The Reynolds number effect from subcritical to high transcritical on steady and unsteady loading on a rough circular cylinder

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ABSTRACT: Force and surface pressure measurements on a 2D rough circular cylinder were carried out over a wide range of Reynolds numbers in the high-pressure wind tunnel in Göttingen. The Reynolds number spanned values from subcritical up to high transcritical \(15 \times 10^3 \leq \text{Re} \leq 12 \times 10^6\). The cylinder had a mean relative surface roughness of \(k_s/D = 1.2 \times 10^{-3}\). By means of piezoelectric balances the unsteady lift and drag forces were measured. The mean surface pressure distribution was obtained with the use of 59 static surface pressure tabs at various span-wise and circumferential locations on the cylinder. Statistical analysis of the time-dependent forces, in combination with the mean surface pressures, provided information on the spatial organization of the flow field properties around the cylinder as function of the Reynolds number. In the critical Reynolds regime two discontinuities at two separate Reynolds numbers were observed. They were accompanied by critical fluctuations in the lift force and the formation of a separation bubble at each side of the cylinder. The discontinuous jumps were initialized by a downstream movement of the separation point and an upstream movement of the transition point. The asymmetric flow field in-between both critical Reynolds numbers led to a steady lift force that was cancelled again after passing the second critical Reynolds number. At the latter Reynolds number the width of the wake and \(C_D\) were minimum. In the super- and transcritical flow states the boundary layer separations took place at about the apex of the cylinder. In comparison to the subcritical and critical regimes all measured flow field properties reached intermediate steady plateaus in the transcritical state. For the Strouhal number this plateau was at \(St = 0.23\), for the base pressure at \(C_{p_{\text{base}}} = -0.9\) and for the drag coefficient at \(C_D = -0.84\).

KEY WORDS: Rough Cylinder; high Reynolds number; Critical flow; Surface roughness; high-pressure Wind Tunnel.

1 INTRODUCTION

The flow around objects with circular cross section has received considerable attention, motivated by its relevance to engineering applications, such as the flow around bridge cables, landing gear systems and television towers. A general characteristic feature of bluff body geometries is the appearance of large-scale vortex shedding in the near wake. The associated fluctuating aerodynamic loads can lead to flow induced vibrations and possible structure damage.

It is well known that for the flow phenomena of circular cylinders the Reynolds number plays a dominant role, since the location of the flow separation on the cylinder wall is Reynolds number dependent. Besides the Reynolds number as a global parameter, local parameters, like the surface roughness of the circular cylinder, also have a substantial effect on the flow phenomena and unsteady aerodynamic loads. The cylinder surface roughness shifts the position of the transition from laminar to turbulent to lower circumferential angles and lower Reynolds numbers. Up to the supercritical regime force measurements on smooth cylinders and isolated surface pressure measurements on rough cylinders have been the subject of numerous investigations [1-5]. However, detailed flow investigations within the critical Reynolds number regime (characterized by flow symmetry breaking) and at very high Reynolds numbers within the transcritical regime at incompressible flow – occurring for example during hurricanes or in the takeoff and landing phase of an aircraft – are relatively rare [6-8].

The specific objective of the presented study is the investigation of the effects of a change in Reynolds number on the flow properties of a rough circular cylinder. To achieve this goal, instantaneous time-dependent aerodynamic forces and mean surface pressure coefficients are obtained with the use of a piezoelectric balance and static surface pressure tabs inside the wind tunnel model. The measurements are conducted in the high-pressure wind tunnel Göttingen (DNW-HDG) from ambient pressure up to about 10 MPa. Reynolds numbers from subcritical up to high-transcritical can reached by variation of only two main flow parameters: the total air pressure inside the wind tunnel and the free stream velocity. Other boundary conditions, like the model diameter or the surface roughness, have been kept constant during this study.

2 EXPERIMENTAL SETUP

2.1 High-pressure wind tunnel

The high-pressure wind tunnel (Figure 1) is a closed circuit low speed wind tunnel, described in detail in [9]. The measurement section of the tunnel is 0.6×0.6 m² and has a length of 1 m. The free stream velocity is adjustable between 4 m/s and 35 m/s in the complete total pressure range, resulting in a Reynolds number regime based on the cylinder diameter of the present model – between \(15 \times 10^5\) and about \(12 \times 10^6\). An airlock system allows the modification or exchange of the model or instrumentation outside the wind tunnel without the need of de-pressurizing the tunnel itself. The free stream flow has a turbulence intensity between 0.3% and 0.4%, depending on the Reynolds number.
2.2 Rough circular cylinder

The wind tunnel model consists of a stainless steel circular cylinder of $D = 60$ mm in diameter and a length $L$ of 600 mm. The surface of the cylinder has been treated in such a way, that a uniform, but Gaussian distributed cylinder surface roughness of $k_s/D = 1.2 \times 10^{-3}$ is obtained over the complete span of the cylinder. Due to the relatively large wall thickness of the cylinder of 3 mm the eigenfrequency of the model is 430 Hz. Since this frequency is well above the vortex shedding frequency in the near wake, no resonance or frequency locking between both frequencies is therefore to be expected.

The cylinder is placed horizontally inside the measurement section. Fifty-nine static pressure transducers are positioned along the span and circumference of the circular cylinder in nine planes orthogonal to the cylinder axis, denoted by planes A and B in Figure 2. Each plane is separated by one cylinder diameter to its neighboring planes. Of these 59 pressure tabs, 35 tabs are positioned in plane B at multiple circumferential angles, marked by the letter “B” in the lower part of Figure 2. They are used to obtain the mean pressure distributions – and thus the base pressure and the upper and lower flow separation angles – at mid-span. The other 24 pressure tabs (denoted by the letter “A” in Figure 2) are distributed along the span of the cylinder at $\theta_{cyl,u} = \theta_{cyl,d} = 90^\circ$ and $\theta_{cyl,u} = \theta_{cyl,d} = 180^\circ$ from the leading edge line at $\theta_{cyl} = 0^\circ$. These span-wise distributions are necessary to observe the two- or three-dimensionality of the flow along the cylinder’s span. The pressure measurements are conducted using an electronic differential pressure measurement unit (Type ESP-HD, Pressure Systems) for 64 channels with a range of ± 200 kPa.

2.3 Aerodynamic force measurements using piezoelectric balances

The fluctuating aerodynamic lift and drag forces acting on the cylinder are measured with a force balance based on 3-component piezoelectric force transducers (Type 9067, Kistler Instruments). The elements have been modified to be applicable in an environment up to 10 MPa. For details on the working principle of the balance and the piezoelectric force-measuring elements the reader is referred to [10]. By a ring locking mechanism the model is fixed to the top plates of the balance that are positioned at both outer sides of the measurement section. A small gap of about 0.5 mm is present in-between the surface of the cylinder and the holes in the wind tunnel walls and foundation plates. The purpose of this gap is to guarantee a freely suspended cylinder and thus a perfect transmission of the forces to the piezoelectric elements.

A high stiffness of the mounting system assures a high eigenfrequency of the balance system, well above the expected Strouhal frequency. Furthermore it ensures a dependency between the measured drag and lift forces of less than 1%. In this way it is for example possible to measure very accurately and simultaneously a small force in lift direction in combination with a large drag force. This is particularly important for accurate measurements within the critical Reynolds number regime, as will be explained in further detail later.

3 RESULTS AND DISCUSSION

The experiments were conducted in the Reynolds number range from subcritical up to high-transcritical between $15 \times 10^3$ and about $12 \times 10^6$. It has to be noted once more that, in comparison to other similar measurements found in literature for rough circular cylinders, in this case the complete Reynolds number range was covered without a modification of the experimental setup, like the cylinder diameter or roughness state, during the experiment. Only the free stream velocity $U_0$ and the total pressure $p_0$ were varied to obtain the required Reynolds numbers. Because of a geometric wind tunnel blockage ratio of 0.1 the measured velocity and drag coefficient data presented hereafter have been corrected for the wall interference effects by making use of the formulas of Allen and Vicenti [11].
3.1 The drag coefficient

In Figure 3(c) the total mean drag coefficient \( C_D \) is shown as function of the Reynolds number. The mean drag coefficient has been determined in two ways: with the use of the piezoelectric balances and with the circumferential mean pressure distribution at the mid-span of the cylinder, plane B in Figure 2. For the latter method the following definition is used:

\[
C_D = \sum_{i=1}^{35} C_{p,i}(\theta) \sin(\theta_i) \sin(0.5d\theta) \tag{1}
\]

The general shape of the \( C_D(Re) \) curve clearly coincides with the measurements of Achenbach [6] and Adachi [7] for rough circular cylinder flow. Starting with a nearly constant value for \( C_D \) of about 1.2 in the subcritical regime, a steep decrease is observed within the critical regime. Two sudden jumps of \( C_D \) take place in the critical regime. The second discontinuity marks the transition from the critical to the supercritical Reynolds number regime at approximately \( Re = 1.9 \times 10^5 \). Here the minimum drag coefficient of \( C_D = 0.4 \) is reached. In the supercritical regime \( C_D \) gradually increases until a plateau is reached where \( C_D \) is nearly constant with \( C_D \approx 0.84 \), in good agreement with Adachi [7]. The beginning of the plateau at \( Re \approx 1 \times 10^5 \) marks the start of the transcritical regime.

A comparison with other known results for rough circular cylinders with similar roughness values shows some significant discrepancies. For the subcritical range Achenbach [6] found a constant \( C_D \) of about 1.3, whereas \( C_D = 1.2 \) was measured by Adachi [7] and in the present study. The end of the critical regime was observed by Achenbach to take place at about \( Re = 2 \times 10^5 \), whereas the measurements by Adachi defined this point at \( Re \approx 3 \times 10^5 \). Furthermore, a significantly higher constant value for \( C_D \) within the transcritical regime was measured by Achenbach namely \( C_D = 1.05 \). These discrepancies are probably caused by the somewhat different roughness values in axial and circumferential direction [7] or by the larger blockage ratio (16%) and higher free stream turbulence level of \( Tu_0 = 0.7% \) [6].

3.2 Distribution the Strouhal number

The dependency of the Strouhal number, \( St = f_i U_i/D \), on the Reynolds number is presented in Figure 3(b). The value of the vortex shedding frequency \( f_i \) is extracted from power spectra based on the lift force fluctuations \( \Phi_{U_i}(f) \), as will be shown in more detail in section 3.4. A nearly constant value of the Strouhal number of \( St = 0.19 \sim 0.2 \) is observed in the subcritical regime. By entering the critical regime, the Strouhal number gradually decreases. At a large section of the critical regime, it is observed that two distinct Strouhal numbers are present. According to the values belonging to these Strouhal numbers, they are related to the sub- and supercritical states. This means that at these critical Reynolds numbers both flow states are present and that a random fluctuation in time and along the span of the cylinder between the sub- and the supercritical state takes place. The two discontinuous jumps that are clearly present as sharp drops in the \( C_D \) vs. Re curve in Figure 3(c) are less pronounced in the distribution of the Strouhal number. At supercritical Reynolds numbers the Strouhal number decreases again from its highest value of \( St = 0.25 \) to \( St = 0.22 \), after which a slight increase in

Figure 3. Distribution of the main aerodynamic parameters as function of the Reynolds number. (a): R.m.s. of the total lift fluctuations; (b): Strouhal number based on the total lift fluctuations; (c): Total mean drag coefficient (the thick symbols represent the data based on the balances, the thin symbols are according to eq. (1)). The letters besides the symbols correspond with the measurement points in Table 1.

Strouhal number to \( St = 0.23 \) is measured within the transcritical regime. For Reynolds numbers in the upper supercritical and the transcritical regime a good agreement is found between the present results and the measurements by Adachi [7] and Shih et al. [4].
3.3 The r.m.s values of the lift force fluctuations

For a clear understanding of the different flow regimes the r.m.s value of the lift fluctuations $\sqrt{\overline{C_L^2}}$ is plotted as function of the Reynolds number in Figure 3(a). A maximum of the r.m.s. value of approximately 1.3 is obtained at the subcritical Reynolds number of $Re = 1.5 \times 10^5$. This maximum correlates with a maximum value of the drag coefficient $C_D = 1.17$ in Figure 3(c). Inside the subcritical regime a steep decrease in the r.m.s value is observed for increasing Reynolds numbers.

By entering the critical regime, $\sqrt{\overline{C_L^2}}$ steadily decreases with $Re$ up to a local minimum value of about 0.077 at $Re = 1.7 \times 10^5$, near the first transition, hence into the asymmetric bistable state. Two slightly pronounced local maximum values are subsequently observed at $Re = 1.7 \times 10^5$ and $Re = 1.9 \times 10^5$, where critical fluctuations occur before both transitions take place. As the Reynolds number is increased further beyond the second transition, the value for $\sqrt{\overline{C_L^2}}$ slightly, but steadily decreases at relatively constant Strouhal numbers. In the transcritical flow regime the lowest values of the r.m.s. of the lift fluctuations are obtained out of the narrowband power spectrum peak.

3.4 Power spectrum densities of the lift force fluctuations

The background of the trend of the $\sqrt{\overline{C_L^2}}$(Re) curve presented in section 3.3 lies in the shape of the power spectrum densities of the lift fluctuations. In Figure 4 ten power spectra of the lift fluctuations for various Reynolds numbers throughout the complete simulated Reynolds number range (see Table 1) are shown. The horizontal axis has been non-dimensionalised to a Strouhal number scale, whereas the vertical axis of the power spectrum $\Phi(f)$ has been transformed into a non-dimensional scale defined by $\Phi(f)\overline{C_L^4}$ with $q_0$ being the dynamic pressure.

By applying this scaling law the square root of the integral of the power spectrum represents the r.m.s. of the lift fluctuations as presented in section 3.3 and defined as [8]:

$$\sqrt{\overline{C_L^2}} = \left[\int \Phi_L(f) \frac{q_0}{\overline{U}_0^4} d \left(\frac{f}{\overline{U}_0}\right)\right]^{0.5} \quad (2)$$

Figure 4. Power spectra of the lift fluctuations. The letters in the figures correspond with Table 1.

### Table 1. Flow field properties for selected measurement points throughout the simulated Reynolds number regime.

<table>
<thead>
<tr>
<th>Meas. point</th>
<th>Flow state</th>
<th>Re</th>
<th>$\overline{C_L}$</th>
<th>$C_D$</th>
<th>$C_D(\theta)$</th>
<th>$\sqrt{\overline{C_L^2}}$</th>
<th>St</th>
<th>$C_{p,base}$</th>
<th>$\theta_s$ [deg]</th>
<th>Lower</th>
<th>Upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>Subcritical</td>
<td>$3.78 \times 10^4$</td>
<td>0.17</td>
<td>1.26</td>
<td>0.46</td>
<td>0.19</td>
<td>-1.30</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(b)</td>
<td>Subcritical</td>
<td>$1.23 \times 10^5$</td>
<td>0.02</td>
<td>1.09</td>
<td>1.12</td>
<td>0.15</td>
<td>0.19</td>
<td>-1.08</td>
<td>85</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>(c)</td>
<td>Critical</td>
<td>$6.10 \times 10^5$</td>
<td>0.07</td>
<td>0.93</td>
<td>0.97</td>
<td>0.09</td>
<td>0.19</td>
<td>-0.92</td>
<td>95</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>(d)</td>
<td>Critical</td>
<td>$6.90 \times 10^5$</td>
<td>0.23</td>
<td>0.77</td>
<td>0.87</td>
<td>0.08</td>
<td>0.17 / 0.23</td>
<td>-0.81</td>
<td>100</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>(e)</td>
<td>Critical</td>
<td>$8.00 \times 10^5$</td>
<td>0.22</td>
<td>0.55</td>
<td>0.66</td>
<td>0.06</td>
<td>0.15 / 0.22</td>
<td>-0.66</td>
<td>135</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>(f)</td>
<td>Critical</td>
<td>$8.40 \times 10^5$</td>
<td>0.03</td>
<td>0.44</td>
<td>0.48</td>
<td>0.07</td>
<td>0.14 / 0.23</td>
<td>-0.57</td>
<td>100</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>(g)</td>
<td>Supercritical</td>
<td>$2.11 \times 10^5$</td>
<td>0.60</td>
<td>0.62</td>
<td>0.07</td>
<td>0.25</td>
<td>-0.72</td>
<td>105</td>
<td>110</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(h)</td>
<td>Supercritical</td>
<td>$3.75 \times 10^5$</td>
<td>0.77</td>
<td>0.80</td>
<td>0.05</td>
<td>0.23</td>
<td>-0.84</td>
<td>100</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(i)</td>
<td>Transcritical</td>
<td>$1.89 \times 10^5$</td>
<td>0.86</td>
<td>0.92</td>
<td>0.03</td>
<td>0.22</td>
<td>-0.95</td>
<td>95</td>
<td>95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(j)</td>
<td>Transcritical</td>
<td>$1.89 \times 10^5$</td>
<td>0.86</td>
<td>0.92</td>
<td>0.03</td>
<td>0.22</td>
<td>-0.95</td>
<td>95</td>
<td>95</td>
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Based on eq. (1) and the mean pressure distribution as presented in Figure 5.

The flow separation angle cannot be accurately determined.
critical stage is entered. Immediately before the transition into the asymmetric bistable state two distinct equal peaks in the power spectrum are visible. These peaks, at $St = 0.17$ and $St = 0.23$, belong to respectively the subcritical and the supercritical flow state. The asymmetric bistable state is defined by the appearance of a separation bubble at one side of the cylinder’s circumference, leading to the occurrence of a steady lift force, see section 3.5. Within the critical regime the flow state is continuously jumping between the sub- and the supercritical state. The separation bubble is randomly occurring at one side of the cylinder in time and its position and occurrence may vary over neighboring sections along the span of the cylinder. As the obtained lift forces are measured by integrating over the complete span of the cylinder, strong lift force fluctuations are obtained at this state, leading to a local increase of the r.m.s. value of the lift fluctuations. This is further emphasized by the broadness of both peaks and a broader low-frequency part of the spectrum, also indicating a continuous jump between both states and thus a very unstable pressure distribution. With growing Reynolds number within the critical regime (Figure 4(e) and 4(f)) the peak in the power spectrum belonging to the supercritical flow state increases in value. In contrast, the peak of the subcritical state slowly increases in width and decreases in height and finally disappears within the measurement noise at the transition from the critical to the supercritical regime. The spectrum shown in Figure 4(g) shows a relatively narrow peak at $Re = 2.11 \times 10^5$. The Strouhal number reaches here its maximum value. A further increase in Reynolds number through the supercritical and transcritical regimes results in a peak that is becoming more and more narrowband (compare Figure 4(h) to 4(j)) – observed in Figure 3(a) as a steady decrease in the r.m.s. value of the lift fluctuations – at constant Strouhal number of $St \approx 0.23$.

3.5 Circumferential pressure distribution

The cause of the asymmetric flow phenomena occurring within the critical state has to be found in the nature of the boundary layer, in particular the transition from laminar to turbulent, and in the appearance of the separation bubbles at both sides at different Reynolds numbers. For a clear understanding of the behavior of the boundary layer at the various flow states, 35 static pressure tabs were positioned along the circumference of the cylinder’s mid-span, Figure 3. In Figure 5 the mean circumferential pressure coefficient distributions over the upper and lower side of the cylinder at mid-span are presented for ten selected measured Reynolds numbers. Note that the results presented in the Figures 5 to 7 are based on the mean time-integrated surface pressure distributions over 10 seconds. The results presented hereafter for the critical Reynolds number regime are based on one measurement series at constant pressure.

The scaling of the axes of the power spectra has been performed for a clear comparison of the shapes and positions of the peaks at the different flow states. For the subcritical state the typical narrowband spectrum at $St = 0.19$ is found in Figure 4(a) to 4(c). At the beginning of the critical stage, Figure 4(c) at $Re \approx 1.61 \times 10^5$, a small low-frequency part can be observed. By further increasing the Reynolds number, the potential cylinder flow. The letters besides the symbols correspond with the measurement points in Table 1.

Figure 5. Mean circumferential pressure coefficient distribution at mid-span. O: Lower half-cylinder ($0^\circ \leq \theta_{cyl, u} \leq 180^\circ$); □: Upper half-cylinder ($0^\circ \leq \theta_{cyl, d} \leq 180^\circ$); dotted line: potential cylinder flow. The letters besides the symbols correspond with the measurement points in Table 1.

In the subcritical flow state the boundary layer is laminar over both sides of the cylinder’s surface. Separation of the laminar boundary layer takes place at $\theta_{cyl, u} \sim 75^\circ$ and $\theta_{cyl, d} \sim 85^\circ$ at respectively the upper and lower side of the cylinder, Figure 5(a) and 5(b) and Figure 6. The transition from laminar to turbulent occurs over the free shear layers in the near-wake. Subsequently the width of the wake is relatively large, which
of the cylinder are observed (Figure 5(c) and 5(d)). This first sign of an upcoming flow state transition is caused by small perturbations or fluctuations in the approaching free stream in time and space. For the presented measurements, only at the lower side of the cylinder are these perturbations over the complete measurement time strong enough to initiate a flow transition at this Reynolds number. The pressure distribution at the upper side of the cylinder is only changing marginally from Figure 5(a) to (e). It has to be noted, that the side of the cylinder at which the first initiation of the flow transition takes place is completely random. In several detailed measurements (not shown here) it was found that both signs of the resultant steady lift force are obtained, meaning that the initiation is independent of the cylinder side. The growth of the strength of the flow perturbations leads to a gradual upstream shift of the boundary layer transition from laminar to turbulent in the near-wake with increasing Reynolds number. The minimum pressure coefficient at the lower side of the cylinder decreases in value, thereby shifting the lower separation angle downstream to higher cylinder angles (Figure 6(a) point (c) and (d)). The downstream shift of the separation angle leads to a decrease of the spacing of the shed vortices between both sides of the cylinder and thus a smaller width. Hence, a decrease of the drag coefficient and an increase of the base pressure coefficient take place (Table 1). The appearance of an asymmetric circumferential pressure distribution is the source of the generation of circulation around the cylinder and thus to the formation of a steady lift force, Figure 8. By increasing the Reynolds number by just a slight increase of the Reynolds number, the critical point is

![Figure 6. Distribution of the mean flow separation angle at (a) the lower half-cylinder (0° ≤ Θ_s ≤ 180°) and (b) the upper half-cylinder (0° ≤ Θ_s ≤ 180°) as function of the Reynolds number. The letters besides the symbols correspond with the measurement points in Table 1.](image)

![Figure 7. Distribution of the mean base pressure coefficient as function of the Reynolds number. The letters besides the symbols correspond with the measurement points in Table 1.](image)

![Figure 8. Distribution of the absolute mean lift coefficient as function of the Reynolds number. The letters besides the symbols correspond with the measurement points in Table 1.](image)

...reflects in the large negative base pressure coefficient of $C_{p,base} \approx -1$ (Table 1 and Figure 7) and the high mean drag coefficient (Figure 3(c)).

Near the critical Reynolds number small differences in the mean pressure distribution between the upper and lower side...
= 90°. That the upper flow separation position wanders downstream is a marker for the second flow transition being at hand. With a small increase in Reynolds number the free stream flow fluctuations at the upper side of the cylinder become strong enough to initiate a similar flow transition, this time at the upper side of the cylinder. The upper detached boundary layer becomes unstable as is reflected by a second increase of the r.m.s. of the lift force fluctuations in Figure 3(a) and the upper transition location from laminar to turbulent in the detached boundary layer wanders upstream.

At the second critical Reynolds number, the transition position has reached that particular forward position at which reattachment of the boundary layer at the back of the cylinder occurs (Figure 5(f)), hence the supercritical flow state has been entered. The asymmetric flow state and thus the presence of a steady lift force have practically disappeared, although it is noted that at this particular Reynolds number a small difference in pressure distribution and in flow separation angles is still present. Both separation angles are located at the backside of the cylinder, leading to a small wake width. This reflects again in the lowest measured drag force coefficient (Figure 3(c)) and highest base pressure coefficient of $C_{p,base} = -0.54$ (Figure 7), in good agreement with $C_{p,base} = -0.6$ measured by Güven et al. [2]. For both reattached shear layers the boundary layer transition position is located on the separation bubble.

The symmetric flow field remains virtually unchanged throughout the supercritical and transcritical flow state (Figure 5(h) to 5(j)). Both separation angles settle at about $\theta_s = 100°$ in the high transcritical range, which is in good agreement with Achenbach [6], the drag coefficient somewhat increases due to an increase in wake width and the base pressure coefficient levels off to $C_{p,base} \approx -0.9$. The latter parameter is somewhat higher than $C_{p,base} \approx -1$ found by Güven et al. [2] and Shih et al. [4] for the transcritical flow regime. In the critical Reynolds number range $(1.2 \times 10^3 \leq Re \leq 1.9 \times 10^4)$ a separation bubble is formed at each side of the cylinder. Two discontinuous jumps are observed at two separate critical Reynolds numbers, accompanied by critical fluctuations of the lift force. At the first critical Reynolds number a separation bubble is formed at only one side of the cylinder, leading to an asymmetric flow state. At this cylinder side, the separation point has moved downstream over the apex of the cylinder and the transition point has wandered upstream and is situated on top of the separation bubble. The formed bubble has a stabilizing effect on the asymmetric flow state, leading to a steady lift force. The second separation bubble is formed at a somewhat larger second critical Reynolds number, thereby cancelling the asymmetric flow state and thus the steady lift force. Subsequently, at this particular Reynolds number, the width of the wake is minimum, leading to a low drag coefficient and a high base pressure coefficient.

In the supercritical and the transcritical flow states $(Re \geq 1.9 \times 10^4)$ the location of the transition from a laminar to a turbulent boundary layer moves upstream of the separation angle. The boundary layer separation itself takes place at about the apex of the cylinder. In comparison to the subcritical and critical regimes, this leads to an intermediate wake width and drag coefficient. In the transcritical flow regime $(Re \geq 1.0 \times 10^5)$ all measured flow field properties reach intermediate steady plateaus compared to the first two flow regimes. The Strouhal number levels off to about $St = 0.23$, the base pressure settles at $C_{p,base} = -0.9$ and a constant drag coefficient of $CD = -0.84$ is measured.

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