Fluid Flow Through Triangular and Square Cylinders

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ABSTRACT

Characteristics of fluid flowing through triangular and square cylinders have been analyzed experimentally and numerically by CFD at Reynolds number based on square cylinders diameter, ReD = 14,750; 26,040 and 37,192. Ratio of the distance between cylinders to square cylinders diameter (L/D) was varied as 0.0; 1.0; 2.0; 3.0; 4.0; and 5.0 while ratio of the triangular cylinders diameter to square cylinders diameter (d/D) was constant at 0.5. The results showed that the vortex is damped between the triangular cylinders and the square cylinders as L/D is increased so that the flow tends to attach the square cylinder. Consequently, the average drag coefficient (C_D) decreases and reached minimum L/D = 1. Further increase of L/D from 1 strengthens the vortex that tends to deflect the flow direction out of the square cylinder so that separation occurred earlier in the upstream side of square cylinders. As a result, CD increases. In general, the insertion of a triangular cylinder in front of a square cylinder decreases drag on square cylinders by 49%.

INTRODUCTION

Flow over triangular cylinders and square cylinders is very important in many practical application such as in structural engineering, heat exchanger, transportation, and many others. Wind or water loaded on a structure is one of the main factors to be considered in the design. As it is known that the wind or water loaded on a structure has a different characteristic with that loaded on a single structure with the same shape. The combined interference of the flow around a group structures exhibit a variety of unexpected flow phenomena. In particular in transportation such as airplanes, trains, cars and ships, large drag force should be reduced as small as possible to conserve the energy required to move. This is a challenge problem for engineers and researchers today.

At low speed, fluid flowing through objects geometrically similar, which the orientation and roughness has the same value, the drag coefficient was a function of Reynolds number that object (Schlichting, 1979). According to Salam (1999), the drag coefficient of turbulent air flowing through a square cylinder is influenced by the flow separation, boundary layer thickness, and aspect ratio. Lankadasu and Vengadesan (2008) pointed out that vortices at the downstream of square cylinders was affected by the non-dimensional shear parameter, Reynolds number, and Strouhal number.

Summer et al. (2000) observed laminar flow characteristics with Reynolds number (Re) varied from 850 to 1900 flowing around three circular cylinders in tandem. They found that when the ratio of distance between cylinders diameter (L/D) was changed from 1.0 to 5.0 and the axis angle between two cylinders (α) was varied from 0° to 90° the flow characteristic was a shear layer, separation of flow, and vortices changing.

Alam et al. (2006) conducted a study on two circular cylinders in tandem with the same diameter in a narrow channel. The cylinder was rotated on its axis from 0 to 180 degrees whereas the ratio of distance between two cylinders (L) to the cylinder diameter (D) was also changed from L/D = 0 to 8. Their result shows that an extreme condition happened at L/D = 3. Both upstream and downstream cylinders experienced extreme increase at this point, as such that for the upstream cylinder the highest as well as the lowest values of C_D happened at this point. Whereas for downstream cylinder the highest value occurred at this point, yet the lowest one was at L/D = 0.

The aerodynamic flow characteristic due to the interaction between two square cylinders in tandem in laminar flow with low Reynolds number Re < 200 was examined by Etminan et al. (2011). Result of this study
indicated that vortex influenced by the magnitude of the Reynolds number, namely the greater Reynolds number the smaller the coefficient of drag and a very large decreasing in theregion of \(Re < 50\). While the drag coefficient value on the upstream cylinder is larger than that of the downstream cylinder, \(C_{D_{\text{up-stream}}} > C_{D_{\text{down-stream}}}\).

Lee et al. (2004) studied the effect of insertion of a small control rod with diameter of \(d\) in the upstream side of a cylinder with a distance of \(L\). The study was focused on the characteristic of drag and structure of flow. Reynolds number based on the diameter of the main cylinder \((D = 30 \text{ mm})\) was approximately \(Re = 20.000\). The maximum reduction of the total drag coefficient in the whole system covering the main cylinder and control rod at various \(L/D\) and \(d/D\) is approximately 25%. The optimal reduction was found at \(d/D = 0.233\) by laying small control rod at \(L/D = 2.0\) to \(2.08\).

Tsutsui and Igarashi (2002) observed the reduction of drag on circular cylinders. The disturbance rod was put on the upstream side of cylinder. The diameter of cylinder was 40 mm, and the rod diameter range was from 1 to 10 mm. Reynolds number based on the cylinder diameter was from \(1.5 \times 10^4\) to \(6.2 \times 10^4\). It was found that the flow pattern depend on the diameter of disturbance, the distance, and Reynolds number. The total reduction of drag is 63% of that in one cylinder.

Pressure drop on the tandem of circular cylinders and square cylinders which alternately inserted on the upstream side in wind tunnel with height \(H\) was investigated by Daloglu (2008). The ratio of the distance between two cylinders to the diameter \((S/d)\) was varied from 0 to 10. The result showed that the pressure drop was influenced by \(S/d\). The smallest pressure drop was obtained at \(S/d = 1.0\) to \(1.5\) for all Reynolds number.

Widodo and Permana (2011) conducted a numerical simulation utilizing CFD solver FLUENT 6.2 over two cutted cylinders \((t = 65°)\) and two circular cylinders composed in tandem \((L/D = 1.5)\) under the influence of a flat wall at various spacing \((G/D = 0.067; 0.133; 0.2; 0.267)\). The result shows that the narrow \(G/D\) shifted the fluid away from the gap especially shown on the cylinder of type I - 65°. Strong blockage effect occurs at \(G/D = 0.067\) resulting in the higher acceleration when passing through cylinder -1, but decreasing acceleration through cylinder -2. At the same \(G/D\), the interaction between the cylinder of type I - 65° and the wall was stronger than the interaction between the circular cylinders and wall as indicated by the location of reattachment point showing the pressure recovery.

All of these studies discussed the drag reduction circular cylinders or square cylinders composed in tandem or on the insertion of disturbance in front of those cylinders at various ration of distance to the diameter. The question was whether the square cylinders was tandem with triangular cylinders or used triangular cylinders as disturber cylinders in front of square cylinders, that will make the drag coefficient decreased. According to Munson et al. (2002) \(C_{D_{\text{t}}}\) on square cylinders was 2.10 which is larger than that on circular cylinders which is only 1.17and that on the triangular cylinder which is 1.55. According to White (1994), coefficient of drag from square cylinders tends to be smaller when the Reynolds number is increased. The next question is whether \(C_{D_{\text{t}}}\), the distance of point of flow separation, and the vortices from square cylinders will decrease significantly when it was tandem or disturbed with triangular cylinder.

Therefore, the present study provided data of fluid flow characteristic through a tandem of triangular and square cylinders. The analysis is stressed on the estimation of the relationship between the coefficient of drag with the thickness of boundary layer, the flow separation, and the vortex flow that occurred in the interaction of two objects.

**Research Method:**

The experiments were conducted in a Sub-Sonic Wind Tunnel made by Plint & Partners LTD. Engineers England. The test section has a dimension of 500 mm x 310 mm x 310 mm. It was made of transparent acrylic with a thickness of 10 mm for flow visualization. Test object was a tandem of triangular cylinders and square cylinders as shown in Figure 1. Square cylinders length, width, and height were equal referred to as square cylinders diameter \((D) = 30 \text{ mm}\). Triangular cylinders had the same side length, and considered to be triangular cylinders diameter \((d) = 15 \text{ mm}\). The test object was made of acrylic with thickness of 2 mm. The air flow velocity that entered the wind tunnel \((U)\) was ranged from 0 to 26 m/s. The drag was measured by a weight balance system with a measurement range of 0 to 2.5 Newton to balance the front and right side, and of 0 to 16 Newton to balance the front and back side. The result from the measurement of the balance in the front and back side of test object was drag force \((F)\) the test object. The drag coefficient \((C_{D_{\text{t}}})\) was estimated using

\[
C_{D_{\text{t}}} = \frac{F}{\frac{1}{2} \rho U^2 A}
\]

where \(\rho\) = density of air, and \(A\) = cross-sectional area of square cylinder.

This research was conducted in the laminar flow condition at Reynolds number estimated based on the square cylinders diameter as \(Re_{D} = 14.730\); \(26.040\); and \(37.192\) corresponded to the air flow velocity that
entered the wind tunnel of \((U) = 8; 14;\) and 20 (m/s), respectively. The ratio between the two cylinders to the square cylinder diameter \((L/D)\) was varied as 0.0; 1.0; 2.0; 3.0; 4.0; and 5.0, while the ratio of the diameter of the triangular cylinder to the diameter of square cylinder \((d/D)\) was constant at 0.5.

The flow was visualized by smoke produced from kerosene at \(U = 8\) m/s \((Re_D = 14.730)\) at all \(L/D\). The flow behaviour that cannot be clearly captured by the visualization was analyzed by a simulation process using CFD based on FLUENT 6.3.26 with a same condition as the visualization. The model of the test objects is shown in Figure 1. The simulation began with determining the type of meshing used in triangular cylinders in tandem with square cylinders, using Gambit 2.3 before exported to FLUENT 6.3, namely the element quadrial type pave, with interval size of 0.2, as shown in Figure 2.

**Fig. 1:** Model of test object.

**Fig. 2:** Meshing type of test object.

## RESULT AND DISCUSSION

Figure 3, showsthat \(C_D\) decreases with increasing \(L/D\) and reaches minimum at \(L/D = 1\). Further increased of \(L/D\) increases \(C_D\). This tendency occurs at all experimental conditions. The smallest value of \(C_D\) was 1.0287 occurred at \(L/D = 1.0\) and \(Re_D = 26.040\), while the largest value of \(C_D\) was 1.5586 occurred at \(L/D = 5\) and \(Re_D = 14.730\). This result was much less than that of a single square cylinder \(C_D = 2.20\) at \(Re = 10^5\) (Munson, 2002). This shows that the insertion of triangular cylinders in front of square cylinders, and the distance between the two cylinders have a strong influence on \(C_D\). Figure 4 shows that \(C_D\) is smaller at a larger Reynolds number at all experimental range of \(L/D\) with the smallest \(C_D\) is at \(L/D = 1.0\). This result support the data in White (1994) for a flow of fluid through square cylinders.

**Fig. 3:** \(C_D\) on tandem of triangular cylinders and square cylinders vs \(L/D\) at three different \(Re_D\).
This result was explained through flow visualization, as shown in Figure 5. It was obtained that boundary layer thickness ($\delta$) of 3 mm occurred at $L/D = 1.0$. The $\delta$ is becoming thicker when $C_D$ is getting larger. The relationship between $C_D$ and $\delta$ can be seen in Table 1.

The flow visualization shows that at $L/D = 0.0$ flow separation occurs on the upstream side of square cylinders so that the vortex over a square cylinder is very large and the flow was pushed apart from the cylinder wall. Consequently the boundary layer becomes very thick. At $L/D = 1.0$, the flow separation occurred near the downstream side of the square cylinders so that boundary layer was becoming very thin. It was due to the fact that vortex was damped between the triangular cylinders and the square cylinder.

For $L/D = 2.0$, the flow separation was approaching again the upstream side of square cylinders, so that the boundary layer was thicker than that at $L/D = 1.0$. This was caused by the fact that vortex was not damped between triangular cylinders and square cylinders and it pushed the flow apart from the cylinder that causes flow separation earlier in the upstream side of square cylinders. The almost same phenomenon occurs at $L/D = 3.0; 4.0; and 5.0$, namely the vortex was not damped anymore and it rolls the flow apart from the cylinders so that separation of flow occurred earlier.

<table>
<thead>
<tr>
<th>L/D</th>
<th>$\delta$ (mm)</th>
<th>$C_D$</th>
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<tbody>
<tr>
<td>0.0</td>
<td>3</td>
<td></td>
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<tr>
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<td>4</td>
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<td>5.0</td>
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\[ C_D = 1.2 - 1.7 \] for $L/D = 0.0$ to 5.0.
Velocity contour of numerical simulation at various L/D at U = 8 m/s is shown in Figure 6. Figure 6(a) showed that at L/D = 0.0 the flow separation that occurs on the upstream edge of the cylinder pushes the flow apart from the cylinder then the boundary layer became thicker. In addition, it also creates larger vortex in the downstream of square cylinders. At L/D = 1.0 (Fig. 6(b)) the separation of flow is very small which results in a very thin boundary layer. The vortex that occurred in the downstream of square cylinders is also very weak. However, at L/D > 1.0 up to L/D = 5.0 as shown in Figure 6(c), 6(d), 6(e) and 6(f), the flow separation and the boundary layer thickness is increasing with L/D.

Figure 6 also showed that the vortex at the downstream of square cylinders is most stable at L/D = 1.0 because the flow separation and the boundary layer thickness of the square cylinders are the smallest one. Therefore, the vortex does not strong enough to push the flow apart from the cylinder. When L/D > 1.0 the vortex that occurred between triangular cylinders and square cylinders is stronger to push the flow apart from the cylinder. As a result, the separation of flow and boundary layer thickness are getting larger. This condition explained that at L/D = 1.0 the drag is the smallest and at 0.0 < L/D < 1.0 and L/D > 1.0 the drag is increased and reached maximum value at L/D = 5.0.

![Fig. 6: Contour profile of flow velocity magnitude at U = 8 m/s (Re_D = 14.730).](image)

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Numerical simulation result of pressure distribution at various L/D at U = 8 m/s is shown in Figure 7. Figure 7(a) shows that at L/D = 0.0 the pressure changes over a wide region around the square cylinders. The pressure difference between the upstream and downstream is very large. This explained why the coefficient of pressure is larger. At L/D = 1.0 as shown in Figure 7(b), the wake of the triangular cylinder creates very small pressure difference between upstream and downstream of square cylinder that results in the smallest pressure coefficient. The influence of low pressure field created by the triangular cylinder still appears up to L/D = 2.0 (Figure 7(c)) though the pressure difference tends to increase slightly. From L/D = 3.0 to L/D = 5.0 (Figure 7(d), 7(e) and 7(f)) the low pressure field moves toward triangular cylinder and induces high pressure field at the upstream of square cylinder. Consequently, the pressure difference between upstream and downstream of the square cylinders tends to become larger with the largest pressure coefficient is obtained at L/D = 5.0.
Figure 7 also shows that the region of pressure different around the square cylinders is the narrowest at L/D = 1.0. Consequently, the pressure different does not strong enough to push the flow apart from the cylinder. At a larger L/D the region of pressure different around square cylinders is getting larger and strong enough to push the flow apart from the cylinder so that the pressure drop is getting larger. This indicates that the smallest pressure coefficient and drag occurred at L/D = 1.0.

![Contour Profile of flow pressure at U= 8 m/s (ReD = 14.730).](image)

*Fig. 7: Contour Profile on coefficient of flow pressure at U= 8 m/s (ReD = 14.730). (a) L/D=0.0; (b) L/D=1.0; (c) L/D=2.0; (d) L/D=3.0; (e) L/D=4.0; and (f) L/D=5.0.*

Figure 8 shows the comparison between the flow visualization photograph (Fig. 8A) and the stream function of the velocity from CFD(Fig. 8B). All figure shows that there is a simmilar flow pattern between the visualization and the numerical results. The flow pattern shows the movement of vortex between two cylinders, separation of flow, and boundary layer on square cylinders. The interesting thing is seen on the vortex movement between two cylinders, that is, when L/D is enlarged the vortex between the two cylinders moved forward close to the triangular cylinder. This caused the separation of flow over square cylinder occurred earlier and the boundary layer became thicker.

When the flow visualization photograph and contour of stream function are associated with the contour of pressure in Figure 7, it is seen that the contour of the lowest pressure is correspond to the center of the vortex. The strongest vortex occurs at L/D = 2.0. At L/D<2.0 that is at L/D=1.0, the vortex is damped shown by small pressure different (Fig. 7b). At L/D > 2.0, the vortex moves toward the circular cylinder that creates a flow sparation earlier at the upstream region of the square cylinder which resulted in larger pressure difference between the upstream and the downstream edge of the square cylinder (Fig. 7d, 7e, 7f). Consequently, the boundary layer thickness increases as shown in Fig. 8 and so does C_D as shown in Fig. 3.

Simulation result confirmed by research conducted by Dialoglu (2008), Lankadasu and Vengadesan (2008), Lee *et al.*(2004), Sumner *et al.*(2000), and Widodo and Permana (2011), which in comparison of the distance with particular cylinders dimeter (L/D around 1.0 to 3.0) will decrease the coefficient of drag.
Fig. 8: (A) Flow visualization and (B) Contour of stream function from CFD at $U=8 \text{ m/s}(Re_D = 14.730)$. (a) $L/D=0.0$; (b) $L/D=1.0$; (c) $L/D=2.0$; (d) $L/D=3.0$; (e) $L/D=4.0$; and (f) $L/D=5.0$.

Conclusion:
Experimental analysis and simulation of flow through a tandem of triangular cylinders and square cylinders has been done at various $L/D$. The experimental data were validated with the flow visualization and flow simulation. The conclusions are:

a. The flow visualization patterns were identical to the flow pattern shown by the simulation. These flow patterns reveal that the smallest vortex between cylinders and squared cylinder occurred at $L/D = 1.0$ in which the thinnest boundary layer on the squared cylinders was also occurred. This results in the smallest drag coefficient.

b. The greater the distance between two cylinders the stronger the vortex between the cylinders which tends to move toward the triangular cylinder. This produces thicker boundary layer that induces greater drag coefficient.

c. Tandem of triangular cylinders and square cylinder at $L/D = 1.0$ delayed flow separation near the downstream side of square cylinder and resulted the smallest boundary layer thickness which cause the largest decrease of drag.
d. The insertion of the triangular cylinders in front of the square cylinders reduces the drag on square cylinders by 49%, which is characterized by decreasing the coefficient of drag from $C_D = 2.10$ for the single square cylinder to become $C_D = 1.0681$ if it was tandem with triangular cylinders.

e. The largest drag decreasing for all levels of Reynolds numbers, occurred when the tandem of triangular cylinders and square cylinders at $L/D = 1.0$ and $d/D = 0.5$.

REFERENCES


