Investigating Flat Plate Drag Reduction Using Taguchi Robust Design

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ABSTRACT

Research has shown when a rectangular cylinder is located near a flat plate, the flat plate skin friction coefficient changes as a function of the rectangular aspect ratio, gap height between the rectangular and flat plate, distance of rectangular from the flat plate leading edge, and speed of free stream. However, there is no comprehensive experimental study on the comparison of the results of the flat plate skin friction coefficient for all the interactions between effective variables in the presence and absence of the obstacle. On the other hand, testing all possible combinations of effective variables will not be reasonable. In this paper, maximum and minimum ratios of the flat plate skin friction coefficients with and without the rectangular cylinder were determined using robust Taguchi design. Design of experiments method was applied for decreasing the number of experiments without losing the required information in the first step. Then, experimentation was done in a wind tunnel, the maximum speed of which was 13 m/s. Finally, the flat plate skin friction coefficient was optimized using Taguchi method and Minitab software. Results showed that presence of the rectangular cylinder near the flat plate decreased the average skin friction coefficient of the flat plate for all the possible combinations of the effective variables. Additionally, maximum value of the flat plate skin friction reduction was about 40%.

Keywords: Skin friction coefficient; Drag reduction; Design of experiments; Taguchi method; Rectangular cylinder.

NOMENCLATURE

- A: flat plate area
- C: length of the rectangular cylinder
- d: gap height between the rectangular cylinder and flat plate
- F: skin friction force
- H: length of Flat plate
- L: distance of the rectangular cylinder from the flat plate leading edge
- LV: levels
- NTaguchi: minimum number of experiment to be conducted for Taguchi method
- ReH: Reynolds number based on length of flat plate
- ReC: Reynolds number based on cylinder thickness
- t: thickness of the rectangular cylinder
- \( U_\infty \): speed of free stream
- \( \rho \): density of air
- \( \mu \): viscosity of air
- \( \eta \): signal-to-noise (S/N) ratio
- \( \eta_i \): mean of S/N ratio at optimum levels
- \( \eta_m \): mean of S/N ratio

1. INTRODUCTION

The amount of fuel consumption of vehicles has been an important issue in recent years. Frictional drag reduction of vehicles is one of the most important factors for decreasing fuel consumption, Kourta and Gilliéron (2009). Numerous methods have investigated decreasing the frictional drag; one of the simplest ones is inserting an obstacle inside a boundary layer, Bruneau et al. (2012). By doing so, a stagnation point is formed over the frontal area of the insert geometry, providing a driving force to push the flow stream from the gap between the obstacle and wall. The jet passing through the gap is a cause of vortex generation at downstream to the obstacle which in turn makes considerable contribution to the skin friction reduction, as reported by, Inaoka et al. (1998), de Souza et al. (1999) and Ghassabi and Kahrom (2013). Also, Marumo et al. (1985) compared the value of skin friction coefficient of the flat plate with and without circular cylinder insert near the plate. Their results showed that skin friction coefficient decreased in the presence of the obstacle. This result was also
given by other researchers for circular cylinder, Suzuki et al. (1988) and Suzuki and Suzuki (1991). Inaoka et al. (1999) placed a square insert in the turbulent boundary layer and measured the skin friction coefficient. Their results represented that skin friction coefficient was reduced by inserting this insert. They also found the same result for the laminar flow, Inaoka et al. (1998).

Some researchers have studied the effect of insert geometric parameters on the skin friction coefficient. Kahrom et al. (2010) optimized the dimension of a quad insert and the gap height that provided maximum heat transfer and minimum skin friction coefficients. Suzuki and Suzuki (1991) studied effect of the circular cylinder size and gap height on the skin friction coefficient of the flat plate.

This study indicated that gap height was more effective than cylinder size in skin friction coefficient. Also, Sarkar and Sarkar (2010) observed that gap height had a strong influence on shear layer when a circular cylinder was located near the wall. Therefore, researches have shown that skin friction coefficient changes as a function of the obstacle aspect ratio and gap height when an obstacle is located near the wall. However, there is no comprehensive experimental study on the comparison of the results of the flat plate skin friction coefficient for all the interactions between effective variables in the presence and absence of the obstacle. On the other hand, testing all the possible combinations of effective variables will not be reasonable.

The present study aimed to determine optimal conditions that provided minimum and maximum values for the average flat plate skin friction coefficients between all the possible combinations of effective variables in the presence of the rectangular cylinder insert. For this purpose, first, the average skin friction coefficients were calculated experimentally as a function of effective variables.

Also, design of experiments (DOE) method was used for decreasing the number of experiments without losing the required information. Then, Taguchi method was applied for determining maximum and minimum values of the average skin friction coefficients in the presence of the rectangular cylinder insert using Minitab software. Results showed that the rectangular cylinder insert decreased the average skin friction coefficient of flat plate for all the possible combination of effective variables.

2. PROBLEM DEFINITION

When a rectangular cylinder is located near a flat plate as shown in Fig. 1, depending on its dimensions (C, l), its distance from the flat plate leading edge (L), gap height between the rectangular cylinder and flat plate (d), and speed of free stream ($U_{in}$), deformation of the boundary layer is specified.

![Fig. 1. Description of the experimental set up](image)

Thus, the obstacle creates a specific distribution of the skin friction coefficients over the flat plate for each configuration at a special speed, Kahrom et al. (2010). Therefore, the average skin friction coefficient introduced in Eq. (1) is a function of the mentioned parameters. (Eq. (2))

$$C_f = \frac{1}{H} \int_0^H f_{C_f} C_f \, dC_f$$

$$C_f = R_C \left( \frac{C}{L}, \frac{t}{C}, \frac{d}{C}, U_{in}, \rho, \mu \right)$$

By dimensional analysis, the non-dimensional groups of Eq. (2) are:

$$C_f = R_C \left( \frac{L}{H}, \frac{C}{L}, \frac{d}{C}, U_{in}, \rho, \mu \right)$$

These variables can change in an extensive range. Furthermore, if all the interactions between the independent variables are investigated, doing a large number of experiments is required. Thus, for decreasing the number of experiments so that all the required information would not be lost, design of experiments method was used in the present study.

3. EXPERIMENTAL SET UP

Experiments were performed in the subsonic open-circuit wind tunnel with a test section with the following dimensions: 0.3 m (height)×0.3m (width)×2m (length). In the test section, maximum speed was 13m/s and the turbulence intensity of uniform free stream was less than 1.0% so that it can be assumed that flow was laminar in the inlet. However, based on length of flat plate and value of critical Reynolds number ($5 \times 10^5$), flow became fully turbulent in the downstream region. The Dimension of the rectangular cylinder was C (length)×0.3m(width)×t (thickness) mounted normal to free stream direction and was placed d from the bottom of the test section and L from the test section leading edge, as shown in Fig. 1. Thickness of the rectangular was fixed at 8 mm and change of aspect ratio was done by changing the rectangular length. Floating-frame balance method was used for calculating the average skin friction coefficient of the flat plate, Naughton and Sheplak (2002). Friction forces were measured by a load cell with 0.01 gr accuracy, which was connected to the leading edge of the floating surface, as shown in Fig. 1 and Fig. 2.

4. DESIGN OF EXPERIMENTS

Design of experiments is a procedure for generating the required information with the minimum amount of experimentation based on statistical methods, Rajabi and Kakhkhodayan (2013). Several DOE
methods have been developed in the recent years. One of the most popular DOE methods is Taguchi method. This method creates an optimal combination of interaction between independent variables which maximizes sensitivity by a minimum number of experiments. The experimental design proposed by Taguchi involves using orthogonal arrays to organize the independent variables affecting the process and levels at which they should be varied. Instead of having to test all the possible combinations like factorial design, the Taguchi method tests pairs of combinations, which allows for collecting the necessary data to determine which factors have the highest effect on the dependent variable with the minimum amount of experimentation; thus, saving time and resources, Singh and Batra (2013). The first step in the Taguchi method is selection of the levels of the independent variables. Levels of (d/t) is determined based on results of Price et al. (2002). Their results showed the existence of four distinct flow regimes as the cylinder-wall gap size is varied: a) The very small gap flow regime (d/t<0.125) in which vortex shedding is suppressed; b) The small gap flow regime (0.125<d/t<0.5) in which the flow pattern is similar to those of d/t≤0.125 with the exception of a pronounced pairing between the lower shear layer separated from the bottom side of the cylinder and the wall boundary layer; c) The intermediate gap flow regime (0.5≤d/t<0.75) in which vortex shedding becomes intermittent; d) The large gap flow regime (d/t≥0.75) in which there is no separation of the wall boundary layer. Therefore, four levels were considered for d/t, as shown in Table 1.

In Eq. (4), P, is defined as the number of independent variables. In the present study, one independent variable having two levels and the other having three levels, as shown in Table 1. Therefore, minimum number of experiments required based on Eq. (4) is 11. Hence, L12, L16, L18, L32 can be chosen. To improve the accuracy of results, L32 orthogonal array was employed and structure of the array is demonstrated in Table 2.

5. DETERMINING OPTIMAL CONDITIONS USING TAGUCHI ROBUST DESIGN

One of the most applicable methods for the optimization of a function in experimental studies is the Taguchi method, Gardiner and Gettinby (1998). The Taguchi method uses the S/N ratio to measure the quality characteristic deviating from the desired value, Singh and Batra (2013). The terms ‘signal’ and ‘noise’ represent the desirable and undesirable values for the output characteristics, respectively. There are three categories of quality characteristics in the analysis of the S/N ratio: the lower the better (L.B.), nominal is best (N.B.), and the higher the better (H.B.), Gardiner and Gettinby (1998). Based on what was mentioned in the introduction, the

**Table 1** Levels of independent variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Level-1</th>
<th>Level-2</th>
<th>Level-3</th>
<th>Level-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re</td>
<td>5384.8</td>
<td>5920.0</td>
<td>6455.2</td>
<td>7525.6</td>
</tr>
<tr>
<td>C/t</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>d/t</td>
<td>0.125</td>
<td>0.25</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>L/t</td>
<td>37.5</td>
<td>175</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

To study aspect ratio effect of the rectangular cylinder on C/t, C/t was defined as an independent variable. For selection of C/t levels, results of Parker and M.C.Welsh (1983) were used. They suggest that there exist four possible vortex shedding regimes for rectangular cylinders, depending on the chord-to-thickness ratio (C/t).
In Eq. (7), P represents the number of independent variables. Then, predicted value of skin friction coefficient for optimum levels is given using the following equations:

\[
X_{L,B} = \sqrt{10 \frac{\bar{\eta}}{10}}
\]  

(9)

6. RESULTS AND DISCUSSION

To establish the accuracy of the present study, the comparison of \( C_f \) in the absence of the cylinder between the empirical equation, Bergman et al. (2011) mentioned in Eq. (10) and experimental data is presented in Fig. 3 for four Reynolds numbers based on length of flat plate. It is observed that experimental results are in good agreement with the data from the Eq. (10).

![Fig. 3. Comparison of \( C_f \) between the empirical equation and experimental data.](image-url)
Ratios of the flat plate skin friction coefficients with and without the rectangular cylinder insert for all the designed experiments are presented in Table 3. It can be seen that ratios of the skin friction coefficients are less than one for all the experiments. Therefore, the skin friction coefficient decreases for all the designed experiments by inserting the rectangular cylinder near the flat plate.

Table 3 Ratio of skin friction coefficients

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$C_f$ ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.834629</td>
</tr>
<tr>
<td>2</td>
<td>0.781924</td>
</tr>
<tr>
<td>3</td>
<td>0.890734</td>
</tr>
<tr>
<td>4</td>
<td>0.994143</td>
</tr>
<tr>
<td>5</td>
<td>0.787308</td>
</tr>
<tr>
<td>6</td>
<td>0.76459</td>
</tr>
<tr>
<td>7</td>
<td>0.873356</td>
</tr>
<tr>
<td>8</td>
<td>0.927452</td>
</tr>
<tr>
<td>9</td>
<td>0.834345</td>
</tr>
<tr>
<td>10</td>
<td>0.73978</td>
</tr>
<tr>
<td>11</td>
<td>0.873683</td>
</tr>
<tr>
<td>12</td>
<td>0.932842</td>
</tr>
<tr>
<td>13</td>
<td>0.815757</td>
</tr>
<tr>
<td>14</td>
<td>0.655057</td>
</tr>
<tr>
<td>15</td>
<td>0.837222</td>
</tr>
<tr>
<td>16</td>
<td>0.897418</td>
</tr>
<tr>
<td>17</td>
<td>0.827991</td>
</tr>
<tr>
<td>18</td>
<td>0.857315</td>
</tr>
<tr>
<td>19</td>
<td>0.974063</td>
</tr>
<tr>
<td>20</td>
<td>0.962954</td>
</tr>
<tr>
<td>21</td>
<td>0.818991</td>
</tr>
<tr>
<td>22</td>
<td>0.853973</td>
</tr>
<tr>
<td>23</td>
<td>0.973019</td>
</tr>
<tr>
<td>24</td>
<td>0.926172</td>
</tr>
<tr>
<td>25</td>
<td>0.720519</td>
</tr>
<tr>
<td>26</td>
<td>0.850607</td>
</tr>
<tr>
<td>27</td>
<td>0.862319</td>
</tr>
<tr>
<td>28</td>
<td>0.993904</td>
</tr>
<tr>
<td>29</td>
<td>0.702695</td>
</tr>
<tr>
<td>30</td>
<td>0.84876</td>
</tr>
<tr>
<td>31</td>
<td>0.842688</td>
</tr>
<tr>
<td>32</td>
<td>0.913289</td>
</tr>
</tbody>
</table>

To confirm this result for all the possible combinations of effective variables, it would be enough for the maximum value of the flat plate skin friction coefficients ratio with and without rectangular cylinder insert to become less than one between all the possible configurations of experiments. For this purpose, the higher the better category of the Taguchi method was used by Minitab software for determining the maximum ratio of the flat plate skin friction coefficients. Minitab is statistical and graphical analysis software for Windows. Minitab can perform a wide variety of tasks, from the construction of graphical and numerical summaries for a set of data to the more complicated statistical procedures, Chowdhury et al. (2014).

Values of S/N ratio for the designed experiments are presented in Table 2. By averaging the S/N ratios for each factor at a special level, a graph is made, as shown in Fig. 4 and Fig. 5. For instance, average S/N for the first level of $(L/t)$ was calculated by averaging S/N ratio for rows 1 to 16 in Table 2, where the level of factor $(L/t)$ is at level 1. Based on Fig. 4, optimum levels were obtained at the second level of $(L/t)$, first level of $(C/t)$, forth level of $(d/t)$ and second level of $(Re_t)$ for the higher the better criterion.

In Fig. 5, average of the S/N ratios is presented for each factor based on the lower the better criterion. It can be seen that minimum value of the flat plate
skin friction coefficient was obtained at the first level of (L/t), forth level of (C/t), and first level of (d/t), and first level of (Re). It could be inferred that the maximum value of drag reduction occurred in the turbulent region of the boundary layer, which could be attributed to the velocity gradient near the plate for the turbulent region of the boundary layer is much larger than that of the laminar region, Bergman et al. (2011). Also, optimum level of (d/t) is 0.25, as reported in Kahrom et al. (2010). Moreover, it is observed that S/N ratio increases as (C/t) increases. It could be inferred that drag reduction increases as (C/t) increases, which could be attributed to that in a reversed flow behind the rectangular cylinder near the flat plate become larger and stronger when (C/t) increases, Kahrom et al. (2010).

Comparison of the experimental and predicted ratios of flat plate skin friction coefficients with and without the rectangular cylinder insert are presented in Table 4 for optimum levels. It can be observed that the predicted values were in good agreement with the experimental data. Furthermore, as demonstrated in the table, the predicted and experimental values of maximum ratio of $\frac{C_{f}}{C_{f}}$ were less than one, implying that the rectangular cylinder insert decreased the average skin friction coefficient of flat plate for all the combinations of effective variables. Also, it could be observed that the maximum value of the flat plate skin friction reduction was about 40%.

In Table 5, Analysis of Variance (ANOVA) is shown for S/N ratios. In this table, Adj($MS_{i}$) determines adjusted mean sum of squares for factor $i$ and is defined as, Akbarzadeh et al. (2013):

$$F - value = \frac{AdjMS_{E}}{AdjMS_{i}}$$

where Adj($MS_{E}$) is adjusted mean sum of squares for error. Degree of significance of F-value can be determined by looking up F-tables. Larger F-value shows that the variation of the parameter has a larger impact on the output performance characteristics, Akbarzadeh et al. (2013). Therefore, when F-value of a parameter is larger than $F_{\alpha, \nu_{1}, \nu_{2}}$-value provided by the confidence table, then it can be concluded that the parameter is significant. Variables $\alpha$, $v_{1}$ and $v_{2}$ are risk, degrees of freedom (D.F.) associated with input factor, and error, respectively. Additionally, if P-value is less than or equal to the selected $\alpha$, then effect of the variable is significant. A detailed explanation of these statistical terms is described in study of Akbarzadeh et al. (2013). Based on the confidence level 95%, i.e. $\alpha$ is set at 0.05 and the confidence table, (d/t) is the most significant variable for the trend of $\frac{C_{f}}{C_{f}}$, this is due to that the gap height possesses the highest F-value and minimum P-value. However, (L/t) has the least effect on it, since it has the maximum P-value.

### 7. CONCLUSION

In this paper, the flow over a rectangular cylinder near a flat plate was experimentally studied for calculating the average skin friction coefficient of flat plate as a function of all effective variables including gap height, rectangular aspect ratio, distance of rectangular from the flat plate leading edge, and speed of free stream. Also, design of experiments method was applied for decreasing the number of experiments without losing the required information. Then, maximum and minimum ratio of the flat plate skin friction coefficients with and without the rectangular cylinder insert was determined using the robust Taguchi design. The following conclusions were obtained from the analysis of the results:

1. Maximum flat plate skin friction reduction occurred in the turbulent region of the boundary layer and d/t of 0.25.
2. Maximum value of the flat plate skin friction reduction was about 40%.
3. Gap height was the most effective variable in the trend of the average skin friction.
coefficient of flat plate. However, distance of rectangular from the flat plate leading edge had the least effect.

4. The rectangular cylinder insert decreased the average skin friction coefficient of the flat plate for all the possible combinations of effective variables.

REFERENCES


