D2}	C_{L1}	C_{L2}
L/D=1.2	0.9	-0.07	-0.4	0.087
L/D=1.5	0.86	-0.025	-0.137	0.14
L/D=2	0.78	-0.045	-0.04	0.088
L/D=3	0.75	0.013	-0.07	0.073

Table (2) for drag and lift coefficient to first and second cylinder at (G/D=0.5& L/D≥1.2)

G/D=0.5	C_{D1}	C_{D2}	C_{L1}	C_{L2}
L/D=1.2	1	-0.156	-0.21	0.183
L/D=1.5	1.07	-0.125	-0.187	0.237
L/D=2	1.15	0.15	0.123	0.087
L/D=3	1.13	0.37	0.166	0.022

Table (3) for drag and lift coefficient to first and second cylinder at (G/D=1& L/D ≥1.2)

G/D=1	C_{D1}	C_{D2}	C_{L1}	C_{L2}
L/D=1.2	1.067	-0.325	0.011	0.1325
L/D=1.5	1.06	-0.3	-0.17	0.168
L/D=2	1.3	0.34	0.317	0.238
L/D=3	1.38	0.86	0.117	0.1

Table (4) for drag and lift coefficient to first and second cylinder at (G/D=2& L/D ≥1.2)

G/D=2	C_{D1}	C_{D2}	C_{L1}	C_{L2}
L/D=1.2	1.12	-0.52	0.054	0.085
L/D=1.5	1.074	-0.326	-0.18	0.13
L/D=2	1.36	0.3	0.107	0.07
L/D=3	1.3	0.74	0.078	-0.06

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