Fachtagung "Lasermethoden in der Strömungsmesstechnik"
9. – 11. September 2014, Karlsruhe

Die Strömung um partiell porös ummantelte Kreiszylinder

Flow around circular cylinders with partial porous coating

K. Klausmann, B. Ruck
Laboratorium für Gebäude- und Umweltaerodynamik, Institut für Hydromechanik, Karlsruher Institut für Technologie (KIT), Kaiserstraße 12, 76128 Karlsruhe, Germany

Widerstandsreduktion, Kreiszylinder, Strömungswiderstand, teilporöse Beschichtung
Drag reduction, circular cylinder, flow resistance, partial porous coating

Abstract

This paper presents an experimental study of drag reduction consisting of systematic experimental investigations of circular cylinders with constant diameter having a partial porous shroud of foam material on their leeward side with different coating angles, thicknesses and porosities of the coating. The coating angles are arranged symmetrically relative to the horizontal stagnation line. The cylinder models are exposed to a uniform approach flow in a Goettingen-type wind tunnel with velocities up to u = 30 m/s, which corresponds to Re numbers up to Re = $1.4 \cdot 10^5$. The total drag force is measured with a force balance. The results are compared to classical smooth cylinder data and to former investigated configurations. Previous investigations of cylinders fully covered with a porous coating show an increase in the drag coefficient c_d compared to a smooth cylinder, whereas a half-coating of the cylinder on the leeward side results in a reduced drag coefficient compared to a smooth cylinder. The flow was visualized using laser-based measuring techniques.

Introduction

In many engineering applications circular cylinders are fundamental body configurations. Experimental and numerical investigations of cylinders with different surface modifications like dimples, pattern-indented and rough surfaces are well documented in literature. Also cylinders surrounded by for example slats, rods or shrouds were studied in the past. Compared to a smooth cylinder, the rougher the surface of a cylinder, the lower the Re-number where the drop of the drag coefficient c_d ('drag crisis') takes place. Furthermore, there is also a dependency of the lower limit of the drag crisis and the surface roughness of the cylinder. With increasing surface roughness, the minimum drag coefficient c_d after the drag crisis increases, see Achenbach 1971. Compared to a roughened surface, cylinders with a dimpled surface show on the one hand a larger reduction of c_d after the fall of the drag coefficient and on the other hand a lower increase of drag coefficient c_d after the drag crisis, for roughness element height and depth of the dimples of the same magnitude (Bearman and Harvey, 1993).
A pattern-indented surface leads also to a reduced drag coefficient c_d in the critical Re-range compared to a cylinder with a rough surface. Furthermore the drag coefficient c_d is almost constant in the supercritical Re-range, see Miyata et al. 1998. Studying so called "porous" shrouds, Price 1956 was the first who was focusing on shrouded cylinders to suppress vortex-induced vibration. Such a "porous" shroud is mostly designed as a 2D porous-

arrangement, where the orifice of the porous device is normal to the solid body and the fluid can flow through the gap between solid cylindrical structure and porous device without any obstacles, so that there exists an inner and an outer flow, see Wong 1979. Wong 1979 studied the flow around cylinders for different arrangements of slat systems, a cylinder periphery completely surrounded with slats and cylinder configurations partially surrounded with slats for different opening angles on the wind- and leeward-side. Due to this slat arrangement, a suppression of vibrations caused by vortex shedding, a reduced drag force and a weakening of wake buffeting could be achieved, Wong 1979. Typical arrangements are also for example rod and round-holed shrouds and meshes. Galbraith 1981 investigated the flow characteristics close to porous shrouds for $Re = 5*10^3$ and found the effect of 'base bleed' (see Wood 1967) from the gap flow into the base region, which is responsible for the suppression of vortex excited vibration. The formation of the vortex street is displaced downstream from the base region. Due to a strong efflux at $\theta = 90°$ (from the stagnation point) the main flow is deflected away from the shroud and a thicker turbulent shear layer is formed, Galbraith 1981. Zdravkovich 1972 found that cylinders fitted with round shrouds affect the mean pressure distribution around a circular cylinder and the constant part of the pressure coefficient curve is starting at 120° instead of 90° for a $Re = 1.26*10^5$ and thereby the angular width is reduced.

In addition to the above described experimental investigations some numerical studies have been performed. Bruneau and Mortazavi 2006a investigated circular cylinder encased with a porous ring and found that this arrangement leads to more wake stability and reduced vortex induced vibrations. Further numerical studies of Bruneau and Mortazavi 2006b showed a reduction in drag force up to 33% for Ahmed bodies with a porous sheath located on the lateral parts. Some numerical studies of the flow field around circular cylinders wrapped with a layer of 3D porous material exists but for very low Re numbers ($Re < 40$), see Rashidi et al. 2013, and more with respect to improve heat insulation design (Saada et al. 2007). Previous experimental investigations of cylinders fully covered with a porous foam envelope showed significant differences in drag when compared to a smooth circular cylinder. For a fully coating (Klausmann et al. 2011), an increase in drag coefficient c_d was measured, whereas a half-coating of the cylinder ($\beta = 180°$) on the leeward side delivered a reduced drag coefficient c_d, see Klausmann et al. 2011. Additional flow field analyses with LDV measurements and flow visualization techniques indicated that the porous sheath on the leeward side of the cylinder thickens the free shear layer, reduces the rotational velocity of the recirculating mass in the wake and shifts the initial formation of a regular vortex street downstream from the cylinder, see Ruck 2012.

However, the knowledge in the field of cylinders with a partial coating of 3D porosity is fragmentary and limited to few configurations. 3D porosity means a random but homogenous sponge-like porosity, e.g. large-pore foam, where the fluid can flow inside the material in all directions with the same pressure drop per length. This differs from former investigated 'porous shrouds', where an undisturbed gap-flow between solid cylindrical structure and porous shroud takes place. The motivation for this work was to investigate whether interfacial effects of porous walls can be applied to drag reduction of bodies submersed in a flow. Systematic investigations of circular cylinders with an embedded 3D porous layer of foam material on the leeward side have been performed in wind tunnel tests. The coating was symmetrically arranged relative to the horizontal stagnation line and the implications on the body's drag reduction have been analyzed. The questions are whether or not an optimum of the coating angle and the thickness of the porous layer exists to reach a minimum value of drag coefficient c_d and how the porosity (pore sizes) influence the flow around circular cylinders.

Experimental set-up

Test cylinders

The investigated cylinder configurations were made of balsa wood and had a length of $L_{cylinder}$ = 70 cm. The porous sheath was inserted into the cylinder so that the outer diameter of $D_{cylinder}$ = 7 cm remained constant, see Fig. 1. The coating was symmetrical relative to the horizontal stagnation line of the cylinder. For the porous layer, a polyester foam material with high toughness and sponge-like porosity is used. The foam material is from Filteron GmbH, 42699 Solingen, Germany and commonly used as filtration material in ventilating systems. The present study is an extension of already existing investigations (Klausmann et al. 2011) and contains five new configurations with different coating angles β = 220°, 160°, 100°, 70°, 40°, see Fig. 1. Each of these configurations involves 3 different layer thicknesses of d_l = 3, 5, 10 mm and 3 different porosities of 10, 20, 30 PPI (pores per inch).

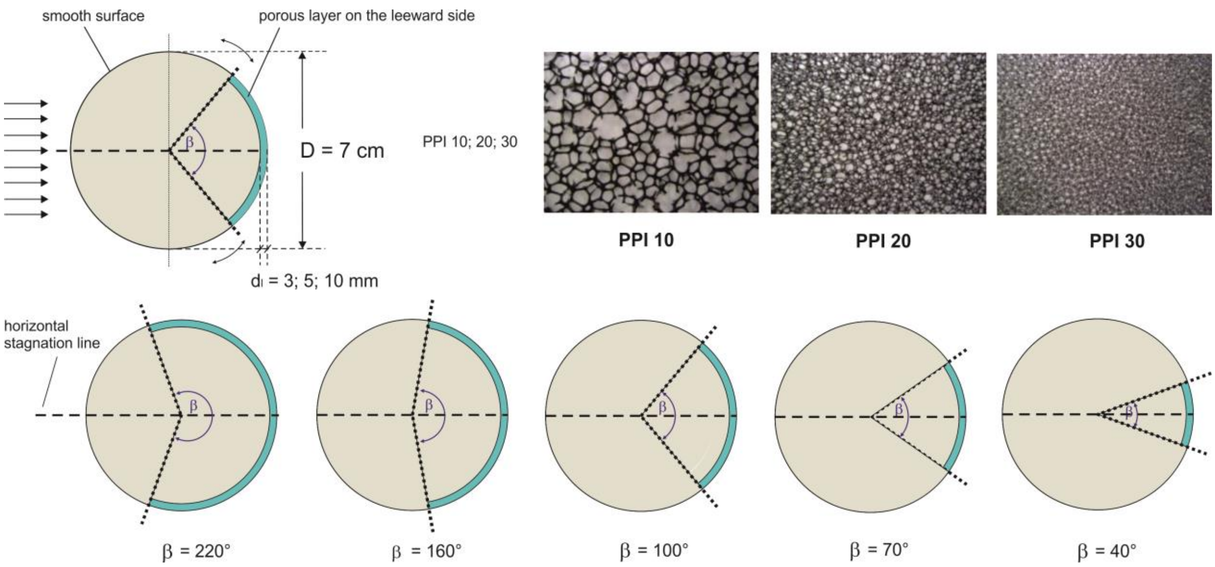

Fig. 1: Sketch of the cylinder configurations with symmetrical partial porous coating on the leeward side and the foam material

Force measurements

The total drag force was measured for the different cylinder configurations with a force balance, see Fig. 2. The measurements were performed in a uniform approach flow in a Goettingen type wind tunnel with low turbulence intensities (< 1%). The investigations were conducted for velocities in the range of 10 to 30 m/s, corresponding to Re numbers up to Re = $1.4*10^5$. The force balance consists of two strain gauge sensors (ALTHEN GmbH) placed outside of the wind tunnel on a solid steel frame. The cylinder models are connected directly to the two sensors, with a nominal force of 50 N each.

In all experiments, the cylinders were fitted with circular end plates ("splitter plates") on both sides of the cylinder in order to avoid 3D-effects of the flow around the two ends of the cylinder. The splitter plates were made of sheet steel with a diameter D_{plates} = 3.5 * $D_{cylinder}$ and a thickness of t_{plates} = 0.6 mm. The splitter plates were fully decoupled from the measurement system and fixed on the plexiglass walls, see Fig. 2 and 3. The geometric blockage by the model in the wind tunnel was about 9.3 %. Corrections for blockage were made by applying the method of Allen and Vincenti,1944 and extended by Dalton, 1971.

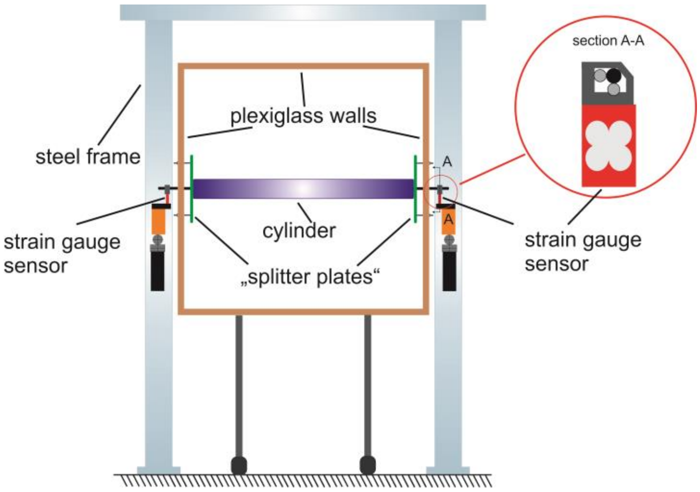

Fig. 2: Sketch of wind tunnel cross section and force balance

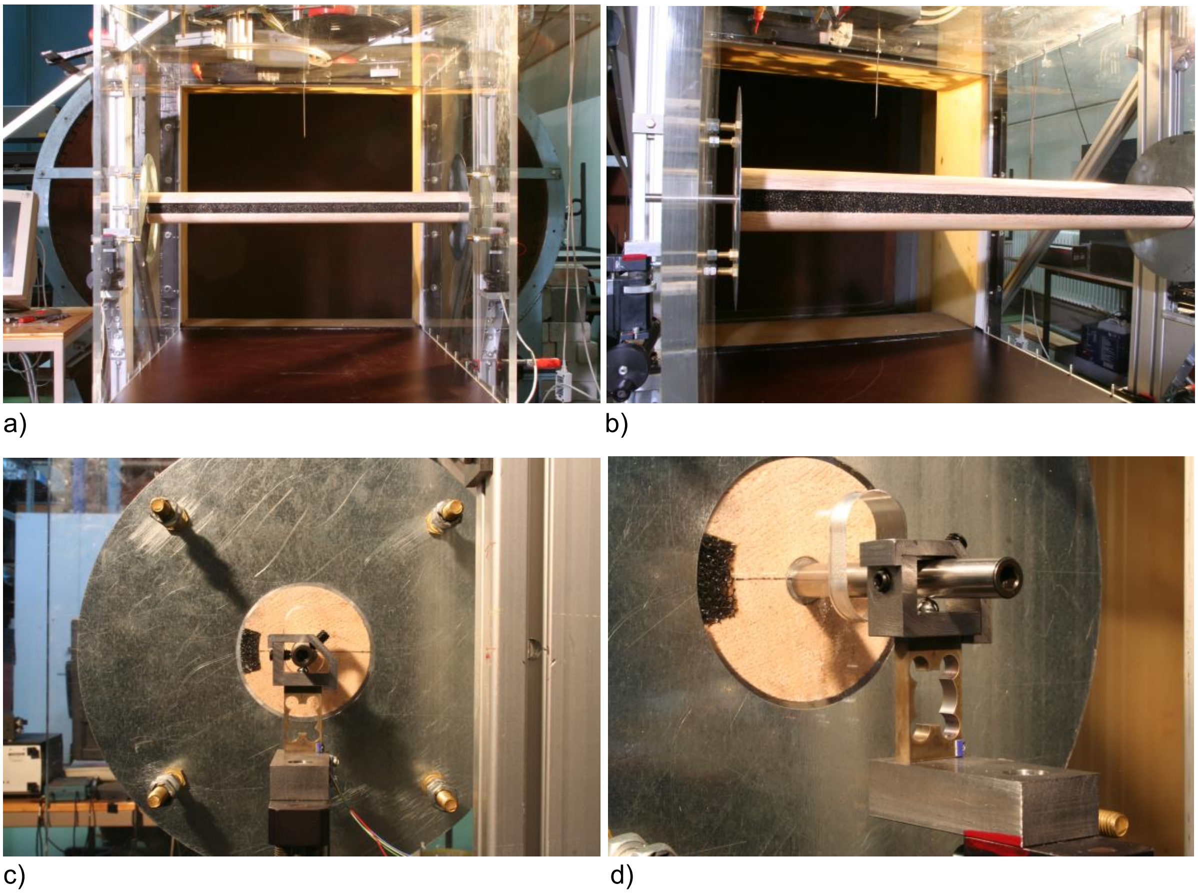

Fig. 3: Front view of cylinder model with coating angle of β = 40° mounted in the wind tunnel (a); gap of the fixed splitter plate and the tunnel wall (b); connection of the cylinder model and strain gauge sensor by guide pins (c), (d)

Results

Results of the drag coefficient c_d for two half coated cylinders with a coating angle of β = 180°, a layer thickness of d_l = 5mm and a porous material of PPI 30, are compared to a fully coated (same foam material and layer thickness) and a smooth cylinder, see Fig. 4. The results show that the c_d coefficients of the half coated cylinders depend on the position of the porous layer. For the layer on the windward side, the c_d coefficient is higher compared to a fully coating of the model. In contrast to the porous material embedded on the leeward side, a drag force reduction is found when compared to the smooth cylinder. Apparently, the split coverage of the cylinder with a smooth windward side and a porous layer on the leeward side leads in summa to a drag reduction of the body for the studied range of Re-numbers.

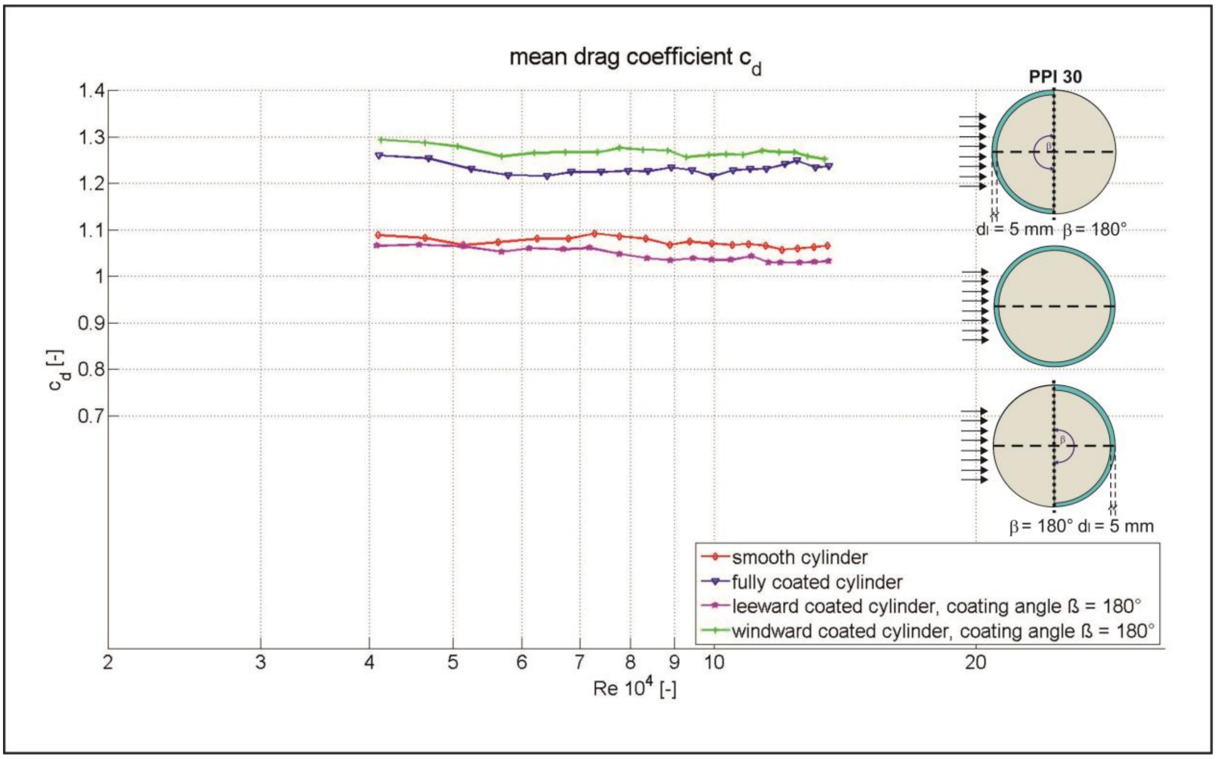

Fig. 4: Comparison of drag coefficient c_d for a coating angle of β = 180° with different arrangements of the porous layer: windward, leeward, fully porous coated and a smooth cylinder; for the force measurement system, see Klausmann et al. 2011

Results of the force measurements of the cylinder models for different coating angles are shown in Fig. 5. Models with a coating angle of β = 160° and 40°, a porous layer thickness of d_l = 10mm and a PPI 10 porosity were studied. Obviously the coating of the cylinders for the two different coating angles of β = 160° and β = 40° influences the drag force, so that there is a dependency on the coating layer length. For both, a significant reduction of the drag coefficient c_d is noticeable. The coating angle of β = 160° leads to a drag reduction of up to 13,5 % when compared to a smooth cylinder. The small coating angle of β = 40° affects the reduction of drag force less than the coating angle of β = 160°. However even a small coating angle of β = 40° on the leeward side has an effect on the drag and leads to a lower drag coefficient c_d, relative to the smooth cylinder. Obviously, also the new results presented in this paper support the findings of former investigations that a porous sheath on the leeward side of a cylinder leads to a thickening of the free shear layer and an increase in base pressure, which in turn decreases the drag of the body. The fundamental wake flow between a smooth and a fully porous coated cylinder can be seen in Fig. 6, where laser-based visualization was applied (high-speed camera type PCO 1200HS; frame rates of 636 fps at full resolution of 1280 x 1024 pixels; internal memory of 4 gigabytes, data rates of up to 1 Gigabyte/sec; laser light sheets generated at high repetition rate by two Nd:YAG lasers from LEE in pulse mode;

maximum lamp power 6 kW, Q-switched operation 10 kHz with an average power of 44.9 W for laser 1 and 48.8 W for laser 2).

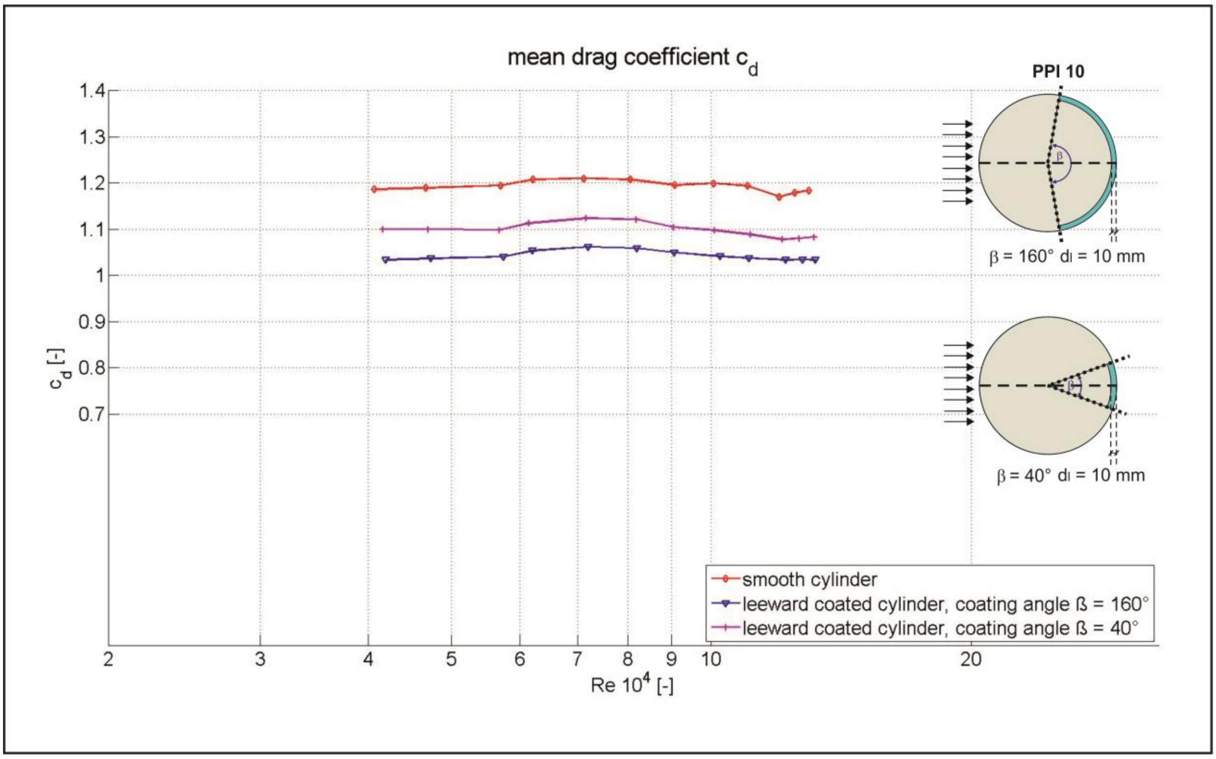

Fig. 5: Results of the corrected drag coefficient c_d for a partial porous coated cylinder with a coating angle of ß = 160°, a partial porous coated cylinder with a coating angle of β = 40° (both with PPI 10 porosity and d_l = 10mm) and a smooth cylinder

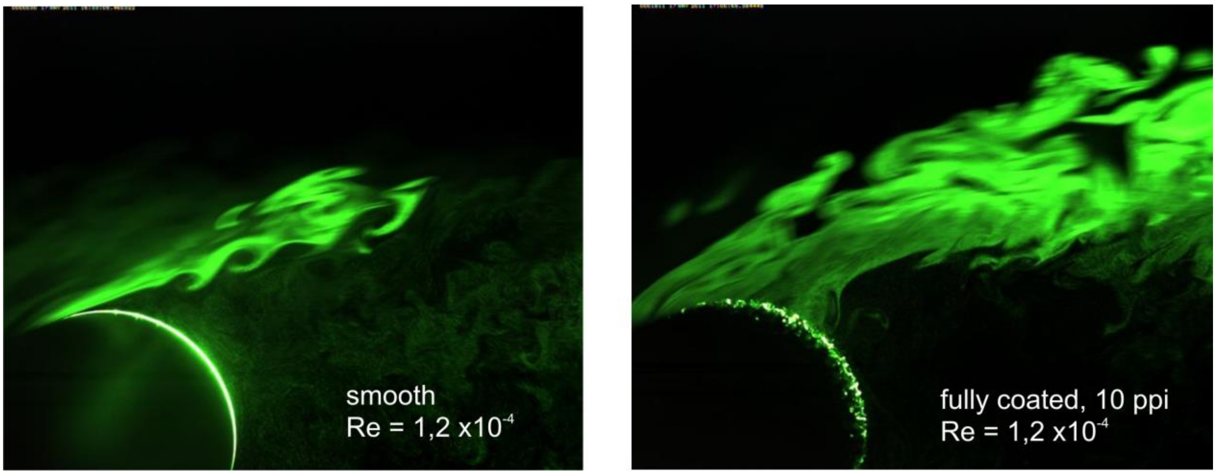

Fig. 6: Bleeding the wake and reducing the velocity of the recirculating mass by porous coating of a cylinder, see Ruck et al 2012

Conclusion and Outlook

The present study illustrates the influence of a partial porous coating with foam material on the leeward side of circular cylinders with a constant diameter. Different coating angles, thicknesses and porosities were realized. The cylinder configurations were exposed to a uniform approach flow in a Goettingen-type wind tunnel with velocities up to u = 30 m/s, which corresponds to Re numbers up to Re = $1.4*10^5$. The total drag force was measured with a force balance. The results of the porous coated cylinders were compared to a classical smooth cylinder and to former investigated configurations. Previous investigations of cylinders fully covered with a porous coating showed an increase in drag coefficient c_d when compared to a smooth cylinder. For a half-coating of the cylinder with coating angle of β = 180° the drag coefficient c_d depends on whether the porous layer was on the wind- or on the leeward side. The porous layer on the leeward side resulted in a reduced drag coefficient when compared to a smooth cylinder whereas the porous layer on the windward side resulted in an increased drag coefficient. For a coating angle of β = 160° and 40°, a porous layer of d_l = 10mm and a PPI 10 porosity, a reduction of the drag coefficient c_d could be achieved. Furthermore a dependency of the coating angle of the porous layer on drag reduction was observed. For the smaller coating angle of β = 40° the reduction was less than for the coating angle of β = 160°, but had obviously an effect on the drag when compared to a smooth cylinder.

Further drag force measurements of more partial porous cylinder configurations for coating angles of β = 220°, 160°, 100°, 70°, 40°, d_l = 3, 5, 10 mm and the PPI 10, 20, 30 porosities are currently in progress. Additional studies of the partial porous coated cylinders are planned for the near future, e.g. investigations of the flow field with LDV and PIV, of the pressure distribution, of the separation angle and of the free shear layer.

Acknowledgement

The authors acknowledge the financial support of the German Research Foundation for this project (DFG research grant No. Ru 345/34-1).

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