Wind and Structures, Vol. 11, No. 5 (2008) 377-389 377
DOI: http://dx.doi.org/10.12989/was.2008.11.5.377

Evaluation of base shield plates effectiveness in reducing the drag of a rough circular cylinder in a cross flow

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(Received February 3, 2008, Accepted July 15, 2008)

Abstract. An experimental investigation has been conducted to determine the effectiveness of base shield plates in reducing the drag of a rough circular cylinder in a cross flow at Reynolds numbers in the range $3\times10^4 \leq Re \leq 10.5\times10^4$. Three model configurations were investigated and compared: a plane cylinder (PC), a cylinder with a splitter plate (MC1) and a cylinder fitted with base shield plates (MC2). Each configuration was studied in the sub and supercritical flow regimes. The chord of the plates, L, ranged from 0.22 to 1.50*D* and the cavity width, *G*, between the plates was in the range from 0 to 0.93*D*. It is recognized that base shield plates can be employed more effectively than splitter plates to reduce the aerodynamic drag of circular cylinders in both the sub- and supercritical flow regimes. For subcritical flow regime, one can get 53% and 24% drag reductions for the MC2 and MC1 models with $L/D = 1.0$, respectively, compared with the PC model. For supercritical flow regime however, the corresponding drag reductions are 38% and 7%.

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

1. Introduction

The aerodynamic drag of bluff bodies has been the subject of many scientific studies. Research in the last few decades, motivated in part by increased fuel prices, has led to significant advances in understanding of drag reduction mechanisms for two dimensional bluff bodies (Igarashi 1986, Igarashi, *et al*. 1994, Yajima and Samo 1996, Bouak and Lemay 1998, Choi and Choi 2000, Isaev, *et al*. 2002, Kwon, *et al*. 2002, Tsutsui and Igarashi 2002, Alam, *et al*. 2003, Leea, *et al*. 2004, Zhang, *et al*. 2006, Hwang and Yang 2007).

The main contributions to aerodynamic drag arise from boundary layer separation, causing pressure recovery losses and a periodic and alternate shedding of vortices in the wake. When these vortices form near the base of the body, the low pressure of the vortex centers is communicated to the base producing a low-base pressure. Because the pressure drag of bluff bodies is affected by the strength and proximity of the vortex street, any attempts in drag reduction must be aimed at weakening the vortex shedding and displacing the vortex formation position further down stream (Zdravkovich 1997). A number of different methods of achieving this have been proposed in the past, e.g., splitter

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plates, trailing-edge serrations and base cavities. All three of the above methods have proved to be highly successful for two-dimensional base flows, with optimum shapes being capable of reducing the pressure drag coefficient by over 50% (Nash, *et al*, 1963, Tanner 1972, Kruiswyk and Dutton 1990, Anderson and Szewczyk 1997, Rathakrishnan 1999, Hwang, *et al*, 2003, Hwang and Yang 2007).

In a previous study, the author (El-Khairy 2003), proposed the use of base shield plates as a drag reducing mechanism for a circular cylinder in a cross-flow. The proposed method consists of attaching two plates at a gap *G* downstream of the separation points to from a cavity at the base region. (see Fig. 1). Therefore, this method includes two of the three devices mentioned in the previous paragraph namely, splitter plates and base cavities. The study showed that significant drag reductions from that of a plain cylinder, up to 55%, may be achieved by proper sizing of the base shield plates and the base cavity. However, this investigation was carried out mainly on smooth cylinders in the subcritical flow regime in which the boundary layers separate laminarly.

A large number of engineering structures involve circular cylinder elements that experience wind and hydrodynamic loads. The flow around such elements produces a flow regime in which the boundary layers become fully turbulent well before the separation points. This flow regime begins at Reynolds number greater than 6×10^5 for smooth cylinders. In wind tunnel tests, the Reynolds number is often limited to values that are very much smaller than those producing turbulent boundary layer flows. It is well known from studies of the flow that with increasing roughness parameter, K/D, the critical Reynolds number for a rough circular cylinder decreases. This means that at a given point on the surface of the cylinder, the boundary layer undergoes transition from laminar to turbulent flow at decreasing Reynolds number (Achenbach 1971, Nakamura, *et al*. 1982). A turbulent boundary layer can travel further along the surface into the adverse pressure gradient on the rear portion of the cylinder before separation occurs. The result is a thinner wake and smaller pressure drag than those for the subcritical flow regime. Therefore, studies of the drag reducing effects of base shield plates on a rough circular cylinder will be of interest from the points of view of fundamental research as well as of applications.

The present investigation focuses on the evaluation of the effectiveness of base shield plates and base cavities in increasing the base pressure and consequently in reducing the pressure drag of a rough circular cylinder in the sub- and supercritical flow regimes.

2. Experimental apparatus and procedure

The experiments were conducted in a low speed open circuit suction type wind tunnel having a

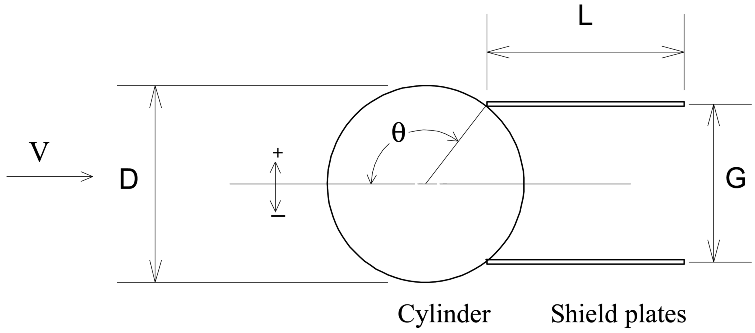


Fig. 1 Coordinate system and symbols

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. Cylinder surface roughness was provided by commercial sand paper which was carefully wrapped around the cylinder. A two-sided adhesive tape was used to stick the paper, with the seam located at the rear of the cylinder. The commercial grit number of the paper used was P100 with average particle size K of 177 Micron (as quoted by the manufacturer), giving a non-dimensional ratio K/D of 3.77×10^{-3} and a roughness Reynolds number Re_k, in the range from 56 to 414.

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 span wise stations.

The chord L of the plates examined was within the range 0.22 to 1.50 D, and the gap G between them was within the range 0 to 0.93 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 micro-manometer 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. In order to obtain system symmetry and to minimize the flow of high pressure air from the cylinder front to the base pressure, a gap of less than 1 mm was allowed between the side of the wind tunnel and the cylinder free end. The conditions at the ends of a cylinder are known to influence force measurements and end plates have been used in wind and water tunnels (Stansby 1974, West and Apelt 1982), but this would have reduced the already small aspect ratio H/D of the present arrangement. However, it is thought that no significant end effects occurred in the present setup as the drag coefficients obtained previously using splitter plates (El-Khairy 2003) were generally in good agreement with published data. The flow about any body in a closed jet wind tunnel is subjected to the confinement effects of the tunnel walls. 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 currently in use for correction of blockage effects applies to the models tested in the present study, the results are presented without correction for blockage. The models will be referred hence forth as ‘PC’ for the plane cylinder configuration, ‘MC1’ and ‘MC2’ for the modified configuration fitted with a wake splitter plate and base shield plates, respectively. 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 %.

3. Experimental results and discussion

3.1. *Circular cylinder without wake control*

Comparisons of the well known curves of C_d versus Re for smooth and uniformly rough circular cylinders reveals that rough cylinders have C_d curves to the left of smooth cylinders and, therefore, experience the critical range at lower Re. Roughness promotes turbulent transition and generally, the greater the roughness, the greater the shift of the C_d curve to the left. Although a greater degree of uniform surface roughness promotes an earlier critical Re, it is accompanied by a smaller drop in C_d and a shorter critical Re range. In addition, rough cylinders often have higher C_d than smooth cylinders in the supercritical regime (Achenbach 1971).

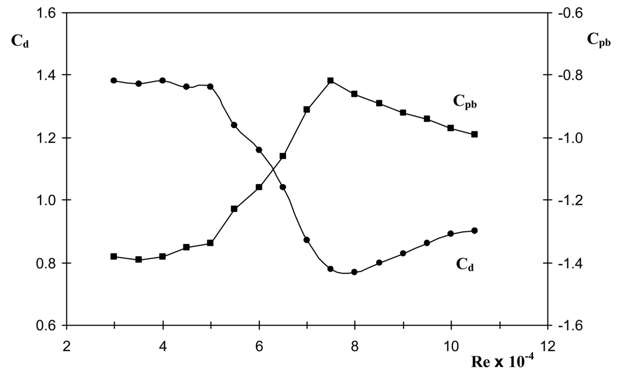


Fig. 2 C_d and C_{pb} versus Re for the PC model

The type of flow past a rough surfaced circular cylinder depends on the values of the Reynolds number and the roughness parameter K/D (Achenbach 1971, Szechenyi 1975). Fig. 2 shows the variations of C_d and C_{pb} with Reynolds number for the PC model. It is evident that the variation of C_d with Re can be divided into three parts. In the first part, C_d is nearly constant and the flow is not yet influenced by surface roughness (subcritical flow regime). At Re of about 5×10^4, C_d starts to drop and reaches a minimum value at $Re = 7.5\times10^4$ (critical flow regime). Above this Reynolds number, it is seen that the value of C_d increases with increasing Re, which denotes the existence of the supercritical flow regime. Hence, the change to supercritical flow regime occurs at a roughness Reynolds number $Re_k = 283$. This is in agreement with the results of Ribeiro (1991) and those of Szechenyi (1975), who established that a correct surface roughness condition will provoke supercritical flow for $Re_k > 200$.

Each of these flow regimes is characterized by a special boundary layer behavior described by Achenbach (1975): subcritical (purely laminar separation), critical (laminar bubbles followed by turbulent reattachment and delayed final separation), and supercritical (direct transition from laminar to turbulent boundary layer ahead of separation).

For subcritical flow conditions, the separation points are at the front portion of the cylinder at an angular position $\theta = 82^o$ (Zdravkovich 1987). Consequently, the recovery of the base pressure is the lowest obtained. The result is a wide turbulent wake and a high pressure drag. In the critical flow range, C_{pb} rises rapidly with Re (as shown in Fig. 2) because the separation points move to the rear portion of the cylinder and the pressure gain in the rear of the cylinder is substantial. Over the supercritical flow range, there is a direct transition from a laminar to a turbulent boundary layer at a position some degrees downstream of the maximum cross-section. Consequently, the wake width and the pressure drag are smaller than those for the subcritical flow regime.

In the sub-and supercritical flow regimes, both steady and fluctuating forces are created on a circular cylindrical member due to flow separation and vortex shedding. Each time a vortex is shed from the cylinder, it alters the local pressure distribution, and the cylinder experiences a time-varying force at the frequency of vortex shedding. Thus, in addition to a mean drag force, circular cylinders are also subjected to fluctuating lift and drag components (Kim and Sakamoto 2006). If the natural frequency of the cylinder is sufficiently close to the dominant frequency of vortex shedding, and if the cylinder damping is sufficiently low, sustained vibrations of the cylinder can be excited. The "steady" drag forces on the cylinder remain essentially unaltered when the cylinder vibrates in the in-line direction, but these increase as a function of vibrational-amplitude when the

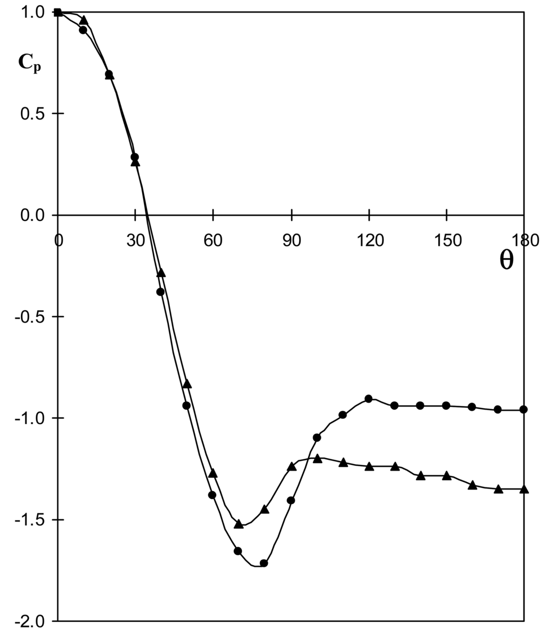


Fig. 3 Pressure distribution around the PC model with:- ▲, wide wake; ●, narrow wake

cylinder vibrates in the cross-flow direction. The severity of problems associated with sustained vibrations depends to a great extent upon the use or nature of the cylindrical member. Cross-flow vibrations of cylinders and cables tend to produce material fatigue (Robertson, *et al*. 2001, Uematsu, *et al*. 2001, Peil and Behrens 2002) and also cause increases in quasi-steady drag forces which, in turn, can decrease fatigue life.

Unless otherwise stated ,all the data presented in this paper were measured at two Reynolds numbers of 4.5×10^4 and 10.5×10^4 based on the cylinder diameter, $D = 47$ mm. These Reynolds numbers were chosen, respectively, to represent laminar separation producing a wide wake and turbulent separation producing a narrow wake. Fig. 3 shows the mean pressure distribution around the PC model with a wide and narrow wake mode.

3.2. Circular cylinder with wake control

A wake splitter plate has been used frequently as a successful means of wake stabilization, as it tends 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. Previous investigations have demonstrated the extent to which the vortex shedding characteristics could be altered by a splitter plate (Bearman 1965, Nakamura 1996, Anderson and Szewczyk 1997, Ozono 1999, Dalton, *et al*. 2001, and Ozono 2003). It was shown (Apelt, *et al*. 1973) that the introduction of a splitter plate in the range of Reynolds numbers from 10^4 to 5×10^5, significantly narrowed the wake width and also had an extremely strong influence on the drag of the cylinder with a reduction in some cases of up to 36%. These results were for a circular cylinder with an attached splitter plate. The effects of a gap between the cylinder and the splitter plate were studied by Akilli, *et al*. (2005), and earlier by Unal and Rockwell (1987) whose measurements indicate that when a splitter plate is located sufficiently close to the body, the vortex street cannot develop, and the wake is dominated by an instability of the shear layer separating from the cylinder. Drag reduction on a circular cylinder using dual detached splitter plates was numerically studied by Hwang, *et al*, (2007) for laminar flows ($Re = 100$ and 160). Two splitter plates with the same length as the cylinder diameter were placed along the horizontal centerline; one upstream of the cylinder and the other in the near-wake region, respectively. It was concluded that the upstream splitter plate reduced the stagnation pressure by friction, while the downstream one increased the base pressure by suppressing vortex shedding. The maximum net effect has been computed to be 38.6% reduction of drag compared to the case without splitter plates.

The effects of base shield plates placed at a gap G in the wake region of a smooth circular cylinder at subcritical flow regime have been reported in details by EI-Khairy (2003). Drag forces on the model at a given G/D and L/D were measured at a range of Reynolds numbers from $4{\times}10^4$ to 10^5. Depending on the cavity width G/D, two flow regimes were observed: (a) flow regime A, for $G/D \leq 0.86$, 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.

It was concluded that the action of the plates in flow regime A is to shift the separation points to the rear portion of the cylinder and to develop an intermediate buffer region of a quasi-steady fluid between the plates that decreases the strength of the vortex street. This leads to a substantial increase in base pressure and a decrease in drag. The greatest effects on the drag coefficient C_d and base pressure coefficient C_{pb} were observed for $G/D = 0.86$ and $L/D = 1$.

Kruiswyk and Dutton (1990) experimentally investigated the effect of a cavity at the base of a slender two-dimensional body as a measure to reduce the drag. Flow visualization and hot wire measurements showed that the vortex formation location was shifted down stream and the vortex street was weakened by the base cavity. Both effects yielded higher pressures in the near wake, increased the base pressure on the order of 10 to 14% relative to the blunt-based configuration.

3.2.1. Shield plates optimum configurations

The next study was carried out to identify the optimum configurations giving maximum base pressure in the sub- and supercritical flow regimes. The rough circular cylinder was first fitted with base shield plates of chord $L = D$ and base pressure measurements were made for values of G/D from 0.00 to 0.93 at Re of $4.5{\times}10^4$ and $10.5{\times}10^4$ in the sub-and supercritical flow regimes, respectively. The variations of C_{pb} with G/D are shown in Fig. 4.

In the case of wide wake mode, it is seen that as the cavity width was increased from G/D of 0.00 to 0.86, the base pressure coefficient gradually rise from -0.95 to -0.62. In the case of narrow wake mode, the base pressure coefficient is seen to rise from -0.83 to -0.58 as the cavity width G/D was increased from 0.00 to 0.78. Thus, compared with the case of a wake splitter plate where $G/D = 0.00$, one can get 35% base pressure increase for wide wake and 30% increase for narrow wake by using base shield plates at the optimal cavity widths of 0.86 and 0.78, respectively. This implies that for base shield plates at the optimum cavity width there exists some flow mechanism other than that which only splits the wake into two parts, thereby weakening the vortex shedding and resulting in higher base pressure and reduced drag.

Fig. 4 shows that the optimum value of G/D for maximum C_{pb} is slightly higher when the wake mode is wide than when it is narrow, mainly because of the size of the wake. Fig. 4 shows also that

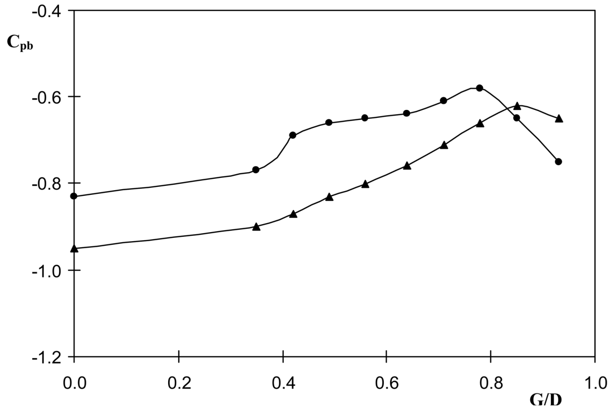


Fig. 4 C_{pb} versus *G*/*D* for the MC2 model with:- ▲, wide wake; ●, narrow wake.

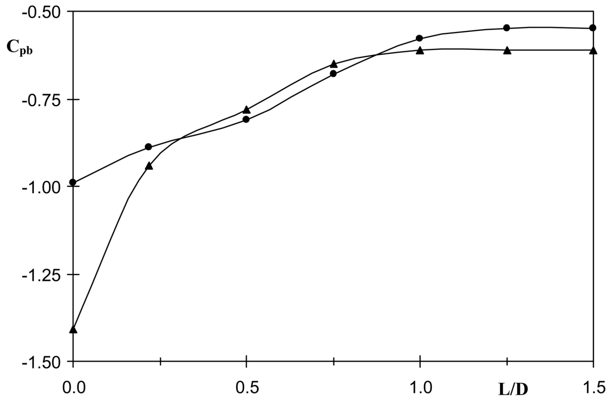


Fig. 5 C_{pb} versus *L*/*D* for the MC2 model with; ▲, wide wake and $G/D = 0.86$; ●, narrow wake and $G/D = 0.78$.

the base pressure cannot be continuously increased with increasing *G*/*D* because, at some critical cavity width, the path of the separating shear layers would be impeded by the plates during part of the shedding cycle. It has been shown by EI-Khairy (2003) that increasing the cavity width to a value larger than the critical would cause an opening of the wake and a decrease in the base pressure. This leads to flow regime B, in which the shear layers reattach onto the shield plates with the final separation pointes at the trailing edges of the plates.

To study the effects of the shield plates chord *L*/*D* on C_{pb}, base pressure measurements were made for values of *L*/*D* from 0.0 to 1.5. Fig. 5 shows the variations of C_{pb} with *L*/*D* at the optimum cavity widths *G*/*D* of 0.86 and 0.78 in the sub- and supercritical flow regimes, respectively. The graph shows clearly that the base pressure reaches a maximum value with a shield plates chord equal to one cylinder diameter and that increasing the plates chord to 1.5 cylinder diameter yields only slightly greater base pressure benefits. This was precisely the same conclusion arrived at in the case of smooth cylinder fitted with shield plates in the subcritical flow regime (EI-Khairy 2003). Fig. 5 shows that the increase rate in C_{pb} as *L*/*D* was increased from 0.0 to 1.0 is higher when the wake mode is wide than when it is narrow. Compared with the case of PC model where $L/D = 0.0$, it can be seen that base shield plates of chord 1.0 D at the optimum *G*/*D* caused the base pressure to increase by 54% and 41% for the wide and narrow wake modes, respectively. A similar increase in base pressure was noted by Nash, Quincey and Callinan (1963) when they added a trailing edge cavity to a blunt-based aerofoil section. The rear section of the aerofoil was parallel-sided and the cavity was formed by adding thin extensions to the upper and lower surfaces. Generally, they have found base drag reductions of 15-20% in the subsonic speed range and no effect into the supersonic speed range. They concluded that the lack of any effect at supersonic speeds is evidence that the cavity acts on the vortex street since vortex shedding ceases at Mach numbers just beyond 1.0.

3.2.2. Effects of shield plates on the drag and pressure coefficients

Figs. 6 and 7 show the pressure distributions around the circumferences of the MC2 model with $L/D = 1$ at the optimum cavity widths G/D of 0.86 and 0.78, in the sub-and supercritical flow regimes, respectively. In addition, each of the two diagrams shows the pressure distribution around the circumference of the PC and MC1 models at the same Reynolds number for comparison.

These figures show that the profiles of the front surface of the MC2 model up to $\theta \leq \pm 60^{o}$ come close to those of the MC1 and PC models. In both types of flow regime, it is seen that the pressure distributions on the rear parts of the MC2 model exhibit the most substantial deviation from those of the PC and MC1 models. These profiles show that the MC2 model has the advantage of having a substantial pressure increase within the cavity region at $\theta \geq \pm 130^{o}$ for wide wake mode (Fig. 6) and at $\theta \geq \pm 140^{o}$ for narrow wake mode (Fig. 7). Compared with the case of PC model, the increase in the essentially constant pressure within the cavity region is substantially greater when the wake mode is wide than when it is narrow. Therefore it is expected that this increase in pressure within the cavity region will be the major cause of drag reduction and that the magnitude of the drag

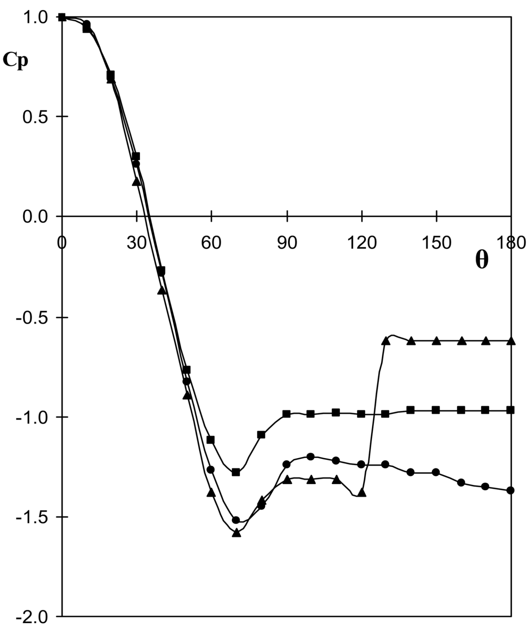


Fig. 6 Pressure distribution around the models with wide wake mode:- ●, PC ($C_d = 1.36$); ■, MC1($C_d = 1.04$); ▲, MC2 with $G/D = 0.86$ ($C_d = 0.64$).

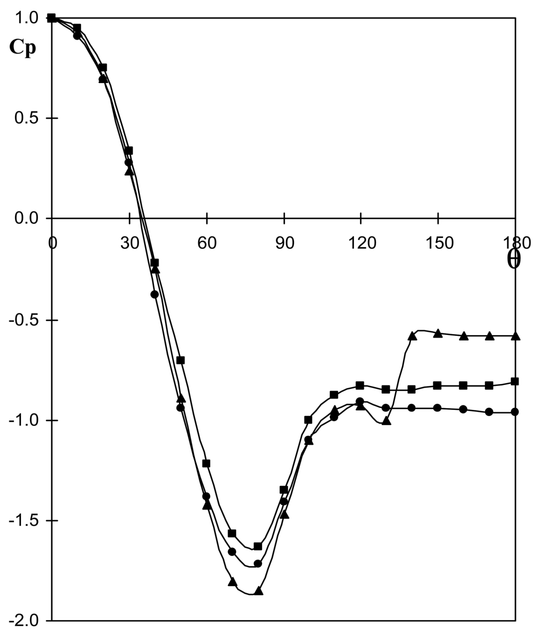


Fig. 7 Pressure distribution around the models with narrow wake mode:- ●, PC ($C_d = 0.90$); ■, MC1 ($C_d = 0.84$); ▲, MC2 with $G/D = 0.78$ ($C_d = 0.56$).

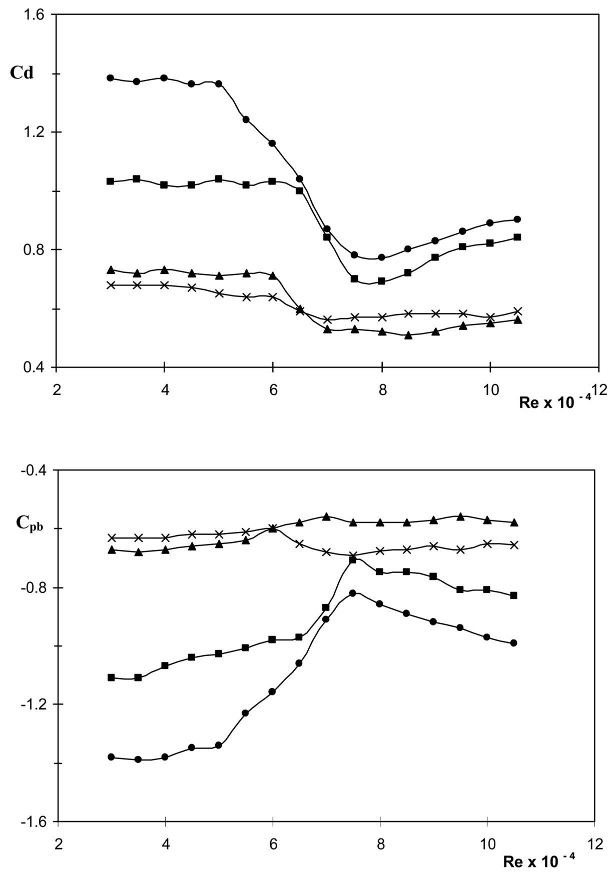


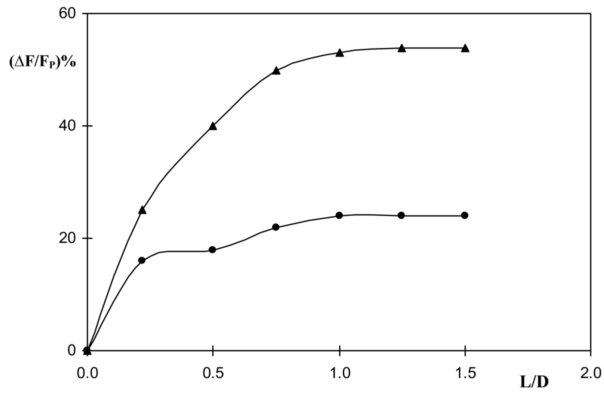
Fig. 8 C_d and C_{pb} versus *Re* for the models; ●, PC; ■, MC1; ▲, MC2 with $G/D = 0.78$; ×, MC2 with $G/D = 0.86$.

reduction would be more significant when the wake mode is wide.

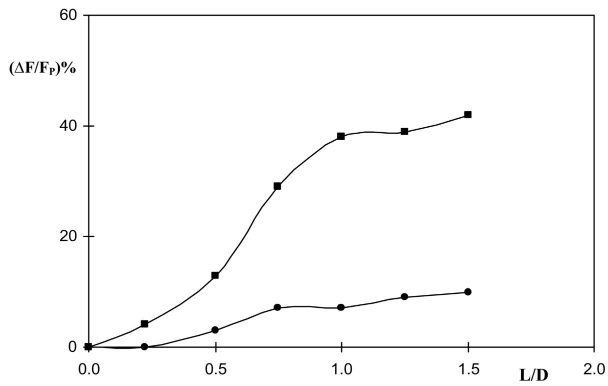
The variations of C_{pb} and C_d with *Re* for the PC and MC2 models at the optimum *G*/*D* are shown in Fig. 8. To identify the effect of the base cavity of the MC2 model, the experimental results for the MC1 model, where $G/D = 0.00$, are also presented in Fig. 8.

It is seen that over the whole range of *Re* tested, shield plates and splitter plates result in a significant increase of base pressure and reduction in drag when compared with those of the plane cylinder. This is because both devices divide the wake into two parts, and therefore the interaction between the shear layers is delayed and vortices can only form beyond the end of the plates. Thus the formation of strong vortices at the cylinder base is prevented which results in a significant increase of the base pressure. This influence is associated with drag reduction and the trailing edges of the plates provide a fixed formation region for the vortices.

The variations of C_{pb} with *Re* for the PC model in Fig. 8 illustrate why larger drag reductions are accomplished, when using splitter plates or shield plates for the subcritical range than for the supercritical one. This is because of the already smaller wake width and higher base pressure of the PC model in the supercritical flow regime. Previous investigation (Apelt, *et al.* 1973, Anderson and Szewczyk 1997, El-Khairy 2003) have shown that the effect of attaching splitter plates or base shield plates to a circular cylinder in the subcritical flow regime, is to shift the separation points to



a) Wide wake mode



b) Narrow wake mode.

Fig. 9 Percentage drag reduction versus *L*/*D* for the models; ●, MC1; ▲, MC2 with *G*/*D* = 0.86; ■; MC2 with *G*/*D* = 0.78.

the rear portion of the cylinder which causes a decrease in the wake width and a recovery in the base pressure. Fig. 8 shows also that over the whole range of *Re* tested, the base pressures of the MC2 cavity are substantially higher than those of the MC1 model. This is in agreement with the findings of Kruiswyk and Dutton (1990) who observed that the vortex street was weakened by the base cavity due to the enhanced fluid mixing occurring at the entrance of the cavity. The weaker vortex street yielded higher pressures in the near wake of the cavity and increased the base pressure coefficients.

It is evident from Fig. 8 that both C_{pb} and C_d of the MC1 model depend strongly on Reynolds number and that the trend of the drag coefficient followed approximately that of the base pressure, suggesting a relation between the two. However, the dependence of C_{pb} and C_d of the MC2 model on *Re* is true to a much lesser extent. For the MC2 model, the trend of the reduction in drag followed the trend of the increase in the base pressure. This result gives support to the theory that the drag reduction is tied to the effect of the base cavity in weakening of the vortex shedding and displacing the vortex formation position further down stream.

The MC2 model with $G/D = 0.86$ had lower values of C_d than the MC2 model with $G/D = 0.78$ from *Re* 3.0×10^4 to 6.0×10^4. Conversely, the MC2 model with $G/D = 0.78$ had the lowest C_d values from *Re* 7.0×10^4 to 10.5×10^4. The fact that the C_d curves of the MC2 models do not drop sharply with *Re* as it does for the PC model may be important, because rapid changes in aerodynamic forces can damage a structure.

The effects of shield plates chord L/D on the percentage drag reduction are summarized in Fig. 9 (a) and (b) in the sub-and supercritical flow regimes, respectively. It can be seen that shield plates at the optimum G/D caused large reductions in drag for both wide and narrow wake modes when compared to the drag reductions caused by splitter plates of the same chord. For wide wake mode and with $L/D = 1.0$, one can get 53% and 24% drag reductions for the MC2 and MC1 models, respectively, compared with the PC model. For narrow wake mode however, the corresponding drag reductions are 38% and 7% for the modified configurations with and without the base cavity, respectively.

4. Conclusions

An experimental investigation has been conducted to determine the effectiveness of base shield plates in reducing the drag of a rough circular cylinder in a cross flow at Reynolds numbers in the range $3\times10^4 \leq Re \leq 10.5\times10^4$. Three model configurations were investigated and compared: a plane cylinder, a cylinder with a splitter plate and a cylinder fitted with base shield plates. Each configuration was studied in the sub- and supercritical flow regimes. The chord of the plates, *L*, ranged from 0.22 to 1.50*D* and the cavity width between the plates, *G*, was in the range from 0 to 0.93D.

The conclusions drawn are:-

1) -In the subcritical flow regime, substantial increases in C_{pb} of the MC2 model are generated by the following mechanisms:-
   A) -The shifting of the separation points to the rear portion of the cylinder which causes a decrease in the wake width.
   B) -The delay in the interaction between the shear layers, thus the formation of strong vortices at the cylinder base is prevented.
   C) -The base cavity effects in weakening of the vortex shedding and displacing the vortex formation position further down stream.
2) -In the supercritical flow regime, somewhat less increases in C_{pb} of the MC2 model are produced, as these are generated by mechanisms B and C only.
3) -It is recognized that base shield plates can be employed more effectively than splitter plates to reduce the aerodynamic drag of circular cylinders in both the sub and supercritical flow regimes. This is due to the drag reducing potential of the base cavity.
4) -For subcritical flow regime, one can get 53% and 24% drag reductions for the MC2 and MC1 models with $L/D = 1.0$, respectively, compared with the PC model. However, the corresponding drag reductions for supercritical flow regime are 38% and 7%.

Nomenclature

C_d	Drag coefficient = $F/(0.5\ \rho\ H\ D\ V^2)$
C_p	Pressure coefficient = $(P - P_0)/(0.5\ \rho V^2)$
C_{pb}	Base pressure coefficient at $\theta = 180$ deg
D	Cylinder diameter

F	Drag force
G	Gap between shield plates (cavity width)
H	Span of cylinder and shield plates
K	Roughness particle diameter
L	Chord of shield plates
P_0	Static pressure in free stream
P	Local pressure on cylinder
Re	Diametral Reynolds number = $\rho\ V\ D\ /\ \mu$
Re_k	Roughness Reynolds number = $\rho\ V\ K\ /\ \mu$
μ	Dynamic viscosity of air
V	Free stream velocity
ρ	Density of air
θ	Circumferential angle on the cylinder

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