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Flow Separation Across Three Square Cylinders Arranged in Serial and Parallel Tandem Configuration

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Abstract – *Experiments have been carried out in a wind tunnel by measuring the distribution of fluid flow complemented with flow visualization. Measurements of the flow pressure distribution around the test object have been conducted with the help of taping connected to the manometer. Test objects have consisted of 3 square cylinders made of acrylic material with a thickness of 2 mm with identical lengths of their sides in 50mm hydraulic diameter. The three cylinders are configured in serial and parallel. Each configuration has been given 2 types of distance arrangement, assigned as model I and model II. Model I has varied ratio of the distance between cylinder 1 and cylinder 2 to the diameter of cylinder (M/D) and constant ratio of distance between cylinder 2 and cylinder 3 to cylinders' diameter (N/D) at 1.2. Models II has M/D and N/D altered in a gradually varied distance. Both models were given a treatment of speed of 14 m/s. The experiment has taken place at a single Reynolds number (Re) 43,844. The experimental results have shown that the flow separation in serial and parallel configurations in model I and model II can be dissipated, even on cylinder 2 where the optimum or dominant pressure coefficient value has been positive. From the interactions of the three cylinders, it has been found that the smallest flow separation for serial and parallel configuration of model I is at M/D = 0.6, and is at M/D and N/D = 0.6 for model II.*

Keywords: *Flow Separation, Pressure Coefficient, Reynolds Number, Serial and Parallel Configuration, Three Tandem Square Cylinder*

Nomenclature

A	Sectional area of plates
C_d	Drag coefficient
C_p	Pressure coefficient
Re	Reynolds number
U	Velocity of the air flow before the test object
D	Hydraulic diameter of the square cylinder
υ	Kinematic viscosity of the air
hsm	Static head of manometer
h	Static head at each tapping point
htm	Total head of pitot tube
L/D	Ratio of distance to the diameter of cylinder
M/D	Ratio of the distance between cylinder 1 and cylinder 2 to the diameter of cylinder
N/D	Ratio of distance between cylinder 2 and cylinder 3 to the diameter of cylinder

I. Introduction

When the fluid flows through a square cylinder, there will be loss of energy due to the drag force either by the influence of boundary layers and by flow separation. In the former category, drag is directly generated by viscous effects of tangential stress and is called viscous drag or friction drag. The latter category, although indirectly caused by viscosity, is caused by pressure, and in this case, due to normal forces and is therefore called the pressure drag. This is one of the problems faced by the transportation industry, in improving the efficiency and stability of its system [1]-[30]. In order to reduce this energy loss, an appropriate cross-sectional shape of the object can be designed, so that fluid flow can pass through the object without flow separation [25]-[30] and produce a uniform flow after passing through the object. Researches on rectangular cylinders and tandem bodies have been widely developed. Bruno et al. [1] have analyzed the flow in rectangular cylinders with computer simulations. The analysis results have shown that the flow vortex on the top side is similar to the one at the bottom side and the vortex starts from the separation on the front side of the cylinder. Efforts to reduce the drag force have been carried out by many researchers. The research on tandem three-cylinder square has been inspired by the dense traffic flow of vehicles on the freeway where inevitable vehicle position could occur in parallel, serial or a combination of the two. The studies mainly focus on how to reduce the drag force on cylinders that are single or tandem arranged with various methods. Lee et al. [2] have investigated the effect of mounting a small control rod on the upstream of a cylinder with a focus on the characteristics of drag and flow structure. A maximum reduction in the total drag coefficient of the entire system including the maon cylinder and the control rod at Re=20,000 is around 25%. It has been obtained that the ideal ration of disturbance

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rod diameter as a small control rod was at the ratio d/D=0.233, and the placement of this small control rod at the ratio of distance to the diameter of cylinders or L/D=2.0-2.08. Etminan et al. [3] have investigated the aerodynamic characteristics of flow due to the interaction of two tandem square cylinders on laminar flow or low Reynolds numbers. One of their findings has been that the flow vortex has been influenced by the magnitude of the Reynolds number, while the action of the forces has differed between the up-stream cylinders versus the down-stream cylinder, resulting in differences in the characteristics of the value of the drag coefficients.

Tsutsui et al. [4] investigated the reduction of the drag force on a circular cylinder in the air flow, by installing a disturbance rod mounted on the upstream part of the cylinder. Their study has revealed that the flow pattern will change depending on the diameter of the disturbance, distance and Reynolds number from 1.5×10^4 to 6.2×10^4. The reduction in the total drag, which includes drag from the rod, has differed by 63% compared to that on one cylinder. Daloglu [5] has investigated the relationship of tandem circular cylinders with square cylinders in wind tunnel channels as high as H then it has been alternately placed on the upstream side. The distance between the two cylinders has varied with the ratio of S/d from 0 to 10. The results of this study have shown that the pressure drop characteristics are influenced by the ratio of the diameter of the two cylinders and the ratio of the cylinder distance to the diameter of the circular cylinder (S/d). The optimum result at S/d=1.0-1.5 has been the smallest pressure drop value for all treatment changes in diameter, position and Reynolds number. Lankadasu et al. [6] has investigated the interference effect of two square cylinders mounted in tandem. The treatment given has been to change the ratio of the distance of the two cylinders (L) to the width of the cylinder (d) or change the amount of L/d from 2 to 7 and the dimensionless shear parameter (K) from 0.0 to 4, at a fixed Reynolds number of 100. The results of this study have indicated that the parameters K and L/d are very influential on the magnitude of the Strouhal number (St).

Salam et al. [7] have examined the use of circular cylinders as disturbance cylinders in front of 2 square cylinders arranged in tandem. It has been found out that, in the ratio of the distance of the disturbance cylinder to the diameter of the tandem cylinder (L/D) of 0.43 and the ratio of the diameter of the disturbance cylinder to the diameter of the tandem cylinder (d/D) of 0.14, a decrease in drag coefficient (C_d) of 21,596% has been obtained.

Until recently, research into flow across cylinders has remained an important one in fluid mechanics. In addition, the importance of studies on cylinders as objects emerges because the cylindrical shape projections can be applied to various objects or equipment used in industry, especially in the field of transportation, as well as in larger applications. Munson et al. [8] have suggested that the drag coefficient (C_d) of the 2.10 square cylinders is considerably large when compared to the one of the circular cylinder, which is only of 1.17. Alam et al. [9] have investigated the flow of fluid through a circular cylinder arranged in tandem where in front of the two cylinders a T disturbance plate has been given, with a 5 mm head width and the distances from the cylinder have been varied in order to obtain an optimal position, where the optimal results have been obtained on a variation range in distance to cylinders' diameter T/D of 1.0-1.5.

Islam et al. [10] have examined the characteristics of flow across four square cylinders mounted in a rectangular configuration by numerical simulation methods. The ratios of the distance between the two cylinders in the horizontal and vertical direction (L) with the cylinder diameter (D) are the same, with a change in L/D from 0.5 to 10.0 in the Reynolds number 100. The results of this study have shown that the higher the number cylinder in the in-line configuration is, the smaller the drag coefficient is. It has been found out that i=2.5 has been the optimum distance ratio, obtaining the smallest average C_d of 0.1 and the smallest Strouhal number (St) of 0.128. Hasabe et al. [11] have conducted a study on two square cylinders mounted in tandem with variations in L/D ranging from 2 to 5, where pressure taps have been installed on half of the circumference of each cylinder. The results of this study have shown that the distribution of the average pressure coefficient at each tap position has been different for each change in L/D. The negative average value of pressure coefficient on the top and on the back of each cylinder has indicated flow separation in the investigated section. The smallest value has been obtained at i=4 and at the position of the GH taps or the back of the second cylinder which has been around -1.6. Wang and Zhou [12] have examined the interaction of vortex on two side-by-side circular cylinders. This research has been conducted by changing the ratio of the vertical distance of the two cylinders (T) to the diameter of the cylinder (d) or T/d from 1.13 to 3.0. The results of this study have shown the visualization of the interaction of vortex formed and its movements in a very short time. Mingyue et al. [13] have conducted an experimental study of flow characteristics passing through four square cylinders arranged in a square configuration. The results have consisted of flow patterns, drag and lift, and Strouhal numbers. It has been also proven that the drag and lift forces acting on the cylinder have differed slightly between the various L/D values, and the peak force fluctuated at L/D=4.14. Lift force of the downstream cylinder has reached a maximum around α=15°. Ehsan et al. [14] have investigated the flow through a pair of adjoining square cylinders at Re=100 with the two-dimensional Immersed Boundary Lattice Boltzmann Method (IB-LBM) at various radii. Numerical simulations have been carried out simultaneously, by varying the center distance between the two cylinders (1.5 D-5.0 D) in the transverse direction and by changing the radius of the angle (R) from R/D = 0.0 (square) to 0.5 (circular) with an increase of 0.1. Prasenjit and Ajoy [15] have performed a numerical analysis of two-dimensional steady flow on the triangular extended solid (thorn) attached to square cylinder positioned at front of stagnation point and at rear stagnation point separately at low Reynolds number (Re=40). The study has evaluated the variation of thorn length (*lo*=0.2, 0.4 and 0.6) and slope angle (*H*=50, 100, 150 and 200) and their effect on drag, stress, tensile stress, boundary layer, inertia and viscosity force.

Derakhshandeh and Alam have investigated the instability created by the presence and the location of square dimple and its influence to the structure of wake on a sequence of two cylinders and they have found out that it is significance as the Strouhal number increases. [16]. Calculations of drag coefficient of three types of cylinders (circular, square and rectangular) have been performed by Ostapenko amd Bulanchuk with the help of lattice Boltzmann method for variable speed of sound in lattice form [17] and the influence of Reynolds number and Mach number to the flow pattern and drag cofficient and to the resolution of computational grid have been shown. Investigation of Mach number variation and ground effect in a computational study using a finite-volume RANS on circular cylinder has also found out that there has been complex and significantly varied flow field, respect to ground effect conditions and Mach numbers [18]. Wang et al have studied the effect of an upstream cylinder on wake dynamics of cross flow on two tandem cylinders with different diameters [19]. Pang et al. [20] have performed simulations in quest of dynamic responses of two separately oscillating tandem identical square cylinders. A study regarding the noise aspect of tandem square cylinder has been performed by Dawi and Akkermans, which have found out that two different stable flow states across cylinders which have been a quiet state and a loud state, which have been characterized by the absence of vortex shedding in the upstream cylinders and the presence of separated shear layers intermittent flow in the space between the cylinders, respectively [21]. Aerodynamic characteristics of two tandem square cylinders in horizontal and diagonal arrangement have been investigated by Baoqing et al., who have found out that there have been multiple peaks in the power spectra of diagonal tandem cylinders [22]. Another finding has been that the Strouhal numbers at the same spacing ratio on diagonal tandem cylinders were considerably smaller than the ones of horizontally arranged tandem cylinders. An experimental investigation on the flow-induced vibrations of two tandem circular cylinders has been conducted by Qin et al. [23]. The study has concluded that initial states of cylinder, in term of vibration or stillness, can give effect to the other's vibration. More et al. [24] have investigated flow around parallel square cylinders and the effect of the oscillation of cylinder. The study has found out that spacing had significant influences the flow structure, as well as to the vortex shedding mechanism. Salam et al. [25] have investigated the distribution of the flow pressure across tandem triangles with square cylinders.

This study has analyzed experimentally the flow pressure on Reynolds numbers based on square cylinder diameter for Re=48,708 to Re=152,449. The ratio of the distance between the two cylinders with the diameter of the square cylinder (*L*/*D*) has varied between 0.5, 1.0 and 1.5, while the ratio of the diameter of a triangular cylinder to the diameter of a square cylinder (*d*/*D*) is constant at 0.5. The experimental and the numerical simulation results have shown that the distribution pattern of changes in pressure around the test object and the value of the pressure coefficient (C_p) has decreased with increasing *L*/*D* and has reached the lowest value at *L*/*D*=1.0, at all levels of Reynolds numbers. The results have been due to the *L*/*D* vortex damping flow between the triangular cylinder with a square cylinder and this delays the occurrence of flow separation in the square cylinder. The biggest drag decrease occurred when triangular cylinder were arranged in tandem with a square cylinder at *L*/*D*=1.0 and *d*/*D*=0.5. The research on three-tandem square cylinders has been inspired by the dense traffic flow of vehicles on the freeway where it is inevitable for the vehicles to be on adjacent positions, in parallel, series or the combination of both.

The paper is organized in four sections. Section I is the introduction, covering previous research about the topic. Section II presents methodology of the experiments, containing information of the test objects, design of experiments and measurement techniques.

Section III exposes the results of the experiments, comprising the presentation of results on pressure coefficient (C_p) measurements for all configurations as well as the discussion of the relationship of pressure coefficient (C_p) with the position of measurement points of cylinders in concerns. Some explanations on visualizations of flow on some key configurations are depicted in the last parts of discussion. Conclusions drawn are presented in Section IV, at the end of the paper.

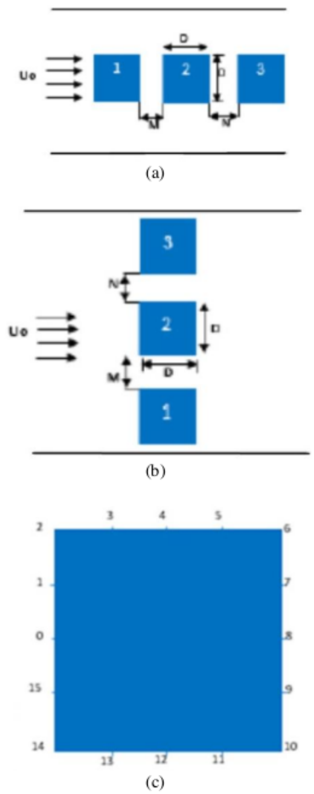
II. Method

Square cylindrical specimens arranged in tandem are three in serial and parallel configurations, as shown in Fig. 1. The treatments have been to change the distance of the three square cylinders arranged in tandem by 7 levels (0, 10, 20, 30, 40, 50 and 60) mm for serial configuration or for parallel configuration, then has been flowed at flow velocity (*U*) of 14 m/s. The treatment distance of the three cylinders is in 2 models. Model I, the ratio of the distance between cylinder 1 and cylinder 2 to cylinder diameter (*M*/*D*) has been varied, while the ratio of distance between cylinder 2 and cylinder 3 to cylinder diameter (*N*/*D*) remains at 1.2. Model II, with the ratio of the distance *M*/*D* and *N*/*D* altered simultaneously with the same distance. The square cylinder specimens have been made in identical width, height and length and the diameter, manufactured from acrylic with a thickness of 2 mm. The diameter of the specimen is 50 mm, adjusted to the size of the wind tunnel in order to obtain better results. The ratio of the cross-sectional area of the specimen to the cross-sectional area of the channel or the wind tunnel test section should not be greater than 1:3. Figs. 1 show the position of three square cylinders arranged in tandem in serial and parallel configurations and the taping position of each cylinder. In order to measure the distribution of static heads around each square cylinder (h), 16 taping positions (Z) have been installed, designated as position 0 to position 15, with the distance of each taping position that has been 12.5 mm. The wind tunnel used in this experiment has been a low speed wind tunnel based on Plint [26], made by Plint & Partners LTD Engineers, where the velocity of air flow through the test section (300 mm×300 mm) has been maximum on 22 m/s.

Cengel et al. [27] have argued that, in order to illustrate the characteristics of fluid flow across an object or square cylinder, the magnitude of the Reynolds number (Re) should be determined, as follows:

$$Re = \frac{UD}{\upsilon} \tag{1}$$

Variables incorporated in equation (1) have been the velocity of the air flow before the test object (U), the hydraulic diameter of the square cylinder (D) and the kinematic viscosity of the air (υ).



Figs. 1. Three square cylinders arranged in tandem in (a) serial and (b) parallel configuration and (c) taping position of each cylinder

Whereas, in order to determine the pressure coefficient (C_p), the following equation (2) has been used:

$$C_p = \frac{hsm - h}{hsm - htm} \tag{2}$$

Several variables in equation (2) have designated the static head of the air flow manometer before crossing the test object (hsm), the static head at each tapping point at the intersection of the test object (h), and the total head of the pitot tube air flow manometer before crossing the test object (htm). The kinematic viscosity value of air, determined based on temperature and pressure conditions in a laboratory room, has been measured using a thermometer and a barometer. Based on the side length of a square cylinder of 50 mm and a constant air flow velocity treatment of 14 m/s or at Reynolds Re=43,844, the experiment has taken place in a laminar flow region or Re$<10^5$ in external flow, i.e. at the Reynolds number calculated based on the diameter square cylinder.

III. Results and Discussion

The experimental results have been in the form of head distribution measurement and analysis of the pressure coefficient around the square cylinder, at the location or position of the taping where the flow separation has occurred. Table I to Table IV show the value of the pressure coefficient on each cylinder for each configuration and model. The values of the pressure coefficient have been compared to the measurement position of the taping in the middle of each side of the square cylinder, for the front side of the cylinder (Z0), the top side of the cylinder (Z4), the back side of the cylinder (Z8) and the bottom side of the cylinder (Z12), at the same Reynolds number of Re=43,844. Table I illustrates the flow separation characteristics of each cylinder for the three square cylinders of the model I serial configuration, i.e. the M/D ratio changes from 0.0 to 1.2 while the N/D ratio is constant at 1.2 in numbers Reynolds are constant at Re = 43,844. From Table I, it is shown that at the taping position Z4, the flow separation on cylinder 1 is damped on cylinder 2 as well as on cylinder 3.

This shows that changes on cylinder 1 position towards cylinder 2 (M) affect and minimize the occurrence of flow separation on cylinder 2. Similarly, in Z8 taping position, flow separation has been damped in both cylinder 2 and cylinder 3.

Table II illustrates the flow separation characteristics of each cylinder for the three square cylinders of the model II serial configuration, i.e. the ratio of M/D and N/D changes from 0 to 1.2 at a constant Reynolds number of Re=43,844. Table II also shows that the pattern of flow separation at the taping position Z4 is the same as the ones shown in Table I, i.e. the flow separation on cylinder 1 is damped on cylinder 2 as well as on cylinder 3.

TABLE I

PRESSURE COEFFICIENT (C_p) OF THREE TANDEM SQUARE CYLINDER MODEL I SERIAL CONFIGURATIONS OR M/D CHANGE FROM 0 TO 1.2 WHILE N/D IS CONSTANT AT 1.2 AT THE MEASUREMENT POSITION OF TAPING Z0, Z4, Z8 & Z12 ON THE CYLINDER 1 (S1), CYLINDER 2 (S2) AND CYLINDER 3 (S3), AT Re = 43,844

M/D	Cylinder 1 (S1)				Cylinder 2 (S2)				Cylinder 3 (S3)			
	Z0	Z4	Z8	Z12	Z0	Z4	Z8	Z12	Z0	Z4	Z8	Z12
0,0	0,6	-2,4	1,0	-2,7	1,1	1,0	0,7	1,0	0,3	0,4	0,1	0,3
0,2	0,7	-2,3	-1,4	-2,7	-1,3	0,7	0,9	0,7	0,0	-0,7	0,1	-0,4
0,4	0,3	-2,4	-1,7	-2,6	-1,7	1,4	0,9	1,0	0,0	-0,3	0,1	-0,4
0,6	0,3	-2,3	-1,7	-2,4	-1,1	0,9	0,9	0,9	0,4	0,9	0,9	0,9
0,8	0,3	-2,3	-1,4	-2,4	-1,3	0,7	0,9	0,9	0,0	0,7	0,1	0,7
1,0	0,0	-2,4	-1,4	-2,4	-1,4	0,7	0,7	0,6	0,1	0,4	0,1	0,3
1,2	0,3	-2,0	-1,4	-2,3	-1,6	0,7	0,9	0,6	-0,1	0,4	0,1	0,6

TABLE II

PRESSURE COEFFICIENT (C_p) OF THREE TANDEM SQUARE CYLINDER MODEL II SERIAL CONFIGURATIONS OR M/D AND N/D CHANGES FROM 0 TO 1.2 AT THE MEASUREMENT POSITION POINTS Z0, Z4, Z8 & Z12 ON CYLINDER 1 (S1), CYLINDER 2 (S2) AND CYLINDER 3 (S3), AT Re = 43,844

M/D	Cylinder 1 (S1)				Cylinder 2 (S2)				Cylinder 3 (S3)			
	Z0	Z4	Z8	Z12	Z0	Z4	Z8	Z12	Z0	Z4	Z8	Z12
0,0	0,3	-1,6	-1,6	-1,3	-1,0	0,8	1,4	0,6	2,3	0,8	0,1	0,0
0,2	0,3	-1,6	-1,8	-1,3	-1,4	0,5	1,5	0,8	2,0	0,8	0,0	0,0
0,4	0,1	-1,6	-1,6	-1,3	-1,4	0,8	1,1	0,8	1,9	1,0	0,0	0,0
0,6	0,4	-2,0	-1,9	-1,6	-1,7	0,4	1,0	0,7	0,1	0,4	1,0	0,7
0,8	0,1	-2,1	-2,1	-1,6	-1,4	0,4	0,7	1,0	1,6	0,6	0,0	0,0
1,0	0,4	-2,0	-2,0	-1,6	-1,3	0,6	0,7	0,9	1,9	0,6	0,1	0,0
1,2	0,4	-2,0	-1,9	-1,6	-1,1	0,6	0,7	0,7	1,7	1,0	0,1	0,0

The table also shows the changes in position of cylinder 1 towards cylinder 2 (M) and the changes in position of cylinder 3 towards cylinder 2 (N), influencing and minimizing the occurrence of flow separation on cylinder 2. Similarly, in the Z8 taping position, the flow separation has been damped on both cylinder 2 and cylinder 3. Table III illustrates the flow separation characteristics of each cylinder for the three square cylinders of the parallel configuration of model I, i.e. the *M/D* ratio changes from 0 to 1.2 while the *N/D* ratio is constant at 1.2 at the Reynolds number constant of Re=43,844.

From Table III, it is found out that at the taping position Z4, the flow separation on cylinder 1 has been damped or not occurring on cylinder 2. However, on cylinder 3, the flow separation has still occurred in smaller form.

This shows that the change cylinder 1 position towards cylinder cylinder 2 (M) has affected and minimized the occurrence of flow separation on cylinder 2. In the Z8 taping position, no flow separation has occurred on cylinder 2, whereas on cylinder 3 the flow separation has still occurred despite its smaller magnitudes than the flow separation occurred on cylinder 1.

Table IV illustrates the characteristics of flow separation in each cylinder for the three square cylinders of the model II parallel configuration, where the ratio of M/D and N/D changes from 0 to 1.2 at a constant Reynolds number of Re = 43,844. From Table IV, it is obtained that, at the taping position Z4 the flow separation on cylinder 1 is damped on cylinder 2 as well as on cylinder 3.

TABLE III

PRESSURE COEFFICIENT (C_p) OF THE THREE TANDEM SQUARE CYLINDER IN MODEL I PARALLEL CONFIGURATION OR *M/D* CHANGES FROM 0 TO 1.2 WHILE *N/D* IS CONSTANT AT 1.2 AT THE MEASUREMENT POSITION POINTS Z0, Z4, Z8 & Z12 ON CYLINDER 1 (S1), CYLINDER 2 (S2) AND CYLINDER 3 (S3), AT Re = 43,844

M/D & N/D	Cylinder 1 (S1)				Cylinder 2 (S2)				Cylinder 3 (S3)			
	Z0	Z4	Z8	Z12	Z0	Z4	Z8	Z12	Z0	Z4	Z8	Z12
0,0	3,3	-3,8	-5,5	-5,8	0,5	0,3	0,3	1,8	3,3	-1,3	-1,5	-1,8
0,2	0,2	-4,8	-3,8	-4,8	0,6	0,6	0,6	0,0	3,4	-0,4	-1,0	-1,4
0,4	-1,5	-4,8	-4,5	-7,3	0,8	0,8	0,8	-0,3	3,3	-0,8	-1,3	-1,5
0,6	-0,3	-4,8	-4,5	-7,0	0,8	0,0	0,8	0,3	3,5	0,0	0,8	0,3
0,8	-2,3	-5,8	-4,8	-7,0	0,8	-0,3	0,8	0,0	4,0	-0,3	-1,0	-1,5
1,0	-2,7	-8,5	-6,0	-9,0	0,0	-0,7	0,7	-0,3	5,0	-1,3	-2,0	-2,3
1,2	-2,5	-7,0	-5,0	-7,3	0,3	-0,3	0,8	-0,3	3,8	-1,0	-1,3	-1,5

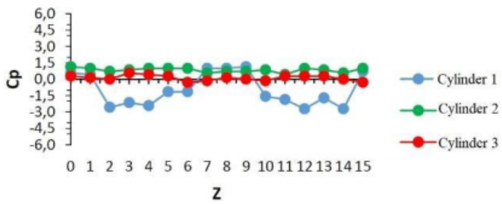
TABLE IV

PRESSURE COEFFICIENT (C_p) OF TANDEM THREE SQUARE CYLINDER IN MODEL II PARALLEL CONFIGURATION OR *M/D* AND *N/D* CHANGES FROM 0 TO 1.2 AT THE MEASUREMENT POSITION POINTS Z0, Z4, Z8 & Z12 ON CYLINDER 1 (S1), CYLINDER 2 (S2) AND CYLINDER 3 (S3), AT Re = 43,844

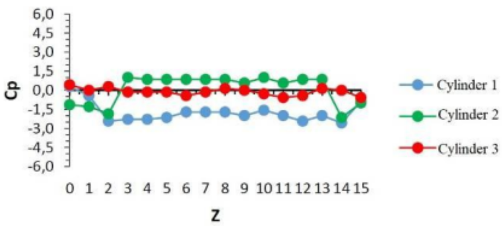
M/D & N/D	Cylinder 1 (S1)				Cylinder 2 (S2)				Cylinder 3 (S3)			
	Z0	Z4	Z8	Z12	Z0	Z4	Z8	Z12	Z0	Z4	Z8	Z12
0,0	0,6	-2,4	1,0	-2,7	1,1	1,0	0,7	1,0	0,3	0,4	0,1	0,3
0,2	0,7	-2,3	-1,4	-2,7	-1,3	0,7	0,9	0,7	0,0	-0,7	0,1	-0,4
0,4	0,3	-2,4	-1,7	-2,6	-1,7	1,4	0,9	1,0	0,0	-0,3	0,1	-0,4
0,6	0,3	-2,3	-1,7	-2,4	-1,1	0,9	0,9	0,9	0,4	0,9	0,9	0,9
0,8	0,3	-2,3	-1,4	-2,4	-1,3	0,7	0,9	0,9	0,0	0,7	0,1	0,7
1,0	0,0	-2,4	-1,4	-2,4	-1,4	0,7	0,7	0,6	0,1	0,4	0,1	0,3
1,2	0,3	-2,0	-1,4	-2,3	-1,6	0,7	0,9	0,6	-0,1	0,4	0,1	0,6

This shows that the changes on cylinder 1 position towards cylinder 2 (M) and the changes on cylinder 3 position towards cylinder 2 (N) affected and minimized the occurrence of flow separation on cylinder 2. In the Z8 taping position, the flow separation has been dissipated.

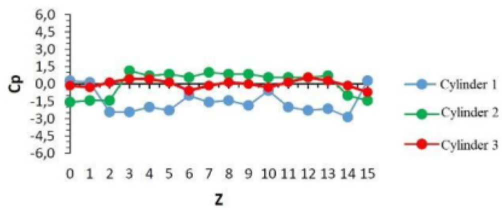
In other words, no flow separation has occurred on cylinder 2 while on cylinder 3 the flow separation, which was smaller than the flow separation on cylinder 1, has still occurred. Tables I to IV show that the interaction of three square cylinders has reduced the flow separation as well as the flow drag. Regarding the flow separation on the cylinder 2, it has been damped due to the changes of cylinder 1 and cylinder 3 distance positions, both in serial and parallel configurations, for either model I or model II. In connection with the above results, it is seen that, for serial and parallel configurations both in model I and in model II, the ratio of the cylinder distance to the cylinder diameter of 0.6 has given the best flow separation values. Figures 2 to 5 show graphs of the relationship between the pressure coefficient with the taping position on cylinder 1, cylinder 2 and cylinder 3, for serial and parallel configurations on model I and model II at 3 levels of changes on cylinder distance ratio, i.e. 0.0; 0.6 and 1.2; while the constant Reynolds number is at Re=43,844. Figs. 2 shows the trends of the pressure coefficient (C_p) in relationship with the position of cylinder 1, 2 and 3 at Re=43,844, for three levels of *M/D* ratio for model I serial configuration; a) *M/D*=0.0, b) *M/D*=0.6 and c) *M/D*=1.2. Fig. 2(a) shows immense flow separation on cylinder 1. No flow separation has occurred on cylinder 2. On cylinder 3, there is also no flow separation but it had a smaller C_p value.



(a) Model I serial configuration, *M*/*D*=0.0 on Re=43,844



(b) Model I serial configuration, *M*/*D*=0.6 on Re=43,844



(c) Model I serial configuration, *M*/*D*=1.2 on Re=43,844

Figs. 2. Relationship of pressure coefficient (C_p) with the position of measurement points of cylinders 1, 2 and 3 at Re=43,844, three tandem square cylinder in model I serial configuration, (a) *M*/*D*=0.0, (b) *M*/*D*=0.6 and (c) *M*/*D*=1.2

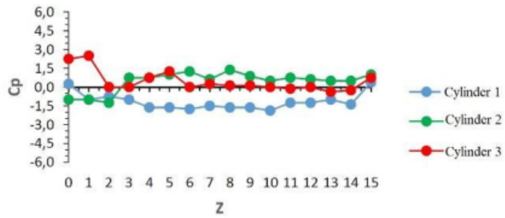
Fig. 2(b) shows considerable flow separation on cylinder 1, while on cylinder 2, the flow separation has been damped starting from taping position Z3 to Z13, whereas on cylinder 3 the flow separation has occurred but in smaller value than the one on cylinder 1.

Fig. 2(c) shows almost similar trends of flow separation, but with some differences, as for cylinder 1 in the Z6 and Z10 positions, a smaller flow separation has occurred compared to the one on other taping positions in.

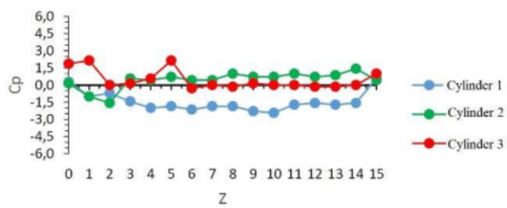
For cylinder 2, the flow separation has been damped from taping position Z3 to Z13. In on cylinder 3, the flow separation has occurred but in smaller form than the one recorded on cylinder 1.

Based on Figs. 2, the characteristics of the three square cylinder for Model I serial configurations have shown that the change in the position of cylinder 1 to cylinder 2, while the positions of cylinder 3 to cylinder 2 fixed at 60 mm, have been able to reduce the flow separation, where the largest attenuation has been obtained at *M*/*D*=0.6.

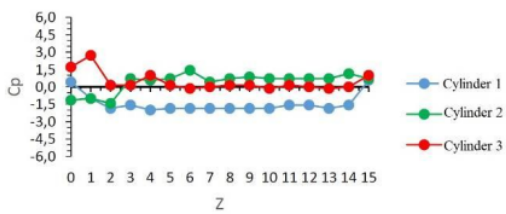
The characteristics of the pressure coefficient (C_p) in relationship with the position of measurements on cylinder 1, 2 and 3 at Re=43,844, for model II serial configurations at three levels of M/D and N/D ratios of 0.0, 0.6, and 1.2, are presented in Figs. 3.



(a) Model II serial configuration, *M*/*D* and *N*/*D*=0.0 on Re=43,844



(b) Model II serial configuration, *M*/*D* and *N*/*D*=0.6 on Re=43,844

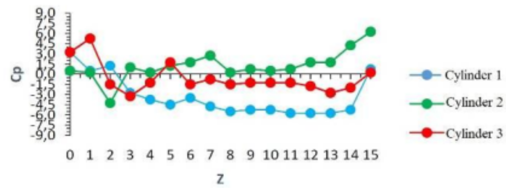


(c) Model II serial configuration, *M*/*D* and *N*/*D*=1.2 on Re=43,844

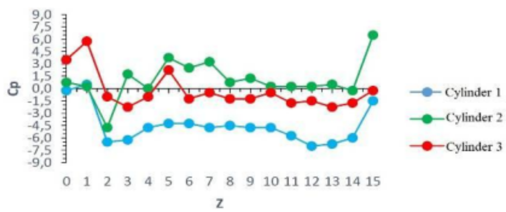
Figs. 3. Relationship of pressure coefficient (C_p) with the position of measurement for cylinders 1, 2 and 3 at Re=43,844, three tandem square cylinder in model II serial configuration, (a) *M*/*D* and *N*/*D*=0.0, (b) *M*/*D* and *N*/*D*=0.6 and *M*/*D* and *N*/*D*=1.2

Fig. 3(a) shows large flow separations on cylinder 1, while on cylinder 2 the flow separation does not even occur. On cylinder 3, where smaller C_p values have been obtained, there has been no flow separation. Fig. 3(b) shows that there is a large flow separation on cylinder 1.

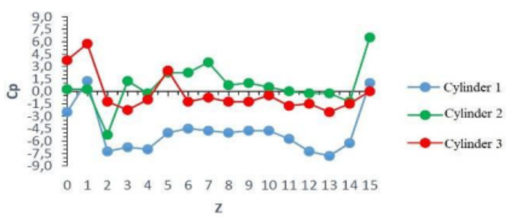
For cylinder 2, the flow separation has not occurred from the taping position Z3 to Z15, whereas on cylinder 3 there is no flow separation for all the positions. Figure 3(c) shows that there is a large flow separation on cylinder 1 except in Z0 and Z15 positions where there is no flow separation. On cylinder 2, the flow separation has not occurred on taping positions Z3 to Z15. No flow separation has been recorded on cylinder 3. Based on Figs. 3, the characteristics of the interaction of three square cylinder in model II serial configuration can be understood, showing that, the changes in position of cylinder 1 to cylinder 2 and the changes in distance of cylinder 3 to cylinder 2 simultaneously at the same distance, can inhibit flow separation, where the largest effect has been obtained at *M*/*D* and *N*/*D*=0.6. Figs. 4 show the characteristics of the pressure coefficient (C_p) in relationship with the position of cylinder 1, 2 and 3 at the position of Re=43,844, arranged in parallel configuration for model I at three levels of *M*/*D* ratios, namely (a) *M*/*D*=0.0, (b) *M*/*D*=0.6 and (c) *M*/*D*=1.2.



(a) Model I parallel configuration, *M/D*=0.0 at Re=43,844

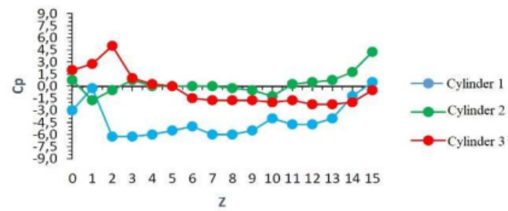


(b) Model I parallel configuration, *M/D*=0.6 at Re=43.844

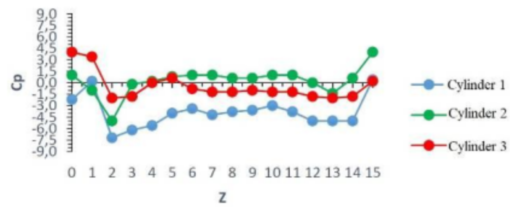


(c) Model I parallel configuration, *M/D*=1,2 at Re=43.844

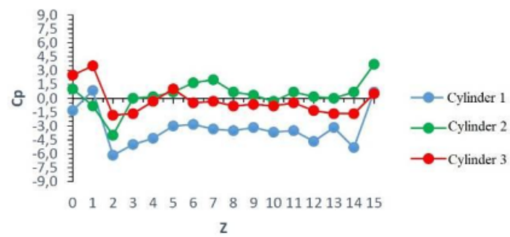
Figs. 4. Relationship of pressure coefficient (Cp) and the position of measurement points of cylinders 1, 2 and 3 at Re=43,844 for three tandem square cylinder in model I parallel configuration (a) *M/D*=0.0, (b) *M/D*=0.6 and (c) *M/D*=1.2



(a) Model II parallel configuration, *M/D* and *N/D*=0.0 at Re=43,844



(b) Model II parallel configuration, *M/D* and *N/D*=0.6 at Re=43,844



(c) Model II parallel configuration, *M/D* and *N/D*=1.2 at Re=43,844

Figs. 5. Relationship of pressure coefficient (C_p) and the position of measurement points of cylinders 1, 2 and 3 at Re=43,844, three tandem square cylinder in parallel configuration model II, (a) *M/D* and *N/D*=0.0, (b) *M/D* and *N/D*=0.6 and *M/D* and *N/D*=1.2

Fig. 4(a) shows that there have been large flow separations on cylinder 1 and cylinder 3. However, on cylinder 2, the flow separation has not occurred in except at Z2.

Fig. 4(b) shows almost the same results. Fig. 4(c) shows that there is a large flow separation on cylinder 1 and cylinder 3 except in the Z6 and Z10 positions where the flow separation is smaller than the ones on the other taping positions on cylinder 1, while on cylinder 2 the flow separation has been damped. In fact, there is no flow separation starting from the taping position Z3 to Z13, whereas on cylinder 3 the flow separation has occurred but the flow separation is smaller than what happened on cylinder 1.

From Figs. 4, the characteristics of the interaction of three square cylinders of the parallel configuration of model I are shown where the change in the position of cylinder 1 to cylinder 2, and the position of cylinder 3 to cylinder 2 fixed at 60 mm, can dampen the flow separation, and the largest damping effect has been obtained at *M/D*=0.6.

Figs. 5 show the characteristics of the pressure coefficient (C_p) relationship with the position of cylinders 1, 2 and 3 at Re=43,844, arranged in on model II parallel configuration at three levels of *M/D* and *N/D* ratios of , namely (a) *M/D* and *N/D*=0.0, (b) *M/D* and *N/D*=0.6 and (c) *M/D* and *N/D*=1.2.

Fig. 5(a) shows that there is a large flow separation on cylinder 1, however on cylinder 2 the dissipated flow separation even from Z3 to Z15 does not occur in flow separation except at Z10, whereas on cylinder 3 the flow separation occurs but the C_p value is smaller from cylinder 1. Fig. 5(b) shows that there is a large flow separation on cylinder 1. However, on cylinder 2, the flow separation has not even occurred from the taping positions Z3 to Z15 except in Z13, whereas on cylinder 3 the flow separation has occurred with Cp value smaller than the one on cylinder 1. Fig. 5(c) shows that there is a large flow separation on cylinder 1 except that in Z1 position there is no flow separation. However, on cylinder 2, the flow separation has not occurred from taping position Z3 up to Z15, while on cylinder 3 there is no flow separation where the value of C_p is smaller than the one on cylinder 1. Based on Figs. 5, the characteristics of the interaction of three square cylinders in a parallel configuration of Model II can be obtained, and it also shows that the changes in the position of cylinder 1 to cylinder 2 and changes in distance of cylinder 3 to cylinder 2 happen simultaneously at the same distance, dampening the occurrence of flow separation. In addition, it shows that the largest and damping effect is obtained at *M/D* and *N/D*=0.6.

Visualization of the flow of the three tandem square cylinder serial configuration model I in Figs. 6 shows the flow characteristics at M/D 0.0 where the flow separation has occurred at the upstream side of cylinder 1 and cylinder 2, creating significantly large vortex above the two cylinders. Furthermore, at *M/D*=0.6 the flow separation has still occurred on cylinder 1 and it has been thinner on cylinder 2 when compared to *M/D*=0.0. This is due to dissipated flow vortex between cylinder 1 and cylinder 2. For *M/D*=1.2 the flow separation became larger again on cylinder 1 and cylinder 2, than the ones occurring at *M/D*=0.6. This is because the flow vortex is less damped between cylinder 1 and cylinder 2, and the flow vortex has generated upward flow causing an earlier flow separation at the upstream side of cylinder 1. Flow separation occurring on cylinder 3 for the three *M/D* values abovementioned has followed the pattern of flow separation occurring on cylinder 2. The visualization of flow of the three tandem square cylinder in model II serial configuration is shown in Figs. 7, depicting the flow characteristics at *M/D* and N/D=0.0 where the flow separation has occurred at the upstream side of cylinder 1, so that the flow vortex above cylinder 2 and cylinder 3 has become large enough. Furthermore, at *M/D* and *N/D*=0.6 flow separation has occurred on cylinder 1, but it has been thinner on cylinder 2 than in *M/D* and *N/D*=0.0. This is due to damped flow vortex between cylinder 1 and cylinder 2 and between cylinder 2 and cylinder 3. For *M/D* and *N/D*=1.2, the flow separation is greater on cylinder 1 and cylinder 2, when compared to the ones at *M/D* and *N/D*=0.6. This is because the flow vortex is less damped between cylinder 1 and cylinder 2, and the flow vortex has generated upward flow causing an earlier flow separation on the upstream side of cylinder 1. Flow separation that occurs on cylinder 3 for the three *M/D* and *N/D* values abovementioned has followed the pattern of flow separation that occurs on cylinder 2. The visualization of the tandem flow of the three square cylinder parallel configuration model I in Figs. 8 shows the flow characteristics at *M/D*=0.0 where the flow separation has occurred at the upstream side of cylinder 1 and cylinder 3, so that the flow vortex next to the two cylinders has become significantly larger. Furthermore, at *M/D*=0.6, the flow separation has occurred on cylinder 1, but it has been thinner on cylinder 2 compared to *M/D*=0.0. This is due to damped flow vortex between cylinder 1 and cylinder 2 and between cylinder 2 and cylinder 3. For *M/D*=1.2, the turning flow separations have been larger on cylinders 1, 2 and 3, than the ones at *M/D*=0.6. This is because the flow vortices have not been damped between cylinder 1 and cylinder 2 and between cylinder 2 and cylinder 3, and the flow vortices pushed the flow to the side causing an earlier flow separation at the upstream side of the three cylinders. The visualization of the flow of the three tandem square cylinder in model II parallel configuration in Figs. 9 shows the flow characteristics at *M/D* and *N/D*=0.0, where the flow separation has occurred at the upstream side of cylinder 1, so that the flow vortex at side parts of the cylinder 2 and cylinder 3 have been notably large. Furthermore, at *M/D* and *N/D*=0.6 flow separation has occurred on cylinder 1, but it has been thinner on cylinder 2 than the ones at *M/D* and *N/D*=0.0.

This is due to damped flow vortex between cylinder 1 and cylinder 2 and between cylinder 2 and cylinder 3.

For *M/D* and *N/D*=1.2, the flow separation has become larger again on cylinder 1 and cylinder 2, so the flow separation has been greater when compared to the ones at *M/D* and *N/D*=0.6. This has happened because the flow vortex has been less damped between cylinder 1 and cylinder 2 and between cylinder 2 and cylinder 3, and the flow vortex pushed the flow to the side parts causing an earlier flow separation at the upstream side of cylinder 2. The separation of flow occurred at cylinder 3 for the three M/D and N/D values has resembled the pattern of flow separation on cylinder 2.

(a) *M/D* = 0,0 (b) *M/D*=0,6 (c) *M/D*=1,2

Figs. 6. Visualization of flow in three tandem square cylinder in model I serial configurations or (a) *M/D*=0.0; (b) *M/D*=0.6 and (c) *M/D*=1.2 while *N/D* is constant at 1.2 at Re=43,844

(a) *M/D*=0,0 (b) *M/D*=0,6 (c) *M/D*=1,2

Figs. 7. Visualization of flow in three tandem square cylinder in model II serial configurations or (a) *M/D* and *N/D*=0.0; (b) *M/D* and *N/D*=0.6 and (c) *M/D* and *N/D*=1.2 at Re=43,844

(a) *M/D*=0,0 (b) *M/D*=0,6 (c) *M/D*=1,2

Figs. 8. Visualization of flow in three tandem square cylinder in parallel configuration model I or (a) *M/D*=0.0; (b) *M/D*=0.6 and (c) *M/D*=1.2 while *N/D* is constant at 1.2 at Re=43,844

(a)M/D = 0,0 (b) *M/D*=0,6 (c) *M/D*=1,2

Figs. 9. Visualization of flow of three tandem square cylinder parallel in parallel configuration model II or (a) *M/D* and *N/D*=0.0; (b) *M/D* and *N/D*=0.6 and (c) *M/D* and *N/D*=1.2 at Re=43,844

IV. Conclusion

From the results, it can be concluded the optimum position of the tandem object will reduce the value of the drag coefficient and the pressure coefficient and will delay the flow separation on tandem cylinders, leading to the reduction of aerodynamic energy and fuel consumption. For this reason, research is conducted on serial and parallel configurations with 2 treatment models for the interaction distances of the three cylinders. Model I has the ratio of distance between cylinder 1 to cylinder 2 to cylinder diameter (*M/D*) change, while the ratio of distance between cylinder 2 to cylinder 3 to cylinder diameter (*N/D*) is fixed. Model II has the ratio of the distance *M/D* and *N/D* change with the same distance. As for the treatment distance given is as much as 7 levels (0; 10; 20; 30; 40; 50; and 60) mm for serial configuration and for parallel configuration, then air is flowed at the same air flow velocity of 14 m/s. This study has aimed to determine the visualization characteristics of flow across three square cylinders arranged in tandem with serial and parallel configurations and is expected to produce a description of flow characteristics and the value of the drag coefficient and optimum pressure coefficient and flow separation across three arranged square cylinders the tandem. The results of this study indicate that the characteristics of fluid flow separation across three square cylinders arranged in serial and parallel configuration of model I and in model II increase if *M/D* and *N/D* are enlarged. The smallest flow separation obtained in serial and parallel configurations, namely for model I at *M/D*=0.6, while for model II the same as model I at *M/D* and *N/D*=0.6. Interaction of cylinder 1 with cylinder 2 and interaction of cylinder 3 with cylinder 2, resulting in smaller flow separation on cylinder 2. This is indicated by obtaining the optimum positive pressure coefficient value across three square cylinders arranged in tandem in serial and parallel configurations, both for model I and for model II, on cylinder 2.

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