VERRINGERUNG DES WIDERSTANDS UMSTRÖMTER KÖRPER DURCH LEESEITIGE PORÖSE BESCHICHTUNG

DRAG REDUCTION OF BODIES BY LEEWARD POROUS COATING

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Widerstandsverminderung von Körpern, poröse Beschichtung, permeable Wandschicht
Drag reduction, flow resistance of bodies, leeward porous coating, wall permeability

Abstract

Coating of bluff bodies with high permeable porous media seems to be a possibility of passive flow control, however, it is not known and not understood completely how full or partial porous coating changes the fluid mechanical properties of bodies. In order to investigate these phenomena, the drag resistance of cylinders with porous coating in the lee has been investigated qualitatively and quantitatively in wind tunnel experiments. The size of the leeward porous-coated area of the cylinders was altered in the experiments. The Reynolds number was systematically varied in the range from 10^4 to $1.3*10^5$. The results show that a partial coating on the leeward side can decrease the flow resistance of the body. This effect seems due to the fact that the recirculating velocity and the underpressure in the wake is reduced significantly through a leeward porous coating. Thus, combining a smooth non-permeable windward side with a porous-coated leeward side can lead to a reduction of the body's flow resistance. These findings could be applied advantageously in many technical areas, such as energy saving of moving bodies (cars/trains/planes) or in reducing fluid loads on submersed bodies.

Introduction

Fluid mechanical research in the field of porous permeable media has been centered in the past mainly on low porosities. To describe flow and pressure losses, typically, Darcy's law (Darcy 1856, Bear 1972) and the Darcy-Forchheimer law (Forchheimer 1914-1916) were used. However, deviations from these laws can be induced by flow velocities, which are no longer small, or by unsteady flow effects or by the fact that the pore volume of the porous medium is so large that turbulence can be sustained or even be generated in the porous medium. Consequently, researchers have developed different approaches and models to extend these laws in order to account for nonlinearities from viscous, inertial, thermal or drag effects, see e.g. Scheidegger 1974, Bear 1972, Barak and Bear 1981, Hassanizadeh and Gray 1987.

The boundary layer flow at a porous medium/fluid interface has been investigated by several authors see e.g. Vafai and Thiyagaraja 1987 and Vafai and Kim 1990, Hahn and Choi 2002, Breugem et al. 2006. Theoretical, numerical and experimental studies exist on this topic. Zagni and Smith 1976 carried out flow experiments over permeable beds consisting of spheres and showed that the friction factor is increased when compared to the impermeable wall with the same roughness. They concluded that the increase in friction factor is due to an enhanced energy dissipation caused by momentum transfer perpendicular to the interface. Similar results were found by Zippe and Graf 1983, who investigated a turbulent flow over a permeable bed of grains in a wind tunnel study. Apparently, the experiments carried out in the past have underlined that wall permeability changes the turbulent flow structure in the boundary layer along the interface and increases the friction factor when compared to the non-permeable wall.

There are only few studies that indicate that one could use the interfacial effects of porous walls advantageously in drag reduction of bodies submersed in a flow. Coating surfaces with porous materials could be energy-saving as stated by Bruneau and Mortazavi 2006 a, who found in a numerical simulation that the flow resistance of vehicles could be reduced up to 45%. The reason for this might be an increase in base pressure in the lee of the vehicle induced by thin porous layers attached to the rear part of the vehicle. Other numerical simulations indicated that the amplitude of vortex shedding, which may lead to destructive structure oscillations, can be reduced by applying a porous outer layer (sheath) on the body, see Bruneau and Mortazavi 2006 b and also Bhattascharyya and Singh 2011. From a fluid mechanical point of view, these findings correspond to those of Price 1956 and Wong 1979, who reported about a delay in vortex formation and about a suppression of vibration of shrouded cylindrical pillars realized by slats. According to Price 1956, the mechanism of vibration suppression is induced by the delay in vortex street formation. The latter can be seen clearly in the visualization study of Galbraith 1980, who analyzed the flow pattern around a shrouded cylinder at Re = $5*10^3$ and who reported about a significant base bleed. He concluded that the greater the amount of base bleed the longer the vortices take to form and the lower the drag. This seems to hold not only for permeable shrouds, but also for high-porous permeable homogeneous surface layers.

Since the few existing studies are mainly of numerical type and subject to well-know limitations (DNS only at very low Reynolds numbers; subgrid scale modelling of LES cannot predict real interfacial flow phenomena; wall functions of k-ε models cannot resolve correctly flow physics at surfaces / interfaces), experimental investigations are lacking, which contribute to the fundamental understanding of the phenomena involved. A first experimental investigation on the drag reduction of cylinders with permeable coatings has been presented by Klausmann et al. 2011. They found that, indeed, drag reduction of bluff bodies can be obtained when the body's leeward side is coated with a thin permable layer of porous medium.

Experimental details

Test cylinders

In order to measure the fluid mechanical effect of high-porous coating, cylinders were made of balsa wood cores. The length was for all cylinders L = 70 cm and the outer diameter remained constant for all cylinders with D = 70 mm. In the case of full jacketed cylinders, the wood core was encased with a high-porous shell.

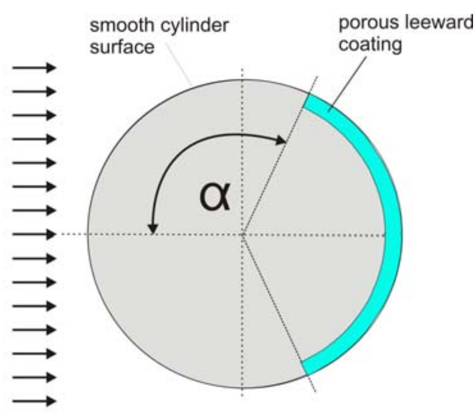


Fig. 1: Porous-coating in the lee of cylinders

In the case of only leeward coated cylinders, only a part of the leeward surface was covered with an inserted porous layer not changing the outer diameter of the cylinders, see Fig.1. The porous coating of the cylinder was made of the technical Poret foam-Ester from EMW Filtration GmbH, 65582 Diez, Germany. Poret-Ester foam is conventional polyester foam with high toughness and sponge-like porosity available in a wide range of sizes and shapes and widespread in engineering. The used foam varied according to the layer thickness and the chosen porosity. Two measurement series have been performed. The first series relates to a symmetrical (to the horizontal axis of flow) porous coating in the lee and comprises the configurations shown in Fig. 2. The second series relates to a 160° cylinder coating whose axis was tilt to the approach flow, see Fig. 3.

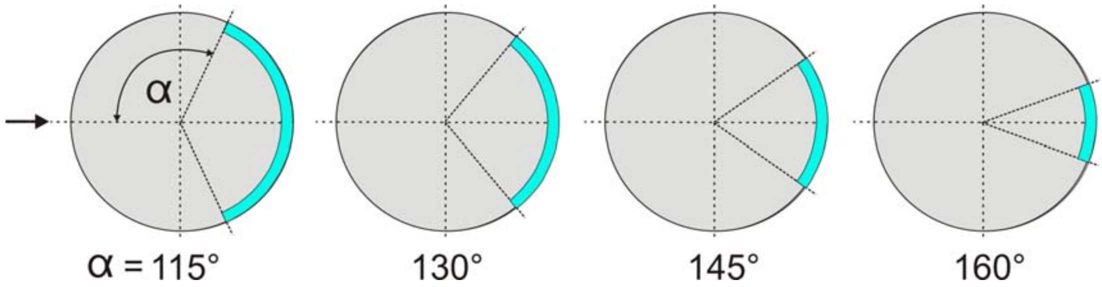


Fig. 2: Series 1 - Sketches of the configurations investigated in the wind tunnel; symmetrical porous coating in the lee of cylinders

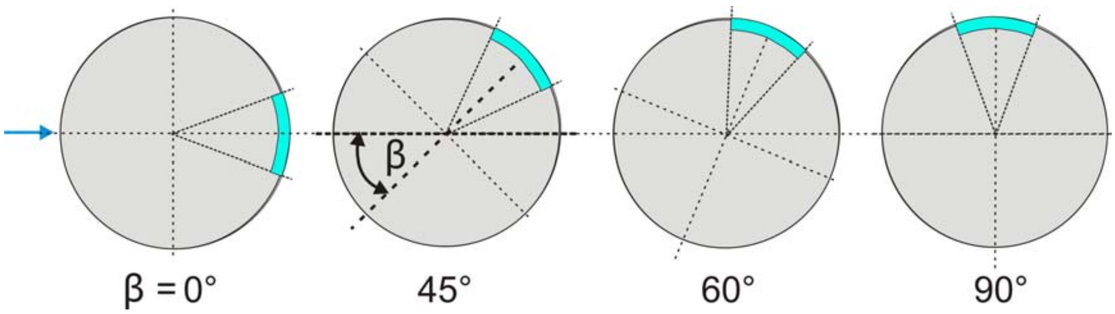


Fig. 3: Series 2 - Sketches of the 160° configurations investigated in the wind tunnel; unsymmetrical orientation of porous coating with respect to approach flow

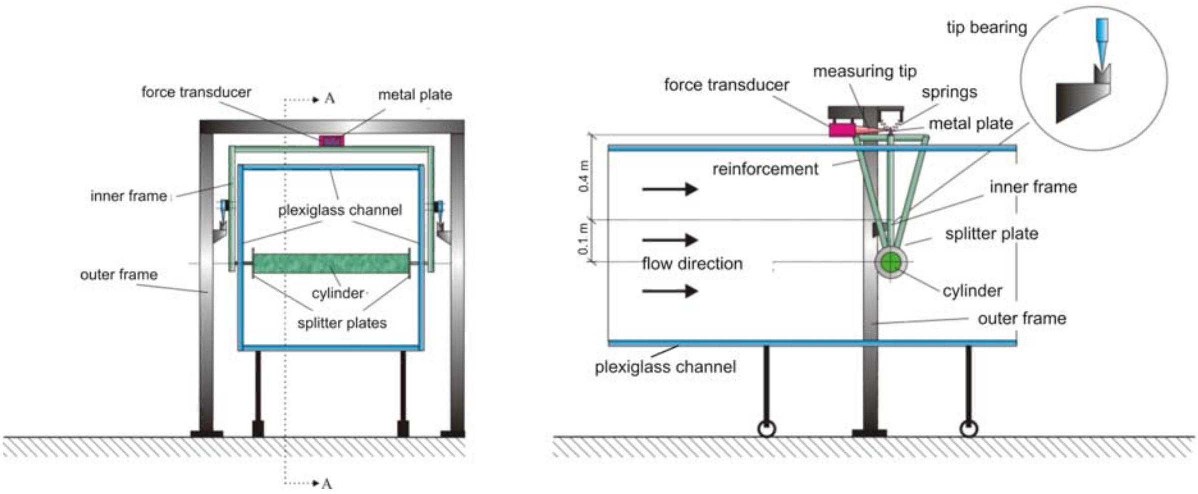


Figure 1: Force balance built in wind tunnel

Drag measurements

In order to measure the flow resistance of porous-coated cylinders in the wind tunnel experiment, a force balance was used, see Fig. 1. For the measurements, the Reynolds number was systematically varied in the range from 10^4 to $1.3*10^5$. In each measurement series, a completely smooth (varnished) cylinder was measured as reference case.

Results

As can be inferred from Fig. 5, the 115°, 130° and 145° configurations deliver a drag reduction when compared to the values of the smooth cylinder. In the whole range of Reynolds numbers investigated, the values of the leeward coated cylinders fall below the curve of the smooth cylinder. Apparently, there must be at least a certain area in the lee covered by porous media in order to obtain drag reduction. For the 160° configuration, the drag reducing effect seems to decrease.

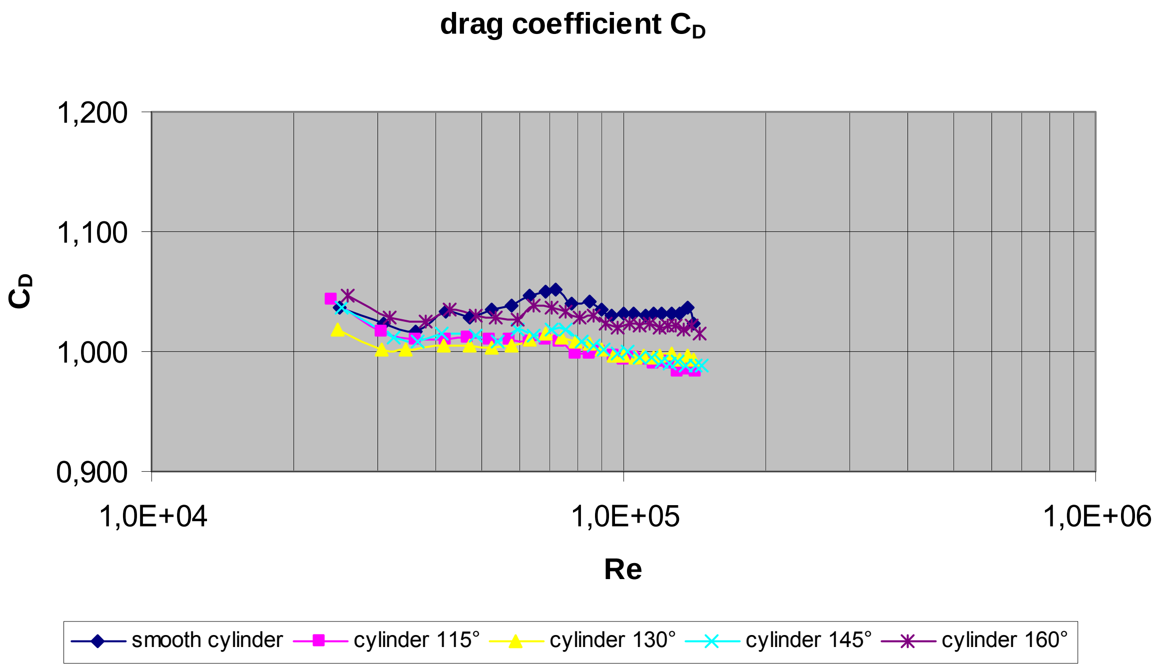


Fig. 5: Reduction of drag coefficient with porous coating only on the leeward side of cylinders; constant porosity 20 ppi; layer thickness 5 mm

On the other hand, it is surprising that the curves for the 115°, 130° and 145° configuration do not differ more from each other. The results shown in Fig. 5 are obtained with a porous medium characterized by a layer thickness of 5 mm and a porosity of 20 ppi yielding a pressure loss coefficient of the medium of about $\lambda \approx 500/m$.

The fundamental results of series 1 shown here (115°, 130°, 145°, 160° configuration) and the results of Klausmann et al. 2011 (90° configuration) revealed the following for axisymmetric orientation of the coating with respect to the approach flow direction:

<u>Full porous coating of cylinders</u> has the following fluid mechanical consequences in comparison to a smooth cylinder flow:

- Occurrence of momentum cross-exchange between the flowing medium and permeable layer

• leakage on side and rear section of the cylinder (base bleed)
• widening of the wake zone
• reduction of recirculation velocity in the wake
• formation of a thick free shear layer
• increase of base pressure in the separation region
• disappearance of the "drag crisis", i.e. there is no change in the flow field observed over a wide Reynolds number range
• much later development of vortex street downstream of the cylinder
• increase of drag on the windward side
• decrease of drag on the leeward side
• increase of the total resistance of fully porous-coated cylinder

Partial porous coating on the leeward side of cylinders has the following fluid mechanical consequences in comparison to a smooth cylinder flow:

• Formation of a thick free shear layer
• reducing the rotational velocity of the recirculating mass in the wake
• increase of base pressure in the separation region
• much later development of vortex street downstream of the cylinder
• no change of drag on the windward side
• decrease of drag on the leeward side
• decrease of the total resistance of leeward porous-coated cylinder

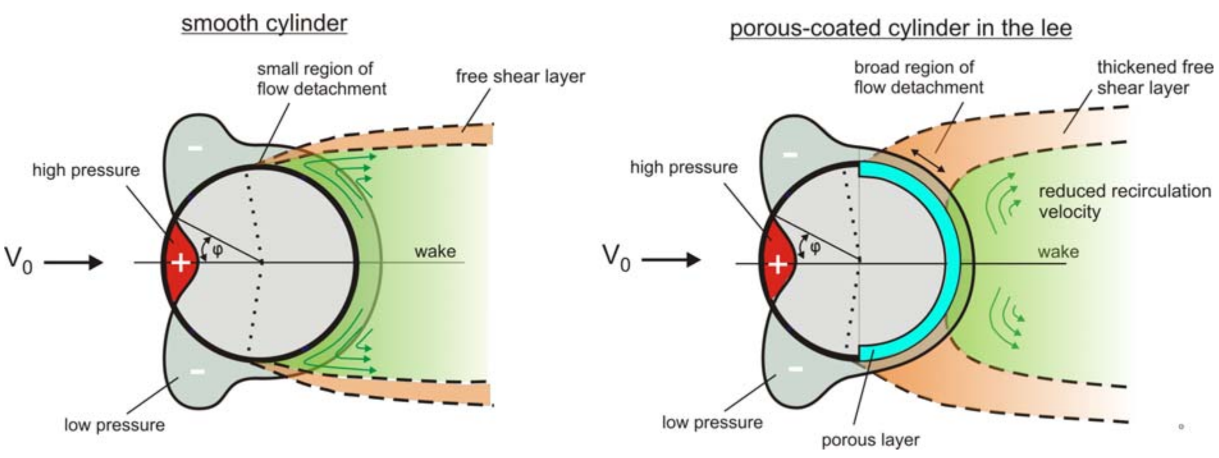
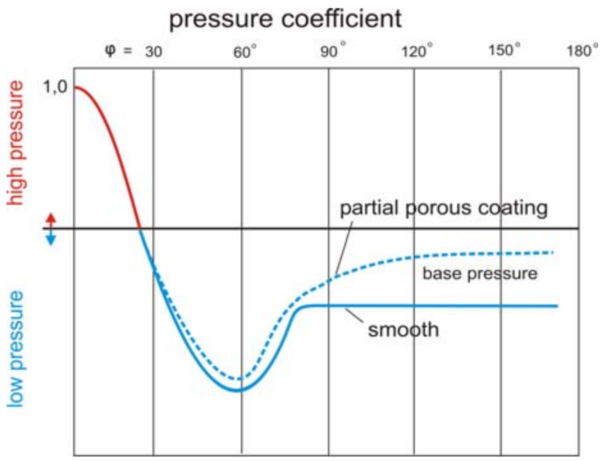


Fig. 6: Phenomenology of the flow around a cylinder porous-coated in the lee

Thus, it could be shown experimentally that axisymmetric partial coating by thin porous layers in the lee of a body can lead to drag reduction. It can be conceived of as the combination of the positive effects of a smooth surface (lowest surface friction) on the windward side with the positive effects of a permeable wall layer on the leeward side (increasing base pressure and decreasing recirculation velocity in the wake), see Fig. 6 and 7. Thus, it is possible to reduce the total flow resistance of a body in a flow. This phenomenon could be demonstrated clearly.



The drag reduction measured for the (only one) investigated thickness layer of 5 mm and porosity of 20 ppi was up to 8%. It is most likely that an optimization of this effect by variation of porous layer thickness, starting angle, porosity and relevant ratios like pore diameter to cylinder diameter or layer thickness to cylinder diameter leads to a further drag reduction.

Fig. 7: Qualitative pressure distribution around a cylinder porous-coated in the lee

In order to investigate, whether the drag reduction might result from the suppression of alternating vortices in the wake, measurement series 2 was performed, see Fig. 3. The results are given in Fig. 8 and show that at least for the investigated 160° configuration (which gives not the best results for axisymmetric orientation of the coating to the direction of the approach flow), the drag coefficient is getting worse with increasing angle β.

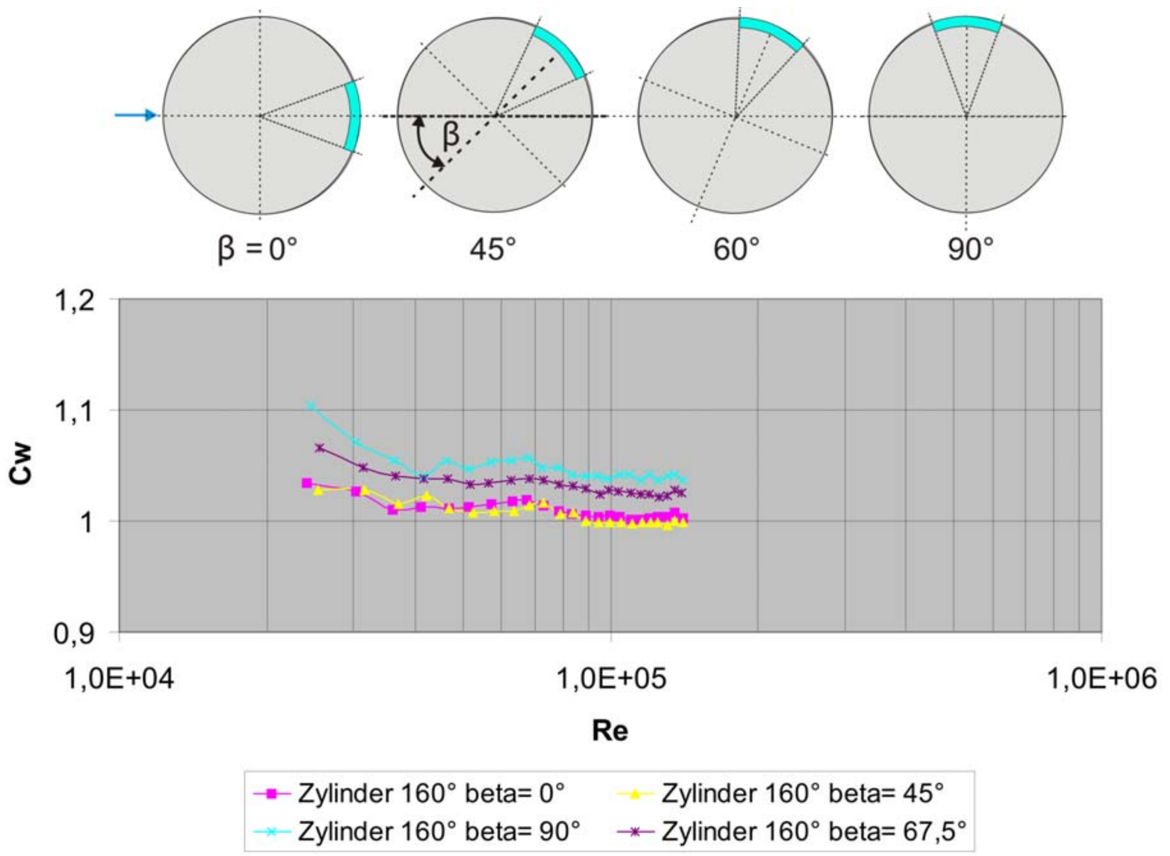


Fig. 8: Drag coefficient for the 160° configuration at different orientation to the approach flow direction

Additional work on the subject is currently underway and is based on measurements at higher Reynolds numbers, different starting angles α, different porosities of the porous medium used and different geometries of the body as well as on the vibrational behaviour of porous-coated cylinders.

Acknowledgement

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