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Drag reduction of a circular cylinder at subcritical flow regime using base shield plates

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Abstract. Experimental studies on drag reduction of a circular cylinder of diameter D were conducted in the subcritical flow regime at Reynolds numbers in the range $4\times10^4 \le Re \le 10^5$. To shield the cylinder rear surface from the pressure deficit of the unsteady vortex generation in the near wake, two shield plates were attached downstream of the separation points to form a cavity at the base region. The chord of the shield plates, L, ranged from 0.22 to 1.52 D and the cavity width, G, was in the range from 0 to 0.96 D. It is concluded that significant drag reductions from that of a plain cylinder may be achieved by proper sizing of the shield plates and the base cavity. The study shows that using a pair of shield plates at G/D of 0.86 and angular position θ of $\pm121^\circ$ results in a configuration with percentage drag reduction of 40% for L/D of 0.5, and 55% for L/D of 1.0.

Keywords: drag reduction; circular cylinder; shield plates; base cavity; separation; wake.

1. Introduction

Various methods have been developed to reduce the drag force on a circular cylinder in the subcritical flow regime (Choi, B. and Choi, H. 2000, Bouak and Lemay 1998, Isaev, *et al.* 2002, Yajima and Samo 1996, Igarashi, *et al*. 1994). Reducing this force is of great significance since it may permit a reduction in the required strength of a structure, its weight and therefore its cost. The magnitude of the pressure drag depends very much on the size of the wake and this, in turn, depends on the position of separation. For subcritical flow conditions and Reynolds numbers in the range $4\times10^4 \le Re \le 10^5$, the separation points are at the front portion of the cylinder (Achenbach 1971) and thus the recovery of the base pressure is low. The result is a wide turbulent wake and a high pressure drag. The shifting of the separation points to the rear portion of the cylinder leads to a decrease in the wake width, a recovery of the base pressure and therefore, to a reduction of the drag force. Available methods for shifting the boundary layer separation points include cylinder surface roughness (Achenbach 1971), tripping wires (Igarashi 1986), splitter plates (Apelt, *et al*. 1973), and introducing turbulence into the flow (Lesage and Gartshore 1987).

The present paper is concerned with an alternative method for drag reduction of a circular cylinder using a pair of spanwise base plates to shield the base region from the negative pressure of the wake. The proposed method consists of attaching two shield plates of chord L at a gap G between them to the rear surface of a circular cylinder of diameter D, to from a cavity at the base

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region. This investigation was carried out to examine the influence of the shield plates and the base cavity on the drag and base pressure of the circular cylinder and to identify the optimum G/D and L/D ratios for least drag force.

2. Experimental apparatus and procedure

The experiments were conducted in a low speed open circuit suction type wind tunnel having a working section of 300×300 mm. The tunnel is capable of producing a free stream velocity of 36 m/s with a turbulence intensity level of about 0.2%.

The model consisted of a 47 mm diameter PVC circular cylinder which was mounted horizontally in the tunnel working section center plane. Two full-span shield plates 1 mm thick could be attached to the rear surface of the cylinder parallel to the free stream direction at angles of $\pm\theta$ from the front stagnation point. The gap G between the two plates could be varied by small diameter circular spacers located at two spanwise stations. The chord L of the shield plates examined was within the range 0.22 to 1.52 D, and the gap G between them was within the range 0 to 0.96 D. The configuration is shown in Fig. 1. A single piezometer hole 1.0 mm diameter was drilled at the mid length of the test cylinder, and the pressure was read on a digital micromanometer type DMDC. The test cylinder and the shield plates were connected from one side to a strain gauge balance in order to measure the overall drag on the system.

All tests were performed at least twice to check their repeatability. It was found that the time average force and pressure measurements were repeatable to within ±3%. Unless otherwise stated, all the results presented in this paper are for a Reynolds number of 8×10^4 based on the cylinder diameter, $D=47$ mm. This Reynolds number was chosen to represent the subcritical flow regime. It is within a range of *Re* where the flow past the plain cylinder is virtually independent of Reynolds number. The blockage ratio, defined as the cylinder diameter divided by the working section height, was equal to 15.6%. As there is real doubt whether any of the procedures (Maskell 1963, Allen and Vincenti 1944) currently in use for correction of blockage effects applies to the case of a cylinder with shield plates attached, it was judged best not to attempt to correct for blockage effects. The raw results and the relevant data are presented so that blockage corrections can be made when a suitable procedure for correction has been demonstrated. However, corrected results are included for the case of a cylinder with splitter plate attached so that comparisons with other work may be made.

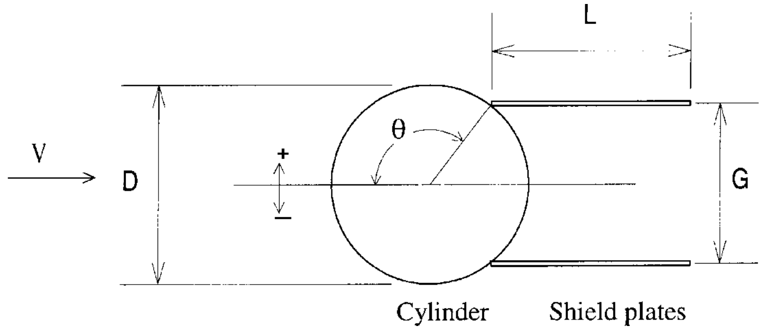


Fig. 1 Coordinate system and symbols

3. Experimental results and discussion

3.1. Cylinder with wake splitter plates

The effects of splitter plates placed along the center line of the wake of a circular cylinder in cross flow at subcritical flow regime have been reported in detail by Bearman (1965), Apelt, *et al.* (1973) and Nakamura (1996). A short splitter plate ($L/D \leq 1$) in this regime was found to cause an increase in the base pressure of the cylinder, a reduction in the drag and narrowing of the wake, compared with the values for a plain cylinder. It was concluded that the action of a splitter plate was to stabilize the separation points on the cylinder and to reduce the wake width with increasing L/D (Apelt, *et al.* 1973).

In the subcritical flow regime, vortex shedding from a plain circular cylinder is periodic, resulting in an alternating circulation that generates fluctuating pressures and forces. Thus, in addition to a mean drag force, plain circular cylinders are also subjected to fluctuating lift and drag components. Splitter plates have proved a successful means of wake stabilization, as they tend to suppress alternate vortex shedding and create instead a symmetric vortex pattern. Thus, the fluctuating lift and drag components caused by alternate shedding are reduced accordingly (Every, *et al.* 1982).

In the present study, the cylinder with splitter plate data is used as a reference case for the rest of the experiments and to verify the experimental procedure. Hence, measurements of the drag and base pressure of the model fitted with splitter plates were made at a Reynolds number of 8×10^4 for values of L/D from 0 to 2.0. Fig. 2 shows the variations of C_d and C_{Pb} with L/D. The results are shown compared with the measurements of C_d and C_{Pb} made by Apelt, *et al.* (1973) and the measurements of C_{Pb} made by Nakamura (1996). The comparison is made between results corrected for area blockage according to the method of Allen and Vincent (1944). The blockage ratio for the Apelt, *et al.* work was 6%; Nakamura's value was 1.7%.

It is observed in Fig. 2 that the drag and base pressure coefficients obtained in this study show the same trend as those obtained by Apelt, *et al.* and Nakamura. Admittedly, there are some differences in the base pressure coefficients values being compared. However, looking at the trend and values of the drag coefficients in the figure, it is concluded that the present procedure gives reasonable results.

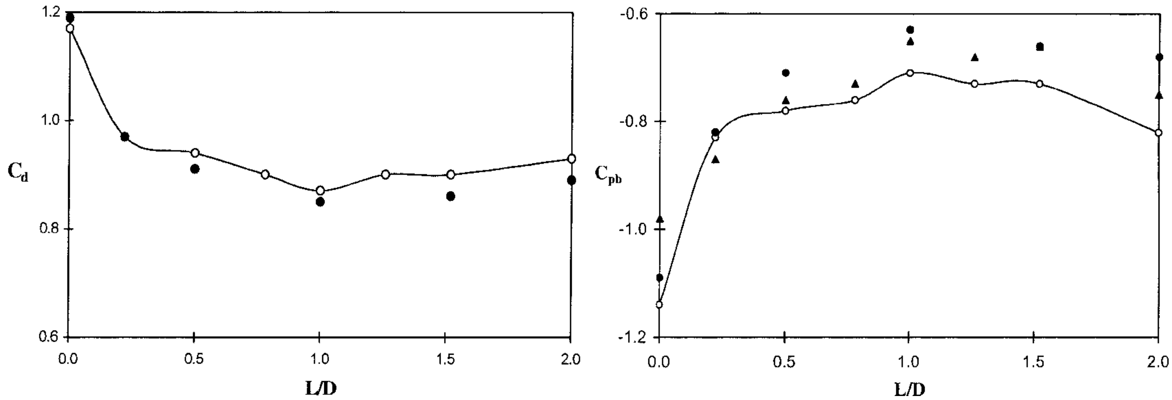


Fig. 2 C_d and C_{Pb} versus L/D for a circular cylinder fitted with splitter plate (corrected for blockage): ○, present results ($Re=8\times10^4$); ●, Apelt, *et al.* (1973) ($Re=3\times10^4$); ▲, Nakamura (1996) ($Re=1.5\times10^4$)

3.2. Cylinder with shield plates

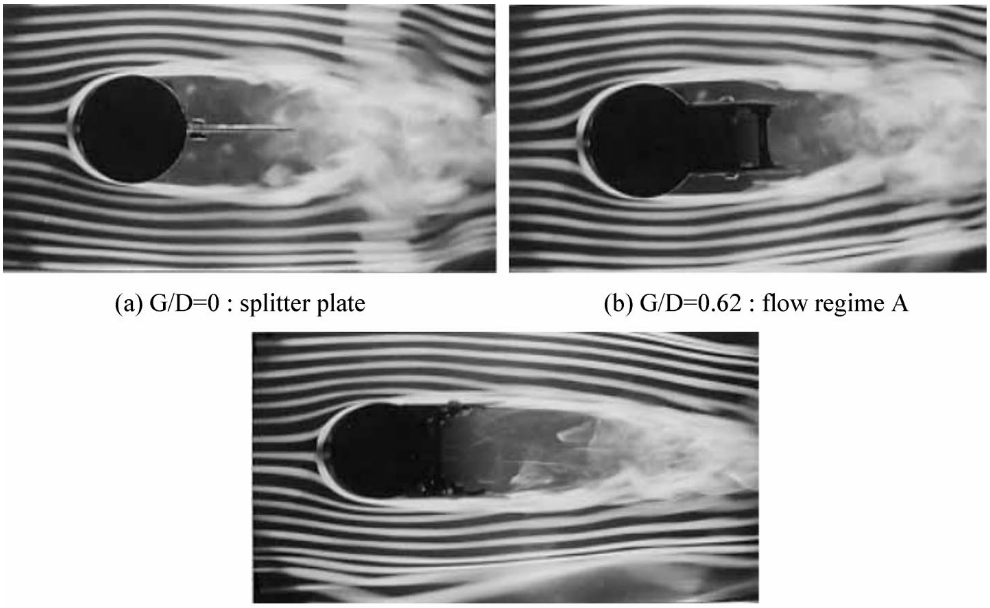
3.2.1. Flow visualization

Flow visualization experiments were conducted in a smoke tunnel at $Re=0.8\times10^4$. Fig. 3 shows typical flow patterns around a circular cylinder fitted with a pair of shield plates of chord $L=D$ for G/D values of 0, 0.62 and 0.96.

Two flow regimes were observed, depending on the cavity width G/D. The switch in flow regime occurred at a critical cavity width G/D of 0.86. Flow regime A was observed for $G/D\leq0.86$. In this flow regime, the separated shear layers from the circular cylinder do not reattach onto the shield plates and the vortex formation region develops beyond the ends of the plates. Typical flow pattern of this regime is shown in Fig. 3(b). Flow regime *B* was observed for $G/D>0.86$, and corresponds to the case of reattachment of the shear layers onto the shield plates with the final separation points at the trailing edges of the plates. Consequently, the vortex formation region shifts downstream and the wake width becomes narrower compared with that of flow regime *A*. Typical flow pattern of this regime is shown in Fig. 3(c).

3.2.2. Pressure distribution

The first case to be examined was for the model without shield plates. Fig. 4 shows the pressure distribution around the circumference of the plain cylinder at mid-span. From the present flow visualization studies for a plain cylinder and a cylinder fitted with shield plates, certain comments about the flow field can be made. A plain cylinder has its vortex formation region well forward



(a) G/D=0 : splitter plate (b) G/D=0.62 : flow regime A

(c) G/D=0.96 : flow regime B

Fig. 3 The flow around a circular cylinder fitted with a pair of shield plates of chord $L=D$.

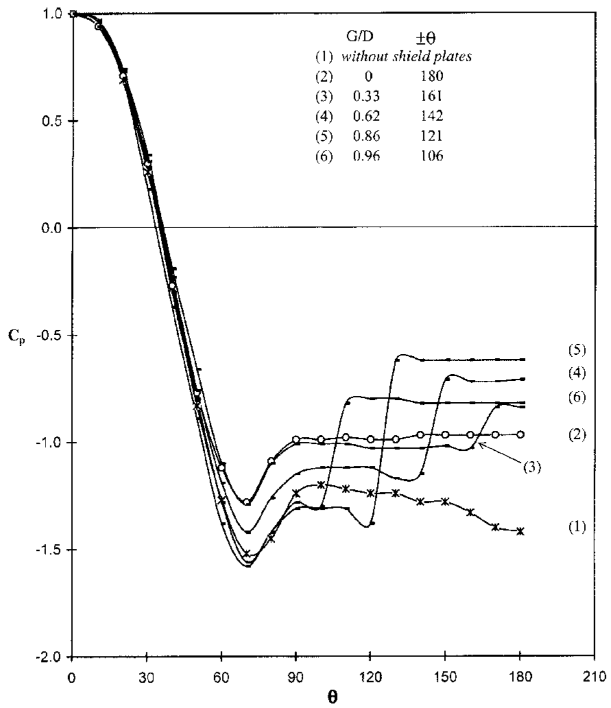


Fig. 4 Pressure distribution around a circular cylinder fitted with shield plates of chord $L=D$ at various gaps

close to the base region. Due to the boundary layer separation on the front portion of the cylinder, which results in a wide turbulent wake, the recovery of the pressure at the rear is the lowest obtained. During vortex formation, the growing vortices and, to a lesser extent, the shear layers draw in fluid from the base region. It is suggested that it is this continual air entrainment process that sustains the low base pressure (Nakagawa 1986, Roshko 1954, Gerrard 1966). The low pressure on the rear portion of the plain cylinder is evident in Fig. 4.

A pair of shield plates of chord $L=D$ was then fitted, and the pressure distributions around the circumference of the cylinder were measured for values of G/D from 0 to 0.96. The pressure distributions are shown in Fig. 4. Positions of the shield plates on the surface of the cylinder are indicated using the angle θ which is measured from the front stagnation point. For $G/D=0$, shield plates are located at $\theta=\pm180^{\circ}$ and act as a splitter plate. It is known that a short splitter plate ($L/D\leq1$) in the wake delays the interaction between the shear layers and vortices can only form beyond the end of the plate. Consequently, two independent regions of quasi-steady flow are developed between the free shear layers and the splitter plate which increase the base pressure. The additional effect of a splitter plate, as shown in Fig. 3(a), is to shift the separation points to the rear portion of the cylinder which causes a decrease in the wake width and a recovery in the base pressure. Fig. 4 shows how a splitter plate affects the pressure distribution over the cylinder circumference.

For $0<G/D\leq0.86$, the flow regime is *A* and as shown in Fig. 3(b), separation occurs towards the rear portion of the cylinder. Apparently, the additional effect of the plates is to develop a third buffer region of a quasi-steady fluid between the plates that blocks the influence of the unsteady vortex generating pressure deficit. Fig. 4 shows the effectiveness of the plates in increasing the

pressure at the base region. It is seen that the pressure is constant within the cavity region and increases as cavity width G/D was increased from 0 to 0.86. These constant pressures can have values as high as –0.59 for G/D of 0.86, while the pressure coefficient for the plain cylinder at the same region ranges from –1.24 to –1.42.

For G/D=0.96, the flow regime is *B* and the trailing edges of the shield plates provide fixed separation points for the reattached shear layers which causes the vortex formation region to shift downstream. Fig. 3(c) shows that in flow regime *B*, the upper and lower quasi-steady flow regions no longer exist and the base cavity is exposed to the influence of the unsteady vortex generation . Fig. 4 has already shown that the constant pressure within the cavity region decreases when G/D was increased from 0.86 to 0.96. This indicates that there is an optimum cavity width for the drag reduction of the model.

3.2.3. Drag and base pressure coefficients

To identify the optimum configuration giving a minimum drag, the model was first fitted with a pair of shield plates of chord $L=D$ and the gap G between the plates was increased in small increments from 0 to 0.96 D. The base pressure, which was found to be constant within the cavity region, was measured at $\theta=180^{\circ}$ from the front stagnation point. Fig. 5 shows a plot of C_d and $-C_{Pb}$ against G divided by D. It is seen that as the cavity width was increased under flow regime *A* from G/D of 0 to 0.86, the base pressure coefficient gradually rise from –0.92 to –0.59. This shows that the pressure deficit of the unsteady vortex generation is not able to sustain the low base pressure at an increased buffer region width. However, this trend is reversed as G/D was increased from 0.86 to 0.96 where the flow regime is *B*.

The variation of C_d with G/D has a quite interesting behavior. It is clear that the experimental curve can be divided into three parts. In the first part, C_d is nearly constant and the overall drag is not yet influenced by the base cavity. This is an indication that shield plates in this part have the effect of wake splitter plates where $G/D=0$. At G/D of about 0.47, C_d starts to drop and reaches a minimum at a critical cavity width of $G/D=0.86$ with a value C_d=0.63 which is 55 percent below the plain cylinder value. Beyond G/D=0.86, the drag coefficient is seen to increase slightly to 0.68 as G/D was increased to 0.96.

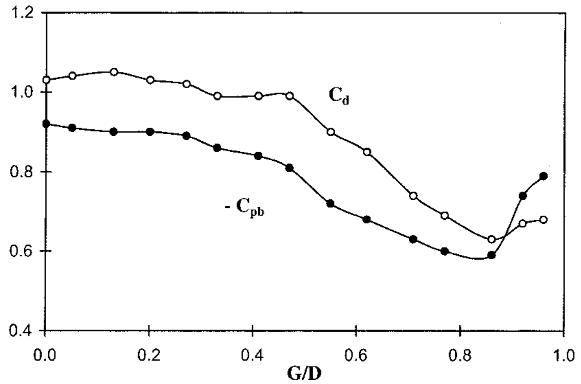


Fig. 5 C_d and $-C_{Pb}$ versus G/D for a circular cylinder fitted with shield plates of chord $L=D$

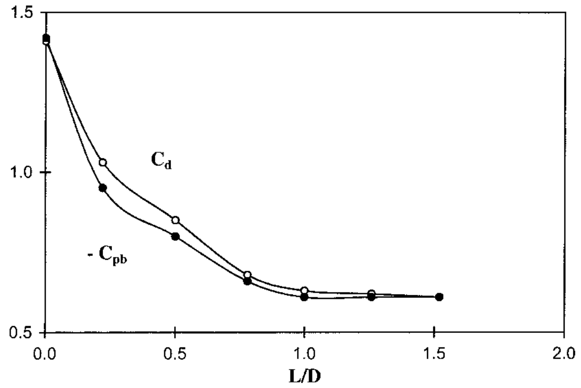


Fig. 6 C_d and $-C_{Pb}$ versus L/D for a circular cylinder fitted with shield plates at a gap G=0.86 D

The next study was carried out to see how the drag force and the base pressure vary with the shield plates chord L at the optimum cavity width G/D of 0.86 and angular position θ of ±121°. The variations of C_d and $-C_{Pb}$ with L/D are shown in Fig. 6. The graph shows clearly the effectiveness of the shield plates chord in increasing the base pressure and consequently decreasing the system drag coefficient. It is seen that there is a sharp increase of base pressure and reduction of drag as the shield plates chord was increased from L/D of 0 to 1.0. Beyond L/D of 1.0, it is seen that there is no significant changes in C_d and $-C_{Pb}$.

Measurements of wind forces on the model fitted with shield plates of chord L=D at various gaps were made at seven speeds giving a range of Reynolds numbers in the subcritical flow regime $4\times10^4 \leq Re \leq 1\times10^5$. The values of the drag coefficients for a given G/D were identical for all speeds. Fig. 7 shows the variation of C_d with Re for values of G/D from 0 to 0.96 and demonstrates that, over the range tested, C_d is independent of Reynolds number.

A comparison of the effects of shield plates at G/D=0.86 and splitter plates on the percentage drag reduction at Re=8×10^4 is summarized in Fig. 8. The comparison is made between results uncorrected for area blockage. It can be seen that a pair of shield plates at a gap of 0.86D attached to a circular cylinder in a cross-flow caused large reductions in drag. With shield plates of chord

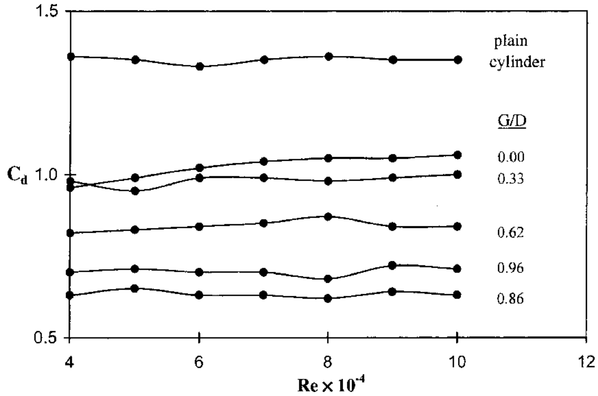


Fig. 7 C_d versus Re for a circular cylinder fitted with shield plates of chord L=D at various gaps

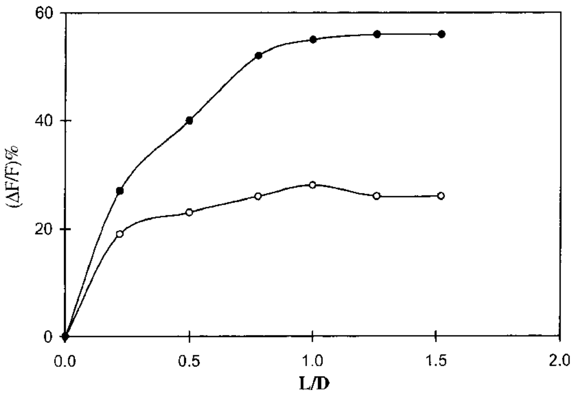


Fig. 8 Percentage drag reduction versus L/D for a circular cylinder: ○, with splitter plate; ●, with shield plates at a gap $G=0.86\ D$

0.5*D* the drag force was reduced by 40% of the value measured for the plain cylinder. For shield plates of chord 1.0 *D* the drag force was reduced by 55% of the plain cylinder value, but no significant changes in drag resulted when the shield plates chord was increased up to 1.52 *D*. Fig. 8 shows also that if the shield plates were replaced by a single splitter plate of the same chord, then the percentage drag reduction would be considerably lower. With a splitter plate of chord 1.0 *D* attached to the cylinder, the drag force would be reduced by only 28%.

4. Conclusions

Experimental study on a circular cylinder fitted with a pair of shield plates was carried out in the subcritical flow regime at Reynolds numbers in the range $4\times10^4 \le Re \le 10^5$. The chord of the shield plates, *L*, ranged from 0.22 to 1.52*D* and the cavity width, *G*, was in the range from 0 to 0.96 *D*. The conclusions drawn are:

(1) Significant drag reduction from that of a plain cylinder may be achieved by the introduction of a pair of shield plates downstream of the separation points. This finding demonstrates that the high drag is associated with the wide turbulent wake and the unsteady vortex generation in the near wake.

(2) Two flow regimes were observed, depending on the cavity width G/D:

[a] Flow regime *A*, for $G/D \le 0.86$, is a complete separation type in which the separated shear layers do not reattach onto the shield plates.

[b] Flow regime *B*, for $G/D > 0.86$, is a reattachment flow type in which the separated shear layers reattach onto the shield plates.

(3) The action of the shield plates in flow regime *A* is to shift the separation points to the rear portion of the cylinder and to develop a third buffer region of a quasi-steady fluid between the plates that blocks the influence of the unsteady vortex generation. This leads to a substantial increase in base pressure and a decrease in drag.

(4) The study shows that using a pair of shield plates at G/D of 0.86 and angular position θ of $\pm 121^\circ$ results in a configuration with percentage drag reduction of 40% for L/D of 0.5, and 55% for L/D of 1.0.

Notation

C_d	Drag coefficient $=F/(0.5\ \rho HDV^2)$
C_p	Pressure coefficient $=(P-P_0)/(0.5\ \rho V^2)$
C_{pb}	Base pressure coefficient at θ=180 deg
D	Cylinder diameter
F	Drag force
G	Gap between shield plates (cavity width)
H	Span of cylinder and shield plates
L	Chord of shield plates
P_0	Static pressure in free stream
P	Local pressure on cylinder
Re	Reynolds number $=\rho VD/\mu$
μ	Dynamic viscosity of air
V	Free stream velocity
ρ	Density of air
θ	Circumferential angle on the cylinder

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