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NUMERICAL SIMULATION OF CROSS-FLOW AROUND FOUR CIRCULAR CYLINDERS IN-LINE SQUARE CONFIGURATION NEAR A PLANE WALL

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ABSTRACT

Flow cross around circular cylinders arrangement could be found in many engineering application, such as reaction tower, cooling tower, shell and tube heat exchangers, and tube banks. When flow crosses the bodies, it would form particular flow pattern according to the body's arrangements. Author [19], investigated a four circular cylinders arrangement near wall with spacing ratio (L/D) = 1.5 and gap ratio (G/D) of 0.2. They found that interaction between cylinders and wall caused a difference stagnation point in upstream cylinders and shear layer of upstream cylinders reattach in downstream cylinders. In this research, it would be investigated numerically flow characteristics on four circular cylinders in in-line square configuration near a plane wall. A gap ratio between the surface of lower cylinders and the wall (G/D) would be varied. It is set at G/D= 0.1, 0.3, and 1.0, while spacing ratio between centre of cylinders (L/D) was fixed at 4.0. To analyze flow characteristics around cylinders is used FLUENT 6.3.26 software. Two-dimensional Unsteady Reynolds Averaged Navier Stokes equations and SST k-ω turbulence equations are solved with finite volume method. This simulation was performed at Reynolds number 53000 based on a single circular cylinder diameter. The numerical results show that an increasing of gap ratio cause of stagnation point of the upstream cylinder of lower row move to front of cylinder, while the upstream cylinder of upper row tends to not change. At the gap ratio G/D= 0.1 and G/D= 0.3, shear layer of the upstream cylinder of lower row cover the downstream cylinder of lower row, while a different phenomenon occur in the downstream cylinder of upper row. Shear layer of the upstream cylinder of upper row reattach on surface of the downstream cylinder of upper row.

Keywords: numerical simulation, four circular cylinders, in-line square, plane wall.

INTRODUCTION

Cross-flow around a group of circular cylinders would cause a flow interference phenomenon between the cylinders. It means that an existence of one cylinder could influence the flow around of another cylinder, and this make flow pattern become complex. There were many studies have been conducted on the subject of flow interference phenomenon around circular cylinders arrangement, and one of them was four circular cylinders in equispaced arrangement. The authors [1, 2, 3, and 4] have investigated the effects of flow interference of this array which be placed in centreline to force coefficients on a single cylinder in a group of four equally spaced cylinders, the mean pressure distribution and force coefficients of the cylinders, and the mean and fluctuating force coefficients with varying spacing ratio (L/D) and angles of incidence by experimental. While other authors [5, 6, 7, and 8] have conducted studies the effects of flow interference to flow pattern and velocity distribution around of the cylinders by flow visualization and numerical. Generally, results of these studies showed that in a large spacing ratio (L/D), 3.94 < L/D < 5.96, at a Reynolds number of 2100, the wake formation regions of the downstream cylinders were much shorter than the upstream ones. And the vortex shedding frequency values of the four cylinders were close to that a single cylinder. This was same as [1] result which conducted at a Reynolds number of 30000, that an upstream cylinders behaved as a single isolated cylinder in a two dimensional flow field. The four cylinders in this spacing range could be thought of as a pair of identical tandem arrangements. Meanwhile, from visualization and numerically results in large L/D of four circular cylinders in equispaced arrangement were found the flow pattern which a vorticed shed of the upstream cylinders impinged on the downstream cylinders. All of these results agree with [9] proposed about basic interference flow regimes, that there was no interference flow pattern in large spacing ratio.

In addition, the flow interference phenomenon also could occur when one circular cylinder or two circular cylinders arrangement be placed near wall. A boundary layer of wall would affect a shear layer of cylinders, and could cause interesting phenomenon occur in the upstream-downstream region and flow pattern around of cylinders. Some of authors [10, 11, 12, 13, 15, 16, 17, 18, and 19] had investigated flow interference between a

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ARPN Journal of Engineering and Applied Sciences

single circular cylinder and two circular cylinders in tandem and side-by-side arrangement which be placed near wall. The results of those studies showed that a gap ratio (G/D) influenced force coefficient, but drag coefficient was more affected by boundary layer of wall. It means that when the cylinders submerged in boundary layer of wall then the value of drag coefficient would change drastically. According to the results of flow visualization of [14], if the cylinder was located near a plane wall, the stagnation point would moved to lower-side of cylinder, and its moved far from 0^0 as a position of the cylinder closer to the plane wall. An existence of the plane wall made a recirculation region on its upstream the cylinder, that make a flow on a gap was constricted. The scale of recirculation eddies was larger as a position of the cylinder closer to the plane wall. Author [18] which researched two circular cylinders in tandem arrangement near a plane wall, at $G/D \leq 0.2$, also found there was not stagnation point with $C_p = 1$ in a front-side of upstream cylinder. This was caused of blockage effect of flow on a gap that a large part of fluid flows to upper-side of the cylinder. Beside that, those separation point were aft compare with its position in a centre-line.

There are many studies about effects of flow interference between cylinders arrangement in centreline, and between one or two cylinders arrangement which be placed near wall have been carried out. However, as far as we know, there is no study published in journal concerning with flow interference between four circular cylinders in-line arrangement is located near a plane wall. While, this array is applied as a fundamental element of shell and tube heat exchanger and tube banks. Nevertheless, author [19] has investigated experimental and numerically the four circular cylinders in equispaced arrangement near a plane wall. They still conducted this studies at small spacing ratio (*L/D*)= 1.5 and gap ratio (*G/D*)= 0.2, and result of its showed that there was flow interaction between the upper cylinder and the lower cylinder, also the lower cylinder and the plane wall on the upstream cylinders. While behind the downstream cylinders occurred a bistable flow, which means narrow and wide wake were formed behind the cylinders. This study would focus on four circular cylinders in in-line equispaced configuration with large spacing ratio, *L/D* = 4.0, and varying a gap ratio (G/D) at 0.1, 0.3, and 1.0. Here, L is the centre-to-centre distance between two cylinders; D is the cylinder diameter; and G is gap distance between the lower cylinder surface and the plane wall. A Computational Fluid Dynamics (CFD) technique would be applied in this research using finite-volume method. Even though it has limitation with the issue of numerical uncertainty, but generally it is be able to replicate the overall flow features. Futhermore, a value of instantaneous of full-field pressure and velocity distribution which is found from its analysis be able to understand the physics and the associated effects of such flow patterns. That simulation, respectively, would be reported here at Reynolds number of 5.3 x 10^4 (based on diameter cylinder *D* and the free stream velocity U_∞).

Governing Equations and Numerical Scheme

The governing equations are the continuity equation and the two dimensional (2-D) incompressible unsteady Navier-Stokes equations, which could be written as follows:

a. Continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

b. Momentum equations:

x-momentum:

$$\frac{\partial u}{\partial t} + \frac{\partial (u^2)}{\partial x} + \frac{\partial (uv)}{\partial y} = -\frac{\partial p}{\partial x} + \frac{1}{\mathrm{Re}}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{2a}$$

y-momentum:

$$\frac{\partial v}{\partial t} + \frac{\partial (uv)}{\partial x} + \frac{\partial (v^2)}{\partial y} = -\frac{\partial p}{\partial y} + \frac{1}{\mathrm{Re}}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \tag{2b}$$

where the velocity components *u* and *v* are in the x- and y-directions respectively, *p* is ratio of pressure and density, $\mathrm{Re} = U_\infty D/\upsilon$ is the Reynolds number, U_∞ is the free stream velocity, D is the cylinder diameter, υ is the fluid kinematic viscosity, and *t* is the non dimensional time. The arrangement and computational domain for the cylinders and the wall configuration are shown in Figure-1, where (x and y) denote the coordinates along the stream direction. The coordinate origin O (0, 0) is located at the wall which perpendicular with the centre of upstream cylinders.

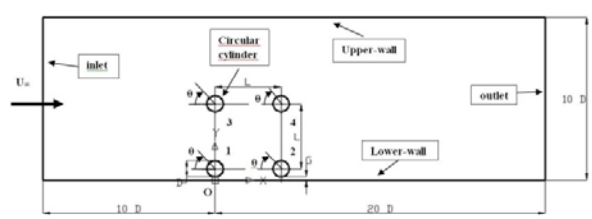

Figure-1. Arrangement and computational domain for four circular cylinders near wall.

METHODS

A phase for running the numerical model could be detailed as follows: First, creating geometry set up of four circular cylinders and wall in two dimensional use Gambit 2.4.6 software as computational domain. According to author [20], that computational domain with

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16D upstream, 14D downstream (minimum), and 10D on either side of the cylinders, in this case the cylinders were located in centre-line, would provide better compromise between accuracy and computational costs for the flow around the cylinders. In this research, it is chosen the computational domain with 10D upstream, 20D downstream, and 10D on side of the cylinders. All these distances are measured from the coordinate origin. Second, with the same software is generated mesh and it is chosen structured quadrilateral-map mesh. Finally, these data are transferred to FLUENT software, and be runned using the 2-D U-RANS numerical simulation, with k-ω SST as turbulence viscous model, is the technique which be employed to visualize the gap effect on the flow interaction between the wake behind the upper and lower cylinders and the flat plate boundary layer. As a boundary conditions are defined a uniform and constant mainstream velocity at the inlet of the computational domain, no slip boundary condition on all cylinder surfaces and lower-wall, constant standard pressure at the inlet-side and outflow at the outlet-side. The initial condition is assumed to be a uniform incoming flow. It used a commercial software, FLUENT 6.3.26, and run based on a second order finite volume discretization and the SIMPLE pressure correction technique. The unsteady computation is terminated after the solution reaches periodic stability.

Validity Checking

In order to validate the accuracy of the above scheme, a group of 2D simulation of the flow around single circular cylinder was carried out, and this result would be compared with the result published in the literature. Table-1 gives the details of grid independence test carried out on single circular cylinder at Re= 53000 with six mesh refinements, and value of y^+ and the mean back pressure coefficient (C_{pb}) as a determining parameters. A selection the value of y^+ as one of determining parameter is based on a reason that need for analysis. According with FLUENT guidelines, working on near-wall mesh use the log law, which is valid for equilibrium boundary layers and fully developed flows, provides upper and lower bounds on the acceptable distance between the cell and centroid and the wall for wall-adjacent cells. The distance is usually measured in the wall unit, y^+. As much as possible, the mesh should be made either coarse or fine enough to prevent the wall-adjacent cells from being placed in the buffer layer, y^+= 5~30. While, selection C_{pb} as another determining parameter same like the other authors. Based on the variation of the value of y^+ and C_{pb}, grid D has been chosen as model of mesh for computational scheme.

Table-1. Grid independence test carried out for flow past a circular cylinder at Re= 53000.

Na-me	Num-ber of nodes	Num-ber of faces	Va-lue of y^+	C_{pb}	C_{pb}
Grid A	132157	263451	22.2	-0.639	Merrick and Bitsuam-lak (experiment) -0.984
Grid B	143600	286300	22.2	-0.636	
Grid C	197020	392980	20.2	-0.755	
Grid D	255740	510140	5.4	-1.019	
Grid E	319100	636800	14.4	-0.881	
Grid F	347900	694400	14.4	-0.914	

RESULTS AND DISCUSSIONS

Pressure Distribution

Figure-2 shows the distributions of pressure coefficient (Cp) on the upstream cylinders for various the gap ratios (G/D), and it is also completed with the experimental result as comparing. Figure-2a shows that the stagnation point on cylinder-1, the cylinder which be located near wall, is around θ= 355^0 for G/D= 0.1 and it shifts to become θ= 357^0 for G/D= 1.0. This change is caused of the blockage effect, due to the very small gap between the cylinder and the wall. Flow would past with high acceleration in small gap, and begin to deccelarate when the gap increases. This phenomenon could be identified with a change of position of minimum pressure at the lower-side of cylinder-1. Further, when G/D increase, it could be seen the separation point of the lower-side of cylinder-1 move to front-side, while the separation point of the upper-side of cylinder-1 move to back-side. Meanwhile, from the figure-2b the stagnation point on cylinder-3 tends to remain for various of gap ratios. The value of stagnation point on cylinder-1 relatively same with cylinder-3 indicate that there is no flow interference between flow around the cylinder-1 and cylinder-3, and it is agree with Zdravkovich, that there is no interference at large spacing ratio (L/D). A minimum pressure on cylinder-1 is bigger than cylinder-3, it indicates that there is interaction between cylinder-1 and wall. Both figures also shows pressure coefficient which is found from experimental result, and generally they have an enough

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agreement. A difference in the value of pressure coefficient, especially in cylinder-1, could be happen cause location of this cylinder near wall. It is required accurate to set position of the cylinder near wall, that an error in measurement can be reduce.

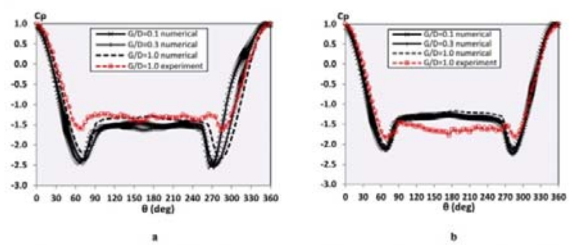

Figure-2. Comparison of pressure distribution between numerical and experiment around of upstream cylinder: (a) cylinder-1, (b) cylinder-3.

Figure-3 shows the distributions of pressure coefficient of the downstream cylinders, cylinder-2 and cylinder-4 for various the gap ratios. From figure-3a, it could be seen that for a small gap ratio the cylinder-2 have a negative value of pressure coefficient and its increase when gap ratio increasing. It means that at small gap cylinder-2 is covered by shear layer upstream cylinders, in this case is cylinder-1. But in large gap ratio makes shear layer of cylinder-1 reattach on the surface of cylinder-2. While for cylinder-4, for all of various gap ratios shear layer from upstream cylinder, cylinder-3 reattach on surface of cylinder-4, as seen on figure-3b. Both figures also shows pressure coefficient obtained by experimental, and its generally have an enough agreement. A differences value of pressure coefficient and in reattachement phenomena occur, especially in cylinder-2, could be happen cause location of this cylinder near wall. It is required accurate to set position of the cylinder near wall, that an error in measurement can be reduce.

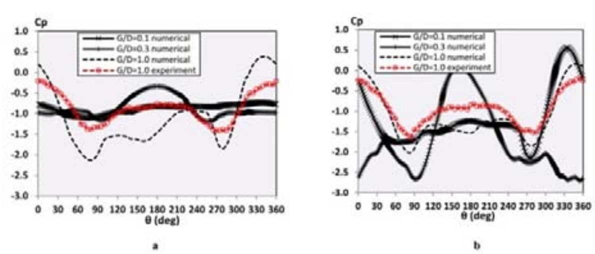

Figure-3. Comparison of pressure distribution between numerical and experiment around of downstream cylinder: (a) cylinder-2, (b) cylinder-4

Figure-4 show the distributions of pressure coefficient on the wall for various gap ratio in range $-8 < x/D < 10$. It can be seen that for all various of gap ratio, the existence of cylinder-1 and cylinder-2 cause a blockage effect on the gap between the bottom of the cylinder and the wall, and it is characterized by a positive pressure distribution. The two minimum pressures values are observed on the downstream of each cylinders. As the flow moves downstream, the negative pressure recover to static. The pressure from which the surface pressure starts to recover the static pressure value is varying, and agree with value of the gap ratio which increase of gap ratio make the position of recover more back. Those figure also show the comparison of pressure distribution between the experiment and numerical results. As indicated in figure, both of pressure distribution on plane wall have a good agreement.

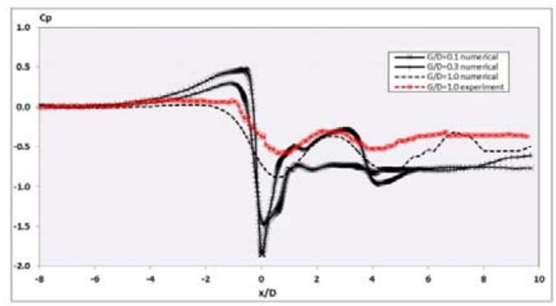

Figure-4. Comparison of pressure distribution between numerical and experiment along the plane wall as function of the gap-to-diameter ratio.

Flow Patterns Around the Array

Figure-5 shows the vorticity contours and pathlines vector of four circular cylinders in equispaced configuration near wall for various gap ratio. From this pictures can be seen flow patterns around the cylinders, such as the shear layers of the upstream cylinder shield on the downstream cylinder, the shear layers of the upstream cylinder reattach on contour surface of the downstream cylinder, vorticed shed from the upstream cylinder impinge on the downstream cylinder, or combination of various flow pattern. To explain effects of the wall, this flow pattern would be compared with the flow patterns if the cylinders arrangement is located in centre-line. From Figure-5a can be seen that shear layers the upstream cylinders impinge on the downstream cylinders, and each of cylinders form the vorticed shed. At gap ratio G/D= 0.1, Figure-5b, shows that outer shear layers of cylinder-3 shield on upper-side cylinder-4, while inner shear layers reattach on lower-side cylinder-4. Whereas, inner shear layers of cylinder-1 form vorticed shed and impinge on upper-side of cylinder-2, while outer shear layers cylinder-1curl up to cylinder-2 be caused of blockage effect from wall. At gap ratio G/D= 0.3, Figure-5c, the flow pattern of cylinder-3 shows a same phenomena which occur at G/D= 0.1. A difference with the first ratio is a position of reattachement of inner shear layers move to downside of cylinder-4. Whereas, inner shear layers of cylinder-1 form vorticed shed and impinge on upper-side of cylinder-2, while outer shear layers cylinder-1reattach on down-side cylinder-2. This is caused the blockage effect of wall begin to decrease. At gap ratio G/D= 1.0, Figure-5d, the flow pattern of the upper cylinders, in this case cylinder-3 and cylinder-4, same like the lower cylinders, cylinder-1 and cylinder-2. So that in this gap ratio, the wall have no affect to flow around the lower cylinders. At this ratio, shear layers the upstream cylinders impinge on the downstream cylinders.

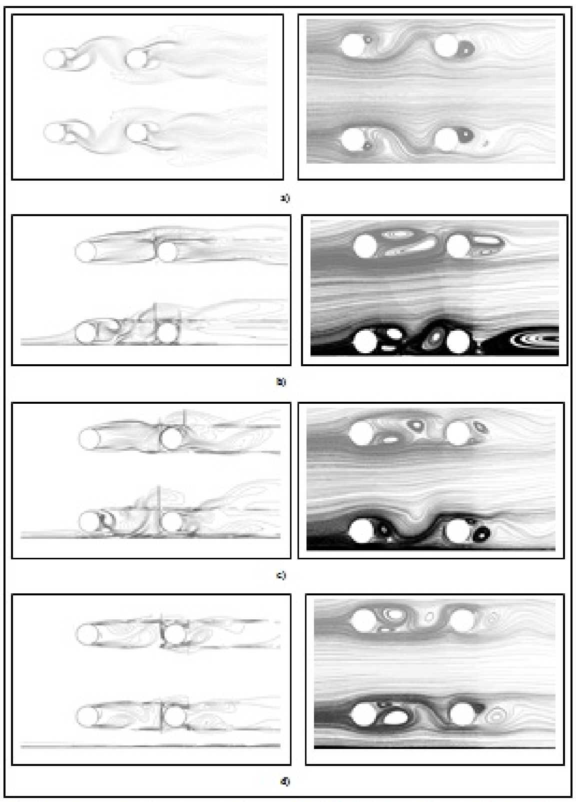

Figure-5. Vorticy contours and pathline vector around four circular cylinders in equispaced arrangement for 2-D simulation at Re=53000: a) centre-line; b) G/D= 0.1; c) G/D= 0.3; d) G/D= 1.0.

CONCLUSIONS

The result of this numerical simulation may be summarized as follows:

a) Flow interaction between lower cylinder and plane wall produce a difference stagnation point on its, and it moves to front-side when the gap ratio (G/D) increase,

b) Flow interaction between lower cylinder and plane wall also produce a difference reattachement point on downstream cylinder, and increasing gap ratio (G/D) make a transformation of flow pattern type which is reattachment phenomena to become impinge phenomena,

c) Flow interaction between cylinder-1 and cylinder-2, and plane wall produce a pressure recovery in wall, and its values depends on values of gap ratio,

d) On large spacing ratio (L/D), there is no interference flow between the upstream cylinders.

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