Wind and Structures, Vol. 12, No. 6 (2009) 541-551
DOI: http://dx.doi.org/10.12989/was.2009.12.6.541

Wind-tunnel blockage effect on drag coefficient of circular cylinders

J. Anthoine*

Von Karman Institute for Fluid Dynamics - Chaussée de Waterloo, 72 - B-1640 Rhode-St-Genèse, Belgium

D. Olivari

AirSR, Belgium and von Karman Institute for Fluid Dynamics - Chaussée de Waterloo, 72 - B-1640 Rhode-St-Genèse, Belgium

D. Portugaels

Service Public de Wallonie, Namur, Belgium

(Received April 8, 2009, Accepted August 20, 2009)

Abstract. This paper explains how to correctly measure the drag coefficient of a circular cylinder in wind tunnels with large blockage ratios and for the sub-critical to the super-critical flow regimes. When dealing with large blockage ratios, the drag has to be corrected for wall constraints. Different formulations for correcting blockage effect are compared for each flow regime based on drag measurements of smooth circular cylinders performed in a wind tunnel for three different blockage ratios. None of the correction model known in the literature is valid for all the flow regimes. To optimize the correction and reduce the scatter of the results, different correction models should be combined depending on the flow regime. In the sub-critical regime, the best results are obtained using Allen and Vincenti's formula or Maskell's theory with $\varepsilon = 0.96$. In the super-critical regime, one should prefer using Glauert's formula with $G = 0.6$ or the model of Modi and El-Sherbiny. The change in the formulations appears at the flow transition with a variation of the wake pattern when passing from sub-critical to super-critical flow regimes. This parameter being not considered in the known blockage corrections, these theories are not valid for all the flow regimes.

Keywords: drag coefficient; blockage effect; wind tunnel measurement; bluff body; circular cylinder; flow transition.

1. Introduction

The flow around a circular cylinder has been widely investigated (Houghton and Carpenter 2003, Zdravkovich 1997, Comolet 1994, Roshko 1993, Coutanceau and Defaye 1991, Williamson 1996, Simiu and Scanlan 1996). Depending on the Reynolds number, the flow field downstream the

* Corresponding Author, E-mail: anthoine@vki.ac.be

cylinder is complex and different flow regimes can be characterized. This complexity comes from the evolution of the position of the separation points along the cylinder circumference. The evolution from each flow regime to the next corresponds to a change in the position of the laminar to turbulent transition. This transition does not appear simultaneously in the whole wake, but as successive laminar to turbulent transitions initiated first in the far wake before moving back progressively to the cylinder surface up to the separation point (sub-critical flow regime). When the Reynolds number reaches a value in the vicinity of $3\cdot10^5$ the laminar boundary layer undergoes transition to turbulence almost immediately after separation and a separation bubble is formed. At this critical flow regime the separation point in the turbulent layer moves suddenly downstream, because of the better sticking property of the turbulent layer. With further increase in Reynolds number, the turbulent separation points slowly move upstream along the boundary layer towards the stagnation point (super-critical flow regime).

The transitions correspond to distinct flow regimes that affect pressure distribution over the body, and then the resulting drag force. The evolution of the drag coefficient (C_D) with the Reynolds number (Re) for a circular cylinder appears in many references (Houghton and Carpenter 2003, Zdravkovich 1997, Comolet 1994, Roshko 1961, Hoerner 1965, Batchelor 1967, Simiu and Scanlan 1996) and is given in Fig. 1. The drag evolutions in the critical regime vary significantly from one author to another, as reported in the literature (Batchelor 1967, Williamson 1996). This could be explained by the high sensitivity of the boundary layer transition to external parameters, such as the cylinder roughness, the turbulence intensity of the upstream flow, the blockage ratio (ratio between the model and the wind tunnel cross-section areas), the aspect ratio of the model and the geometry of the end plates. The critical regime being associated to a strong decrease of drag coefficient, the only regimes for which the drag force is important for an aerodynamic design are the end of the sub-critical and the early super-critical regimes, characterized by constant C_D values ($C_D=1.2$ and 0.3 respectively). Later in the super-critical regime, both the Re and the C_D are still higher but the wind velocity is out of the common practical range (<200 km/h).

In order to cover the Reynolds number range up to the early super-critical flow regime ($Re=1.3\cdot10^6$), cylinders of large diameters have to be used. For the low speed wind tunnel L1-A of the von Karman Institute (VKI), the maximum velocity being limited to 50 m/s, cylinders up to a

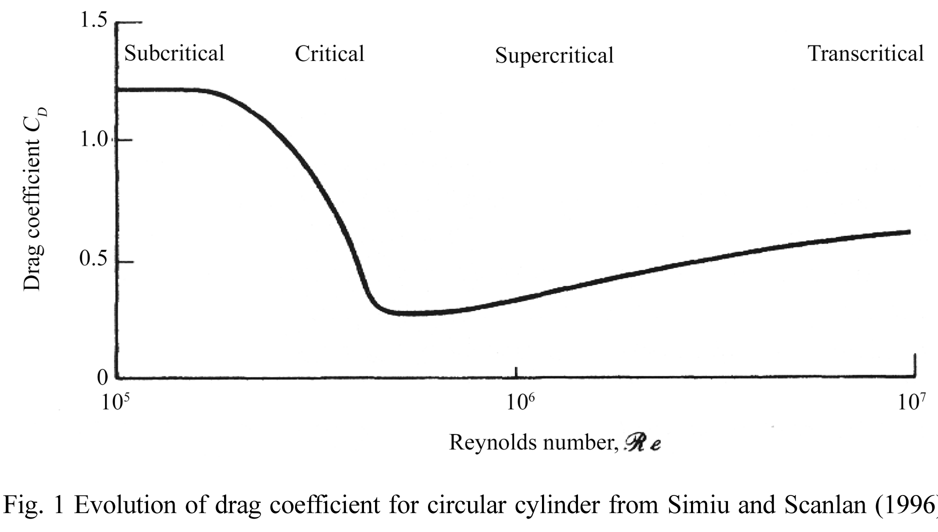

Fig. 1 Evolution of drag coefficient for circular cylinder from Simiu and Scanlan (1996)

diameter of 0.4 m were used to reach the targeted Reynolds number. In practice, one can neglect blockage effect of bluff bodies when the wind tunnel cross-section is at least 30 times larger than the bluff body cross-section (blockage ratio smaller than 3%). The test section of the VKI L1-A wind tunnel having a height of 2.36 m, the maximum blockage ratio corresponding to a cylinder of 0.4 m diameter is equal to 17%. In such conditions, the blockage effect cannot be neglected.

Cheung and Melbourne (1980) have already investigated the wind tunnel blockage effects on a circular cylinder in both smooth and turbulent flows. They did not propose formulations but empirical procedures for blockage correction and the blockage ratio they considered was ranging from 3% to 11% and the Reynolds number was limited to $6\cdot10^5$. However, their results will be compared to the present investigation. Other authors have also investigated blockage effects among which Cooper (1998), Gould (1970), Farell, *et al.* (1977), Cowdrey (1967), Maskell (1965), Hackett and Cooper (2001), and Chen and Doepker (1975). Parkinson (1984) has proposed a blockage-tolerant wind tunnel using a slatted-wall configuration of the test section, whose design is based on the potential flow theory, to limit the blockage effect when performing bluff body aerodynamic tests. In a similar version of the blockage-tolerant wind tunnel but adapted for wind engineering investigations, Kong and Parkinson (1995) tested models simulating large-truck trailer combinations and found drag coefficients unaffected by blockage for values as high as 29%.

When testing models in a non-slatted-walls wind tunnel with blockage ratio larger than 3%, corrections should be applied. Several authors have proposed formulations for blockage correction (Maskell 1965, Fage 1929, Lock 1929, Glauert 1933, Modi and El-Sherbiny 1973, Allen and Vincenti 1944). The objective of the present paper is to compare these existing formulations to correct blockage effect on the drag coefficient measurements of bluff bodies in closed wind tunnels and for different flow regimes. The bluff bodies considered in this paper are smooth circular cylinders.

2. Wind tunnel experiments

The measurements have been performed in the free jet test section of the VKI low speed wind tunnel L-1A. The test section of 3 m diameter and 4.5 m length is adapted with a rectangular insert with solid side, top and bottom walls that is used for tests of 2-D models. The flow velocity can vary continuously from 2 to 50 m/s. The contraction ratio is 4 with a typical turbulence level of

(a) (b)

Fig. 2 VKI low speed wind tunnel with rectangular insert equipped with strain gauge balances and one of the circular cylinder: (a) front view; (b) back view

Table 1 Characteristics of the smooth circular cylinders

Diameter (mm)	Blockage ratio (%)	Maximum Reynolds number	Aspect ratio	Non-dimensional surface roughness
160	6.8	$5.2 \cdot 10^5$	8.12	$1.25 \cdot 10^6$
320	13.6	$1.0 \cdot 10^6$	4.06	$6.25 \cdot 10^7$
400	17	$1.3 \cdot 10^6$	3.25	$5.00 \cdot 10^6$

0.3%. The insert is equipped with a transversal model support with strain gauge balances for the measurement of lift and drag (Fig. 2). For the present work, tests have been made on three smooth cylindrical models with circular cross-sections of different diameters to vary the blockage ratio (Table 1). The absolute surface roughness is equal to 0.2 μm for all the three cylinders which is far below the critical roughness value to be considered all as smooth. The three circular cylinders are in aerodynamic similitude.

When testing in a wind tunnel, the model has a finite length and the model extremities and side walls could introduce secondary effects (Fox and West 1990, Norberg 1994). Slaouti and Gerrard (1981) demonstrated that these effects have a strong influence on the near wake and then on the drag coefficient. To guarantee a two-dimensional flow around the cylinder, end plates are added perpendicularly to the cylinder axis. This is the reason for using the rectangular insert. Chen and Doepker (1975) showed that to guarantee the two-dimensional flow at high Reynolds numbers ($3.5 \cdot 10^5 < Re < 1.2 \cdot 10^6$), the cylinder aspect ratio should be higher than 3 times the model diameter. Achenbach (1968) reported also that in the critical flow regime, there was an effect on the drag force for an aspect ratio lower than 3 and found no systematic influence between the aspect ratios of 3.33 and 6.66. In our experiments, the end plates are separated by 1.3 m, leading to aspect ratio provided in Table 1. The end plates need also to be very large. Their size influences strongly the length over which the flow can be considered as two-dimensional. In our experiments, the ratio between the total length of the end plates (upstream and downstream the model) and the diameter of the cylinder ranges from 10 to 26 depending on the cylinder diameter. Finally, if the upstream or the downstream length of the end plates is too small, secondary effects could influence the upstream flow or the wake. In our experiments, the length of the end plates downstream the model is equal to 1.75 m, which is higher than 4.25 times the model diameter as suggested by Kubo, *et al.* (1989). The upstream length of the end plates is equal to 2.5 m, which proved to be sufficient since a reference plane with uniform pressure distribution (static and dynamic) has been identified at 1.8 m upstream of the model, for the 3 cases tested.

The free stream reference flow velocity was measured using a Pitot tube connected to a pressure transducer. The position of the Pitot tube, inside the rectangular insert at 1.2 m upstream and 0.4 m below the model, has been chosen based on the potential flow theory. The drag force was measured using two strain gauges balances connected to both extremities of the cylinder. The instantaneous drag results are recorded on a PC, before being averaged. It was checked that the mean value is independent of the number of acquisition points.

Fig. 3(a) shows the drag evolutions obtained for the three cylinders and the evolution obtained by Wieselberger (1923). One distinguishes the sub-critical, the critical and the early super-critical regimes. The drag force is increasing with the blockage ratio and should be corrected. The corresponding base pressure coefficients are given in Fig. 3(b). The differences observed between the curves of Fig. 3 come from the blockage effect.

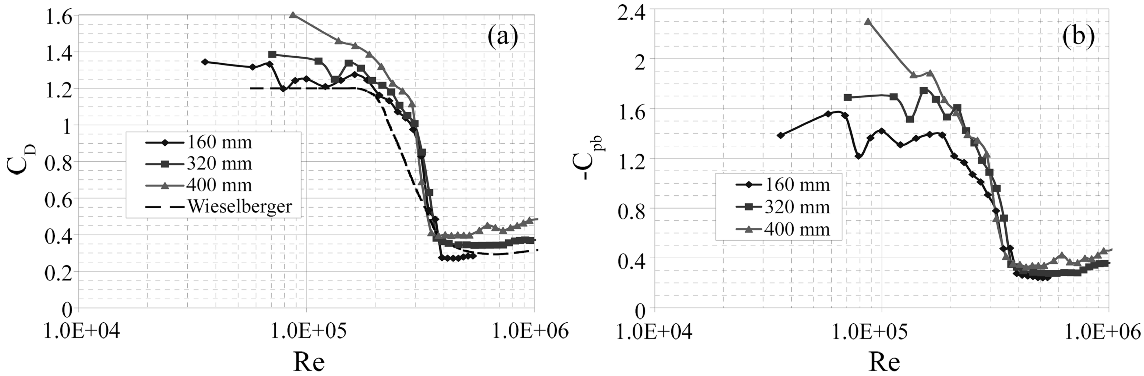

Fig. 3 Uncorrected drag coefficient (a) and uncorrected base pressure coefficient (b) evolutions

3. Blockage Effect

In a closed test section, the lateral walls prevent the flow to expand when passing around the cylinder (Fig. 4(a)). The flow around the cylinder is then accelerated compared to the value expected if the cylinder was put in an infinite space. When speaking about infinite space, one should consider that the cylinder is not surrounded by wall and that the velocity extends over an infinite cross-section. In these infinite conditions, the flow over the cylinder will be referred to U_c (corrected velocity). The flow acceleration obtained for a closed test section generates an over-estimation of the drag coefficient ($C_D > C_{D,c}$).

In an open test section wind tunnel, the model is placed in an "infinite" space. The flow can expand laterally (Fig. 4(b)), but the velocity extends only over a finite cross-section (the nozzle exit of the wind tunnel). This jet injection generates air entrainment from the surroundings. It results in an over-expansion of the flow around the cylinder corresponding to an under-estimation of the drag coefficient ($C_D < C_{D,c}$).

Blockage corrections are necessary for both closed and open test section wind tunnels. Fig. 5 shows a comparison of the closed and open test sections in the case of normal flat plates and rectangular blocks, both wall-mounted and centrally-mounted in the test section (Cooper 1998). The

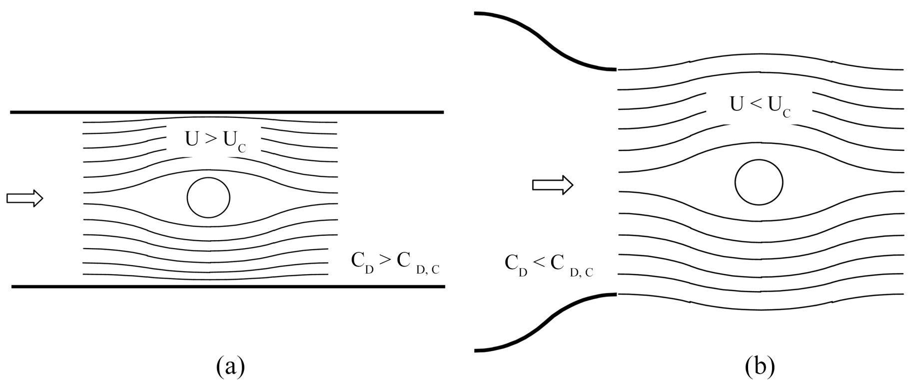

Fig. 4 Blockage effect in open (a) and closed (b) test section wind tunnels

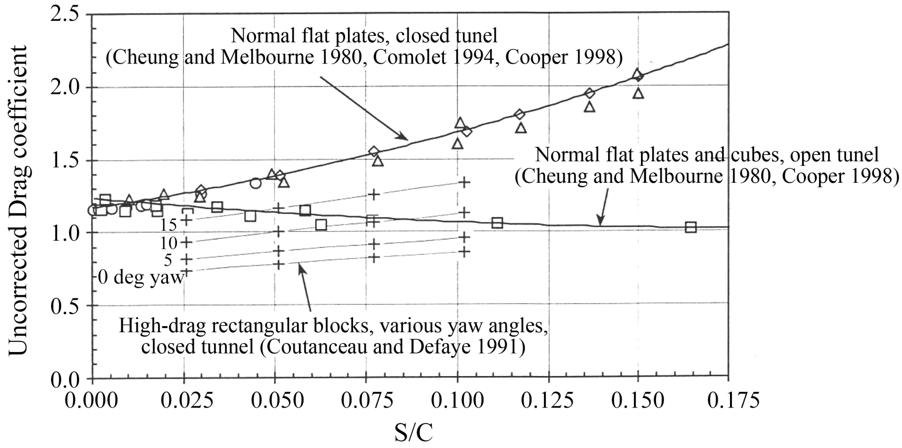

Fig. 5 Bluff-body blockage effects on drag in closed and open test sections (Cooper 1998)

models considered in this figure are three-dimensional bluff-bodies. As expected, the closed test section shows a drag increase with model area while the open test section shows a drag reduction. The blockage effect in the open test section is less than in the closed one. However it is more suitable to perform measurements in a closed test section since the correction formulations are better developed and the boundaries are more precisely defined in this case. The corrected drag coefficients obtained from a closed test section are certainly more reliable than those measured in an open test section without correction.

The present tests were performed by inserting the cylindrical models within a rectangular insert corresponding to a closed test section.

3.1. Theories for blockage correction

A mathematical prediction of blockage effects on flow past cylinders in the closed test section involves a complete solution of the Navier-Stokes equations. However, most theoretical models are based on the inviscid potential flow theory or general momentum balance (Zdravkovich 2003).

The three first theoretical corrections (Fage 1929, Lock 1929 and Glauert 1933) were derived for bodies of small drag such as aerofoils and not for high drag bodies like circular cylinders. They are based on the two-dimensional potential flow around Rankine's ovals (the circular cylinder appears as a special case) between straight and parallel walls. These correction formulations provide the ratio between the corrected and uncorrected drag coefficients. This ratio does not depend on the drag coefficient and on the base pressure coefficient but depends only on the blockage ratio and on an empirical factor. Within these three theories, the most advanced one is the theory of Glauert who suggested the next semi-empirical formula:

$$\frac{C_{D,c}}{C_D} = \left[\frac{1 - G(S/C)}{1 + 0.822(S/C)^2}\right]^2 \tag{1}$$

where S is the projected section perpendicular to the wind direction, C is the cross-section of the test section and G is an empirical factor. Glauert (1933) found a value of $G = 0.3$ for circular

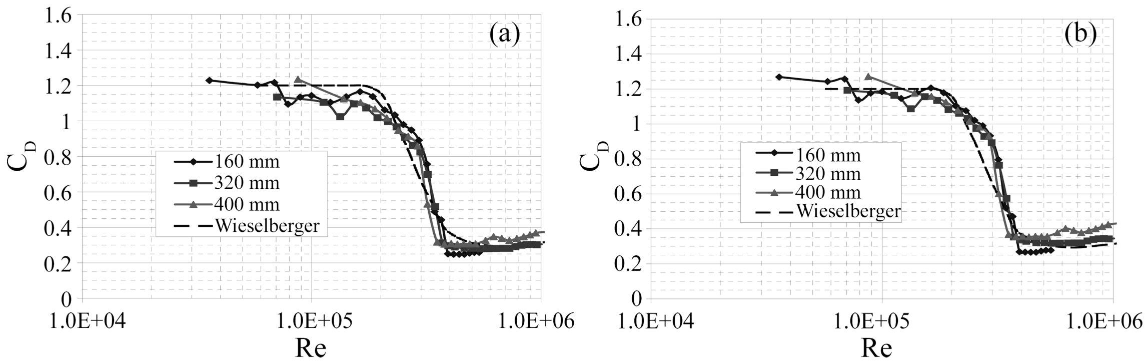

Fig. 6 Drag coefficient corrected by Glauert with $G=0.6$ (a) and by Allen and Vincenti (b)

cylinders. Modi and El-Sherbiny (1973) applied Glauert's formula to their drag measurements and showed that changing the empirical factor to $G=0.6$ gives a considerable improvement and reduces scatter of points. Fig. 6(a) shows the corrected drag coefficient using Glauert's formula with $G=0.6$. The scattering of the three curves is well reduced compared to raw data (Fig. 3(a)). Eq. (1) works well in the super-critical regime while it is over-correcting in the sub-critical regime.

Allen and Vincenti (1944) derived a theoretical model for the wake blockage by considering an inviscid, compressible and two-dimensional flow in a closed wind tunnel. Two stations in the wind tunnel are considered, far upstream from the cylinder and far enough downstream so that the wake has spread to the walls and the velocity is again uniform across the tunnel. The difference in static pressure between the two stations is evaluated as a function of the measured cylinder drag. The tunnel walls are simulated by an infinite system of sources placed directly above and below the position of the cylinder at intervals equal to the breadth of the tunnel. The drag coefficient correction terms are all negative and tend to reduce the measured drag coefficient. The final expression is:

$$\frac{C_{D,c}}{C_D} = 1 - \frac{\pi^2}{4}\left(\frac{S}{C}\right)^2 - \frac{C_D}{2}\left(\frac{S}{C}\right) \tag{2}$$

Fig. 6(b) shows the corrected drag coefficient using Allen and Vincenti's relation. In the super-critical regime, the scatter is higher than when using Glauert's formula (Fig. 6(a)), while Allen and Vincenti's formula works much better in the sub-critical regime.

Maskell (1965) has developed a semi-empirical model for axisymmetric wake and aerofoils. He also applied his theory to flat plates perpendicular to the flow, even for very high blockage ratios up to 20%. His theory is based on conservation of momentum between a cross-section upstream of the body where the flow is not perturbed and a downstream cross-section where the wake presents its maximum width. The assumptions made by Maskell are that:

- the pressure distribution is invariant under wall constraint,
- separated flows from three-dimensional bodies tend to become axially symmetric far downstream,
- the base pressure is constant over the separated region and is equal to the static pressure on the wake boundary,
- the constraining effect of the test section walls reduces the expansion of the wake and that this reduction is in proportion to the contraction of the external stream around the wake.

The final form of Maskell's theory is given by:

$$\frac{C_D}{C_{D,c}} = 1 + \varepsilon C_D \frac{S}{C} \tag{3}$$

where ε is the blockage constant. From best linear fit of experimental data, Maskell showed that ε =0.96 for bidimensional bluff bodies with sharp edges and with a wake width of the order of the bluff body dimension. This coefficient is theoretically linked to the base pressure coefficient by:

$$\varepsilon = \frac{-1}{C_{pb}} \tag{4}$$

Using Eq. (3), it is possible to correct the drag coefficient. Since the flow around the cylinder is accelerated compared to the value expected if the cylinder was put in an infinite space, the model is subject to a higher force due to the flow. However, the drag force measured with the strain gages is considered as being correct but the free stream velocity measured upstream the model is corrected through Eq. (3) to provide a reference velocity which is consistent with the measured drag force in the closed test section. A corrected Reynolds number can then be computed from this reference velocity. Eq. (3) assumes the use of the value 0.96 or the use of measured base pressure coefficients (Eq. (4)) for the blockage constant. Both possibilities have been compared on the data of Fig. 3 since the base pressure was measured. It was concluded that the use of Maskell's theory with blockage constant deduced from the base pressure coefficient (Eq. (4)) is not providing better results compared to Allen and Vincenti's formula in the sub-critical regime and to Glauert's formula in the super-critical regime. Fig. 7(a) shows the corrected drag coefficient using Maskell's theory with ε=0.96. This value works well in the sub-critical regime, the results being similar to those obtained with Allen and Vincenti's formula. However, scatter is observed in the super-critical regime proving that a single constant value for ε will never provide good results both in the sub-critical and super-critical regimes.

The blockage derivation of Modi and El-Sherbiny (1973) is based on the flow around a circle between parallel walls. The near-wake is simulated by two sources attached to the downstream side of the circle and by two sinks placed at the circle center. The source strength is determined by the location of the separation points. This model has been developed for two kinds of two-dimensional bodies: the flat plate and the circular cylinder. The experiments carried out to validate the model covered a wide range of blockage ratios (up to 35%) and Reynolds numbers ($10^4 < Re < 1.2 \cdot 10^5$). According to the authors, the theoretical model predicted the drag coefficient quite well, even for high

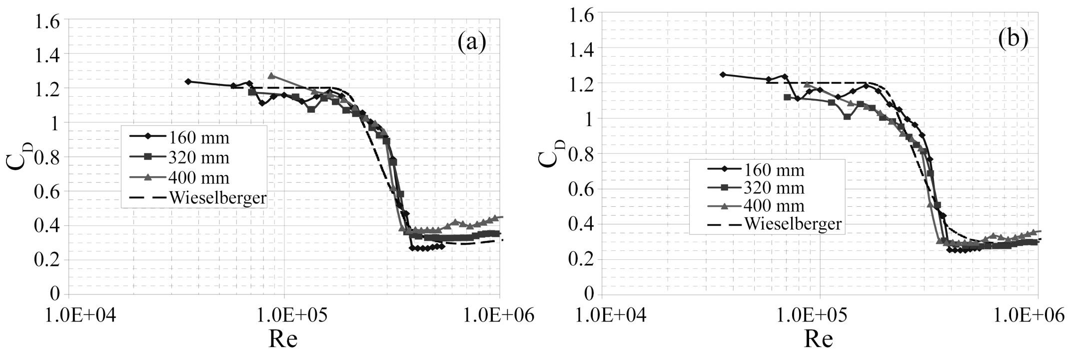

Fig. 7 Drag coefficient corrected by Maskell with ε=0.96 (a) and by Modi & El-Sherbiny (b)

values of blockage ratio, and the validity of the model does not seem to be limited to these values of Reynolds numbers, although this was not demonstrated because of a lack of experimental data in these conditions. The only limitation of the model is the concept of the wake without eddy street.

Fig. 7(b) shows the corrected drag coefficient using Modi and El-Sherbiny's theory. The formula works well in the super-critical regime while it is over-correcting in the sub-critical regime. The conclusion is similar to the one derived from Glauert's formula with $G=0.6$.

3.2. Blockage effect at different flow regimes

The results from Figs. 6 and 7 indicate that it is possible to correct drag coefficients when measured in a wind tunnel under high blockage ratio. However, to optimize the correction and reduce the scatter of the results, different correction models should be applied depending on the flow regimes. In the sub-critical regime, the best results are obtained using Allen and Vincenti's formula or Maskell's theory with $\varepsilon=0.96$. In the super-critical regime, one should prefer using Glauert's formula with $G=0.6$ or the model of Modi and El-Sherbiny. It should also be noted that the blockage corrections to the drag coefficient applied in this study have been compared and are consistent with the results of Cheung and Melbourne (1980) obtained through empirical procedures.

It seems strange that none of the aforementioned model is valid for all the flow regimes. Indeed, the theories developed up to now are considering that the wall constraint depends only on the blockage ratio, the measured drag coefficient and an empirical factor, except that Maskell considers also the effect of the base pressure, when used with Eq. (4). So, all the theories aforementioned should provide an accurate correction for blockage effect whatever the flow regime since neither the Reynolds number nor the wake properties appear explicitly in the correction model. However, this is not the case for circular cylinders, for which we found a unique theory is not valid. Maskell's theory, when based on the base pressure, has also proved to fail for circular cylinders.

Some theories, like the Maskell's theory with $\varepsilon=0.96$, assume that the base pressure evolution is proportional to the drag coefficient evolution. So, as observed in Fig. 3, if the drag coefficient is increased, the base pressure coefficient is increasing (in absolute value) so that

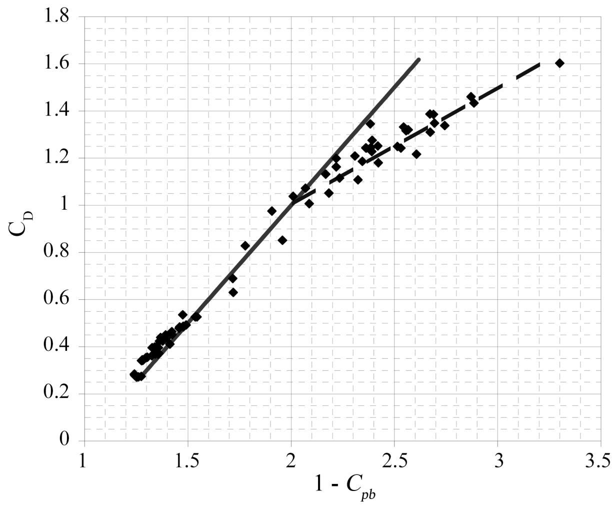

Fig. 8 Drag coefficient versus $(1-C_{pb})$ for circular cylinders

$$\frac{C_D}{1 - C_{pb}} = \text{constant} \tag{5}$$

Fig. 8 shows the evolution of the drag coefficient versus $(1-C_{pb})$ for the three circular cylinders. The values of drag coefficients are located along two different slopes. The change in the slope appears at $C_D=1$, which corresponds to the flow transition when passing from sub-critical to super-critical flow regimes. During that transition a variation of the wake pattern is occurring that is not considered as a parameter in the blockage corrections presented above. This might explain why the theories are not valid for all the flow regimes, since they are defined with only one empirical factor in place of one factor per slope as in Fig. 8.

There is no reason indicating that the theories cannot be applied to the different flow regimes but the empirical factor should be adapted for each regime associated to a different slope in Fig. 8. For example, it is probably possible to apply Maskell's theory (Eq. (3)) with a blockage constant of $\varepsilon=0.96$ for the sub-critical flow regime, when the slope is along the solid line of Fig. 9, and another value of this parameter for the super-critical regime. However, up to now this value is not yet known.

4. Conclusions

It is really difficult to avoid wall effects when investigating the drag coefficient of circular cylinders. Different formulations for correcting blockage effect on drag evolution are compared for each flow regime based on drag measurements of circular cylinders performed in a large low-speed wind tunnel for three different blockage ratios. None of the correction models known in the literature is valid for all the flow regimes. It is shown that the formulation providing the best correction for cylinders depends on the flow regime. To optimize the correction and reduce the scatter of the results, different correction models should be combined depending on the flow regimes. In the sub-critical regime, the best results are obtained using Allen and Vincenti's formula or Maskell's theory with $\varepsilon=0.96$. In the super-critical regime, one should prefer using Glauert's formula with $G=0.6$ or the model of Modi and El-Sherbiny. The change in the formulations is appearing at the flow transition with a variation of the wake pattern when passing from sub-critical to super-critical flow regimes.

Acknowledgments

This study has been proposed and financed by the Service Public de Wallonie through the "convention de services 451A.00.01". The authors are grateful to the Ministère wallon de l'Equipement et des Transports for authorizing them to publish and present the results obtained within the research contract.

References

Achenbach, E. (1968), "Distribution of local pressure and skin friction around a circular cylinder in cross flow up to $R=5\times10^6$", *J. Fluid Mech.*, **34**, 625-639.

Allen, H.J. and Vincenti, W.G. (1944), "Wall interference in a two-Dimensional flow wind tunnel, with consideration for the effect of compressibility", NACA Tech. Rep., No. 782.

Batchelor, G.K. (1967), *An introduction to Fluid Dynamics*, Cambridge University Press.

Chen, P.Y. and Doepker, P.E. (1975), "Flow-induced forces on a cylinder for different wall confinements at high Reynolds numbers $(3.5\times10^5)<\mathrm{Re}<(1.2\times10^6)$", *J. Press. Vess. T.*, **85**, 110-117.

Cheung, C.K. and Melbourne, W.H. (1980), "Wind tunnel blockage effects on a circular cylinder in turbulent flows", *Proc. of the 7th Australian Hydraulics and Fluid Mechanics Conf.*, Brisbane, 127-130.

Comolet, R. (1994), *Mécanique expérimentale des fluides. Tome 2, dynamique des fluides réels, turbomachines*, 4ème édition, Masson, Paris.

Cooper, K.R. (1998), "Bluff-body blockage corrections in closed- and open-test-section wind tunnels", AGARGograph 336 "Wind Tunnel Wall Corrections", chapter 6, NATO.

Coutanceau, M. and Defaye, J.R. (1991), "Circular cylinder wake configurations: a flow visualization survey", *Appl. Mech. Rev.*, **44**, 255-305.

Cowdrey, F. (1967), "The application of Maskell's theory of wind-tunnel blockage to very large solid models", NPL Aero Rep., No. 1247.

Fage, A. (1929), "On the two dimensional flow past a body of symmetrical cross-section mounted in a channel of finite breadth", Brit. Aero. Res. Council, Rep. and Memo., *No. 1223.*

Farell, C., Carrasquel, S., Guven, O. and Patel, V.C. (1977), "Effect of wind-tunnel walls on the flow past circular cylinders and cooling tower models", *J. Fluids Eng.*, **99**, 470-479.

Fox, K.A. and West, G.S. (1990), "On the use of end plates with circular cylinders", *Exp. Fluids*, **9**, 237-239.

Glauert, H. (1933), "Wind tunnel interference on wings, bodies and airscrews", Brit. Aero. Res. Council, Rep. and Memo., No. 1566.

Gould, R.W.F. (1970), "Wake blockage corrections in a closed wind tunnel for one or two wall-mounted models subject to separated flow", Brit. Aero. Res. Council, Rep. and Memo., No. 3649.

Hackett, J.E. and Cooper, K.R. (2001), "Extensions to Maskell's theory for blockage effects on bluff bodies in a closed wind tunnel", *Aeronaut. J.*, **105**, 409-418.

Hoerner, S. (1965), *Fluid dynamic drag*, published by the author.

Houghton, E.L. and Carpenter, P.W. (2003), *Aerodynamics for engineering students*, 5th edition, Butterworth & Heinemann, Oxford.

Kong, L. and Parkinson, G.V. (1995), "Road vehicle testing in a blockage tolerant wind tunnel", *J. Wind Eng. Ind. Aerod.*, **57**, 137-143.

Kubo, Y., Miyazaki, M. and Kato, K. (1989), "Effects of end plates and blockage of structural members on drag force", *J. Wind Eng. Ind. Aerod.*, **32**, 329-342.

Lock, C.N.H. (1929), "The interference of a wind tunnel on a symmetric body", Brit. Aero. Res. Council, Rep. and Memo. No. 1275.

Maskell, E.C. (1965), "A theory of the blockage effects on bluff bodies and stalled wings in a closed wind tunnel", Brit. Aero. Res. Council, Rep. and Memo., No. 3400.

Modi, V.J. and El-Sherbiny, S.E. (1973), *On the wall confinement effects in the industrial aerodynamics studies*, BNES Vibration in Nuclear Plant, paper 116, ed. Wakefield, J., Keswick, UK.

Norberg, C. (1994), "An experimental investigation of the flow around a circular cylinder: influence of aspect ratio", *J. Fluid Mech.*, **258**, 287-316.

Parkinson, G.V. (1984), "A tolerant wind tunnel for industrial aerodynamics", *J. Wind Eng. Ind. Aerod.*, **16**, 293-300.

Roshko, A. (1961), "Experiments on the flow past a circular cylinder at very high Reynolds numbers", *J. Fluid Mech.*, **10**, 345-356.

Roshko, A. (1993), "Perspectives on bluff body aerodynamics", *J. Wind Eng. Ind. Aerod.*, **49**, 79-100.

Simiu, E. and Scanlan, R.H. (1996), *Wind effects on structures: fundamentals and applications to design*, 3rd edition, John Wiley, New York.

Slaouti, A. and Gerrard, J.H. (1981), "An experimental investigation of the end effects on the wake of a circular cylinder towed through water at low Reynolds numbers", *J. Fluid Mech.*, **112**, 297-314.

Wieselberger, C. (1923), *Der Widerstand verschiedener Korper*, Ergebnisse der Aerodynamischen Versuchsanstalt zu Gottingen, II. Lieferung, ···, S. 33-34.

Williamson, C.H.K. (1996), "Vortex dynamics in the cylinder wake", *Ann. Rev. Fluid. Mech.*, **28**, 477-539.

Zdravkovich, M.M. (1997), *Flow around circular cylinders, Vol. 1: Fundamentals*, Oxford Science Publications, Oxford.

Zdravkovich, M.M. (2003), *Flow around circular cylinders, Vol. 2: Applications*, Oxford Science Publications, Oxford.

JH