

# Drag Crisis Characterization on Cylinders with Double Layer Fabrics

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by

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*Lihao Guo  
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# Abstract

This thesis project examines the drag crisis trigger mechanism for double layer fabrics on cylindrical cross-flow. The primary goal is to discover why the double layer fabric is able to trigger the drag crisis much sooner than conventional surface roughness.

The methodology employed in this research follows an experimental approach, using balance measurements to determine the aerodynamic drag at varying Reynolds numbers for different configurations. Particle Image Velocimetry (PIV) measurements are performed to examine the boundary layer, flow separation point and other flow phenomena occurring near the cylinder surface.

Over the course of this research, eight different double layer configurations have been the subject of study, as well as six single fabric configurations and two reference configurations consisting of a bare cylinder and a cylinder with zigzag trips. Balance measurements have been performed on all of the configurations to determine which configurations are deemed relevant to be studied with PIV techniques. Thus, PIV measurements have been performed on two double layer configurations with a varying underlayer and the same overlayer, as well as the study of the individual fabrics employed to make up the two-fabric construction. That is to say, the two underlayers and one overlayer used have been studied on their own.

The balance results uncover that the minimum drag coefficient across all double layer configurations is achieved with the smallest rib spacing. Conversely, this minimum drag coefficient is located at the highest critical Reynolds number across all configurations. Additionally, a relationship between the critical Reynolds number and the underlayer rib spacing has been determined for the studied configurations. Furthermore, the PIV measurements provide insight into the normalized velocity fields and reconstructed pressure fields. With these results, the development of the boundary layer on the fore-side of the cylinder with double layer fabrics can be studied. Examining the flow near the surface, it can be seen that the presence of the ribs results in a localized flow convergence (upstream of the rib) and divergence (downstream of the rib), these geometric effects accelerate and decelerate the flow locally, causing static pressure oscillations on the foreside of the cylinder. With the appearance of localized adverse pressure gradients on the foreside of the cylinder, flow instabilities are seeded eventually trigger the transition of the boundary layer to a turbulent state, thus allowing the flow to remain attached to the cylinder surface for longer, ultimately delaying separation and reducing pressure drag.

While the study has provided valuable insights regarding the trigger mechanism for the drag crisis on double layer fabrics on cylinders, it has also paved the way for further research regarding this topic and the specific effects of rib height, behavior and performance in unsteady flows and whether the two fabric construction is strictly necessary. These considerations are addressed at the end of the conclusions chapter.



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# Nomenclature

## Abbreviations

| Abbreviation | Definition                                                      |
|--------------|-----------------------------------------------------------------|
| FoV          | Field of View                                                   |
| HSL          | High-Speed Laboratory                                           |
| L            | Laminar                                                         |
| PIV          | Particle Image Velocimetry                                      |
| RMS          | Root-mean-square                                                |
| RPM          | Revolutions Per Minute                                          |
| TrBL         | Transition in the Boundary Layer                                |
| TrSL         | Transition in the Shear Layer                                   |
| TrW          | Transition in the Wake                                          |
| 05UL         | Underlayer with 5 <i>mm</i> spacing Configuration               |
| 07UL         | Underlayer with 7 <i>mm</i> spacing Configuration               |
| 10UL         | Underlayer with 10 <i>mm</i> spacing Configuration              |
| 20UL         | Underlayer with 20 <i>mm</i> spacing Configuration              |
| RO           | Rough Overlay Configuration                                     |
| RO05         | Double Layer Configuration with 05UL Underlayer and RO Overlay  |
| RO07         | Double Layer Configuration with 07UL Underlayer and RO Overlay  |
| RO10         | Double Layer Configuration with 10UL Underlayer and RO Overlay  |
| RO20         | Double Layer Configuration with 20UL Underlayer and RO Overlay  |
| SM           | Bare Cylinder Configuration                                     |
| SM05         | Double Layer Configuration with 05UL Underlayer and SMF Overlay |
| SM07         | Double Layer Configuration with 07UL Underlayer and SMF Overlay |
| SM10         | Double Layer Configuration with 10UL Underlayer and SMF Overlay |
| SM20         | Double Layer Configuration with 20UL Underlayer and SMF Overlay |
| SMF          | Smooth Overlay Configuration                                    |

## Symbols

| Symbol          | Definition                                     | Unit    |
|-----------------|------------------------------------------------|---------|
| $A$             | Reference Area                                 | $[m^2]$ |
| $C$             | Duplex nozzle cross-section area (Corrections) | $[m^2]$ |
| $C_d$           | Drag Coefficient                               | $[-]$   |
| $C_{d,min}$     | Minimum Drag Coefficient                       | $[-]$   |
| $C_{dfriction}$ | Friction Contribution to the Drag Coefficient  | $[-]$   |
| $C_{dfriction}$ | Pressure Contribution to the Drag Coefficient  | $[-]$   |
| $D$             | Drag Force                                     | $[N]$   |

| Symbol          | Definition                                          | Unit                    |
|-----------------|-----------------------------------------------------|-------------------------|
| $D$             | Cylinder Diameter                                   | [m]                     |
| $F_{zero}$      | Balance Zero Reading                                | [N]                     |
| $f$             | Vortex Shedding Frequency                           | [Hz]                    |
| $H$             | Boundary Layer Shape Factor                         | [—]                     |
| $h$             | Nozzle height                                       | [m]                     |
| $h_{rib}$       | Rib Height                                          | [ $\mu$ m]              |
| $k_{rms}$       | Root-mean-square roughness height                   | [ $\mu$ m]              |
| $k_s$           | Sand-grain Roughness                                | [ $\mu$ m]              |
| $l$             | Cylinder Length                                     | [m]                     |
| $L_m$           | Model Length (Corrections)                          | [m]                     |
| $p$             | Static Pressure                                     | [Pa]                    |
| $p_\infty$      | Freestream Static Pressure                          | [Pa]                    |
| $q$             | Dynamic Pressure                                    | [Pa]                    |
| $q_{u,n}$       | Uncorrected Nozzle Dynamic Pressure                 | [Pa]                    |
| $R$             | Cylinder Radius                                     | [m]                     |
| $R_n$           | Hydraulic radius of duplex nozzle (Corrections)     | [m]                     |
| $r$             | Radial Direction                                    | [m]                     |
| $Re$            | Reynolds Number                                     | [—]                     |
| $Re_{crit}$     | Critical Reynolds Number                            | [—]                     |
| $S$             | Model Frontal Area (Corrections)                    | [m <sup>2</sup> ]       |
| $S_\mu$         | Sutherland's Law Constant                           | [K]                     |
| $S_k$           | Skewness of Height Probability Density Function     | [—]                     |
| $St$            | Strouhal Number                                     | [—]                     |
| $T$             | Air Temperature                                     | [K]                     |
| $T_0$           | Sutherland's Law Reference Temperature              | [K]                     |
| $t$             | Model Thickness                                     | [m]                     |
| $TI$            | Turbulence Intensity                                | [%]                     |
| $u'$            | Root-mean-square of turbulent velocity fluctuations | [m/s]                   |
| $u_r$           | Velocity in the Radial Direction                    | [m/s]                   |
| $u_t$           | Velocity in the Tangential Direction                | [m/s]                   |
| $U_e$           | Velocity Magnitude Outside of Boundary Layer        | [m/s]                   |
| $U_\infty$      | Freestream Velocity                                 | [m/s]                   |
| $v_r$           | Wall-normal Velocity Component                      | [m/s]                   |
| $v_{u,n}$       | Uncorrected Nozzle Velocity                         | [m/s]                   |
| $V_{corr}$      | Corrected Tunnel Velocity                           | [m/s]                   |
| $V_{tunnel}$    | Uncorrected Tunnel Velocity                         | [m/s]                   |
| $w$             | Nozzle width                                        | [m]                     |
| $w_{rib}$       | Rib Width                                           | [mm]                    |
| $x$             | Streamwise Direction                                | [m]                     |
| $x_m$           | Distance from model center to nozzle (Corrections)  | [m]                     |
| $x_s$           | Distance from source to nozzle (Corrections)        | [m]                     |
| $y$             | Stream Normal Vertical Direction                    | [m]                     |
| $\Delta t$      | Time between PIV exposures                          | [ $\mu$ s]              |
| $\Delta$        | Rib Spacing                                         | [mm]                    |
| $\delta^*$      | Boundary Layer Displacement Thickness               | [mm]                    |
| $\delta_{99}$   | Boundary Layer 99% Thickness                        | [mm]                    |
| $\delta_m$      | Boundary Layer Momentum Thickness                   | [mm]                    |
| $\epsilon$      | Total Blockage Factor                               | [—]                     |
| $\epsilon_n$    | Nozzle Blockage Factor                              | [—]                     |
| $\epsilon_{qn}$ | Perturbation velocity at nozzle plane               | [—]                     |
| $\epsilon_s$    | Solid Blockage Factor                               | [—]                     |
| $\kappa$        | Numerical Fitting Factor for $C_d - Re$ curves      | [—]                     |
| $\lambda_{2D}$  | Body Shape factor                                   | [—]                     |
| $\mu$           | Air Dynamic Viscosity                               | [N · s/m <sup>2</sup> ] |

| Symbol         | Definition                     | Unit       |
|----------------|--------------------------------|------------|
| $\nu$          | Air Kinematic Viscosity        | $[m^2/s]$  |
| $\phi$         | Velocity Potential             | $[m^2/s]$  |
| $\psi$         | Stream Function                | $[m^2/s]$  |
| $\rho$         | Air Density                    | $[kg/m^3]$ |
| $\theta$       | Azimuth                        | $[^\circ]$ |
| $\theta_{sep}$ | Separation Angle               | $[^\circ]$ |
| $\varphi$      | PIV Cross-correlation Function | $[-]$      |

# 1

## Introduction

In athlete-powered racing sports such as cycling, sprinting or ice-skating, aerodynamic drag is the main contributor to the total resistance force on the athlete. In high-speed time trial cycling events, for instance, the aerodynamic drag corresponds to more than 90% of the total resistive force [21].

This thesis project is centered around the passive techniques of drag reduction via modification of the surface properties of the body part. Common techniques of drag reduction are based on disturbing the flow development along the foreside of the body part/cylinder in order to forcefully transition to a turbulent boundary layer and thus delay separation and reduce aerodynamic drag. An example of this implementation in the context of sport sciences is the study performed by Timmer and Veldhuis [34] on *The Impact of Skinsuit Zigzag Tape Turbulators on Speed Skating Performance* where they studied the effects of zigzag strips on ice-skater suits. Another example is the study from Achenbach [2] on *The Influence of Surface Roughness on the Cross-Flow around a Circular Cylinder* where the effects of distributed surface roughness on cylinders were studied in terms of the aerodynamic drag, friction forces and pressure distributions. Finally, another example from Skeide et al. [31] on *The Significant Impact of Ribs and Small-Scale Roughness on Cylinder Drag Crisis* studied the effect of flow-normal ribs and small-scale roughness on the aerodynamic drag of a cylinder. In the research conducted by Skeide et al. there is no mention of the underlying trigger mechanism for the drag crisis.

This research project aims to study the flow around a cylinder covered with a double layer fabric, and what the effects of each of the individual fabrics are on the overall flow. The main aim is to provide newfound knowledge and to expand the existing literature regarding surface distributed trips in the presence of large pressure gradients (cylinder cross-flows) and specifically, the characterization of the drag crisis on cylinders with double layer fabrics.

The development of this thesis combines a total of sixteen unique configurations that have been studied using experimental techniques such as balance measurements and Particle Image Velocimetry (PIV). These configurations range from reference cases such as a bare cylinder and a cylinder with zigzag strips, to the double layer fabric constructions. The employed experimental techniques have allowed the acquisition of the varying aerodynamic drag at different flow regimes, as well as a reconstruction of the flow fields around the cylinder.

Chapter 2 presents extensive background research, including an overview of the relevance of drag reduction in sports sciences, followed by an explanation of different flow topologies around a cylinder from inviscid to viscid. Regarding viscid flow regimes, the different flow regimes based on varying Reynolds numbers are described. This is followed by a brief overview of drag reduction techniques, with special emphasis on passive approaches to drag reduction. Finally, to conclude Chapter 2, the research questions are formulated and presented at the end of the chapter.

Chapter 3 introduces the experimental principles behind the techniques employed during this research. The principles of PIV acquisition and processing are briefly explained. This is followed by a brief overview of the principles behind balance and pressure measurements. To conclude this chapter, the

experimental wind tunnel boundary corrections are presented.

Chapter 4 presents the experimental setup employed in this thesis. Characteristics of the cylinder model, as well as the fabric properties, are first introduced here. This is followed by the wind tunnel setup including the anemometer setup and the computation of boundary corrections. Then, the balance and PIV setups are explained. Finally, the data reduction process for the balance and PIV measurements is described.

Chapter 5 presents an analysis of the results. For each of the configurations, the balance results are first shown. Then, for the relevant configurations, the normalized velocity and pressure coefficient fields are presented. After that, a boundary layer analysis on the foreside of the cylinder is performed. Finally, based on the analysis of the results, Chapter 6 presents the conclusions drawn in relation to the research questions. Finally, considerations and recommendations are made for further research into cylinders with double layer fabrics.

# 2

## Literature Review

### 2.1. Sport Aerodynamics

Sport aerodynamics aims to improve athlete performance through technical means. In disciplines such as cycling, sprinting and ice skating, certain factors such as athlete body positioning and equipment design can have a crucial effect in athlete performance. Understanding aerodynamics allows sport scientists, teams and coaches to refine techniques, minimize drag and enhance efficiency, thus pushing the boundaries of human performance while ensuring safety and fairness in competition.

Aerodynamic drag, or air resistance, results from the relative velocity between the object and the surrounding air.

$$D = \frac{1}{2} \rho U_{\infty}^2 C_D A \quad (2.1)$$

As seen in Equation (2.1), aerodynamic drag is a function of air density  $\rho$ , speed relative to fluid  $U_{\infty}$ , drag coefficient  $C_D$  and a specific area  $A$  related to the body part/object in question. In general, reducing this drag is crucial for performance gains.

In order to achieve performance gains, each of the parameters should be analyzed to look for possible reductions.

- Air density,  $\rho$ . The density of the air depends largely on the location where the sport event is taking place, more concretely the sea-level height map of the venue and the specific atmospheric conditions on that particular day. With decreasing atmospheric pressure and air temperature, the air density will be reduced.
- Velocity relative to the fluid,  $U_{\infty}$ . This is often times the magnitude to maximize, as a higher speed will lead to a better result, therefore, there are no desires to minimize this parameter.
- Drag coefficient,  $C_D$ . Non-dimensional coefficient that indicates how aerodynamic an object is within flow. Generally, the lower its magnitude, the more aerodynamic the body. However, the amount of drag a body generates varies drastically with the way the flow behaves, whether it is laminar or turbulent. When it comes to smaller body parts and limbs, the drag coefficient can vary a lot based on the surface characteristics of the object. Given that the transition from laminar to turbulent flow can be altered with surface roughness and other elements. The minimization of the drag coefficient will be the main topic of this investigation.
- Reference area,  $A$ . This reference area varies according to the object that is being studied. Generally, the front area of the object is taken. In terms of minimization in the context of athletes and sport aerodynamics, teams aim to optimize athlete posture and the use of tight fabrics around the athlete to minimize its frontal area.

In order to quantify and determine the state of the flow regarding its laminar/turbulent behavior, the Reynolds number is often used. It is formally defined as the ratio between the inertial and viscous

forces present in the flow. Its definition for the flow around a cylinder is as follows:

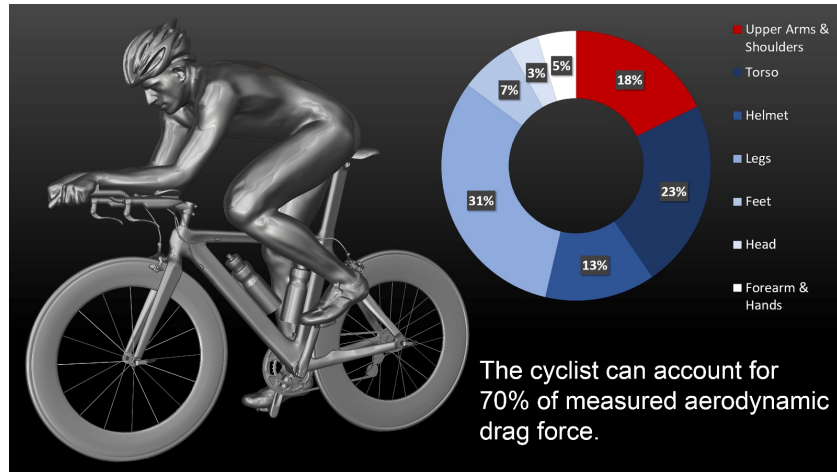
$$Re = \frac{\rho U_{\infty} D}{\mu} = \frac{U_{\infty} D}{\nu} \quad (2.2)$$

where  $\mu$  corresponds to the dynamic viscosity of the fluid,  $\nu$  the kinematic viscosity of the fluid, and  $D$  the diameter of the cylinder.

In high-speed sports like cycling, speed skating and skiing, the athlete's limbs behave much like circular cylinders exposed to oncoming airflow. Therefore, it is a reasonable assumption to simplify these body parts into cylindrical bodies in order to perform an aerodynamic study.

A key challenge is that the flow around a smooth cylinder (or limb) at typical speeds tends to separate early in a laminar state, producing a wide wake and therefore high pressure drag. However, in certain critical Reynolds number regimes, a phenomenon known as the drag crisis occurs, where the drag coefficient drops dramatically as the boundary layer transitions to turbulent flow before separating. By understanding and manipulating this transition, different methods can be exploited to delay flow separation and narrow the wake, thus significantly reducing drag.

In high-speed time trial cycling events, professional cyclists reach speeds of  $15 \text{ m/s}$  or  $54 \text{ km/h}$ . At these speeds, the aerodynamic drag corresponds to more than 90% of total resistive force [21]. The cyclist can account for 70% of the total aerodynamic drag, with its upper arms and shoulders contributing 18% to the drag generated by the cyclist. [16].



**Figure 2.1:** Breakdown of different body parts and their contribution to cyclist aerodynamic drag. [16]

The typical diameter for the upper arm of speed cyclists ranges from  $8 - 12 \text{ cm}$  [19]. For a typical air kinematic viscosity of  $\nu = 1.48 \times 10^{-5} \text{ m}^2/\text{s}$ . At race speeds of  $15 \text{ m/s}$ , this yields a  $Re$  from  $8.1 \times 10^4 - 1.2 \times 10^5$ . Furthermore, the calf diameter of sprint cyclists is around  $12 \text{ cm}$  [19], which yields a  $Re$  of  $1.2 \times 10^5$  at the same velocities.

In track and field events, on the other hand, competitive runners move at significantly lower speeds than cyclists. In sprinting modalities, aerodynamics are not nearly as significant as in cycling due to the shorter duration of the event. Although a significant portion of the athlete's total power is devoted to accelerating, aerodynamics still play an important factor; a difference of a few milliseconds could mean winning or losing the competition.

Professional sprinters can still approach speeds of  $10 - 12 \text{ m/s}$  over the  $100 \text{ m}$  dash. The average thigh diameter for short distance runners is around  $18 \text{ cm}$  [32], which yields a  $Re$  from  $1.2 \times 10^5 - 1.5 \times 10^5$ . Similarly, the diameter of the upper arms in a flexed arm position is around  $10 \text{ cm}$  [32], resulting in a  $Re$  from  $6.7 \times 10^4 - 8.1 \times 10^4$  at race speeds.

In the discipline of speed skating, Timmer and Veldhuis [34], calculated the  $Re$  values corresponding to ankles and calves of elite male speed skaters competing in the distances of  $1500 \text{ m}$  and  $5000 \text{ m}$ . In



addition to variations in the average  $Re$  due to the motion induced by the skating stride shown in Table 2.1:

**Table 2.1:** Reynolds number range of the lower legs as calculated by Timmer and Veldhuis [34].

| Location | Event Distance [m] | Average Velocity [m/s] | $D$ [cm] | Average $Re$ [-]   | $\pm \Delta Re$ [-] |
|----------|--------------------|------------------------|----------|--------------------|---------------------|
| Calf     | 1500               | 13.78                  | 12.5     | $1.18 \times 10^5$ | $2.2 \times 10^4$   |
|          | 5000               | 12.8                   |          | $1.09 \times 10^5$ |                     |
| Ankle    | 1500               | 13.78                  | 6.9      | $0.65 \times 10^5$ | $1.9 \times 10^4$   |
|          | 5000               | 12.8                   |          | $0.60 \times 10^5$ |                     |

In total, across the sports disciplines and events explored and for various body parts, the ranges  $Re$  can be summarized in Table 2.2:

**Table 2.2:** Reynolds number ranges across different events, sports and body parts.

| Sport                  | Body part | $D$ [cm] | $U_\infty$ [m/s] | $Re$ [-]                               |
|------------------------|-----------|----------|------------------|----------------------------------------|
| Speed Cycling          | Upper Arm | 8 – 12   | 15               | $8.4 \times 10^4 - 1.2 \times 10^5$    |
|                        | Calf      | 12       |                  | $1.2 \times 10^5$                      |
| Sprinting              | Thigh     | 18       | 10 – 12          | $1.2 \times 10^5 - 1.5 \times 10^5$    |
|                        | Upper Arm | 10       |                  | $6.7 \times 10^4 - 8.1 \times 10^4$    |
| Speed Skating (1500 m) | Calf      | 12.5     | 13.78            | $1.18 \times 10^5 \pm 2.2 \times 10^4$ |
|                        | Ankle     | 6.9      |                  | $0.65 \times 10^5 \pm 1.9 \times 10^4$ |
| Speed Skating (5000 m) | Calf      | 12.5     | 12.8             | $1.09 \times 10^5 \pm 2.2 \times 10^4$ |
|                        | Ankle     | 6.9      |                  | $0.60 \times 10^5 \pm 1.9 \times 10^4$ |

Note that for all of these sports, the relevant  $Re$  range is subject to a lot of variations. Not only because of changes in geometry from athlete to athlete, but also due to the fact that the air velocity each specific body part encounters is highly variable due to the stride motion and also athlete-to-athlete variance. Therefore, in order to account for all of these disciplines and events, an extensive  $Re$  range should be taken as the region of interest, which from now on will be  $60000 \leq Re \leq 150000$ .

## 2.2. Cylinder Flow

Throughout this research, a circular cylinder is used with its longitudinal axis placed across the oncoming flow. This means that if a 2D slice is taken along the velocity plane, it would cut the cylinder into a perfect circle, as shown in Figure 2.2. Note that in the aforementioned figure, two distinct coordinates systems can be differentiated.

A Cartesian system ( $x - y$ ) will be used to express the aerodynamic forces on the cylinder associated with the wind axes. In this case, the  $x$  axis depicts the direction of free stream flow; therefore, this will imply that the aerodynamic drag force component will be along the said  $x$  axis. Similarly, the "lift" or normal component will be along the  $y$  axis, which is towards the vertical upwards direction.

On the other hand, a polar coordinate system ( $r - \theta$ ), is used for convenience due to the circular nature of the geometry and to simplify the boundary conditions and the surface integrals along the cylinder.

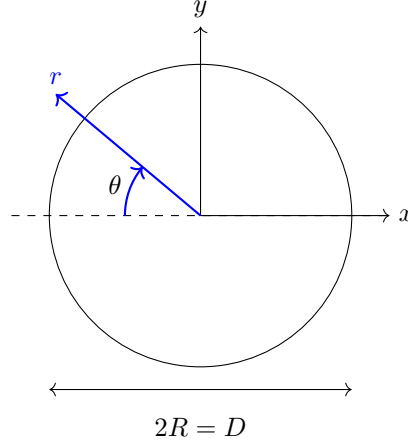
### 2.2.1. Inviscid Flow

Inviscid flow is an idealized type of fluid flow where the effects of viscosity are neglected, meaning there is no internal friction between fluid layers and no shear stresses within the fluid.

The simplest way to model the flow around a cylinder can be done according to potential flow theory.

$$\mathbf{V} = \nabla \phi \quad (2.3)$$

where  $\phi$  is the velocity potential, a scalar field whose gradient corresponds to the velocity vector.



**Figure 2.2:** Scheme depicting the cylinder coordinate systems, Cartesian and Polar.

As such, according to potential flow theory, an inviscid, incompressible and irrotational flow around a cylinder can be modeled from a combination of a uniform flow ( $U_\infty$ ) with a doublet, which constitutes a source and sink element placed infinitely close together, thus creating a dipole field.

Therefore, the combination of all these elements in accordance to the superposition principle results and by imposing the incompressibility of the flow and its non-rotational property, the following partial differential equation is obtained and solving it will result in the expression for the velocity potential:

$$\nabla^2 \phi = 0 \quad (2.4)$$

with the following boundary conditions:

$$\nabla \phi \cdot \hat{n} = 0 \quad (2.5)$$

$$\phi_{(r \rightarrow \infty)}(r, \theta) = U_\infty x = -U_\infty r \cos(\theta) \quad (2.6)$$

These boundary conditions impose a null flow through the surface of the cylinder and the fact that flow at infinity must remain undisturbed [4]. Note that the negative sign appears due to the definition of the  $\theta$  angle:  $x = -r \cos(\theta)$ . Solving the equation with these boundary conditions results in the following expression for the velocity potential:

$$\phi(r, \theta) = -U_\infty r \left( 1 + \frac{R^2}{r^2} \right) \cos(\theta) \quad (2.7)$$

Thus, the velocity components can be obtained by computing the gradient of the potential.

$$u_r(r, \theta) = -\frac{\partial \phi}{\partial r} = U_\infty \left( 1 - \frac{R^2}{r^2} \right) \cos(\theta) \quad (2.8)$$

$$u_\theta(r, \theta) = \frac{1}{r} \frac{\partial \phi}{\partial \theta} = U_\infty \left( 1 + \frac{R^2}{r^2} \right) \sin(\theta) \quad (2.9)$$

Furthermore, the pressure field around the cylinder can be calculated via Bernoulli's Principle:

$$p - p_\infty = \frac{1}{2} \rho (U_\infty^2 - (u_r^2 + u_\theta^2)) \quad (2.10)$$

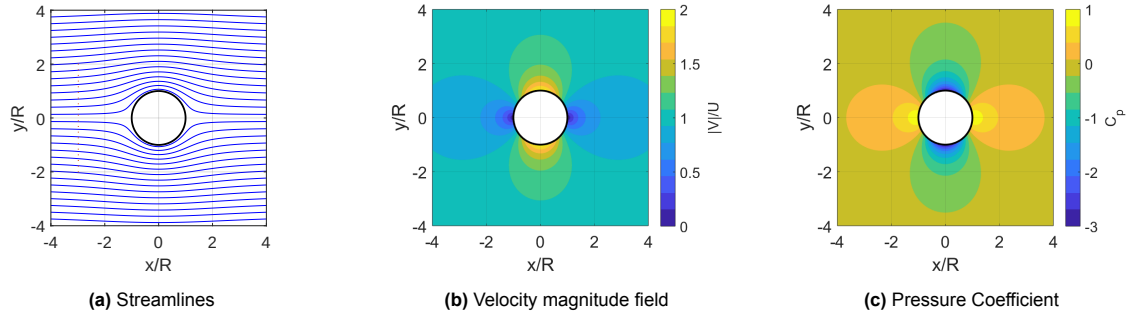
Introducing the pressure coefficient:

$$C_p = \frac{p - p_\infty}{\frac{1}{2} \rho U_\infty^2} = \frac{\frac{1}{2} \rho (U_\infty^2 - (v_r^2 + v_\theta^2))}{\frac{1}{2} \rho U_\infty^2} \Rightarrow C_p(r, \theta) = 1 - \left[ \left( 1 - \frac{R^2}{r^2} \right)^2 \cos^2(\theta) + \left( 1 + \frac{R^2}{r^2} \right)^2 \sin^2(\theta) \right] \quad (2.11)$$

Finally, taking  $r = R$ , the pressure coefficient on the surface of the cylinder is obtained:

$$C_p(r = R, \theta) = 1 - 4\sin^2(\theta) \quad (2.12)$$

All in all, an inviscid flow around a cylinder would result in a field with the following streamlines, velocity, and pressure coefficient distributions:



**Figure 2.3:** Streamlines, velocity magnitude and pressure coefficient distributions around a cylinder in inviscid flow.

### D'Alembert's Paradox

According to the results obtained from the inviscid analysis, given the front-to-back symmetry that can be seen in the pressure field, Figure 2.3c, one would expect a cylinder flowing through the air to have no drag. Contrarily to what is observed through experimentation in the real world, any object placed in a real flowing field will experience aerodynamic drag due to the effect of fluid viscosity and flow separation from the surface of the body.

This discrepancy is referred to as D'Alembert's Paradox. The occurrence of the paradox is due to the neglected effects of fluid viscosity and the disregard of the boundary layer. These combined effects result in an early separation and a consequent low-pressure wake appearing behind the bluff body.

### 2.2.2. Viscid Flow

Viscid flow is a type of fluid flow in which the fluid's viscosity plays a significant role in determining the flow behavior. Viscosity introduces internal friction between adjacent layers of fluid, leading to shear stresses and energy dissipation within the flow.

In viscous flows, the presence of viscosity affects the velocity distribution, especially near solid surfaces where the no-slip condition applies, meaning the fluid velocity matches the velocity of the surface (typically zero). This gives rise to boundary layers, where velocity changes rapidly, and can also cause flow separation, wake formation, and therefore drag.

Unlike inviscid flow (which idealizes the fluid as having no viscosity), viscous flow is essential for accurately describing real-world situations involving air, water, and other fluids.

Based on the value of the Reynolds number, the flow can vary drastically; cylinder flows can be classified based on where the transition to turbulent flow occurs, according to the works of Lupi [24] and Zdravovich [40].

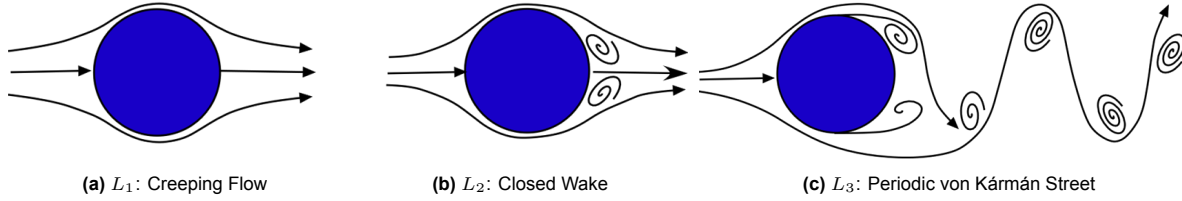
#### Fully Laminar Flow Regime ( $Re \leq 200$ )

For Reynolds numbers under 180 – 200. The flow is fully laminar, meaning that the inertia of the fluid is so weak that viscous diffusion is predominant everywhere in the domain. The boundary layer remains laminar up to separation, and the wake evolves through three sub-states:

- $L_1$ : Creeping Flow ( $Re \leq 4 - 5$ ) Viscous forces overwhelm inertia, the flow is fully symmetric front-to-back with no separation.

- $L_2$ : Closed Wake ( $4 - 5 \leq Re \leq 30 - 38$ ) A steady pair of symmetric recirculation regions form immediately downstream of the cylinder. Flow separation from the cylinder occurs at around  $\theta \approx 80^\circ$  and the shear layers rejoin in a closed wake.
- $L_3$ : Periodic von Kármán street ( $30 - 48 \leq Re \leq 180 - 200$ ) The closed wake becomes unstable to a sinuous oscillation and an alternate vortex shedding begins. Eddies are formed downstream and are eventually shed.

These three sub-states can be seen in Figure 2.4:



**Figure 2.4:** Different wake states for Laminar Flow. Taken from J. Gordon Leishman [22]

### Transition in the Wake ( $180 - 200 \leq Re \leq 350 - 400$ )

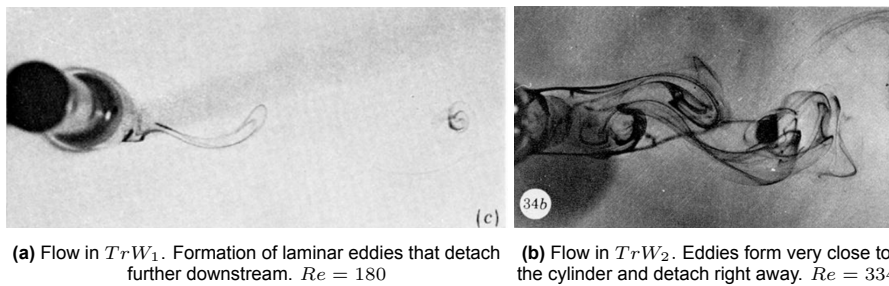
For slightly larger Reynolds numbers, the transition into turbulent flow occurs at various locations of the cylinder wake. Two distinct shedding modes can be identified in this regime.

- $TrW_1$ : Lower-wake Transition ( $180 - 200 \leq Re \leq 220 - 250$ ) Laminar eddies from near the cylinder and become turbulent further downstream. The wake remains periodic. Around  $Re \approx 250$  a jump in the vortex shedding frequency marks the switch from low-speed to high-speed shedding. The jump in frequency is often quantified by means of the non-dimensional Strouhal number  $St$ :

$$St = \frac{fD}{U_\infty} \quad (2.13)$$

- $TrW_2$ : Upper-wake Transition ( $220 - 250 \leq Re \leq 350 - 400$ ) Turbulence spreads upstream in the wake, eddies roll up very close to the cylinder before detaching.

Figure 2.5, shows both flow regimes. Note that the location where the eddies start forming varies drastically, as well as the shedding frequency. Figure 2.5b exhibits a significantly increased shedding frequency, denoting the upper-wake transition.



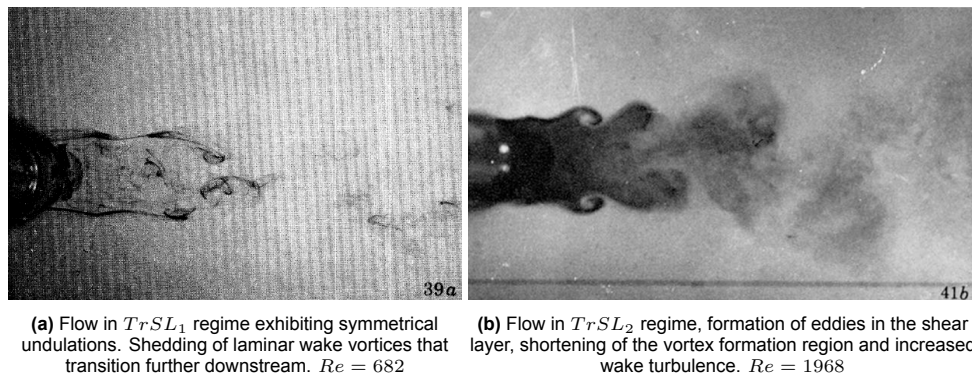
**Figure 2.5:** Flows portraying transition in the cylinder wake. Taken from J. H. Gerrard. [15]

### Transition in the Shear Layer ( $350 - 400 \leq Re \leq 2 \times 10^5$ )

As the Reynolds number further increases, the transition to turbulent flow occurs in the shear layer, further upstream than the previous cases. This regime is also known as the subcritical regime. In this case, the boundary layer remains laminar up to and beyond separation. Transition occurs at the free shear layers, which undergo transition before they roll up into vortices, the flow structures of this state are commonly referred to as transition eddies. In this regime, three sub-cases can be distinguished:

- $TrSL_1$ : Lower-subcritical ( $350 - 400 \leq Re \leq 1000 - 2000$ ) In this regime, undulations of both top and bottom shear layers develop from the separation lines. These undulations are symmetrical and in phase on both sides of the cylinder. Wake vortices are shed in a laminar or early transitional state.
- $TrSL_2$ : Intermediate-subcritical ( $1000 - 2000 \leq Re \leq 2 \times 10^4 - 4 \times 10^4$ ) Chains of transitional eddies form in the shear layers prior to full turbulence. Transition is moved further upstream, shortening the vortex formation region and increasing wake turbulence.
- $TrSL_3$ : Upper-subcritical ( $2 \times 10^4 - 4 \times 10^4 \leq Re \leq 1 \times 10^5 - 2 \times 10^5$ ) The flow is highly turbulent right after separation, the shear layer effectively transitions to turbulent right at the separation point.

The regimes  $TrSL_1$  and  $TrSL_2$  can be seen in Figure 2.6, the characteristic flow structures from each regime, as well as the upstream displacement of the transition point from laminar to turbulent flow.



**Figure 2.6:** Flows portraying transition in the shear layer. Taken from J. H. Gerrard. [15]

### Transition in Boundary Layer ( $10^5 \leq Re \leq 3.5 - 6 \times 10^6$ )

As Reynolds numbers approach  $3 \times 10^5$ , the flow enters the critical regime where the cylinder's boundary layer transitions to turbulence. The transition in boundary layers regime is characterized by the formation of laminar separation bubbles and a dramatic shift in flow behavior known as the drag crisis. In this regime, the laminar boundary layer on the cylinder surface no longer separates to directly form a wake; instead, it begins to transition to turbulent while still attached to the cylinder. This process drastically alters the separation point and wake structure. The following distinctions can be made within this regime:

- $TrBL_0$ : Pre-critical ( $10^5 \leq Re \leq 2 \times 10^5$ ) The beginning of the drag crisis. The drag coefficient begins to fall gradually from its subcritical plateau. The laminar separation point moves slightly downstream and the wake narrows accordingly.
- $TrBL_1$ : Single-bubble ( $3 \times 10^5 \leq Re \leq 3.4 \times 10^5$ ) The drag drop becomes more pronounced. A laminar separation bubble forms only on one side of the cylinder, causing an asymmetric pressure distribution. The flow is bistable, meaning that the bubble could be located on either side. The side in which the bubble is located, the cylinder will experience significant lift. Although the bubble would remain on one side of the cylinder, thus generating a steady lift. In practice, due the inherent flexibility of the cylinder in some setups and its oscillating movement, it will result in the bubble shifting from side to side, thus resulting in oscillations.
- $TrBL_2$ : The two-bubble (critical) ( $3.8 \times 10^5 - 4 \times 10^5 \leq Re \leq 5 \times 10^5 - 10^6$ ) Transition has now occurred on both sides, resulting in symmetric laminar separation bubbles. The wake is significantly narrower by the delayed separation and the drag coefficient reaches its minimum (from 1.2 to 0.4) [2]. This regime is usually narrow in  $Re$  range.
- $TrBL_3$ : Supercritical ( $5 \times 10^5 - 10^6 \leq Re \leq 3.5 \times 10^6 - 6 \times 10^6$ ) Immediately after the drag minimum, the laminar separation bubbles begin to collapse. The turbulent boundary layer starts to form without any laminar bubble as  $Re$  increases beyond critical.

- $TrBL_4$ : Transcritical ( $3.5 \times 10^6 - 6 \times 10^6 \leq Re$ ) The flow starts to transition to a fully turbulent state. The separation is purely turbulent on both sides with no laminar bubble. The wake and forces settle, the drag coefficient slowly steadily increases.

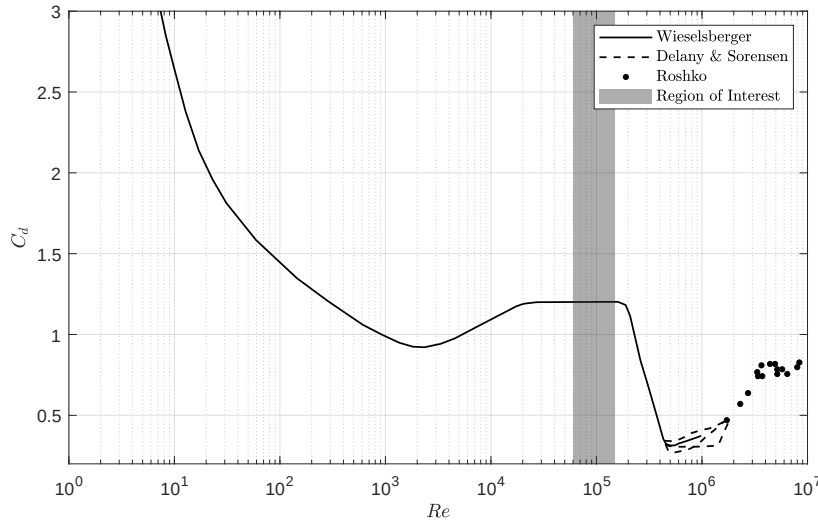
## 2.3. Aerodynamic Drag

Based on the flow regimes explained in Section 2.2.2, the flow can have vastly different characteristics. These differences show themselves as varying flow structures around the cylinder, different pressure distributions around the cylinder and varying values for the drag coefficient ( $C_d$ ) for varying  $Re$ .

$$C_d = \frac{F_D}{\frac{1}{2}\rho U_\infty^2 A} \quad (2.14)$$

where the area  $A$  stands for the frontal area of the cylinder:  $A = D \cdot l$ , where  $l$  is the length of the cylinder.

Figure 2.7, shows the evolution of the drag coefficient as a function of the Reynolds number for a smooth cylinder, these findings were obtained by Wieselsberger [36], Roshko [30] and Delany & Sorensen [10].



**Figure 2.7:** Drag Coefficient ( $C_d$ ) as a function of the Reynolds number ( $Re$ ) for a smooth cylinder. Adapted from: [10], [30], [36]

As seen in Figure 2.7 for low  $Re$  viscous regimes, the drag coefficients are very large due to how the viscous forces scale relative to the dynamic pressure. Given that the drag coefficient is non-dimensionalised with the dynamic pressure ( $U_\infty^2$ ) and the viscous drag in creeping or Stoke's flow scales with ( $U_\infty$ ), therefore for very freestream velocities the drag coefficient becomes unbounded.

As  $Re$  increases,  $C_d$  decreases and settles around 1.2. It remains mostly constant up to the critical regime, corresponding to  $TrBL_1$  and  $TrBL_2$  and a  $Re$  of around  $3 \times 10^5 - 5 \times 10^5$  for a smooth cylinder. Once the cylinder reaches the critical regime, the drag coefficient drops to a minimum of  $C_d = 0.3$ . Then, from this point onward, the flow is supercritical and the drag coefficient rises steadily.

The  $C_D - Re$  curve shown in Figure 2.7, is obtained in a wind tunnel environment under controlled conditions. In such conditions, the flow presents low amounts of turbulence intensity. Turbulence intensity ( $TI$ ) is a dimensionless magnitude that measures the strength of turbulence relative to the mean flow:

$$TI (\%) = \frac{u'}{U_\infty} \times 100 \quad (2.15)$$

where  $u'$  is the RMS of the turbulent velocity fluctuations:  $u' = \sqrt{\frac{1}{3} [(\bar{u}'_x)^2 + (\bar{u}'_y)^2 + (\bar{u}'_z)^2]}$

Generally, wind tunnels devoted to research have a freestream turbulence intensity ranging from (0.05%–0.5%). In contrast, under real world conditions such as sport venues, the turbulence is significantly higher; especially in the low-frequency ranges ( $< \sim 10$  Hz), measured in a speed skating oval [9]. The turbulence in these frequencies is mostly dominated by large-scale vortices created by skater movement and thermal stratification that generate vertical flows.

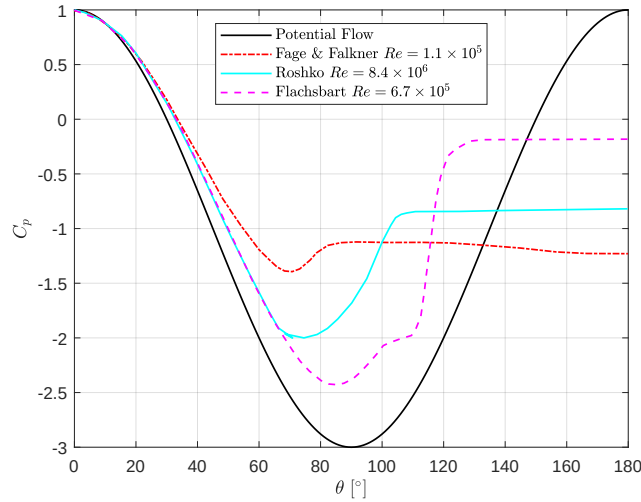
Turbulence intensity has an effect on the development of the boundary layer along the surface of the cylinder. For higher values of freestream turbulence, the boundary layer will transition for the same  $Re$  at an earlier  $\theta$ . This will result in the drag crisis occurring at a lower  $Re$  for increasing  $TI$  [18].

Note that the contributions to drag can be broken down into different factors:

$$C_d = C_{d_{friction}} + C_{d_{pressure}} \quad (2.16)$$

In bluff bodies, the drag coefficient can be separated into individual contributions of friction/viscous drag and pressure drag. The viscous drag results from shear stresses due to velocity gradients at the surface of the body. However, the pressure drag results from the pressure difference from the front of the body to the rear. At the front, there is a high-pressure region due to the stagnation of the incoming flow, and in the rear of the body, there is a low-pressure region due to the flow separating.

In regimes with moderately high  $Re$ , for objects that are not streamlined, the main contributor to the drag coefficient is pressure drag. This can be observed in Figure 2.8, as the  $Re$  approaches the critical value, the recovery value of the pressure coefficient increases, which means that the pressure on the leeward side of the cylinder is higher. Additionally, not only is the recovery value larger, but the separation point is displaced further downstream, which reduces the effective area of low pressure behind the cylinder, resulting in even further gains in drag reduction. All in all, these observations make clear the fact that the drag reduction due to the drag crisis phenomenon is pressure driven.



**Figure 2.8:** Pressure Coefficient ( $C_p$ ) over the surface of a smooth cylinder. Adapted from Anatol Roshko [30]

### 2.3.1. Passive Drag Reduction Techniques

Passive methods achieve drag reduction without any energy input or moving parts. Instead, they rely on shaping or surface texturing of the cylinder to influence the flow. These techniques are particularly powerful in the critical Reynolds number regime, where small modifications can trigger an early transition and precipitate the drag crisis at lower  $Re$ .

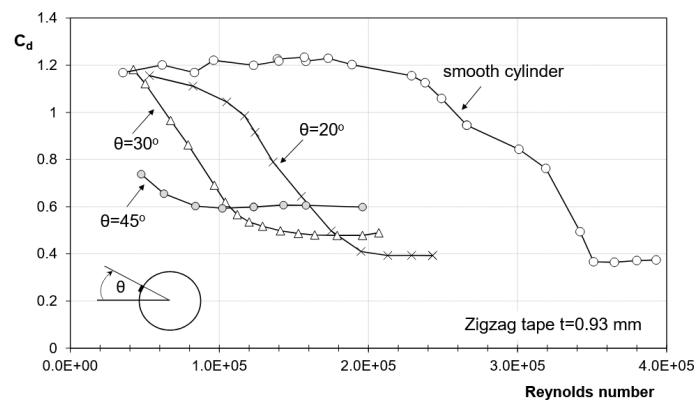
The exact physical mechanism passive techniques rely on is to promote an earlier transition from laminar-to-turbulent in the boundary layer. Therefore, the separation point is delayed and a reduction in wake width is achieved, resulting in a considerable reduction in pressure drag. There is, although, a small penalty, that is a slight increase of viscous drag due to the fact that a turbulent boundary layer has more losses due to skin friction than its laminar counterpart. Furthermore, this means that the cylinder experiences the drag crisis at a lower Reynolds number than it otherwise would.

In sports and engineering, passive drag reduction is often the most practical approach. In the coming subsections, different passive methods (surface roughness, trips, dimples, grooves...) are presented.

### Discrete Trips

Trip wires have been used for decades to deliberately trigger turbulence. A well-positioned wire, zigzag strip or even a seam on a garment near the front of the cylinder ( $20^\circ \leq \theta \leq 45^\circ$ ) can yield large drag reductions. Some studies have quantified the effect of these drag reduction mechanisms. A study by Dobbinga [34] on the effect of trip wires on drag of speed skaters, found that adding two 0.8 mm thick trip wires to the front of a mannequin's leg reduced the drag coefficient of the entire leg by 22%.

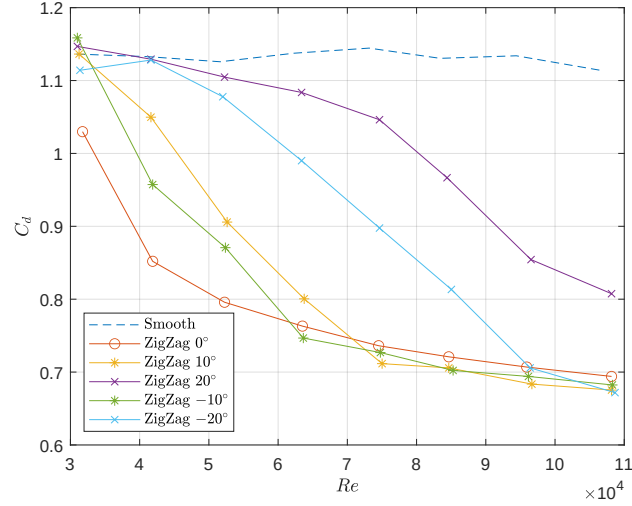
In a different study, by Timmer and Veldhuis [34], the impact on performance of zigzag tape trips has been quantified. In this study, zigzag strips were applied to the lower legs of speed skaters, which produced a total reduction in drag of  $-4.2\%$  to  $-5.3\%$ . This reduction in drag translates into around 0.5 s saved per lap for male skaters.



**Figure 2.9:** Impact of zigzag strip location on the drag coefficient. Cylinder  $D = 11$  cm. Taken from Timmer & Veldhuis [34]

However, a significant downside of this technique is the fact that localized trips are very sensitive to relative rotations of the cylinder, or the presence of cross-winds on the cylinder/bluff-body. This can be observed in a study by Terra, 2021, Figure 2.10. The moment the cylinder is rotated slightly, making the zigzag strips move away from the optimal location, the drag reducing effect is greatly diminished. It is because of this reason that discrete trips become a bit complicated to use for the application of sport aerodynamics.





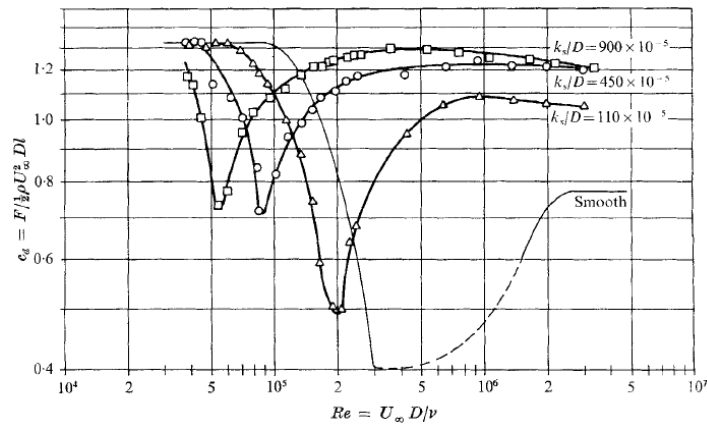
**Figure 2.10:** Impact of cylinder with zigzag strip in yaw on the drag coefficient. Adapted from (Wouter Terra, 2021)

In the thesis of Prajwal Deval, 2023 [12], the effect of polka-dots as discrete tripping elements had been examined. Throughout the research, the effects of polka-dot height, diameter and spanwise spacing had been studied in terms of the  $C_d$  drop in the critical regime, as well as the  $Re_{crit}$ , the critical Reynolds number.

Deval determined that taller polka-dots direct more energy towards the wall with the trade-off of thickening the boundary layer and promoting earlier separation. This resulted in a lower  $Re_{crit}$  and a larger  $C_{d,min}$ . Additionally, when increasing dot diameter, the over-dot flow increased to the larger blockage near the wall, this resulted in the delaying of the crisis and pushed the  $Re_{crit}$  to higher values with a lower value of  $C_{d,min}$ . Finally, when it comes to dot spacing, for a wide spacing, each dot is covered in faster external flow, therefore, its horseshoe vortex drags more momentum down into the wall, resulting in a thinner more resilient turbulent layer after transition. Which, ultimately means that the  $Re_{crit}$  increases with wide spacing and the  $C_{d,min}$  decreases.

### Distributed Trips

Adding roughness to a cylinder's surface is a classic way to promote an earlier transition to turbulence. Even minimal roughness, such as sand-grain texture or a thin wire along the surface of the cylinder can disturb the laminar boundary layer enough to induce turbulence. A study by Achenbach, 1971 [2], studied the effect of surface roughness around a circular cylinder.



**Figure 2.11:** Impact of surface roughness on cylinder drag coefficient. Taken from Elmar Achenbach [2]

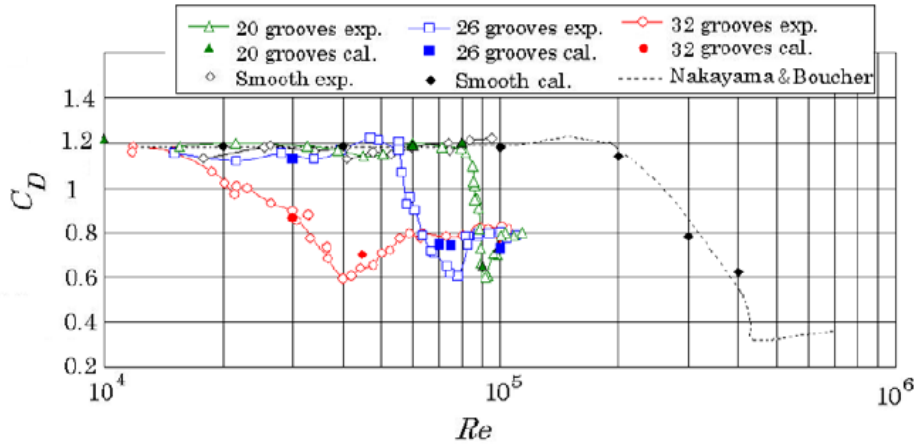
In this Figure 2.11, the variation in critical  $Re$  can be clearly observed based on the sand-grain roughness  $k_s$  applied to the surface of the cylinder. It can be seen that the rougher the surface, the earlier the crisis occurs. On the same note, the earlier the crisis occurs, the higher the minimum  $C_d$ . Implying that there is a compromise in terms of drag reduction and desirable location of the drag crisis, for this technique. These results are inline with the findings of Prajwal Deval and his discrete polka-dots.

In another study by Hsu et al, 2018 [17], a similar experiment was carried out with 38 different samples of fabrics with varying roughness wrapped around a cylinder. The findings of this study result in the empirical relations shown for the  $C_{dmin}$  and  $Re_{crit}$ :

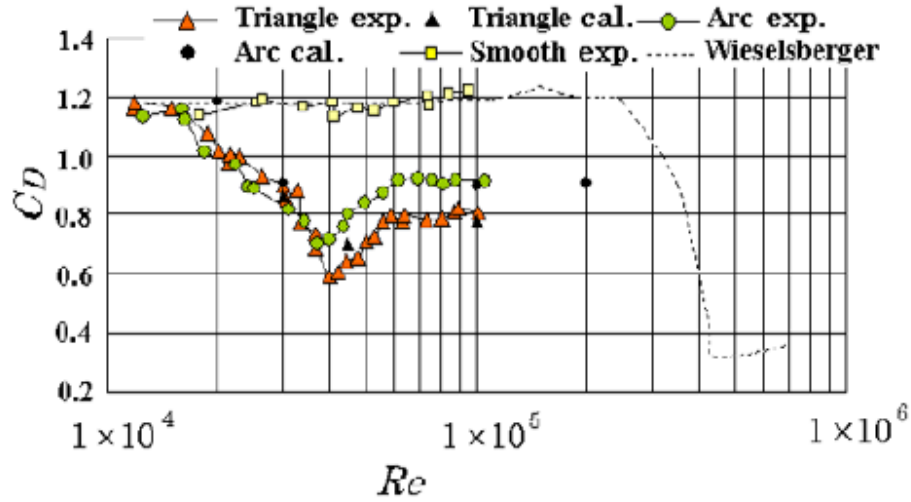
$$\log Re_{crit} = 5.9 - 1.15 \exp 0.7 \left[ 0.2 + 0.7 \log \left( \frac{k_s}{D} \right) \right] \quad (2.17)$$

$$C_{dmin} = 0.24 + 0.75 \left[ 1.8 + \log \left( \frac{k_s}{D} \right) \right] \quad (2.18)$$

Similarly, another technique for applying distributed roughness to a cylinder is to make grooves along the length of the cylinder (perpendicular to the flow).



(a) Effect of number of grooves (triangular grooves)



(b) Effect of groove geometry (32 grooves)

**Figure 2.12:** Effect of groove shape and count on flow around cylinder.  $D = 4.8 \text{ cm}$

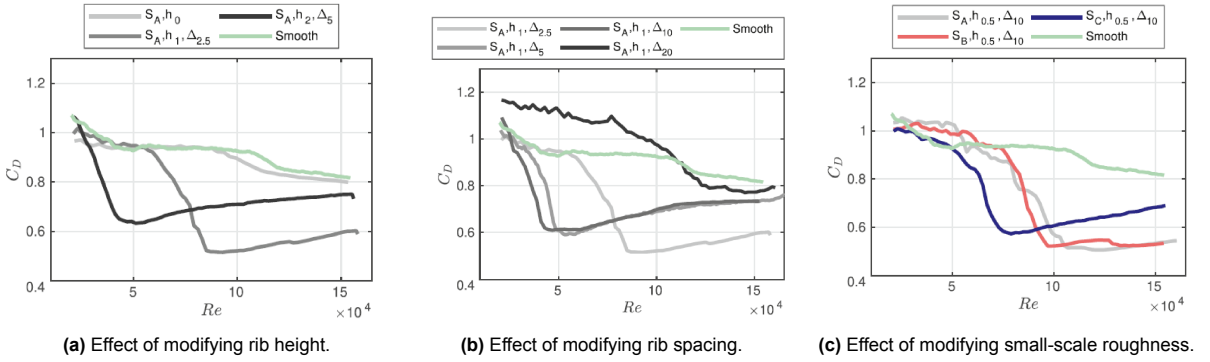
Two articles by Yamagishi & Oki [38] and [39], studied the effect of the number of grooves and the shape of the grooves on the flow characteristics around a circular cylinder. The varying geometry along

the surface of the cylinder creates zones of partial separation and reattachment. This creates small recirculation regions near the cylinder, which will result in the creation of shear layers dividing both flows. In this process, strong shear layer instabilities are created, which aid in the transition from laminar to turbulent boundary layer, thus delaying separation and ultimately reducing the drag coefficient.

Finally, another technique for applying distributed trips to a cylinder is using fabric combinations. Concretely, a two-layer fabric construction wrapped around a circular cylinder. This specific two-layer fabric construction consists of an underlayer with longitudinal ribs along the length of the cylinder (similar to the grooves mentioned above, perpendicular to the flow) and a top layer with small-scale roughness. A study by Skeide et al., 2020 [31] consisted of an experiment that measured the drag coefficient as a function of Reynolds number for 28 different fabric combinations were tested for a range of  $20000 \leq Re \leq 160000$ .

The factors that made up the configurations are three different rib heights ( $h$  [mm] = [0, 0.5, 1, 2]) plus a no-rib configuration, four different rib spacings ( $\Delta$  [mm] = [2.5, 5, 10, 20]) and finally three different small-scale roughness top fabrics ( $S_A$ ,  $S_B$ ,  $S_C$ ); increasing in roughness ( $k_s^{max}$  [mm] = [0.1, 0.2, 0.42]), respectively. By combining all of these factors, a significant drag reduction can be achieved for the  $Re$  range previously mentioned. More specifically, the curve can be optimized according to the desired  $Re$  range by modifying the variables accordingly.

By increasing rib height, the  $C_{d_{min}}$  increased and the  $Re_c$  decreased. By increasing rib spacing, the  $C_{d_{min}}$  increases and the  $Re_c$  decreased. Finally, when micro-roughness was added at increasing levels to the ribbed cylinder, the general trend showed that  $Re_c$  decreased and  $C_{d_{min}}$  increased, which is consistent with the view that larger microscale roughness increases skin friction and makes the crisis occur sooner. These results can be seen in Figure 2.13:



**Figure 2.13:**  $C_d$  as a function of  $Re$  for different configurations. Taken from Skeide et al. [31]

## 2.4. Research Questions

Prior to any experimental work an extensive literature study was carried out. This chapter served as a summary and presents the most relevant findings. Throughout this literature study, several knowledge gaps have been identified and they have laid the foundation to this research. This section presents and exposes the knowledge gaps as well as the research questions formulated.

### 2.4.1. Knowledge gaps

- Limited information of boundary layer development of flow along a cylinder with double layer fabric.
- No available information of pressure distributions along cylinders with double layer fabrics.
- No information or mention regarding the mechanism for the drag crisis behavior present for cylinders with double layer fabrics.

### 2.4.2. Research Questions & Subquestions

**What is the mechanism responsible for the drag crisis behavior of cylinders with double-layer fabrics?**

With the following subquestions:

- Does fabric deformation have an effect on the drag crisis behavior?
- Is fabric porosity significant enough that it would affect the flow around the cylinder, influencing the triggering mechanism for the drag crisis?
- How is the drag crisis influenced by the height and spacing between the ribs of the underlayer?
- What are the differences in the flow fields between the underlayer alone and the doublelayer fabric?

# 3

## Experimental Principles

### 3.1. Particle Image Velocimetry

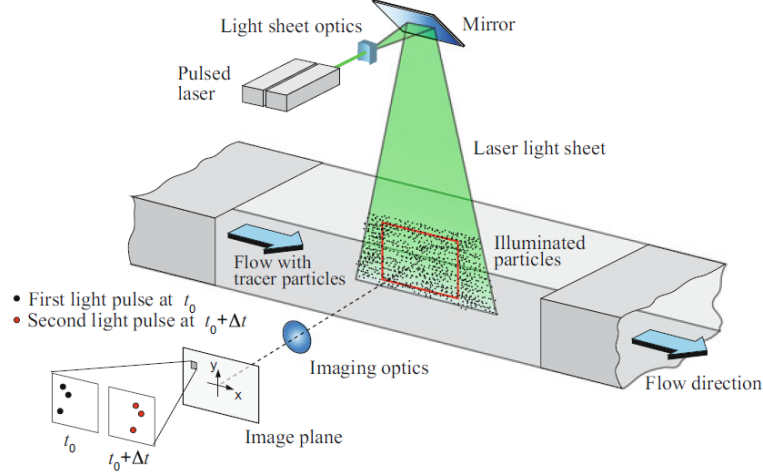
Particle Image Velocimetry (PIV) is a flow measurement technique used in aerodynamic analysis to resolve a velocity field in a domain with high spatial resolution. PIV is a non-intrusive, laser-based optical technique that turns a sequence of flow images into a full quantitative flow velocity field. It works by tracking how seeding particles move between two narrowly time-separated snapshots and by using a statistical correlation approach to compute the velocity field in the given domain.

#### 3.1.1. Principles of PIV

A typical PIV experimental setup consists of several subsystems [29]:

- **Seeding:** Small tracer particles are added to the flow at a location where the flow of interest will not be disturbed. This is usually done upstream at the intake of the wind tunnel. A uniform and moderate particle distribution density in the flow of interest is desired. In gas flow scenarios, the typical particle diameter is  $1\ \mu m$ , this allows for the particles to follow the flow faithfully and therefore accurately depict the flow.
- **Illumination:** For applications in gas flows, a high power light source is used to illuminate the tracer particles, this allows for proper exposure of the particles on the camera sensors. In general, high-power (Class IV) lasers are used for this task, these lasers are extremely hazardous for eye exposure and they can also produce burns on skin and materials. Therefore extreme care needs to be employed when handling and using such instruments.
- **Recording:** The light scattered by the tracer particles has to be recorded on a sequence of frames of a camera.
- **Calibration:** In order to determine the relation between the particle displacement in the camera sensor and the tracer particle displacement in the flow of interest a calibration is required.
- **Evaluation:** The displacement of the particle images between the light pulses can be determined through evaluation of the PIV recordings.
- **Post-Processing:** Invalid measurements and outliers are removed and other complex flow quantities of interests are extracted.

Figure 3.1 shows an elementary PIV (2C-2D; 2 velocity components, in 2D space) arrangement:



**Figure 3.1:** Elementary PIV setup arrangement. Taken from Raffel et al. [29]

The illuminating element is shaped accordingly by means of lenses and optical devices placed at the exit of the laser head. For a 2C-2D setup, a combination involving a cylindrical plus a spherical lens is used to obtain a thin laser sheet illuminating the flow of interest. The cameras are placed such that they obtain a perpendicular view of the plane, as shown in Figure 3.1.

The area of interest is illuminated twice in quick succession by the laser sheet. The exact timing between the illumination pulses and the duration of each pulse itself are dependent on the size of the particles, the velocity of the flow, and the setup of the imaging optics.

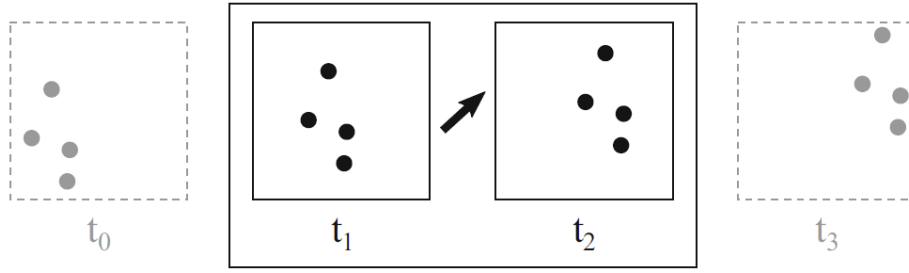
During the evaluation, the digital recordings of the flow of interest can be divided into small subareas called interrogation windows. The displacement vector between the tracer particles of the first and second illumination is determined for each interrogation window by means of statistical methods, specifically cross-correlation.

An example of interrogation windows and cross-correlation is shown in Figure 3.2. To determine the pixel displacement, the cross-correlation function is defined:

$$\varphi(m, n) = \frac{\sum_{j,k=1}^{J,K} I(j, k) \cdot I'(j + m, k + n)}{\text{stdev}(I) \cdot \text{stdev}(I')} \quad (3.1)$$

where  $I$  and  $I'$  correspond to the interrogation windows at the two distinct time instants,  $m$  and  $n$  correspond to the horizontal and vertical pixel shifts, respectively. These  $m$  and  $n$  pixel ranges are effectively the search domain where the second interrogation window ( $I'$ ) will be tried to be matched with the first window ( $I$ ). When that occurs, the cross-correlation function will reach its maximum value of  $\phi = 1$ .

Therefore, for each interrogation window, a cross-correlation map is obtained, and the maximum value of this function within its domain will yield the pixel displacements in both the horizontal and vertical directions ( $m, n$ ).



**Figure 3.2:** Interrogation windows depicting tracer particles at two consecutive instants of time,  $t_1$  and  $t_2$ .

In order to map the pixel displacement on the images to distances in the physical world, a calibration process is required. This process generally consists of taking a picture of an object whose dimensions are exactly known, and then this dimension is matched to the amount of pixels in the image. As such, the pixel displacements can accurately be translated into real-world displacements. Finally, in order to obtain the velocity from the displacement, it is calculated by dividing the pixel displacement by the time between  $t_2$  and  $t_1$ .

### 3.1.2. PIV Processing Techniques

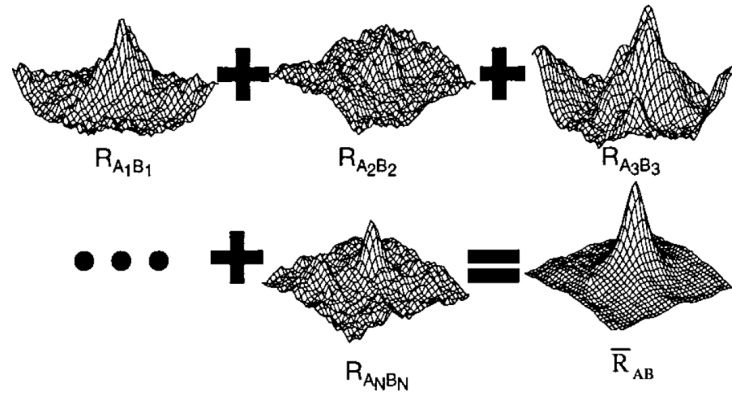
The PIV principle allows for instantaneous velocity fields to be computed. In order to obtain the time-averaged velocity field, there are three distinct methodologies: average velocity method, average image method, and average correlation method [25].

In the average velocity method, the estimate of the average velocity is determined by correlating the two images and determining the peak of instantaneous correlation functions. This operation yields the instantaneous velocity for this set of snapshots, and by repeating it over the rest of the snapshots, the remaining instantaneous velocities at different time instants are obtained. Finally, the average velocity field is obtained by averaging all the instantaneous velocities, therefore yielding the time-averaged velocity field. This method is appropriate when the seeding density is sufficient; in cases where the seeding density is low (low signal-to-noise ratio), this method is unable to determine the instantaneous velocities accurately, resulting in inaccurate results.

On the other hand, the average image method directly applies the averaging operation on the image fields and then correlates them. This method is particularly effective when particle number density is low; by averaging the image fields, the number of particles per interrogation window is increased. However, if the particle number density is not low or a large number of snapshot sets is used, it can result in excessive particles in the interrogation window and thus reduced visibility of individual particles, effectively cluttering and adding noise to the images.

Finally, the third method involves averaging the cross-correlation function. This works by individually calculating the cross-correlation functions for a given window for all image sets, and then performing the averaging operation among all cross-correlation functions for that given interrogation window, as shown in Figure 3.3. This results in a much better-defined peak in the cross-correlation function and a significantly improved signal-to-noise ratio. The drawbacks of this method are the loss of temporal information as the cross-correlation fields are averaged out. Additionally, if the flows are unsteady, with time-varying gradients, the sum of the correlation will bias the estimated displacement towards the mean flow. Finally, this method is more computationally intensive than regular PIV; it requires large amounts of memory to store the correlation map.

Due to the limitations in the image averaging method, this methodology will not be employed during the data processing of this research. The other two methodologies will be used to determine the average velocity fields from PIV.

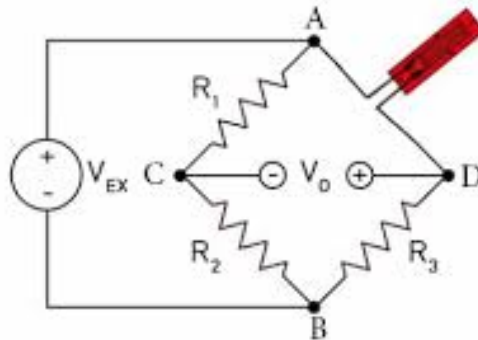


**Figure 3.3:** Visualization of averaging of the cross-correlation function. Taken from Meinhart et al. [25].

## 3.2. Balance Measurements

A load balance is a device that measures the loads applied to the object that is placed on it. A load balance has a component known as a strain gauge; this is a mechanical-electrical component that is able to convert mechanical deformation into a change of electrical properties, specifically resistivity.

The resistor of the strain gauge is placed in a Wheatstone bridge configuration, as shown in Figure 3.4, which allows for the measurement of small variations in resistivity.



**Figure 3.4:** Wheatstone bridge circuit, also known as extensometry bridge.

Such a circuit yields an output voltage  $V_D$ , measured between points  $C$  and  $D$ , that is linear to the resistivity of the strain gauge, measured between points  $A$  and  $D$ . This means that a linear relation can be established between the resistivity and output voltage. Finally, the output voltage can be directly translated into force and load by means of the sensor sensitivity.

## 3.3. Pressure Measurements

In aerodynamics, pressure measurement is critical for understanding airflow behavior; there are three different types of pressure:

Static pressure is associated with the normal force exerted per unit area by the random motion of



molecules in a fluid.

$$p = \lim_{dA \rightarrow 0} \frac{dF_n}{dA} \quad (3.2)$$

The stagnation pressure is the pressure that would be obtained if a moving fluid is brought to rest isentropically, meaning without heat transfer or friction, such that all of its kinetic energy is converted into pressure energy.

Finally, dynamic pressure is the kinetic energy per unit of volume fluid. For incompressible flows, it is the difference between stagnation and static pressure:

$$P = p + \frac{1}{2}\rho V^2 \quad (3.3)$$

A pitot-static tube is a device used to indirectly measure dynamic pressure. A pitot tube measures the stagnation pressure in the flow after an adiabatic compression. Additionally, a static pressure tap is added to the side of the pitot probe in order to provide a static pressure reference. Therefore, the gauge pressure of the pitot measurement relative to the static pressure measurement yields the dynamic pressure. Once the dynamic pressure is obtained, the velocity of the flow at the tip of the pitot tube can be computed:

$$V = \sqrt{\frac{2q}{\rho}} \quad (3.4)$$

where  $q = \frac{1}{2}\rho V^2$  is the dynamic pressure.

### 3.4. Wind Tunnel Boundary Corrections

When performing experiments in a wind tunnel environment, the flow behaves slightly differently compared to real-world (free-flight) conditions. This effect is due to the fact that wind tunnels are finite spaces with physical boundaries. The presence of these boundaries can alter the airflow characteristics around the tested object, causing measured forces to deviate from their true flight values. Next, a breakdown of the different relevant boundary corrections for bluff bodies in open wind tunnels is given:

- **Blockage:** Due to a significant amount of area in the test section being blocked by the presence of the bluff body and its wake, the flow in the test section will experience an acceleration due to the reduction of test area cross section.
- **Streamwise buoyancy:** As a result of the streamwise acceleration, the pressure distribution will change in the streamwise direction as well, with lower pressure downstream and higher pressure upstream, this results in a correction that is a contribution to the drag coefficient.

For the specific setup described in Chapter 4, seen in Figure 4.12, the wind tunnel used is an open jet and the tested body is a bluff body. Particularly, the object is located very close to the tunnel nozzle, resulting in a reduction of the effects of jet expansion and deflection, given that the flow immediately after the nozzle is uniform and has not undergone significant deflection or expansion. On the other hand, when placing the subject very close to the nozzle, new problems such as blockage of the jet and interference by the nozzle walls on the flow arise. Furthermore, in this research, the buoyancy effects will not be contemplated, as there is not a reliable and simple way to measure the streamwise variation of the static pressure.

#### 3.4.1. Method of Mercker and Wiedemann

Kevin Cooper [8] provides an experimental approach to correct for the blockage effects due to the wind tunnel nozzle, based on Mercker and Wiedemann's method [26] [27]

The correction to dynamic pressure is written as:

$$\frac{q_c}{q_{u,n}} = (1 + \epsilon)^2 = (1 + \epsilon_s + \epsilon_n)^2 \quad (3.5)$$

where  $q_c$  is the corrected dynamic pressure,  $q_{u.n}$  is the uncorrected average dynamic pressure at the nozzle plane,  $\epsilon$  is the total blockage factor, and is made up of the solid blockage factor  $\epsilon_s$  and the nozzle blockage factor  $\epsilon_n$ . Note that in the original method of Mercker and Wiedemann [26] [27] collector effects are considered, but in the experimental setup employed in this research there is no collector present in the wind tunnel and thus its contribution has been neglected.

### Nozzle Blockage

The flow velocity at the periphery of the jet increases as the object approaches the nozzle. This effect results from a blockage effect caused by the deceleration upstream of the object extending in the nozzle. It is the reverse of the effect usually ascribed to open tunnels.

It is modeled by treating the solid object as a source of a specific strength related to its frontal area that is located at a certain distance from the tunnel nozzle. The distance from the source to the nozzle is,  $x_s$ :

$$x_s = -x_m + \frac{L_m}{2} - \left( \frac{S}{2\pi} \right)^{1/2} \quad (3.6)$$

where  $x_m$  is the distance from the center of the model to the nozzle (thus the negative sign),  $L_m$  is the length of the model, and  $S$  is the frontal area of the model.

Accordingly, the perturbation velocity at the nozzle plane,  $\epsilon_{qn}$ , due to the nozzle blockage is:

$$\epsilon_{qn} = \frac{\left( \frac{S}{2C} \right) \left( 1 + \frac{x_s}{(x_s^2 + R_n^2)^{1/2}} \right)}{\left[ 1 - \left( \frac{S}{2C} \right) \left( 1 + \frac{x_s}{(x_s^2 + R_n^2)^{1/2}} \right) \right]} \quad (3.7)$$

where  $C = 2 \cdot h \cdot w$  is the duplex nozzle cross-section area, and  $h$  and  $w$  correspond to the height and width of the nozzle, and  $R_n = \sqrt{C/\pi}$  corresponds to the hydraulic radius of the duplex nozzle:

Finally, by means of a vortex ring located at the nozzle exit plane, the velocity perturbation in said plane is projected onto the plane model location. Therefore, the complete expression for the blockage factor at the model due to nozzle blockage becomes,  $\epsilon_n$ :

$$\epsilon_n = \epsilon_{qn} \left[ \frac{R_n^3}{(x_m^2 + R_n^2)^{3/2}} \right] \quad (3.8)$$

### Solid Blockage

The solid blockage term accounts for the effect of jet expansion due to the presence of the model. This expansion results in an overall deceleration of the airflow due to the principle of mass conservation. The expression has the following form [1] [6]:

$$\epsilon_s = -\frac{\pi^2}{24} \lambda_{2D} \frac{t^2}{h^2} \quad (3.9)$$

where  $\lambda_{2D}$  is a body shape factor related to the fineness of the subject,  $t$  is the model thickness, and  $h$  is the nozzle height. This equation is conventionally used for 2D airfoils placed in an open wind tunnel spanning the entire width of the test section, thus the quotient  $\frac{t}{h}$ . In the case of this experimental arrangement, the 2D body is a cylinder and it spans the entire height of the test section rather than the width; therefore, the same quotient for this study case is:  $\frac{D}{w}$ :

$$\epsilon_s = -\frac{\pi^2}{24} \lambda_{2D} \frac{D^2}{w^2} \quad (3.10)$$

# 4

## Experimental Methodology

### 4.1. Physical Model

As stated in Section 2.1, certain body parts such as thighs, upper arms, calves and ankles can be simplified into the shape of a cylinder. Therefore, in order to conduct the research presented in Section 2.4, the physical model consists of a cylindrical PVC pipe.

Based on the formulated research questions in Section 2.4, two distinct types of fabric will be used to formulate all the studied configurations. The two different types of fabric will be referred to as underlayer and overlayer. The testing suite for this research consists of four different underlayers and two different overlayers. This creates eight distinct configurations with different underlayer-overlayer combinations. Furthermore, each of the individual fabrics will be studied in addition to the double fabric constructions.

Moreover, an additional configuration employing zigzag strips placed at  $\theta = 30^\circ$  will be studied. These measurements will be taken to serve as a reference for what a “desirable” drag reduction would be and how the double fabric constructions compare against it.

#### 4.1.1. Cylinder Geometry

The chosen cylindrical PVC pipe has a nominal outer diameter of  $D = 0.09 \text{ m}$ . The exact criterion and procedure for determining this specific diameter will be discussed in Section 4.4.1.

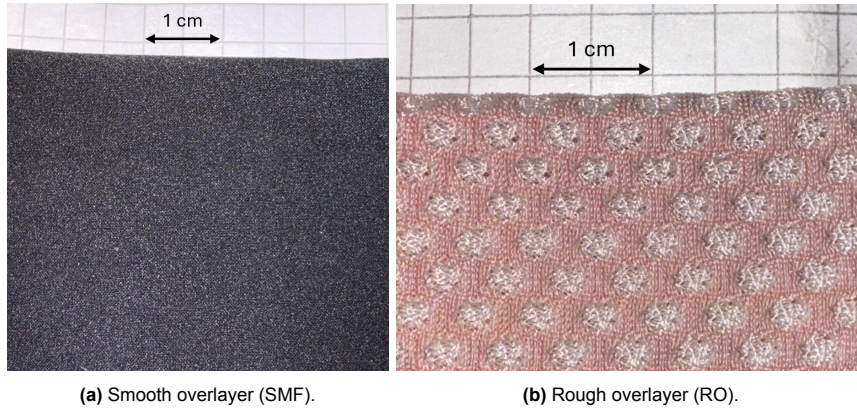
#### 4.1.2. Fabric Properties

The fabrics are crucial to the cylinder’s aerodynamic behavior as they drastically modify its surface characteristics and therefore influence the drag crisis both in  $Re_{crit}$  and  $C_{d,min}$ . Furthermore, the morphology of underlayers and overlayers is distinctively different, as it will be discussed in the coming sections.

All of the fabrics are made up of a fabric sheet that is sewn up, resulting in a singular seam. In order to maintain consistency and isolate the effects of surface properties, during testing, the seam has been placed at the rear stagnation point. This way, its aerodynamic effects are minimized, and the characteristics of the fabrics can be studied independently.

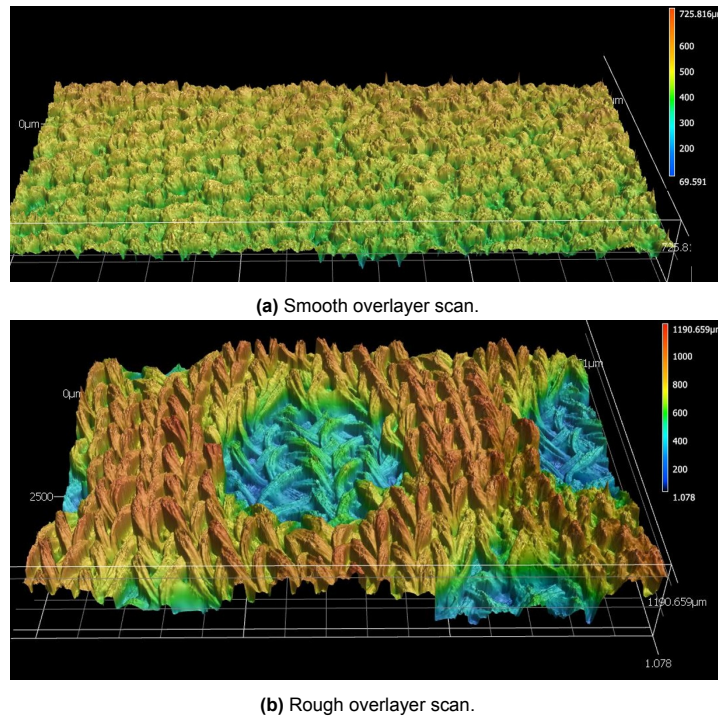
##### Overlayers

The overlayers consist of two different fabrics with drastic differences in roughness. Both overlayers are shown in Figures 4.1. It is clear that the overlayer shown in Figure 4.1a is significantly smoother than the fabric shown in Figure 4.1b.



**Figure 4.1:** Pictures of both overlayers.

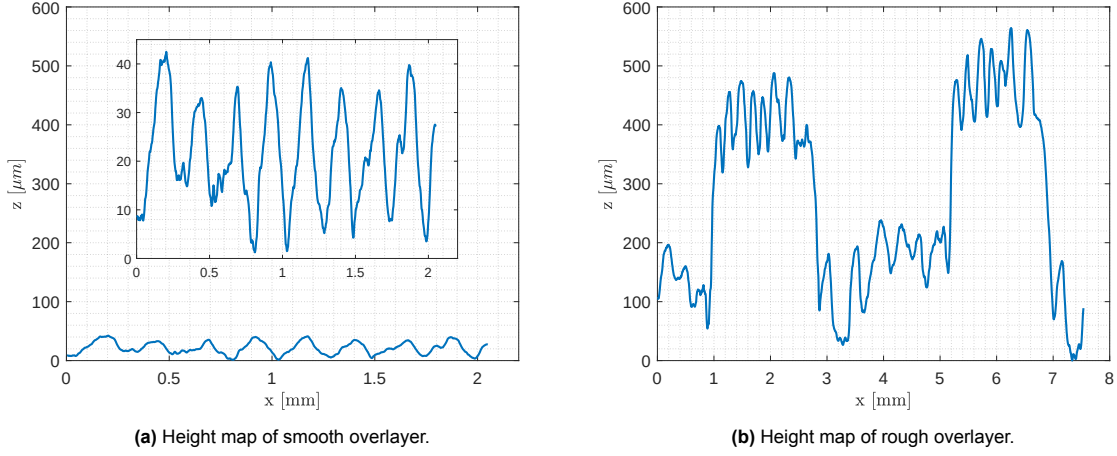
The smooth fabric overlayer consists of a synthetic tightly woven fabric, as seen in Figure 4.2a. For the sake of conciseness in the presentation of results, this smooth overlayer has been codified as SMF. On the other hand, the rough overlayer is a synthetic knitted fabric with dimples and ridges of significant height. The surface of the rougher fabric is not only more coarse because of its knitted structure, but in addition to that, there is a significant amount of macroscale roughness in the shape of dimples and a pattern that is clearly visible to the naked eye. Similarly, the rough overlayer is codified as RO.



**Figure 4.2:** Scans of smooth and rough overlayers.

Fabric parameters such as height map and roughness characteristics are initially unknown. In order to determine these fabric characteristics, the Keyence VK-1000 optical-laser microscope [3] has been employed to obtain the fabric height maps for each of the overlayers. The resulting height maps are shown in Figures 4.3, the smoother fabric is much more uniform, only presenting height variations  $< 45 \mu m$ . Whereas the rougher fabric has dimples with a depth of  $300 \mu m$ . Additionally, when examining the microscopic roughness present at the top of the ridges or at the bottom of the valleys, it can be seen that the height variations are in the order of  $100 \mu m$ . Therefore, it can be concluded that not only

the rough overlayer is rougher because of its macroscopic structure, but also the knitted fabric pattern presents a significant increase in roughness.



**Figure 4.3:** Overlayer height maps.

Additionally, in order to quantify the roughness of each of the overlayers, their respective sand-grain roughness height can be calculated from the height maps.

When it comes to the computation of the sand-grain roughness height, the chosen method is subject to the type of roughness and its distribution. For surfaces that have distinct or repeatable features such as the rougher fabric, the Flack & Schultz [14] method is more appropriate. On the other hand, for surfaces that have a "random" or gaussian roughness distribution, the method described by Kuwata & Kawaguchi [20] is more accurate.

This goes to say that for the smoother overlayer, the method from Kuwata & Kawaguchi [20] has been used, yielding a sand-grain roughness height of  $k_{s,smooth} = 46.3 \mu m$ . Whereas for the rougher overlayer, the method from Flack & Schultz [14] has been employed, yielding a sand-grain roughness height of  $k_{s,rough} = 771.5 \mu m$ . As indicated by the sand-grain roughness, the two fabrics are very different in terms of roughness, by more than one order of magnitude.

Note that the results obtained for both methods far exceed the dimensions of the height profiles given for both fabrics. This is expected as the formulas for the sand-grain roughness for both Kuwata & Kawaguchi [20] and Flack & Schultz [14] have a factor that inflates the sand-grain roughness parameter; the formulas are shown respectively below.

$$k_{s, Kuwata} = 4 k_{rms} (1 + 0.17 S_k)^4$$

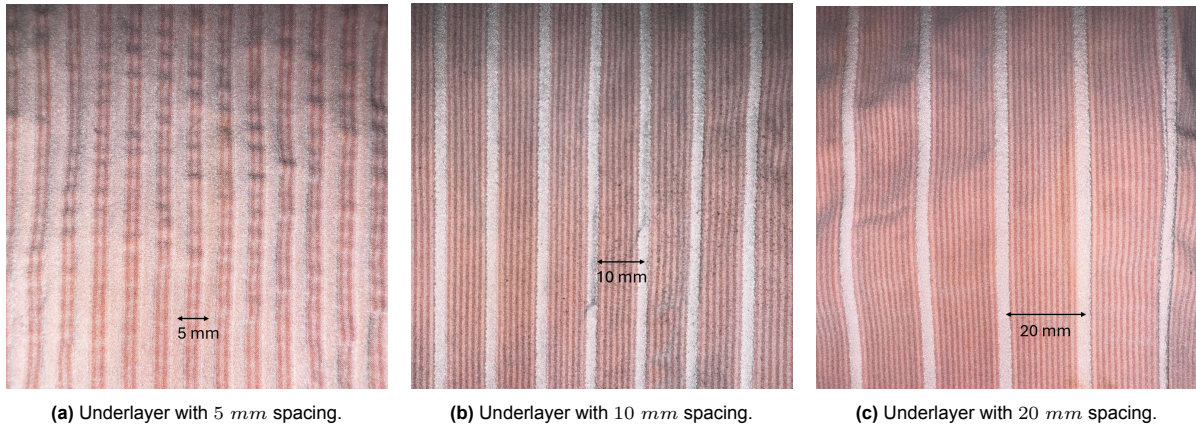
$$k_{s, Flack} = 4.43 k_{rms} (1 + S_k)^{1.37}$$

where  $k_{rms} = \sqrt{\langle z^2 \rangle}$  stands for the root-mean-square roughness height and  $S_k = \frac{\langle z^3 \rangle}{\langle z^2 \rangle^{3/2}}$  stands for the skewness of the height probability density function. These computations result in the sand-grain roughness, which consists of a hydrodynamic length scale, that is to say, it is not the physical geometric roughness of the surface of the fabric, but rather, a measure of the roughness that the flow "feels" or experiences.

### Underlayers

The underlayers consist of an elastic piece of woven fabric with ridges or ribs that run along the length of the cylinder. Previously, it had been said that four different under fabrics were used. In reality, there are only three unique underlayers. These are shown in Figures 4.4. The "fourth" underlayer was achieved by stretching the underlayer shown in Figure 4.4a, thus altering its properties.





**Figure 4.4:** Pictures of the three different underlayers.

The four underlayers are classified based on their rib spacing, these spacings are  $\Delta [mm] = [5, 7, 10, 20]$ . Therefore, each of the underlayers is codified accordingly, as 05UL, 07UL, 10UL, and 20UL, the number denoting the rib spacing and UL as an abbreviation for underlayer.

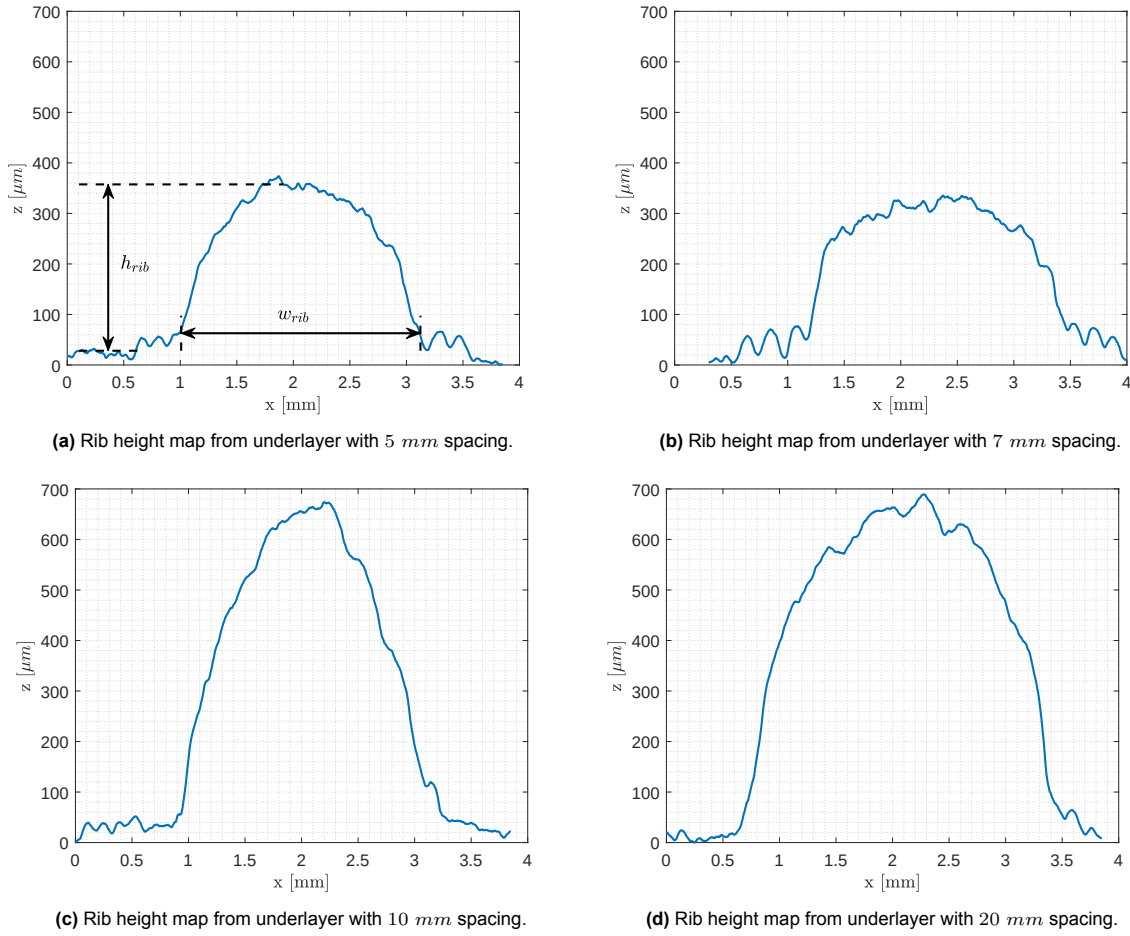
Other underlayer parameters regarding rib geometry are initially unknown. In order to determine additional rib properties accurately, the optical laser scanner has been employed to obtain height maps around the ribs for each of the four different underlayers. Figures 4.5 show the rib height maps for all the underlayers.

The relevant rib parameters regarding each of the underlayers are the following:

- Rib spacing  $\Delta$ : Corresponds to the separation between two consecutive rib peaks. The rib spacing for each of the four underlayers are:  $\Delta [mm] = [5, 7, 10, 20]$
- Rib height  $h_{rib}$ : Corresponds to the height that the rib has relative to the baseline height.
- Rib width  $w_{rib}$ : Corresponds to the width of an individual rib.

Examining the optical laser scans, it can be seen that for 05UL, shown in Figure 4.5a, that the rib height is  $325 \mu m$  and the rib width is  $2.1 mm$ . Then, taking the same fabric and stretching it such that the rib spacing goes from  $5 mm$  to  $7 mm$ , it is observed that the rib height decreases slightly from  $325 \mu m$  to  $300 \mu m$  and the rib width increases from  $2.1 mm$  to  $2.4 mm$ .

For the remaining two underlayers, it is immediately apparent that the rib height for fabrics 10UL and 20UL is significantly higher than 05UL and 07UL. The measured heights are  $650 \mu m$  and  $675 \mu m$ , respectively. Similarly, the rib width measurements for 10UL and 20UL are  $2.2 mm$  and  $2.9 mm$ , respectively. Table 4.1 summarizes all the measured properties of the underlayers.



**Figure 4.5:** Rib height map for underlayers with varying spacing.

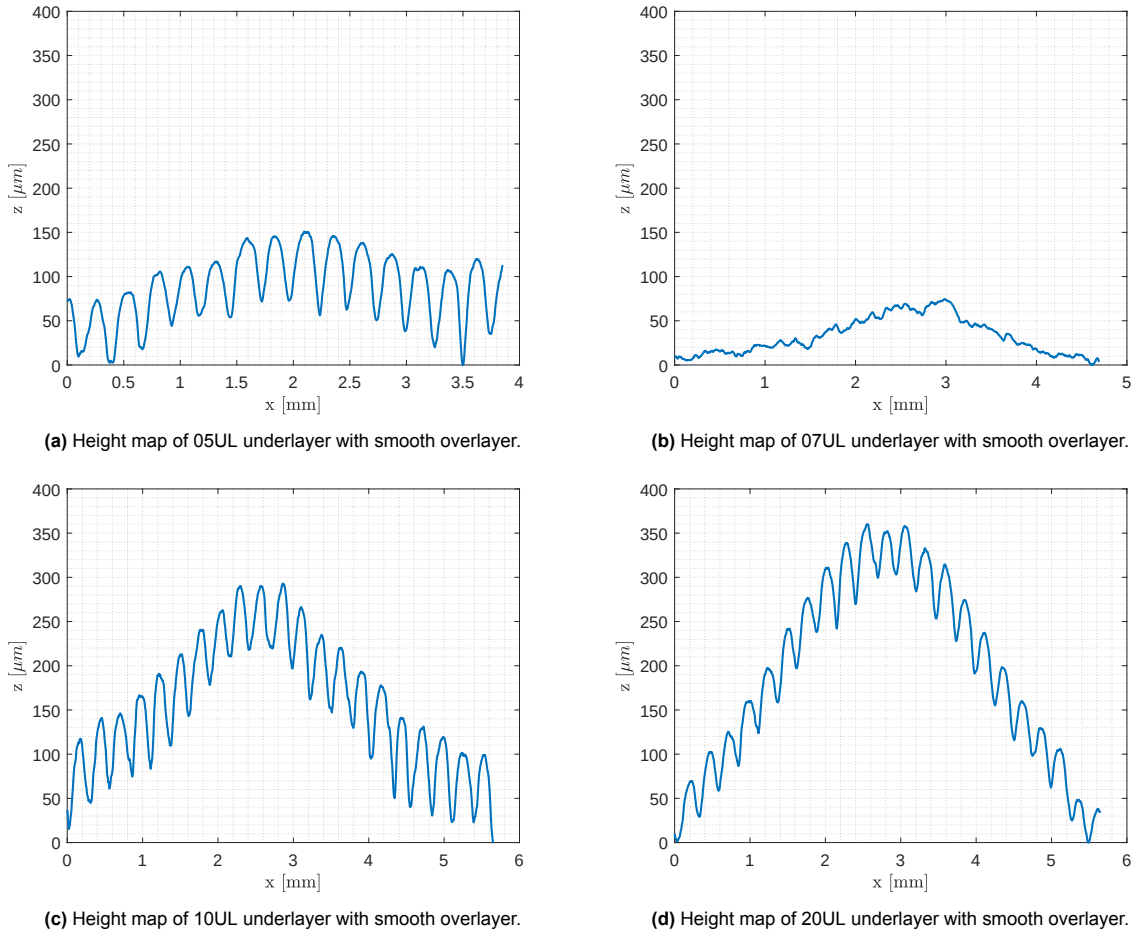
**Table 4.1:** Summary of the significant underlayer properties.

| Underlayer | $\Delta$ [mm] | $h_{rib}$ [ $\mu m$ ] | $w_{rib}$ [mm] |
|------------|---------------|-----------------------|----------------|
| 05UL       | 5             | 325                   | 2.1            |
| 07UL       | 7             | 300                   | 2.4            |
| 10UL       | 10            | 650                   | 2.2            |
| 20UL       | 20            | 675                   | 2.9            |

### Fabric Combinations

In order to achieve the double fabric constructions, each of the four underlayers can be combined with each of the two top layers, resulting in eight different double fabric layer constructions. In the previous sections, each of the individual fabrics has been studied and their properties have been quantified in isolation. However, this raises the question of whether the properties of the fabrics change when they are combined. Therefore, the fabric combinations have been scanned and their height profiles have been mapped following the same methodology.

In the following Figure 4.6, the height maps for the combination of the four underlayers with the smooth overlayer are shown. These fabric combinations are codified as SM05, SM07, SM10 and SM20.



**Figure 4.6:** Rib height map for double layer constructions using all four underlayers and the smooth overlayer.

An overall trend can be observed, with the exception of the combination involving the 07UL. In general, it seems that the combination of the overlayer on top of the underlayer results in a reduction of the rib height by a factor of two to three (measuring from the mid point of the oscillations). Additionally, the effective rib width appears to increase as well. This effect is due to a combination of the underlayer rib being a very defined step but the overlayer remaining in tension while it is wrapped around the underlayer. Meaning that the definition of the step is mellowed out and the rib goes from resembling a step to looking more like a triangular rib. When it comes to the measurement involving 07UL, it seems that the magnitude of the oscillations is significantly smaller than the other cases; this could either be an error made during the measurement procedure or, conversely, the fact that the rib cannot push back against the top layer, resulting in it having less tension.

When it comes to the combination with the rough overlayers, codified RO05, RO07, RO10 and RO20; the effect of the rib height is minimal, meaning that the height profile barely changes relative to the rough overlayer alone, shown in Figure 4.2b. Additionally, the microscope struggles to measure the height map with the same magnification as previously used, due to focus issues. This makes the acquisition of the height profile complicated. All in all, the minimal changes, in addition to the complication of precisely measuring the height maps, resulted in the decision to omit the scans for fabric combinations with the rough overlayer.

## 4.2. Wind Tunnel

The experimental measurement campaign has been carried out at the TU Delft W-Tunnel. The W-Tunnel is located at the High-Speed Laboratory (HSL). The wind tunnel is operated by the Flow Physics



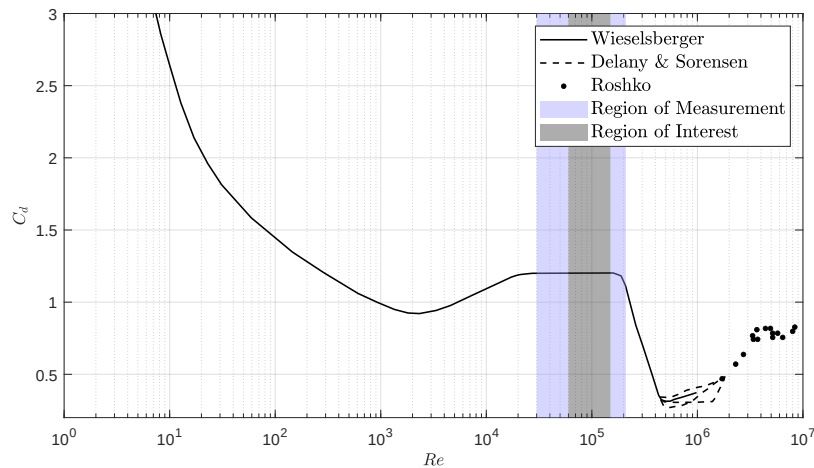
and Technology department from the Aerodynamics section of the Aerospace Engineering faculty at Delft University of Technology. Typical research conducted in this facility consists of static and moving 2D cylinders, flow over delta-wings, flow over cavities, flow control separation, and artificial transition in plate flow [11].

The TU Delft W-Tunnel is an open return, open jet subsonic wind tunnel located at sea level that allows for speeds of up to  $35 \text{ m/s}$  with the  $40 \text{ cm} \times 40 \text{ cm}$  square final contraction section. The minimum velocity at which measurements will be carried out with the  $40 \text{ cm} \times 40 \text{ cm}$  contraction is  $5 \text{ m/s}$ , due to increasing uncertainty in the tunnel control systems.



**Figure 4.7:** TU Delft W-Tunnel located at the High-Speed Laboratory (HSL). Taken from [11].

All in all, for the range of velocities allowed by the wind tunnel, the resulting  $Re$  range that can be studied with a cylinder of  $D = 0.09 \text{ m}$  is:  $3.0 \times 10^4 \leq Re \leq 2.1 \times 10^5$ . Figure 4.8, shows the region of measurement allowed by the wind tunnel:

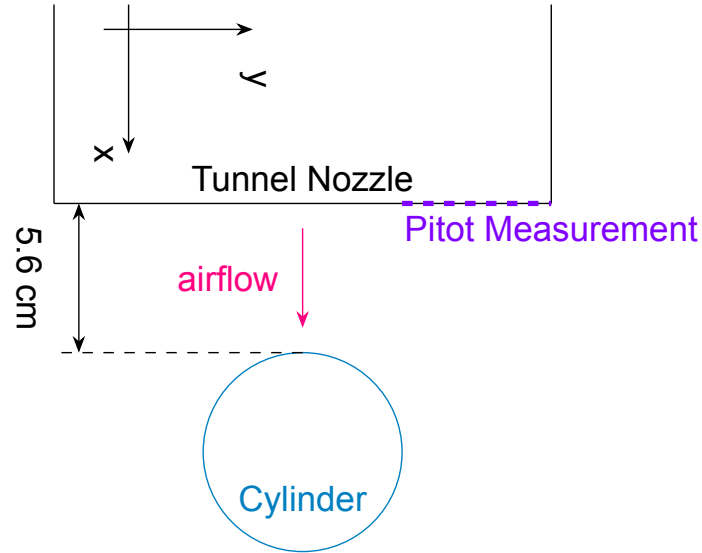


**Figure 4.8:** Drag Coefficient ( $C_d$ ) as a function of the Reynolds number ( $Re$ ) for a smooth cylinder, with the region of measurement as shown in Section 2.3.

As seen in Figure 4.8, the measurement domain of the wind tunnel for this specific experimental arrangement is right before the critical regime for a smooth cylinder. However, with the aid of roughness provided by the distinct fabrics described in Section 4.1.2, the onset of the crisis can be brought to lower  $Re$  regimes. Therefore, this makes the experimental facilities suitable to conduct this research.

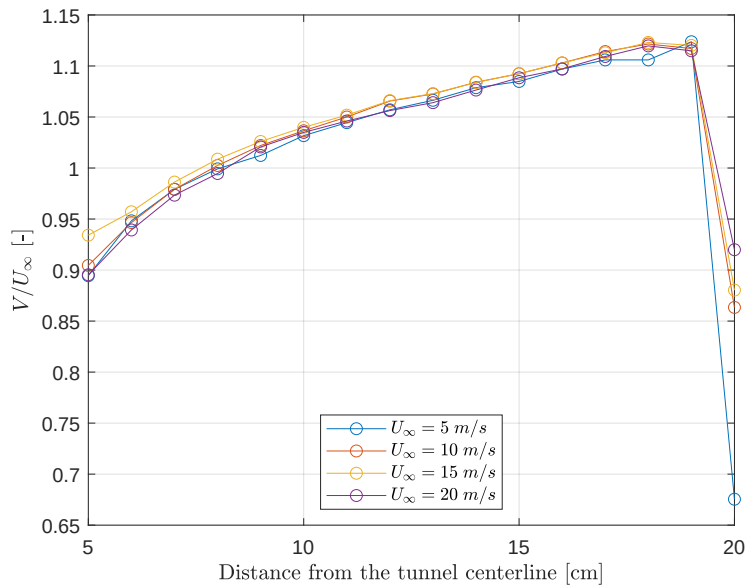
### 4.2.1. Pitot-static Probe Anemometer

Dynamic pressure measurements employing a pitot-static probe have been used to compute the wind tunnel boundary corrections as described in Section 3.4. These measurements have been performed along a straight line on the nozzle plane at an intermediate height, as depicted by the dashed blue line in Figure 4.12.



**Figure 4.9:** Pitot experimental arrangement

Figure 4.9 shows the experimental arrangement; the cylinder is placed very close to the nozzle of the wind tunnel, with an exact separation of  $5.6 \text{ cm}$  from the nozzle plane to the cylinder stagnation point. The nozzle average dynamic pressure is required in order to perform the blockage corrections. The velocity profiles have been measured by means of a pitot tube, and the results are shown in Figure 4.10.



**Figure 4.10:** Velocity profile in the nozzle plane in presence of the cylinder.

As seen in the velocity profile, the presence of the cylinder results in a deceleration in the region near

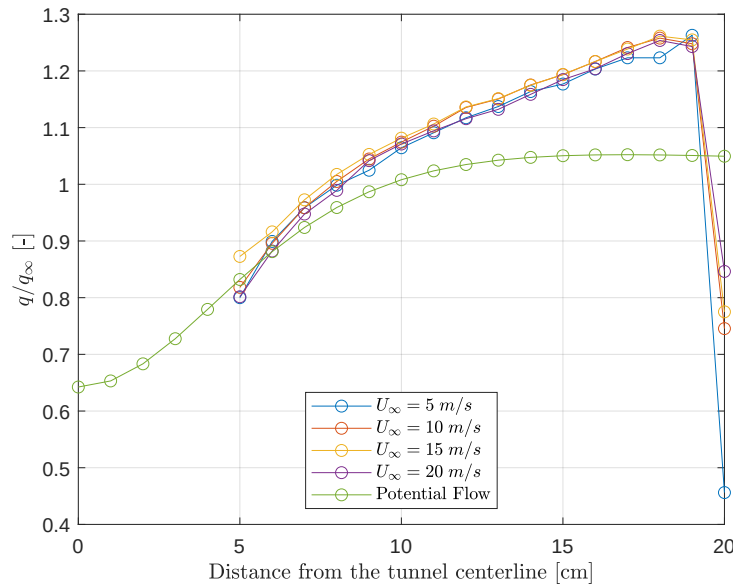
the cylinder and an acceleration of the flow near the outer boundary. This effect in the velocity profile is expected when working with blockages, the flow tends to accelerate near the boundaries of the nozzle and slow down around the object.

Note that because of the physical interference between the pitot probe and the cylinder at the moment of performing the measurements, the velocity profile in front of the cylinder could not be recovered. This presents a hurdle when trying to obtain the average nozzle dynamic pressure required for the blockage corrections. In order to overcome this issue, the velocity profile in front of the cylinder will be calculated according to potential flow theory, as described in Section 2.2.1.

The simplified expression for the non-dimensional velocity magnitude is as follows:

$$\frac{|V_{inviscid}|(r, \theta)}{U_\infty} = \sqrt{1 + \frac{R^4}{r^4} - 2\frac{R^2}{r^2}\cos(2\theta)} \quad (4.1)$$

Figure 4.11 shows a comparison between the measured dynamic pressure profiles and the profile obtained according to potential flow theory. It can be seen that the measured dynamic pressures are closely matched with the theoretical profile in the region near the cylinder; therefore, the theoretical profile will be used for the region in front of the cylinder when computing the nozzle plane average dynamic pressure. Furthermore, the outermost data point, the measurement at the tunnel boundary at 20 cm, will be neglected when computing the average dynamic pressure so as not to skew the average dynamic pressure down because of the boundary layer created at the tunnel walls and nozzle.



**Figure 4.11:** Comparison between the measured dynamic pressure profiles to the theoretical dynamic pressure profile according to potential flow theory.

The average dynamic nozzle dynamic pressures have been computed for the freestream velocities of  $U_\infty [m/s] = [5, 10, 15, 20]$  and are shown in Table 4.2:

**Table 4.2:** Average nozzle dynamic pressures and velocities.

| $U_\infty [m/s]$ | $\bar{q}_{u,n} [Pa]$ | $\bar{v}_{u,n} [m/s]$ |
|------------------|----------------------|-----------------------|
| 5                | 15.0                 | 4.98                  |
| 10               | 60.5                 | 10.00                 |
| 15               | 137.0                | 15.05                 |
| 20               | 240.0                | 19.92                 |

The resulting nozzle average velocities are very similar to the freestream ones, meaning that the presence of the cylinder does not have a significant effect on the average velocity over the nozzle but rather over the velocity profiles as observed in Figures 4.10 & 4.11.

#### 4.2.2. Boundary Corrections

As seen in Section 4.2, the W-tunnel at the TU Delft is an open test section wind tunnel. In this type of wind tunnel, the jet exiting the nozzle forms a shear layer and tends to increase in cross section as the flow moves downstream. Because of the expansion of the jet, the effective velocity in the flow stream diminishes as a result of mass conservation. This is the reason why bodies placed in an open test section experience a negative boundary correction, as explained by Pope et al. [6].

Conversely, as previously stated in Section 4.2.1, the cylinder is located very close to the nozzle, with an exact separation of  $5.6 \text{ cm}$ . The reason for this arrangement is to ensure two-dimensional flow along the entire length of the cylinder. Furthermore, by placing the cylinder near the nozzle of the tunnel, the effective length of the cylinder corresponds to the height of the nozzle.

However, because the cylinder is placed so close to the nozzle of the wind tunnel, it is expected that the blockage effect is different from how it is described by Pope et al. [6]. Due to the fact that a significant area of the nozzle is being blocked by the cylinder being located so close to the nozzle, this results in an acceleration of the airflow as described in Section 3.4.1.

Following the procedure explained in Section 3.4.1, the nozzle and solid blockage correction factors will be computed.

First, the location of the source to the nozzle plane,  $x_s$ , with the distance from the center of the object to the nozzle plane,  $x_m = 5.6 + \frac{D}{2} = 10.1 \text{ cm} = 0.101 \text{ m}$ ; being the separation between the cylinder to the tunnel nozzle added to the cylinder radius. The length of the model is the cylinder diameter,  $L_m = D = 0.09 \text{ m}$  and the model frontal area,  $S = D \cdot h = 0.036 \text{ m}^2$ .

$$x_s = -x_m + \frac{L_m}{2} - \left( \frac{S}{2\pi} \right)^{1/2} = -0.1317 \text{ m}$$

Next, the velocity perturbation on the nozzle plane is,  $\epsilon_{qn}$ . With the duplex nozzle cross-section area,  $C = 2 \cdot h \cdot w = 0.32 \text{ m}^2$  and the hydraulic radius of the duplex nozzle,  $R_n = \sqrt{C/\pi} = 0.319 \text{ m}$ :

$$\epsilon_{qn} = \frac{\left( \frac{S}{2C} \right) \left( 1 + \frac{x_s}{(x_s^2 + R_n^2)^{1/2}} \right)}{\left[ 1 - \left( \frac{S}{2C} \right) \left( 1 + \frac{x_s}{(x_s^2 + R_n^2)^{1/2}} \right) \right]} = 0.0360$$

Then, projecting the velocity perturbation on the plane of the model, the nozzle blockage factor  $\epsilon_n$  is:

$$\epsilon_n = \epsilon_{qn} \left[ \frac{R_n^3}{(x_m^2 + R_n^2)^{3/2}} \right] = 0.0312$$

Finally, the velocity perturbation caused by the solid blockage is computed, with the subject body shape factor  $\lambda_{2D} = 1$ , for a circular cylinder, as described by Pope et al. [6]

$$\epsilon_s = -\frac{\pi^2}{24} \lambda_{2D} \frac{D^2}{w^2} = -0.0208$$

Finally, the total blockage factor is calculated, and the corrected velocities and dynamic pressures are accordingly computed.

$$\epsilon = \epsilon_n + \epsilon_s = 0.0104 \quad (4.2)$$

$$v_c = v_{u,n} (1 + \epsilon) \quad (4.3)$$

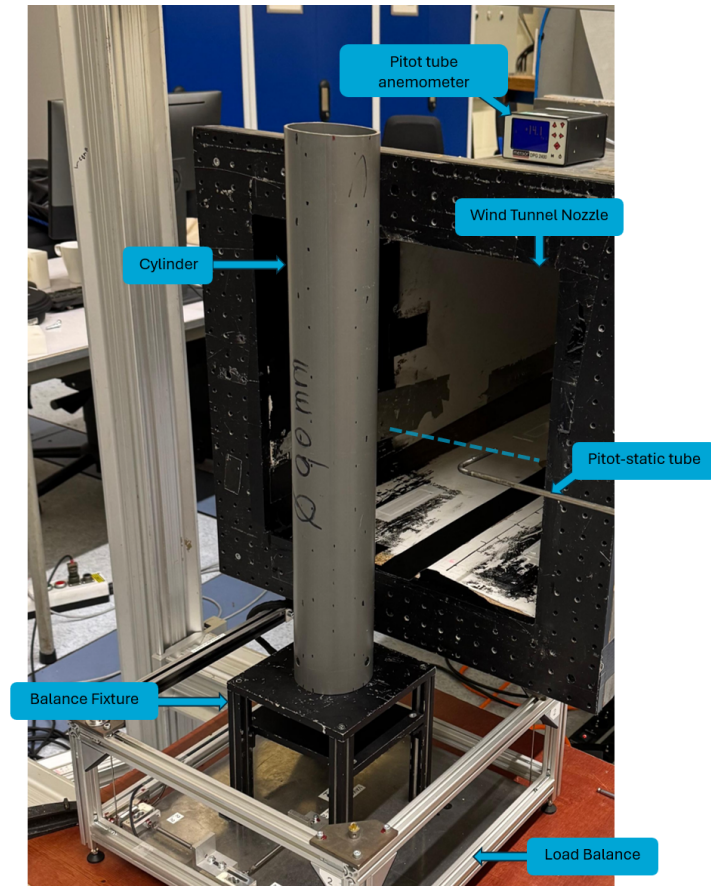
$$q_c = q_{u,n} (1 + \epsilon)^2 \quad (4.4)$$

## 4.3. Balance

Measurements of the cylinder drag were obtained by means of balance measurements at different Reynolds numbers. This section presents the physical details of the setup, balance specifications and the methodology of acquisition.

### 4.3.1. Cylinder Fixture

The cylinder is safely secured onto the load balance plate using a mounting fixture. The fixture consists of a rigid aluminum structure designed to be bolted onto the load balance support plate and the base of the cylinder. Figure 4.12 shows a picture of the cylinder attached to the balance and its positioning relative the jet of the wind tunnel.



**Figure 4.12:** Experimental setup showing the cylinder attached to the load balance by means of the fixture. Dotted line indicates pitot probe path.

### 4.3.2. Details of the Balance

A two axis force balance was used to acquire the drag measurements. The balance has a setup of three load cells, in this setup, one was placed in the flow direction ( $x$ -axis) and two in the flow normal direction ( $y$ -axis), no measurements are taken in the binormal direction ( $z$ -axis).

The balance has a maximum load of  $\pm 50 \text{ N}$  across each of its three load cells. The load cells are S-shaped (specification: KD40s 50N) and an accuracy class of 0.1% [33].

The balance has an acquisition rate of  $25 \text{ kHz}$ , the typical Strouhal number for a cylinder flow in these conditions ranges from 0.2 to a peak of 0.5 [23]. This results in maximum oscillation frequency under  $200 \text{ Hz}$ . In order to avoid aliasing effects, the acquisition or sampling rate has to be larger than twice

the maximum frequency:  $f_{acquisition} > 2 \cdot f_{max}$ , as per the Nyquist-Shannon sampling theorem [7]. Therefore, the sampling frequency of the balance is more than sufficient for the load data acquisition.

The load cells were connected to a data acquisition module that converted the strain from the load cells into a digital signal that was then displayed by the acquisition system. The acquisition system operated and monitored the balance using a custom LabView program specifically designed for the balance in use.

### 4.3.3. Balance Data Acquisition Procedure

Throughout the measurement campaign, the operating procedure for the balance was the following:

1. The wind tunnel was set to  $0 \text{ RPM}$ , then it was calibrated and its details were logged to serve as the 'zero measurements'. The same thing is performed on the balance, while the tunnel velocity is null, the balance was calibrated, zeroed and a zero measurement was taken.
2. Then the tunnel is set to a specific  $\text{RPM}$  value such that the tunnel velocity reaches the desired value. Generally, for the data acquisition campaign, these velocities were:  
 $U_{\infty} = [5, 10, 15, 20, 25, 30, 35] \text{ m/s}$ , for some configurations additional measurements with increments of  $1.66 \text{ m/s}$  were taken around the crisis region to provide more resolution in the  $C_d - Re$  curve.
3. Once, the desired velocity value was reached, the flow was left to settle for around  $5 - 10 \text{ s}$ , this way any dynamic and hysteresis effects are minimized. After the settling period, a time-averaged measurement of the tunnel details and the balance data was taken for  $30 \text{ s}$ .
4. Once the measurement has finalized, the new tunnel set point was set and the same step is followed for the next data point measurement.

## 4.4. Particle Image Velocimetry

PIV has been used in the experimental campaign to obtain information about the flow regarding the effect of double layer fabrics on cylinder flows. This section presents the specific setup and analysis techniques used in this research. Two different PIV setups were employed in this research, one to observe the flow behavior and evolution around the cylinder as well as for the determination of the separation point, and the other one to determine the characteristics and behavior of the boundary layer at a particular location.

### 4.4.1. PIV Setup

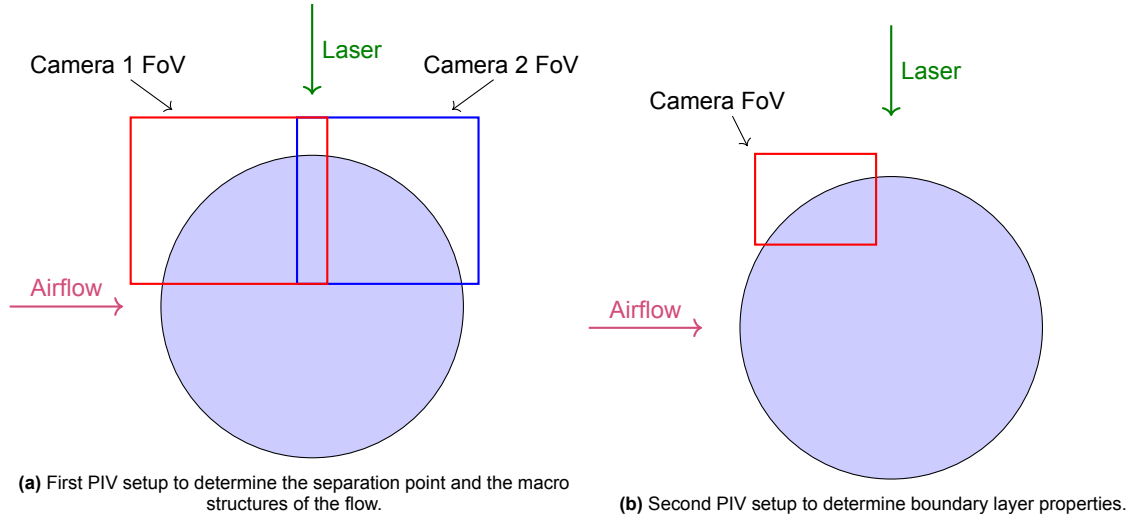
Figure 4.13 shows two schematics portraying both PIV setups used. The goal of the first setup, shown in Figure 4.13a, is to determine the flow separation point with FoV2 and to gather the behavior of the flow at a macroscopic level. On the other hand, the goal of the second setup, shown in Figure 4.13b, is to determine boundary layer properties around the angles of  $40^\circ \leq \theta \leq 85^\circ$  where the transition from laminar to turbulent boundary layer is likely to occur.

Furthermore, the size of the cylinder plays a significant role in the quality of the PIV measurements. This is because a larger cylinder allows for better spatial resolution for the same magnification factor. Conversely, a larger cylinder increases the blockage effect in the wind tunnel, which is detrimental to flow development and maintaining similarity to free-flight.

In the end, a diameter of  $D = 9 \text{ cm}$  had been chosen. Based on the solutions to the Prandtl boundary layer equations on circular cylinders solved by Zdravkovich [40], the ratio between boundary layer height to cylinder diameter at  $\theta = 60^\circ$ ,  $Re = 10^5$  is around  $\frac{\delta}{D} = 0.02$ , which for a cylinder of said diameter would result in a boundary layer height of  $\delta \approx 2 \text{ mm}$ . This height is sufficient such that for the presented PIV setup, the boundary layer can be resolved with good fidelity.

Additionally, note that the balance measurements and the PIV measurements were carried out independently; this is due to the fact that for  $Re$  near the  $Re_{crit}$  the cylinder will start oscillating. These oscillations will complicate the obtention of PIV measurements; therefore, for the PIV campaign, the

cylinder was clamped from both ends in order to guarantee more rigidity in the setup, as suggested by Deval [12].



**Figure 4.13:** Two schematics depicting the two distinct PIV setups used during this research.

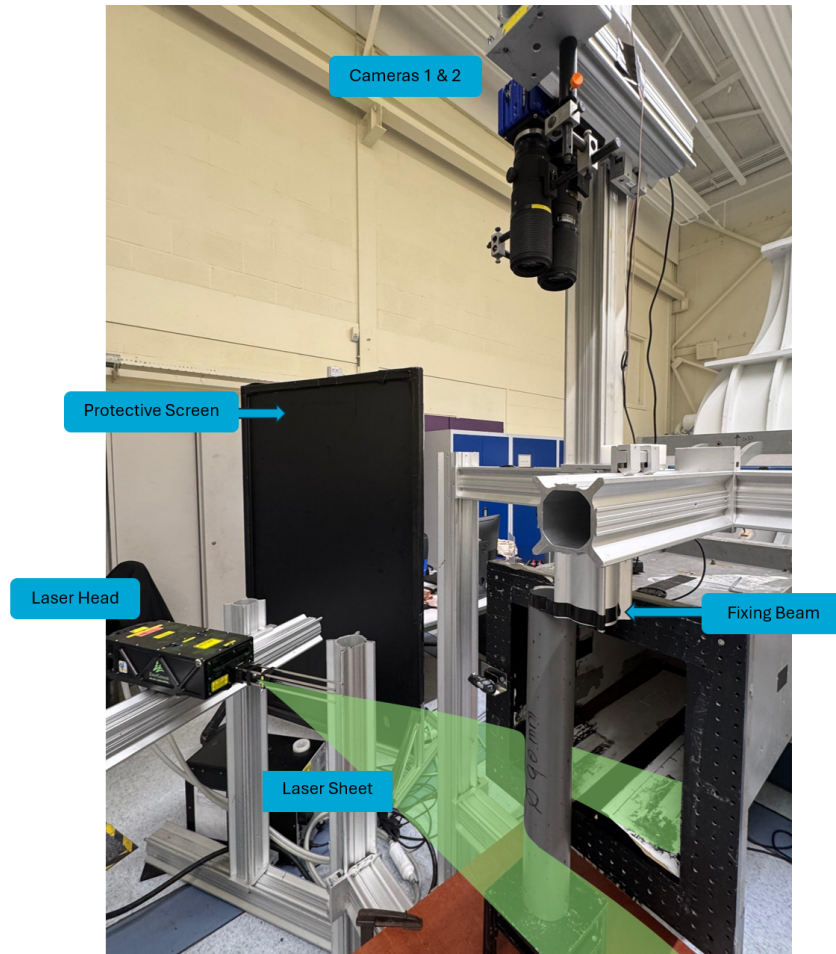
In order to make such a setup possible, all of the other PIV subsystems presented in Section 3.1.1 ought to be present in our experimental arrangement. The following Table 4.3 shows the main specifications of the cameras, illuminating laser, the trigger and sync unit, and the controlling software:

**Table 4.3:** PIV setup equipment specifications.

|                                     |                                    |
|-------------------------------------|------------------------------------|
| Camera                              | LaVision Imager sCMOS              |
| Sensor Size [ $px \times px$ ]      | $2560 \times 2160$                 |
| Sensor Size [ $mm \times mm$ ]      | $16.6 \times 14.0$                 |
| Pixel Size [ $\mu m \times \mu m$ ] | $6.5 \times 6.5$                   |
| Laser                               | Quantel Evergreen <sup>2</sup> 200 |
| Wavelength [ $nm$ ]                 | 532                                |
| Pulse Energy [ $mJ$ ]               | 200                                |
| Repetition Rate [ $Hz$ ]            | 15                                 |
| Timing and Sync Unit                | LaVision PTU X                     |
| Software                            | DaVis 8 & DaVis 10                 |

Figure 4.14 shows a picture of the experimental PIV arrangement that allowed for the measurement campaign. As seen in the picture, the cameras are securely mounted overhead, with additional supports on the lenses in order to reduce vibrations and ensure a steady image. Then, the fixing beam comes down from above and secures the cylinder; this way, any undesirable aerodynamic vibrations are removed and a steady cylinder is guaranteed. Additionally, note that the laser head is pointing towards the cylinder and perhaps most importantly, it is pointing away from the protective screen. This is for safety reasons; the acquisition computer is located behind the protective screen and it is always desirable to have the laser head facing away from where the user is.





**Figure 4.14:** A picture of the first experimental PIV setup.

Finally, Table 4.4 shows additional lenses and optics settings for the PIV cameras, in addition to the timing between both exposures for each of the tested velocities.

**Table 4.4:** PIV optics and timing parameters.

| Parameter                                                   | Setup 1     |             | Setup 2     |
|-------------------------------------------------------------|-------------|-------------|-------------|
|                                                             | Camera 1    | Camera 2    | Camera      |
| Focal Length [mm]                                           | 200         | 200         | 200         |
| Field of View [cm × cm]                                     | 68.3 × 52.2 | 68.3 × 52.2 | 36.4 × 30.6 |
| Magnification Factor [—]                                    | 0.2421      | 0.2421      | 0.455       |
| F-Stop [#]                                                  | 8           | 8           | 8           |
| $\Delta t$ at $U_\infty = 5 \text{ m/s}$ [ $\mu\text{s}$ ]  | 47          |             | 29          |
| $\Delta t$ at $U_\infty = 10 \text{ m/s}$ [ $\mu\text{s}$ ] | 24          |             | 15          |
| $\Delta t$ at $U_\infty = 15 \text{ m/s}$ [ $\mu\text{s}$ ] | 16          |             | 10          |
| $\Delta t$ at $U_\infty = 20 \text{ m/s}$ [ $\mu\text{s}$ ] | 12          |             | 8           |
| $\Delta t$ at $U_\infty = 25 \text{ m/s}$ [ $\mu\text{s}$ ] | 10          |             | 6           |
| $\Delta t$ at $U_\infty = 30 \text{ m/s}$ [ $\mu\text{s}$ ] | 8           |             | 5           |
| $\Delta t$ at $U_\infty = 35 \text{ m/s}$ [ $\mu\text{s}$ ] | 7           |             | 5           |

#### 4.4.2. PIV Acquisition Procedure

Throughout the measurement campaign, the operating procedure for the PIV equipment was as follows:



1. The cameras calibration procedure is carried out. A sheet of millimetric paper is placed in the field of view of both cameras. This way, the magnification factor for each of the cameras is determined, and the relationship between image displacement and real displacement is obtained. Additionally, in case there is more than one camera, a common reference point is set for both cameras, this will enable the merging of the images during the postprocessing.
2. The millimetric paper is removed after the calibration and the wind tunnel is set to 0 *RPM*, then it was calibrated and its details were logged to serve as the 'zero measurements'.
3. Then, the tunnel is set to a specific *RPM* value such that the tunnel velocity reaches the desired value. Generally, only a few data points from the  $C_d - Re$  curve for specific configurations have been studied with PIV techniques.
4. Once the desired tunnel free stream velocity was achieved, the seeding was triggered and some preliminary pictures were taken to ensure enough seeding. The acquisition software employed was DaVis 8.
5. Then, the capture of 450 image pairs was taken with the respective  $\Delta t$  as described in Table 4.4. Out of these 450 image pairs, only one in three would be saved and stored, yielding 150 final image pairs. This was done to ensure a similar capture time between the balance and the PIV system.
6. Finally, the datasets are labeled and stored for future processing.

This procedure is carried out for all the configurations deemed relevant. In order to determine the relevance of a certain configuration, the totality of the balance measurements is taken and partially processed. With the measured balance information, a selection of certain specific configurations at particular Reynolds numbers is chosen to be studied with PIV. For those configurations, all the PIV measurements using setup 1 will be performed; then, one of the cameras is removed and the setup is modified to achieve setup 2. Therefore, this means that among all the measurement techniques outlined in this research, they are all carried out separately. Although an effort has been made to maintain identical flow conditions, there might be slight inconsistencies when comparing results from one measurement set to another.

#### 4.4.3. Data Processing

After the images have been acquired and stored, to obtain the velocity fields from the images, these need to be processed. This section outlines the processing procedure carried out in DaVis 10 software. For each of the setups, a slightly different processing pipeline has been used.

The first setup, as shown in Figure 4.13a, consists of two cameras with the same optical arrangement at two different locations on the cylinder. Each one of these cameras takes an image pair and can be processed together. On the other hand, the second setup, shown in Figure 4.13b, consists of a single camera located closer to the cylinder resulting in a smaller field of view and increased spatial resolution.

1. Background removal: A common preprocessing step in PIV is the removal of the image background; this results in an improvement in the signal-to-noise ratio. This is carried out by taking a subset of images, 9 images in this case, and computing the sliding minimum for each pixel across the subset and subtracting the value for each pixel across the 9 images. By repeating this procedure over all subsets that make up the data set, the image background across all the images is removed.
2. Masking: In the image, there will be regions where no particles will be present, mainly in the cylinder body region. These regions are masked such that they will not be processed by the PIV solver. These first two processing steps are common for both setups.
3. For the first PIV setup:
  - (a) Sequential PIV: Because there are two image pairs stored in four frames, the PIV solver needs to know which images to cross correlate. The first two frames correspond to the image pair from camera 1 and the last two frames correspond to the image pair from the second camera. The purpose of this first setup is to obtain the flow separation point and

macroscopic behavior of the flow. Therefore, because there are no significant spatial resolution requirements, the standard PIV algorithm is used to compute the velocity field. This yields a total of 150 instantaneous velocity snapshots at different time instants for each of the cameras.

- (b) Time averaging: In this study, the relevant field is the time-averaged velocity field. For this setup, the averaging method employed is the velocity field averaging. The resulting fields of these operations are the average velocity field and velocity standard deviation for each of the cameras.
- (c) Field merging: For a more clear result interpretation and more convenient future processing, the average and standard deviation velocity fields will be merged into a single large field with the aid of the aforementioned reference point.

4. For the second PIV setup:

- (a) Sum of correlation PIV: The purpose of this second setup with a smaller field of view is to capture the boundary layer parameters and development in  $40^\circ \leq \theta \leq 85^\circ$ . As spatial resolution becomes a crucial limitation, the sum of correlation PIV algorithm is used, as it will yield a better signal-to-noise ratio. This in turn means a smaller final interrogation window can be used resulting in an increased spatial resolution. One downside however, is the fact that this algorithm does not calculate the velocity standard deviation, it exclusively returns the average velocity field.

- 5. Postprocessing on the velocity fields: This step is common for both setups. A series of non-linear filters and outlier detection algorithms are utilized to smoothen the final velocity field. This step is crucial for further postprocessing such as pressure computation.

## 4.5. Data Reduction

### 4.5.1. Balance Data

The data obtained from the balance is the time-averaged readings for each of the load cells of the balance. For the experimental arrangement portrayed in this thesis, the balance has been placed in such a way that the force in the streamwise direction is given by a singular load cell. As stated in Section 4.3.3, the measurement time consisted of 30 s once the wind tunnel has been left to settle. Simultaneously, the wind tunnel parameters were logged for the same amount of time. Therefore, the force measurements and the tunnel data are obtained in a time-averaged manner.

As stated in Section 4.3.3, after calibrating and zeroing the balance, a zero measurement is taken with the wind tunnel off. This measurement is used to minimize instrumental errors such as balance offsets. The time-averaged reading of the zero measurement is subtracted from all the load measurements for that particular configuration. Furthermore, once the corrections due to nozzle and solid blockage have been computed, corrections are applied to the wind tunnel time-averaged velocity readings. Consequently, this corrected velocity modifies the Reynolds values,  $Re$ , and the drag coefficient values,  $C_d$ . Additionally, the wind tunnel log file includes the values for the air density and the air temperature.

Therefore, the final values for the drag coefficient and the Reynolds numbers for this experimental arrangement are computed in the following manner: firstly, the corrected velocity is calculated:

$$V_{corr} = V_{tunnel} (1 + \epsilon)$$

Next, by using the air density provided by the tunnel and using Sutherland's Law [37] to calculate the air's dynamic viscosity, with  $S_\mu = 111 \text{ K}$ ,  $\mu_0 = 1.716 \times 10^{-5} \text{ N} \cdot \text{s}/\text{m}^2$  and  $T_0 = 273 \text{ K}$ .

$$\mu(T_{tunnel}) = \mu_0 \left( \frac{T_{tunnel}}{T_0} \right)^{3/2} \frac{T_0 + S_\mu}{T_{tunnel} + S_\mu}$$

$$Re = \frac{\rho_{tunnel} V_{corr} D}{\mu}$$

Finally, the drag coefficient is computed as follows:

$$C_d = \frac{F_D - F_{zero}}{\frac{1}{2}\rho_{tunnel}V_{corr}^2 D l}$$

where  $F_D$  is the value measured by the balance load cell,  $F_{zero}$  stands for the value from the zero measurement, and the reference area used for non-dimensionalizing is  $A = D \cdot l$ .

#### 4.5.2. PIV Data

DaVis 10 outputs the velocity and pressure fields for the processed configurations. However, DaVis 10's graphing and plotting capabilities are quite limited. Thus, in order to accurately assess the flow behavior and the occurring phenomena, additional processing of the PIV data is required.

##### Surface Pressure Coefficient Distributions

The pressure coefficient over the surface of the cylinder provides an indication of how the flow is behaving in the near-wall region, as well as insights about flow separation and localized pressure gradients. Furthermore, it also provides information regarding the pressure component of the drag.

In order to determine the pressure coefficient along the surface of the cylinder, a MatLab script has been written. This script is tasked with loading up the dataset and extracting the coordinates for the masked coordinates, which correspond to the cylinder body. Next, after determining the boundary of the masked coordinates, it gathers the static pressure of the fluid in the neighboring elements as well as the coordinates for those fluid points. Once the pressure and the location of the elements on the boundary of the cylinder are obtained, the pressure coefficient can be computed:

$$C_p = \frac{p - p_\infty}{\frac{1}{2}\rho_{tunnel}V_{corr}^2} \quad (4.5)$$

Next, the  $\theta$  angle is determined based on the location of the fluid element relative to the cylinder center, and thus in the end a  $C_p - \theta$  graph can be computed.

##### Streamlines

The separation point is crucial when studying the drag crisis, and related to the separation point, the width of the wake is closely related. There is a plethora of ways to visualize and determine the width of the wake, such as a double-Gaussian fitting to the streamwise component of the velocity fluctuation. However, given the choice of experimental setup, no camera was capturing the broad part of the wake downstream of the cylinder. Therefore, another method of determining the wake width is by the use of streamlines. Concretely, the streamline resulting from the  $\psi = 0$  contour denotes the separating streamline. This particular streamline indicates the separation line between the part of the flow that is attached and the part of the flow that has detached and is recirculating.

In order to determine the location of the separation streamline, a simple numerical integration scheme has been made in order to integrate the value of the stream function,  $\psi$ .

$$u = \frac{\partial \psi}{\partial y} \quad (4.6)$$

$$v = -\frac{\partial \psi}{\partial x} \quad (4.7)$$

The finite-difference integration is a forward-Euler scheme, and it reads as follows:

$$\psi_{i,j} = \psi_{i-1,j} + u_{i-1,j} \cdot \Delta_y \quad (4.8)$$

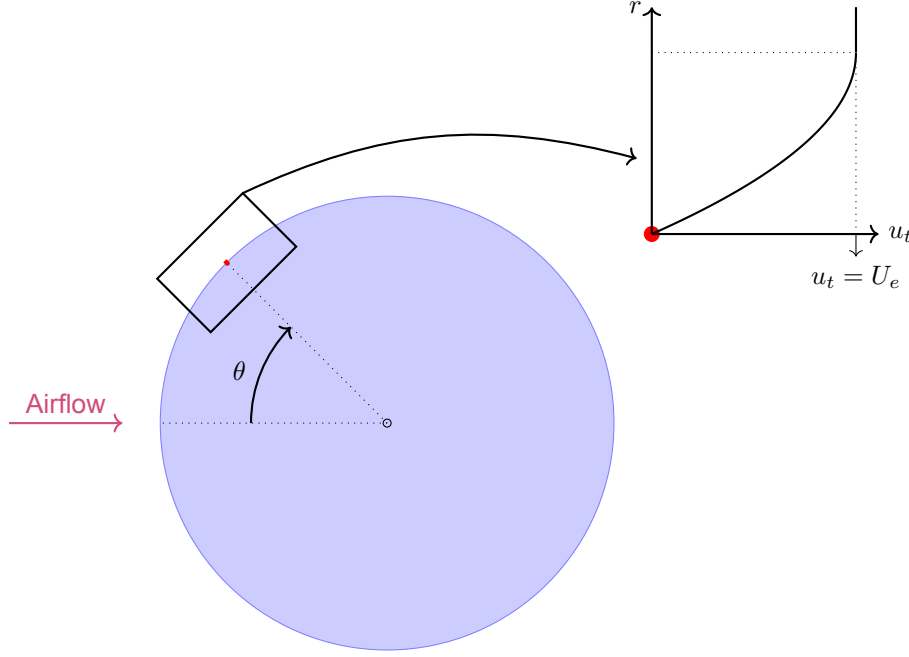
This allows for the computation of the stream function over the discretized domain, and finally the streamline that passes through the separation point is obtained by plotting the  $\psi = 0$  contour.

### Boundary Layer

The purpose of the second PIV setup is to determine the velocity field with greater spatial resolution.

The cylinder has been probed at different azimuth locations. At these locations, an outward line normal to the mask is defined, with a length of 3 mm and the angular tangential velocity along this line is obtained by linear interpolation based on the surrounding velocity data points on the field.

From the boundary layer profile, the following parameters are calculated: 99% thickness,  $\delta_{99}$ , displacement thickness  $\delta^*$ , momentum thickness,  $\delta_m$  and shape factor,  $H$ .



**Figure 4.15:** Scheme depicting the extraction of the boundary layer profile.

The 99% indicates the distance from the surface at which the velocity in the boundary layer reaches 99% of the external velocity. It is used to determine the overall thickness of the boundary layer, its expression is as follows:

$$\delta_{99} = \min\{r \mid u_t(r) = 0.99 U_e\} \quad (4.9)$$

The displacement thickness, ( $\delta^*$ ), corresponds to the distance by which the external inviscid flow is displaced outward due to the presence of the viscous boundary layer. It can also be interpreted as the height increase of the viscous region such that the mass flow in the said region remains the same, as the mass flow decreases near the wall; therefore, the height of this region would have to experience an increment. A low displacement thickness indicates that the boundary layer is thin and the external flow remains close to the surface, leading to a small disturbance on the outer flow due to the boundary layer. Conversely, a large displacement thickness implies the presence of a thicker boundary layer and a greater displacement of the outer flow from the surface of the body. The expression to compute the displacement thickness is as follows:

$$\delta^*(\theta) = \int_0^{r=3mm} \left(1 - \frac{u_t(r, \theta)}{U_e}\right) dr \quad (4.10)$$

The momentum thickness, ( $\delta_m$ ) represents the loss of momentum in the flow due to the presence of the boundary layer. It quantifies the height of a virtual inviscid boundary layer flowing at the velocity of the external flow such that the virtual inviscid boundary layer has the same amount of momentum as the actual viscous boundary layer. A low momentum thickness implies a more streamlined boundary layer

with more orderly flow, typically associated with laminar regimes. On the other hand, a high momentum thickness indicates an increased momentum transfer and mixing, typical of turbulent boundary layers. The expression to compute the momentum thickness is as follows:

$$\delta_m(\theta) = \int_0^{r=3mm} \frac{u_t(r, \theta)}{U_e} \left( 1 - \frac{u_t(r, \theta)}{U_e} \right) dr \quad (4.11)$$

The shape factor is defined as the ratio between the displacement and momentum thicknesses. It provides information regarding the shape of the velocity profile. A high shape factor, ( $H \approx 2.6$ ), results from low momentum thickness relative to the displacement thickness; this suggests a more laminar flow regime with less turbulence and a more streamlined flow. Conversely, a low shape factor, ( $H \approx 1.4$ ), indicates a more blunt velocity profile, with a large momentum thickness relative to the displacement thickness. This indicates a more turbulent regime with a higher degree of mixing and momentum transfer. Furthermore, significantly larger shape factors, ( $H > 3.5$ ), indicate imminent flow separation, as the displacement thickness is large and the boundary layer is full of low-momentum fluid. The expression to compute the shape factor is the following:

$$H = \frac{\delta^*}{\delta_m} \quad (4.12)$$

In order to compute integral quantities, the numerical composite trapezoidal `trapz()` function in MatLab was used. Conversely, the 99% thickness of the boundary layer was computed by means of a linear interpolation.

# 5

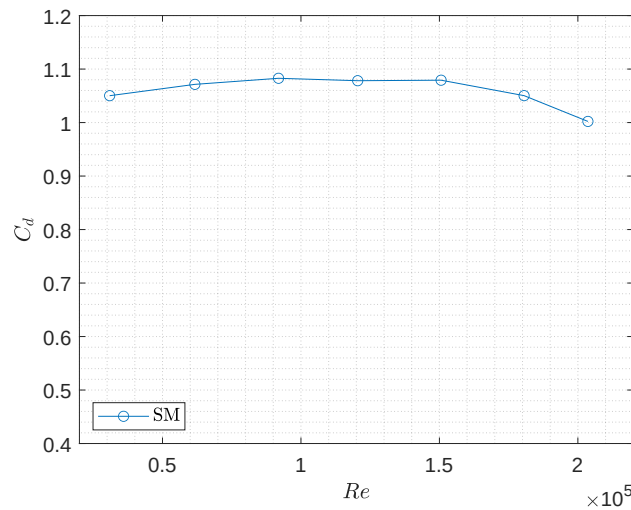
## Results

### 5.1. Bare Cylinder

The first studied configuration will be the bare smooth cylinder without any fabric on top of it. This configuration will provide a baseline and reference results for future comparison. In terms of codification, for the sake of brevity in the plot legends, the smooth bare cylinder is codified as SM, not to be confused with SM05, SM07, SM10 and SM20, that correspond to the double fabric layer configurations with a smooth overlayer.

#### 5.1.1. Balance Results

Following the procedure outlined in Section 4.3.3, the drag coefficient - Reynolds number curve for the bare cylinder is obtained and shown in Figure 5.1.



**Figure 5.1:** Drag coefficient against Reynolds number for bare cylinder.

One clear observation is the fact that the drag coefficient of around 1.1 is slightly below the expected value of 1.2, described by Wieselsberger [36], Timmer & Veldhuis [34] and Achenbach [2] among others. This effect is, on the one hand, due to a missing wind tunnel boundary correction from the effect of buoyancy; and on the other hand, due to possible 3D effects given that no cylinder end plates have been used. In Wieselsberger's study [36], a much more slender cylinder was used in addition to cylinder

end plates such that the cylinder tip effects are completely avoided. With that setup a  $C_d$  of 1.25 for a bare cylinder was obtained.

Although the absolute value of the drag coefficient is slightly lower than expected, the deviation of the results on the Reynolds number is notably smaller. This is seen in Figure 5.1 as the flow regime is subcritical with the onset of the critical regime at the upper limit of the measurement range. This can be observed by the drag coefficient slightly dropping around  $Re \approx 2 \times 10^5$ . This is reinforced by comparing these results to the results from Wieselsberger [36], shown in Figure 4.8, it can be seen that the beginning of the critical regime is at the upper limit of the available measurement range of the wind tunnel, as previously stated.

Despite the discrepancies relative to other studies in the literature, this study focuses on the effect drag reduction mechanisms of double layer fabrics; for that, the results with the double layer fabric configurations will be mainly compared to the bare cylinder currently measured and not the results of the literature. So in that sense, the slight deviation in terms of drag coefficient will not pose a major problem for the purposes of this study.

### 5.1.2. PIV Results

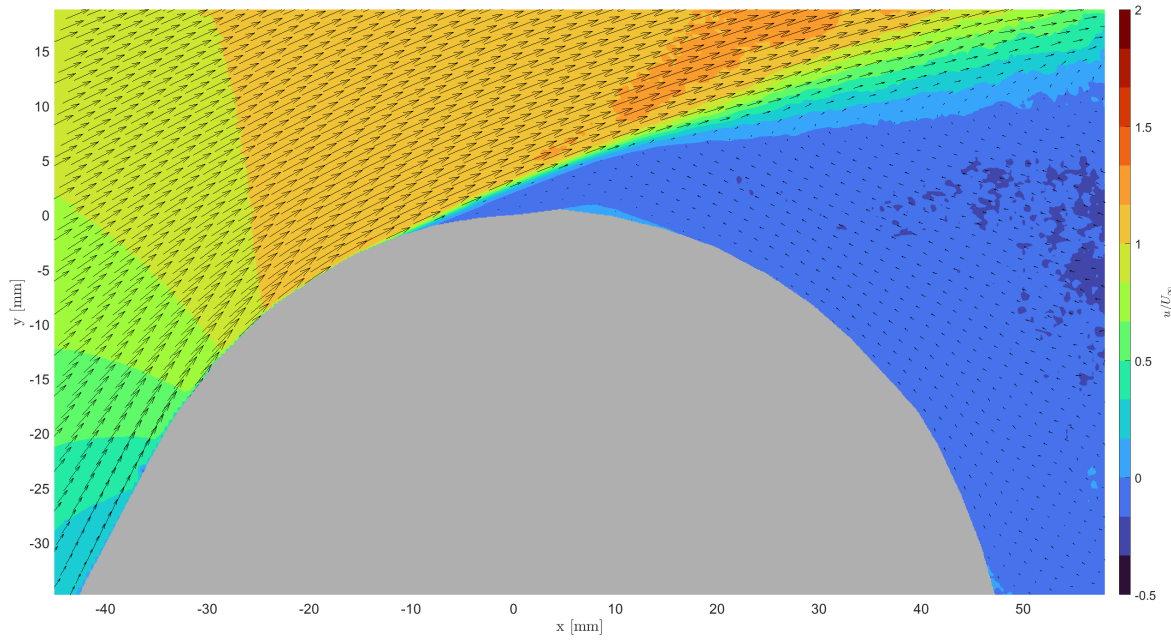
Balance measurements are utilized to identify where the critical regime is located. Thereafter, PIV measurements will be performed to study the critical behavior of the flow. However, for this baseline case of a smooth cylinder, the entire measurement range is in the subcritical regime. This results in the PIV measurements acquired for  $Re = [3.1, 6.2, 9.3, 12.4] \times 10^4$  to have a very large resemblance to each other. The normalized velocity field obtained from the PIV measurements for  $Re = 6.2 \times 10^4$  is shown in Figure 5.2a. Note that the vector visualization portrayed in Figure 5.2a is not representative of the actual density, the vector spacing has been increased for the purposes of legibility and easier visualization.

As expected from the  $C_d - Re$  graph in Figure 5.1, the velocity fields around the cylinder are pretty much identical for all PIV measurements  $Re = [3.1, 6.2, 9.3, 12.4] \times 10^4$ . For that reason, they have not been included in this results section; refer to Appendix A.1.1 for the complete set of normalized velocity fields.

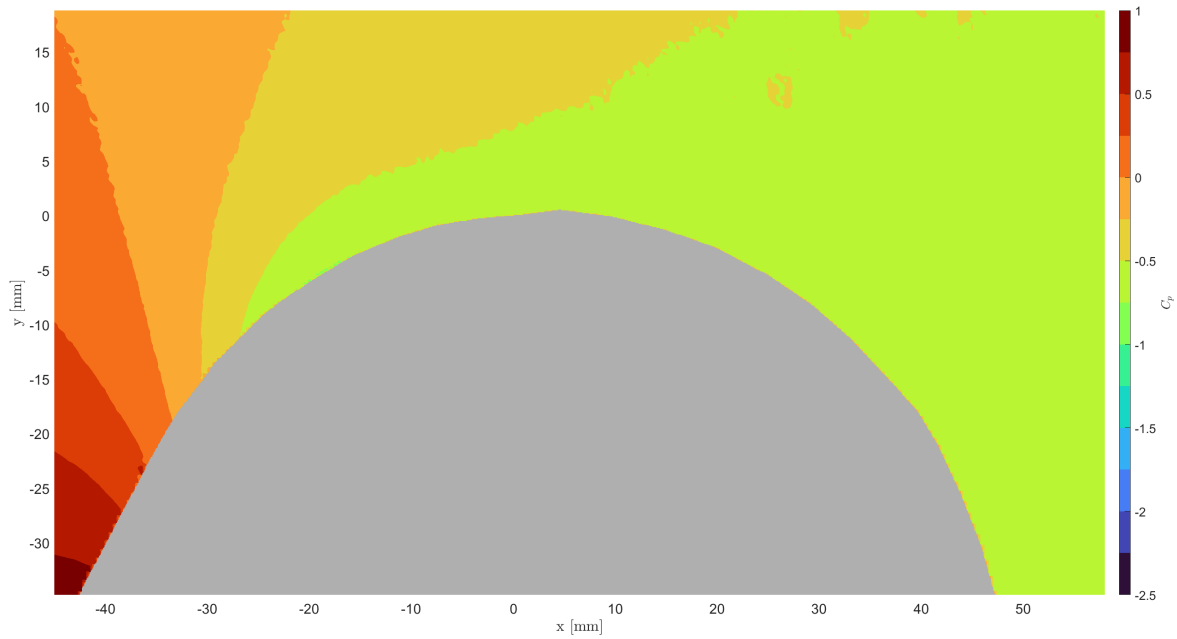
As observed from the velocity field, with increasing freestream velocity, the velocity profile on the fore-side of the cylinder remains invariable. On the backside of the cylinder, the amount of flow recirculation within the wake increases, depicted by the increasing dark area in the contour plot Figures A.1, A.2, A.3 and A.4. Additionally, the flow presents an early separation,  $\theta_{sep} \approx 80^\circ$ , creating a shear layer emanating from the separation point and deflecting the external flow away from the cylinder centerline, leading to a wide wake, a typical behavior of the subcritical regime.

In addition to the velocity fields, DaVis 10's Poisson-based pressure solver has been utilized to compute the static pressure around the cylinder. This result is shown in Figure 5.2b for  $Re = 6.2 \times 10^4$ , and the remaining pressure coefficient fields from this set are shown in Section A.1.1 of the Appendix.

Similar to the velocity fields, the pressure fields remain invariable across this measurement range, which is to be expected given that the flow regime across the measurement points is always subcritical. The peak suction of the pressure coefficient is low in magnitude,  $C_{p,min} \approx -0.75$ , due to the early separation, and the pressure does not recover for the backside of the cylinder, resulting in a very low static pressure in this region and thus a large amount of pressure drag.



(a) normalized velocity field around bare cylinder for  $Re = 6.2 \times 10^4$ .



(b) Pressure coefficient field around bare cylinder for  $Re = 6.2 \times 10^4$ .

**Figure 5.2:** normalized velocity and pressure coefficient fields around a bare cylinder for  $Re = 6.2 \times 10^4$ .

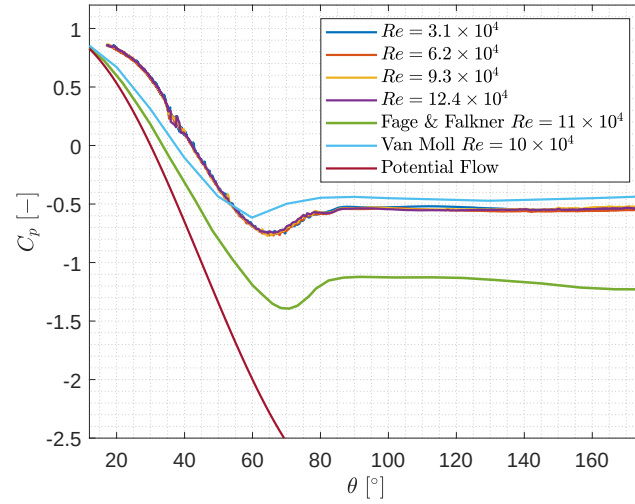
For a more clear visualization, the pressure coefficient over the surface of the cylinder has been computed relative to the azimuthal angle  $\theta$ , shown in Figure 5.3. As previously stated, the pressure distributions for all the experimental runs for this configuration are similar in terms of the separation location and the magnitude of the pressure coefficient.

Additionally, prior to flow separation, a small kink in the  $C_p - \theta$  curve can be observed, which is indicative of a laminar separation bubble leading into laminar separation, though this bubble cannot be observed from the velocity fields.

Finally, comparing the azimuthal pressure distributions with known distributions from experimental

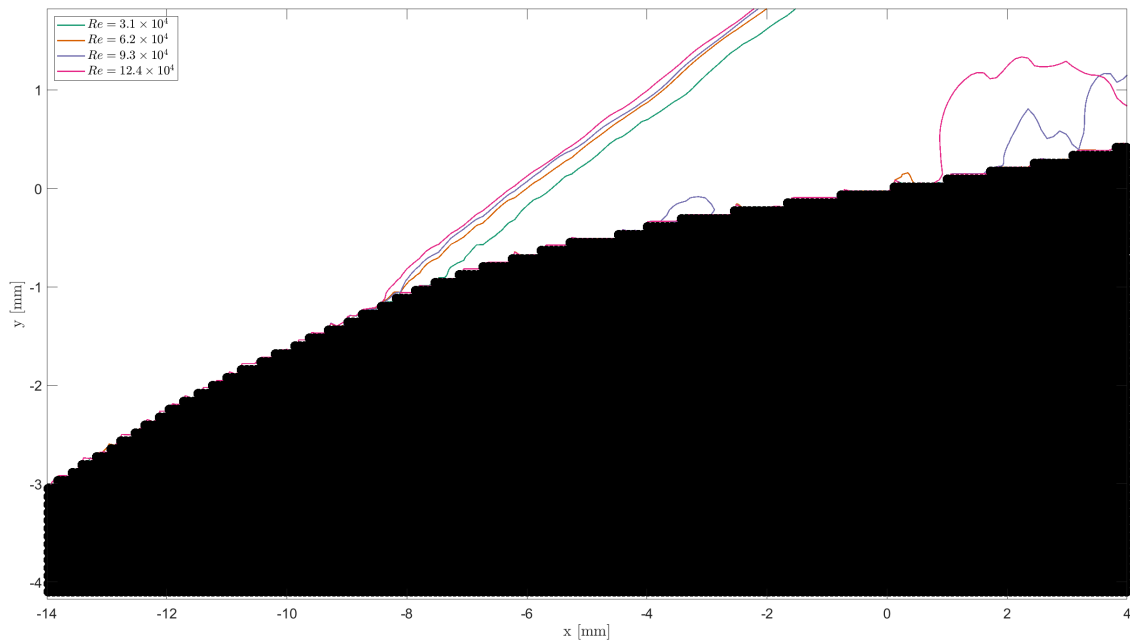


sources in the literature provided by Fage & Falkner [13], a significant discrepancy is observed. This effect is due to the confinement present in the closed test section used by Fage & Falkner. On the other hand, results from van Moll [35] show a better degree of correlation with the obtained results and highlight the effects and differences from performing the measurements in an open test section.



**Figure 5.3:** Pressure coefficient over cylinder surface vs  $\theta$  for  $Re = [3.1, 6.2, 9.3, 12.4] \times 10^4$ .

In order to accurately determine the separation point, the separating streamlines  $\psi = 0$  for the different Reynolds numbers have been computed and are shown in Figure 5.4. Given that the separation points for the different Reynolds numbers are located so closely together, a close-up of the region is shown.



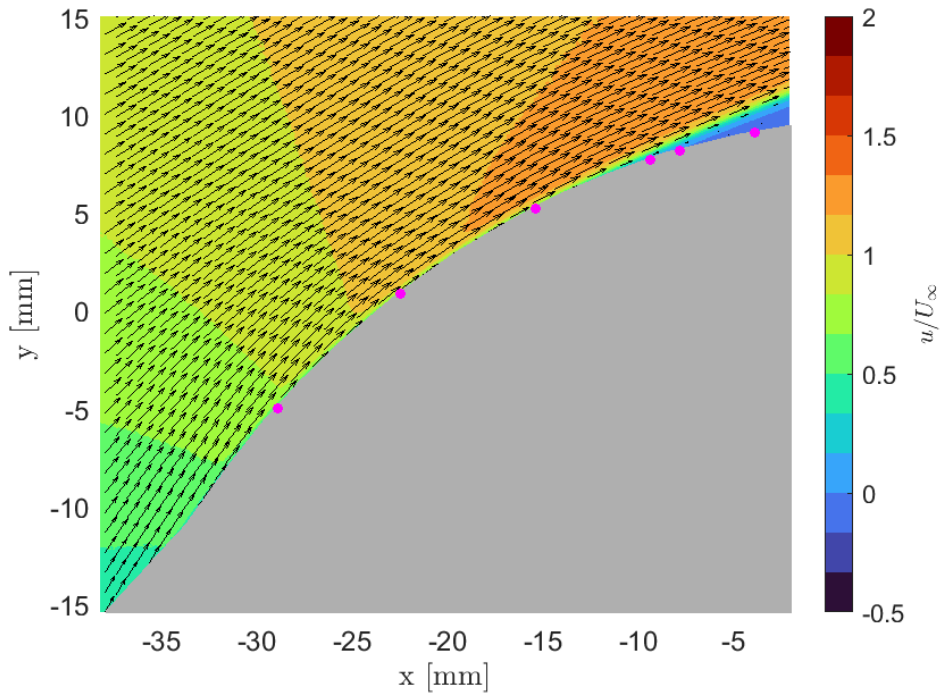
**Figure 5.4:** Separation point streamline for bare cylinder at  $Re = [3.1, 6.2, 9.3, 12.4] \times 10^4$ .

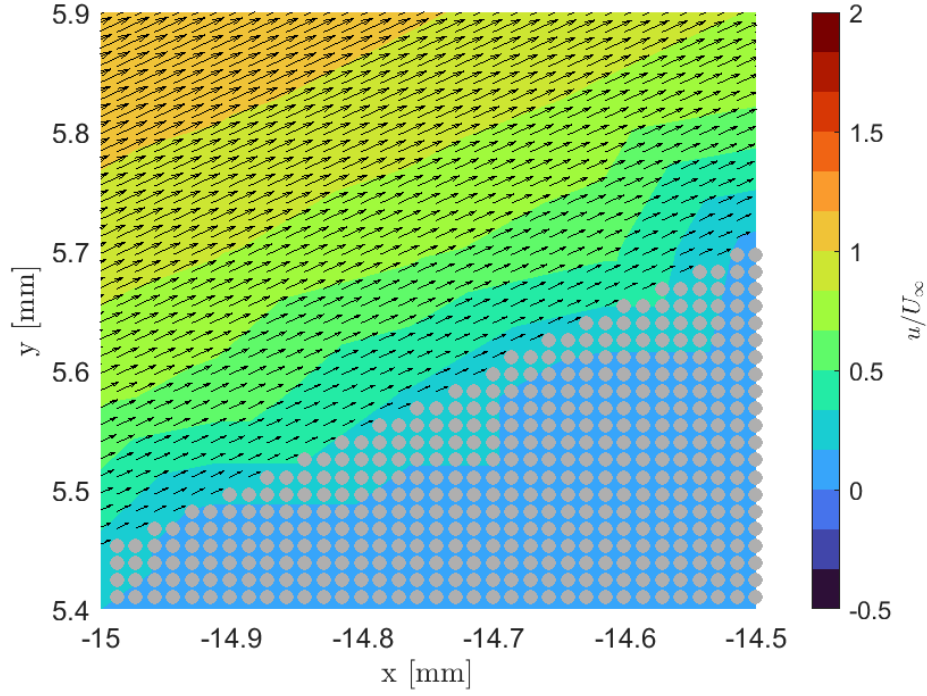
It can be observed that, as the Reynolds number increases, the separation point moves slightly upstream. The exact values of the separation angle are shown in Table 5.1.

**Table 5.1:** Separation point angle  $\theta$  values for bare cylinder at  $Re = [3.1, 6.2, 9.3, 12.4] \times 10^4$ .

| $Re \times 10^4 [-]$    | SM  |     |     |      |
|-------------------------|-----|-----|-----|------|
|                         | 3.1 | 6.2 | 9.3 | 12.4 |
| $\theta_{sep} [^\circ]$ | 81  | 80  | 80  | 79   |

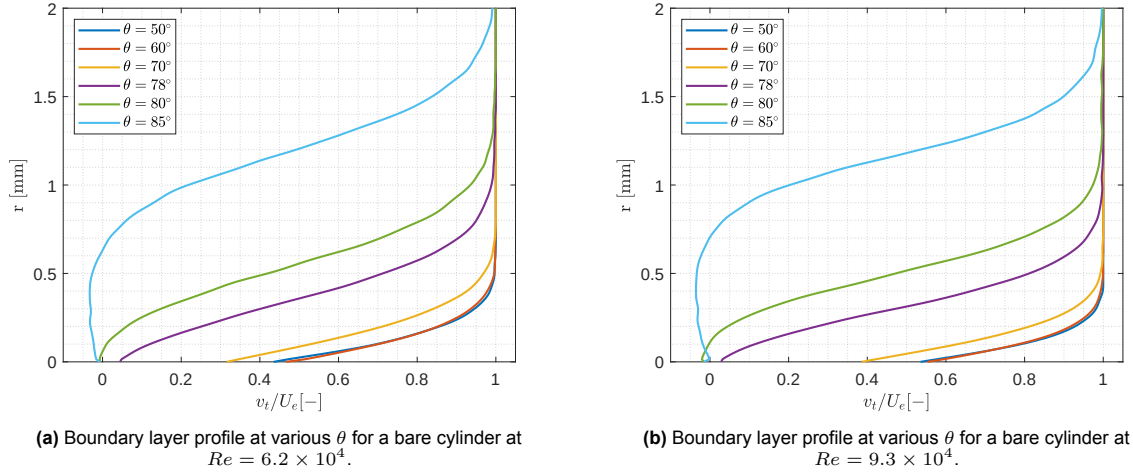
All of these results have been obtained with the PIV measurements of the first setup involving 2 cameras. In order to determine the boundary layer properties with a higher degree of spatial resolution, the results from the second setup have been used, which consists of a single camera and a significantly larger magnification factor. For  $Re = 6.2 \times 10^4$ , and  $Re = 9.3 \times 10^4$  PIV measurements have been performed with the second setup. The normalized velocity field for  $Re = 6.2 \times 10^4$  is shown in Figure 5.5, though with an increased vector spacing for the sake of visibility. A close-up of the velocity field with unitary vector spacing is provided in Figure 5.6, depicting the actual degree of spatial discretization. The normalized velocity field for  $Re = 9.3 \times 10^4$  is not displayed in this section due to its similarity with the velocity field at  $Re = 6.2 \times 10^4$ ; for that reason, the latter is located in the Appendix A.1.1, Figure A.10.

**Figure 5.5:** Close up of normalized velocity field around bare cylinder for  $Re = 6.2 \times 10^4$ .



**Figure 5.6:** Close up of normalized velocity field with unitary vector spacing around bare cylinder for  $Re = 6.2 \times 10^4$ . The gray dots indicate the region where the cylinder is located.

Next, the boundary layer profiles at  $\theta = [50^\circ, 60^\circ, 70^\circ, 78^\circ, 80^\circ, 85^\circ]$  for each of the  $Re$  are computed; these locations are indicated in Figure 5.5 with magenta dots on the cylinder surface.



**Figure 5.7:** Boundary layer profiles plotted vs distance from the cylinder surface,  $r$ , at various  $\theta$  locations for a bare cylinder at  $Re = 6.2 \times 10^4$  and  $Re = 9.3 \times 10^4$ .

Initially, the pressure gradient on the foreside of the cylinder is favorable, until an approximate  $\theta = 65^\circ$  where the suction peak is located, as shown in Figure 5.3. Downstream of  $\theta = 65^\circ$ , the pressure gradient becomes negative, which decreases the near-wall momentum of the boundary layer, ultimately leading to laminar flow separation.

This can be observed in Figure 5.7, for the lower values of  $\theta$ , the boundary layer is fuller and the pressure gradient pushes the boundary layer forward, maintaining the near-wall momentum and creating a very steep velocity profile close to the boundary. Next, once the suction peak is surpassed, the pressure

gradient is now adverse and the wall velocity gradient starts to decrease; this reduces the velocity in the near-wall region, ultimately resulting in flow separation, once the tangential component of the velocity at the wall is null.

Comparatively, at first glance and in qualitative terms, the boundary layer profiles at different Reynolds numbers appear to be almost identical, but once the boundary layer parameters are computed, these paint a full picture.

**Table 5.2:** Bare cylinder boundary layer parameters at  $Re = 6.2 \times 10^4$  and  $Re = 9.3 \times 10^4$  for varying  $\theta$ .

| $\theta$ [°] | $Re = 6.2 \times 10^4$ |                 |                 |         | $Re = 9.3 \times 10^4$ |                 |                 |         |
|--------------|------------------------|-----------------|-----------------|---------|------------------------|-----------------|-----------------|---------|
|              | $\delta_{99}$ [mm]     | $\delta^*$ [mm] | $\delta_m$ [mm] | $H$ [–] | $\delta_{99}$ [mm]     | $\delta^*$ [mm] | $\delta_m$ [mm] | $H$ [–] |
| 50           | 0.43                   | 0.08            | 0.05            | 1.47    | 0.34                   | 0.05            | 0.04            | 1.36    |
| 60           | 0.45                   | 0.08            | 0.05            | 1.42    | 0.37                   | 0.05            | 0.04            | 1.34    |
| 70           | 0.60                   | 0.14            | 0.08            | 1.67    | 0.47                   | 0.10            | 0.06            | 1.56    |
| 78           | 1.01                   | 0.38            | 0.13            | 2.84    | 0.85                   | 0.33            | 0.11            | 3.03    |
| 80           | 1.27                   | 0.57            | 0.15            | 3.92    | 1.13                   | 0.53            | 0.12            | 4.40    |
| 85           | 1.97                   | 1.24            | 0.14            | 8.59    | 1.85                   | 1.21            | 0.11            | 10.71   |

The rapid increase in the shape factor for  $\theta = 80^\circ$  is indicative of flow separation. Additionally, the effect of the favorable pressure gradient is observed on the evolution of all thicknesses. When the pressure gradient is favorable for  $50^\circ \leq \theta \leq 60^\circ$ , the rate of growth of the boundary layer in all terms is considerably lower than for the cases in which the pressure gradient is adverse  $\theta > 65^\circ$ , meaning that an adverse pressure gradient will generally fatten the boundary layer and ultimately cause flow separation.

## 5.2. Double Fabric Configurations

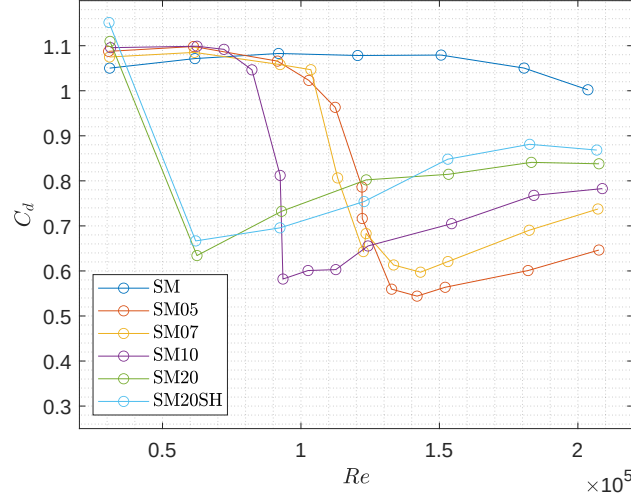
### 5.2.1. Varying Underlayer + Smooth Overlayer

The cylinder was fitted with a combination of two fabrics; the fabric right over the cylinder was each of the four different underlayers with varying rib spacing and height, and over the underlayer, the smooth overlayer was placed. During the experimental campaign, a particular effort had been put into placing the rib of the underlayer right at the stagnation point on the foreside of the cylinder  $\theta = 0^\circ$ . These configurations have been codified as SM05, SM07, SM10 and SM20 based on the rib spacing of the underlayer. Additionally, for the SM20 case, an additional configuration has been tested, in which the fabrics were shifted to exactly place the valley in between two ribs in the front stagnation point, denoted as SM20SH. This was done to determine whether, for larger rib spacings, the drag reduction capabilities of the double layer configurations have significant azimuthal sensitivity.

#### Balance Results

Balance measurements were carried out to determine the drag crisis behavior for each of the double layer configurations. Additionally, the  $Re_{crit}$  and  $C_{d,min}$  are obtained for each of the configurations. The  $C_d - Re$  curves for all the configurations are shown in Figures 5.8 and 5.9.

Figure 5.8 shows a direct comparison of the drag crisis behavior for the double layer configurations and highlights the effect of the underlayer on the crisis location. It can be deduced that with increasing rib spacing, the onset of drag crisis is shifted to lower Reynolds numbers. Similarly, when the critical Reynolds number is shifted to lower values, the minimum drag coefficient rises. This trend is maintained across configurations with the exception of the SM07 case, which presents a significantly higher  $C_{d,min}$  relative to the expected trend. As previously stated, the SM07 case is a bit of a particular case due to the fact that it consists of the 05UL stretched, and as depicted by its height scan, Figure 4.6b. Based on the information provided by the height scan, it could mean that the top fabric is not under the same amount of tension, thus affecting its roughness and causing inconclusive results.



**Figure 5.8:** Comparison between double fabric configuration with the varying underlayer and smooth overlayer.

Table 5.3 compiles the values of  $C_{d,min}$  and  $Re_{crit}$  for each of the configurations.

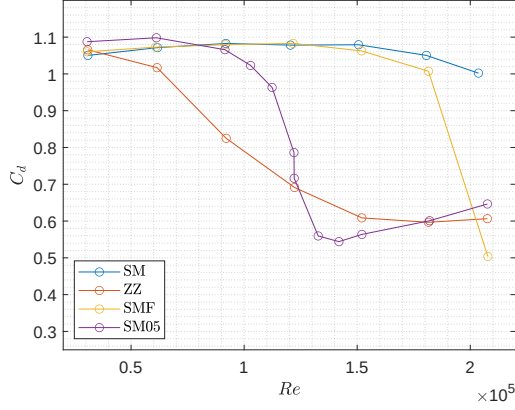
**Table 5.3:**  $C_{d,min}$  and  $Re_{crit}$  values for the double layer smooth overlayer configurations.

|                 | SM05               | SM07               | SM10               | SM20               | SM20SH             |
|-----------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| $C_{d,min} [-]$ | 0.56               | 0.64               | 0.58               | 0.63               | 0.67               |
| $Re_{crit} [-]$ | $13.3 \times 10^4$ | $12.3 \times 10^4$ | $9.35 \times 10^4$ | $6.24 \times 10^4$ | $6.20 \times 10^4$ |

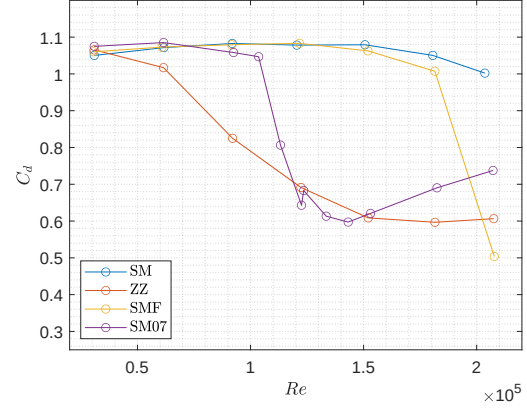
Figure 5.9 shows a comparison for each of the double layer configurations relative to the baseline bare cylinder and a configuration with zig-zag strips on the bare cylinder. Overall, the drag reduction achieved by the double fabric configurations resembles the critical behavior exhibited by bare cylinders and cylinders with superficial roughness. Conversely, for discrete trips such as zig-zag strips, the drag drop is more gradual and over a wide Reynolds range. Additionally, similarly to the bare cylinder baseline, once the large drop in drag coefficient occurs, it tends to rise slightly, as opposed to the supercritical behavior of a cylinder with zig-zag strips.

Figure 5.9d shows the slight differences between the shifted configuration of the same fabric. As it can be seen, it is more desirable for drag reduction purposes for the rib to be located at the stagnation point; this can be interpreted as making the bluff body slightly more streamlined, thus yielding slight aerodynamic improvements, portrayed as a lower drag minimum coefficient. In general terms, double-layer fabric configurations exhibit low sensitivity to azimuthal variations, which is a desirable trait given that it makes their utilization simpler.

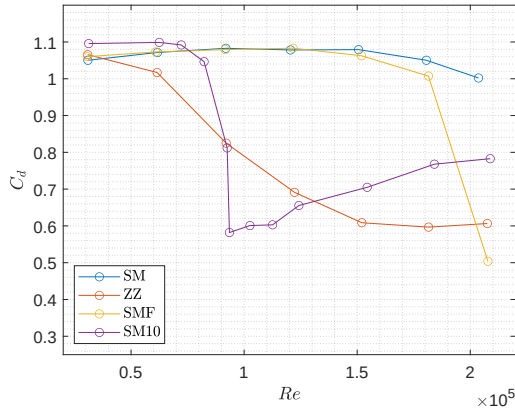
All in all, the balance measurements allow for the choice of which exact configurations to study and the specific velocities using PIV. The PIV results for this configuration are shown in the next section, in addition to the reasoning behind the choice of the particular data points and the respective analysis.



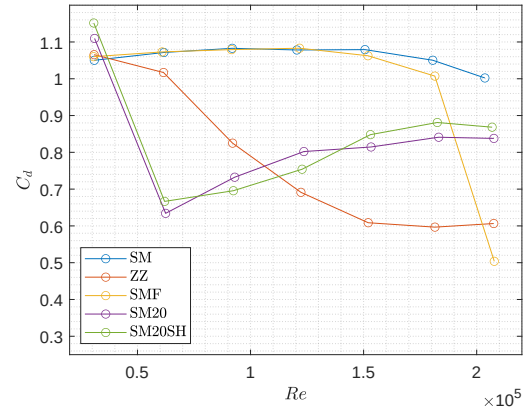
(a) Double fabric configuration with the 5 mm spacing underlayer and the smooth overlayer.



(b) Double fabric configuration with the 7 mm spacing underlayer and the smooth overlayer.



(c) Double fabric configuration with the 10 mm spacing underlayer and the smooth overlayer.



(d) Double fabric configuration with the 20 mm spacing underlayer and the smooth overlayer.

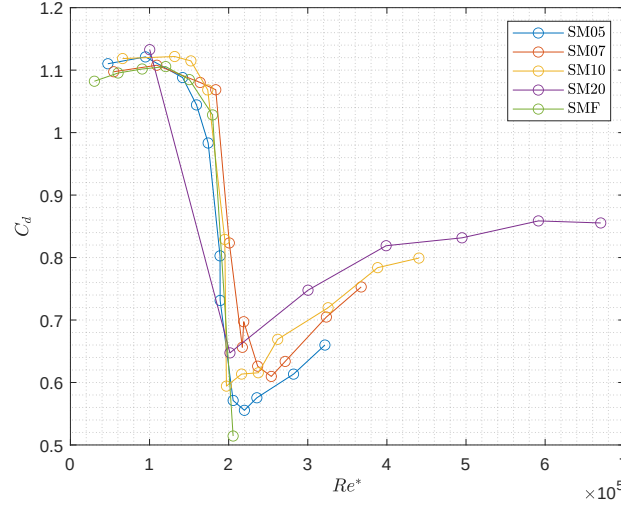
**Figure 5.9:** Double fabric configuration with the varying underlayer and smooth overlayer.

Additionally, given the simple parametrization of the underlayer fabrics displayed in Section 4.1.2 Table 4.1, an attempt to rescale the  $C_d - Re$  curves for all configurations and try to collapse them into a single curve has been made.

As such,  $Re^*$  is first defined, where  $\Delta$  stands for the rib spacing,  $D$  stands for the cylinder diameter, and  $\kappa$  is a fitting constant.

$$Re^* = Re \left( 1 + \kappa \frac{\Delta}{D} \right) \quad (5.1)$$

and for  $\kappa = 10.18$ , the resulting collapsed plot is shown in Figure 5.10. Other attempts with different expressions involving the rib height have been attempted, but this expression that only involves the rib spacing is by far the simplest and the one that yields the best results. Based on this observation, it hints that the rib spacing is far more relevant than rib height when it comes to drag crisis behavior.



**Figure 5.10:** Collapsed  $C_d - Re$  plot for all double layer configuration with smooth overlayer.

### PIV Results

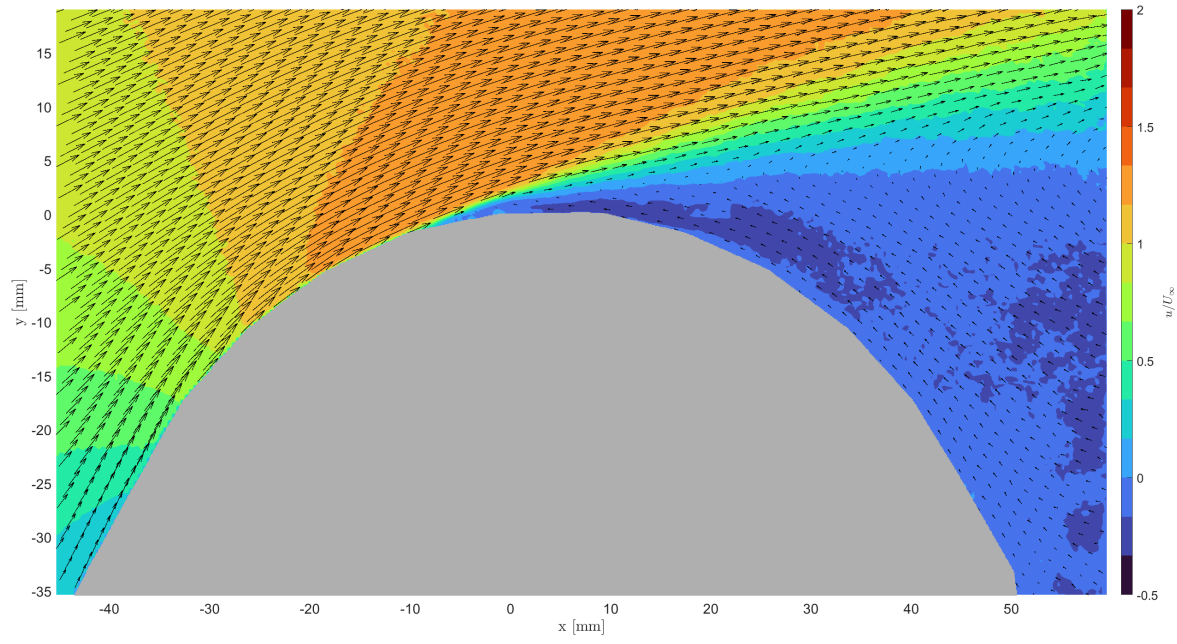
For this set of configurations involving the smooth overlayer and a set of different underlayers, the chosen double fabrics to be studied with PIV are the SM10 and SM20 combinations around the drag crisis location. The two main motives for the choice of these configurations are the fact that a larger rib spacing is desirable for the purposes of better visualization, as a larger rib and rib spacing allow for clearer measurement of the flow around and in between the ribs. For this reason, the SM05 was not considered for PIV measurements. Furthermore, because of the inconsistent drag crisis behavior of SM07, it has also been ruled out of PIV measurements. In the end, the studied configurations have been SM10 at  $Re = [6.2, 7.2, 8.2, 9.3, 10.3, 11.3, 12.4] \times 10^4$  and SM20 at  $Re = [3.1, 6.2] \times 10^4$ .

### SM10 Configuration

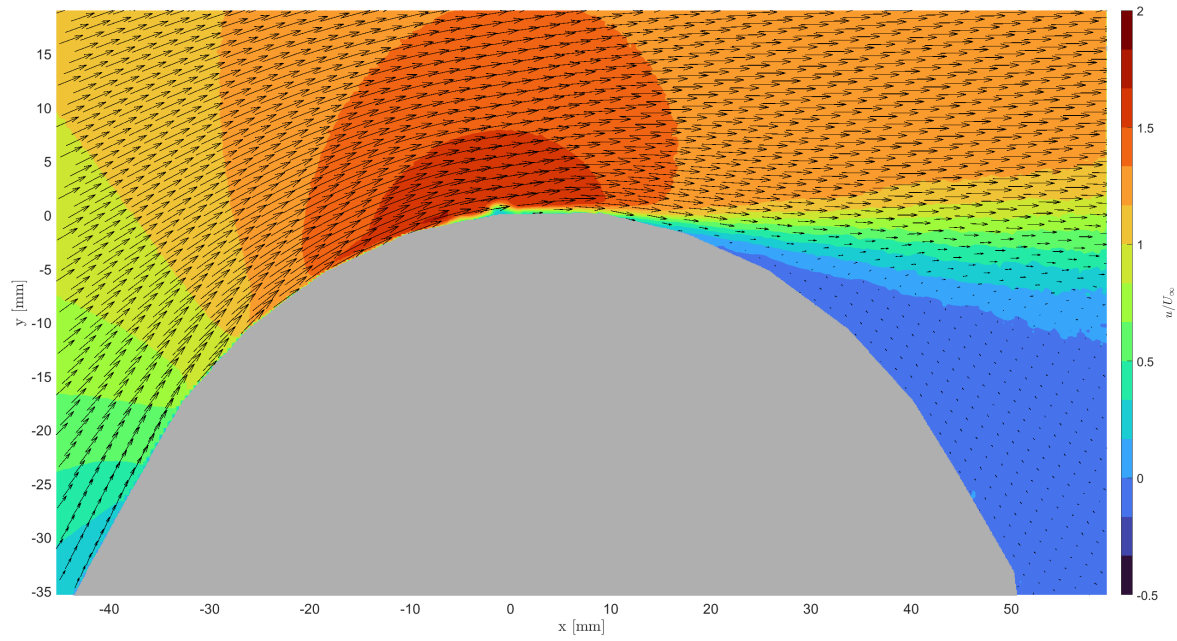
Figure 5.11 shows two time-averaged normalized velocity fields at subcritical and critical flow regimes, respectively. Though the cylinder geometry has been slightly modified relative to the bare cylinder case, the behavior in the subcritical regime still resembles the subcritical behavior portrayed by the bare cylinder. The subcritical case exhibits an early separation with a strong shear layer. On the other hand, Figure 5.11b displays the normalized velocity field at the critical Reynolds number for this configuration. Once the Reynolds number reaches or exceeds the critical value for this configuration, the velocity fields change drastically relative to the subcritical case. When the flow becomes critical and supercritical, the separation point is shifted downstream, meaning that the flow remains attached for longer. This results in a region of fast-flowing air at  $\theta = 90^\circ$ , this fast-flowing air is accompanied by a reduced static pressure at the location, depicted by the pressure coefficient fields shown in Figure 5.12, Figure 5.12b particularly.

Note that for the flow in critical and supercritical states, there appears to be a slight deceleration of the air at  $\theta = 90^\circ$  near the cylinder, displayed in Figure 5.13, resulting in a region of slow-moving air. However, by closely examining the raw PIV image sets, the deceleration appears not to be a physical slowdown of the flow, but rather to result from a reflection of a strand of fabric that leads to inaccurate velocity computation. Furthermore, due to the inaccurate fabric velocity computation, the Davis Poisson solver struggles to resolve the pressure properly, which leads to an inaccuracy in the pressure field as well.





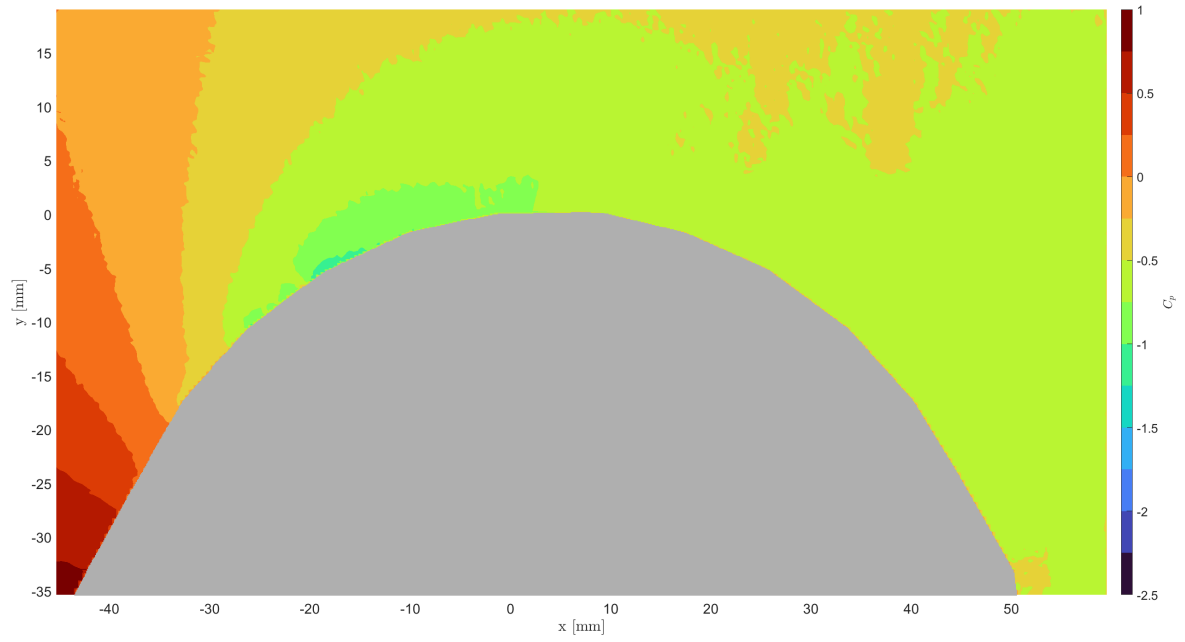
(a) normalized velocity field around double layer cylinder with 10UL underlayer and smooth overlayer at  $Re = 8.2 \times 10^4$ .



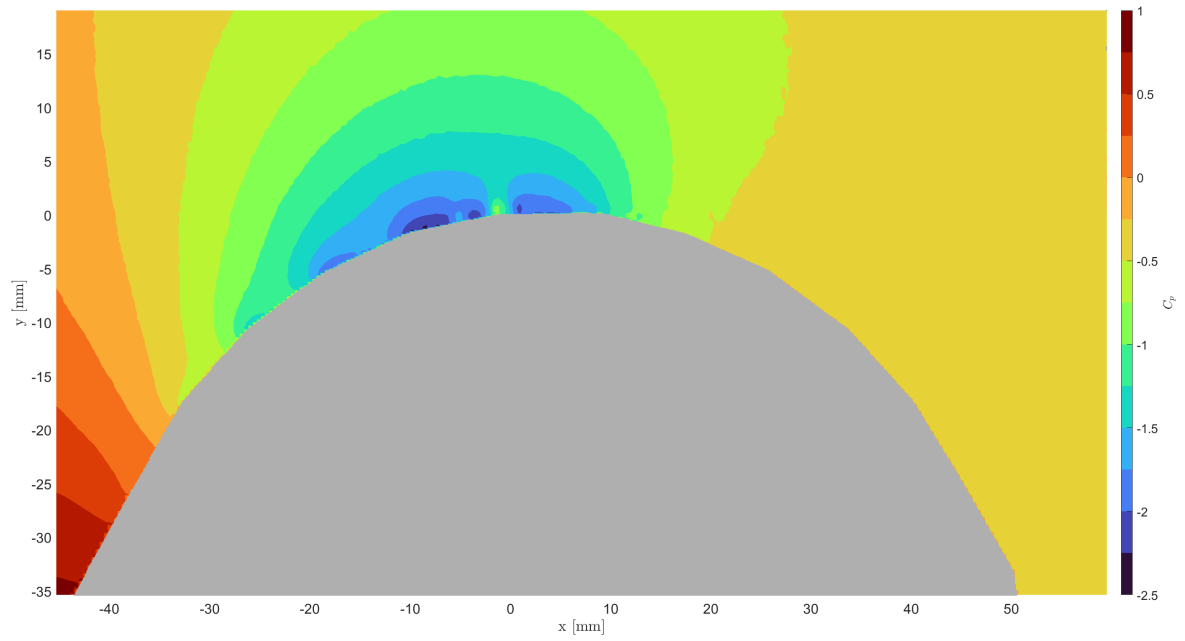
(b) normalized velocity field around double layer cylinder with 10UL underlayer and smooth overlayer at  $Re = 9.3 \times 10^4$ .

**Figure 5.11:** normalized velocity field around double layer cylinder with 10UL underlayer and smooth overlayer at  $Re = 8.2 \times 10^4$  and  $Re = 9.3 \times 10^4$ .



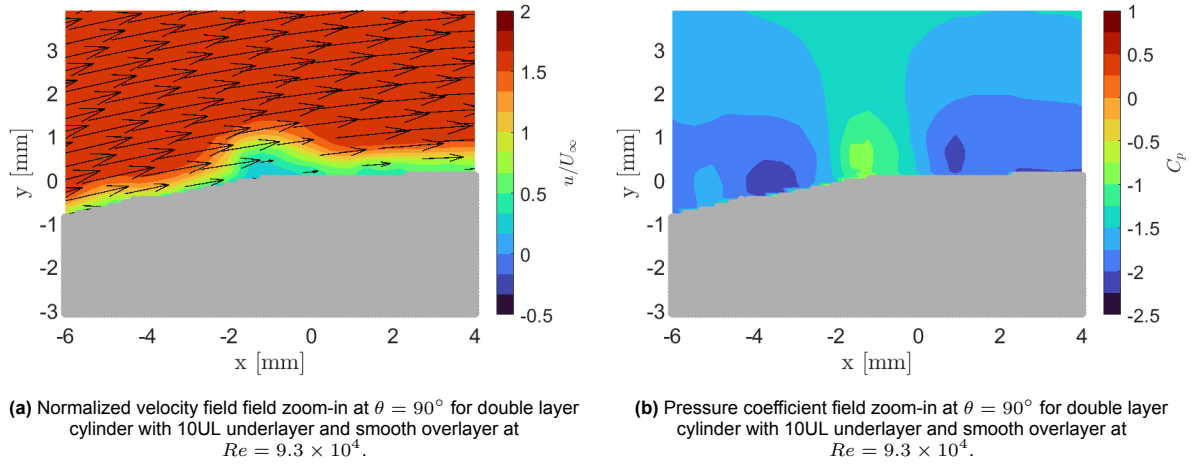


(a) Pressure coefficient field around double layer cylinder with 10UL underlayer and smooth overlayer at  $Re = 8.2 \times 10^4$ .



(b) Pressure coefficient field around double layer cylinder with 10UL underlayer and smooth overlayer at  $Re = 9.3 \times 10^4$ .

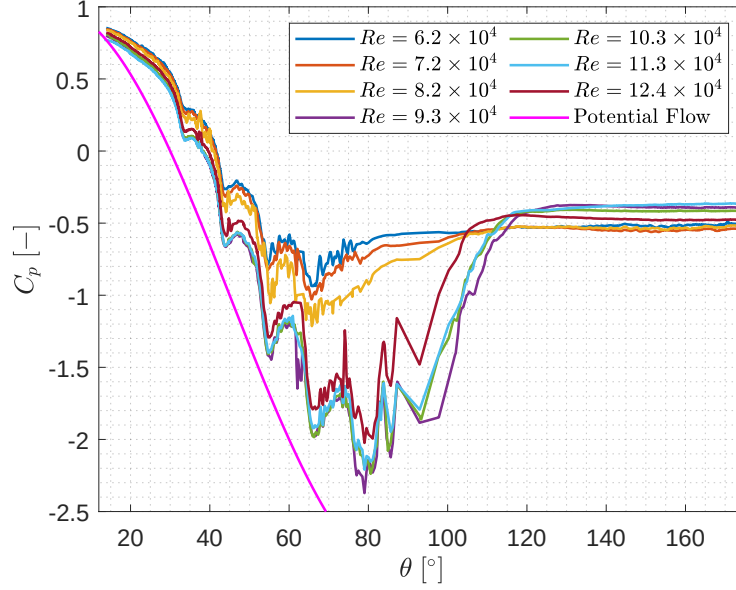
**Figure 5.12:** Pressure coefficient field around double layer cylinder with 10UL underlayer and smooth overlayer at  $Re = 8.2 \times 10^4$  and  $Re = 9.3 \times 10^4$ .



**Figure 5.13:** Normalized velocity and pressure coefficient field zoom-ins at  $\theta = 90^\circ$  for double layer cylinder with 10UL underlayer and smooth overlayer at  $Re = 9.3 \times 10^4$ .

Additionally, the pressure coefficient over the surface of the cylinder with this fabric configuration has been computed and shown in Figure 5.14. It can be seen that the pressure distribution over the cylinder exhibits clear differences relative to the bare cylinder case. These findings are consistent with the pressure distributions over a grooved cylinder obtained by Yamagishi, Y. and Oki, M [38]. The oscillations on the foreside of the cylinder are a result of the flow experiencing a small acceleration as it flows over a rib. Similarly, due to the increase in flow speed, relative to the bare cylinder, there is a small matching drop in static pressure. This results in a set of localized favorable and adverse pressure gradients over the surface of the cylinder. For this reason, throughout the foreside of the cylinder, the pressure gradient will exhibit a more dynamic behavior. This, in turn, will have an effect on the development of the boundary layer, discussed later in this section. Additionally, the pressure spike around  $\theta = 90^\circ$  can also be observed, and as previously stated, the partial separation is avoided by interaction with the outer flow. Additionally, this interaction injects momentum in the near-wall flow resulting in a pressure drop at the surface of the cylinder.

Overall, the suction peak for the critical and supercritical cases appears to be the same, but there is a slight difference in terms of the pressure recovery. For the critical case,  $Re = 9.3 \times 10^4$ , it can be seen that the suction peak range covers a slightly larger range of  $\theta$ , offsetting the pressure recovery along the backside of the cylinder by a few degrees, resulting in a slightly lower pressure behind the cylinder.

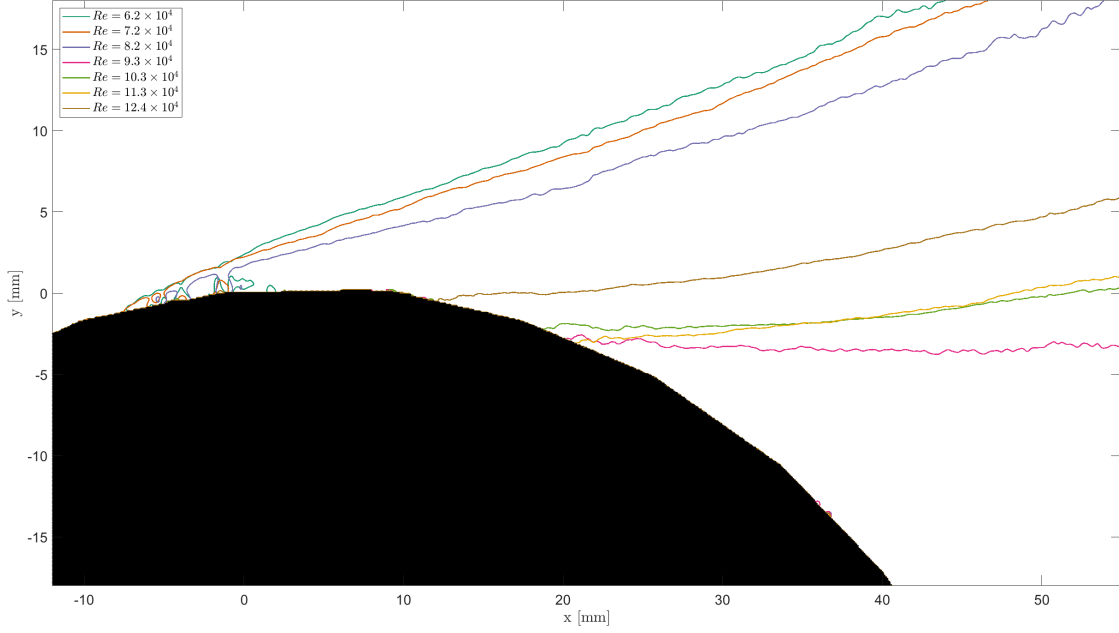


**Figure 5.14:** Pressure coefficient over double layer cylinder with 10UL underlayer and smooth overlayer vs  $\theta$  for  $Re = [6.2, 7.2, 8.2, 9.3, 10.3, 11.3, 12.4] \times 10^4$ .

All the normalized velocity fields measured with PIV for the SM10 configuration are not displayed in this section and have been moved to the Appendix A.1.2. Conversely, for a clear visualization of the changes in wake width for varying Reynolds numbers, the streamline passing through the separation point is shown in Figure 5.15, and the separation angle is compiled in Table 5.4. As it can be observed, in the subcritical regime, increasing the Reynolds number results in a slight reduction in the separation angle. Because of this reduction, a small reduction in the drag coefficient is experienced, as shown in Figure 5.9c; right before the large drop.

Further increases in the Reynolds number result in the flow entering the critical state. One characteristic of critical flow is a large drop in the drag coefficient as well as the displacement of the separation point to its farthest location downstream. From this point onward, increases in the Reynolds number will yield an increase in the drag coefficient. One interesting phenomenon is occurring in the supercritical regime, which is the fact that the separation point moves upstream at first with an increase in Reynolds number  $Re = (9.3 \rightarrow 10.3) \times 10^4$ , from  $\theta = 117^\circ \rightarrow 114^\circ$ . Then, for another increase in Reynolds number,  $Re = (10.3 \rightarrow 11.3) \times 10^4$ , the separation angle moves downstream again  $\theta = 114^\circ \rightarrow 117^\circ$ , though the drag coefficient appears to be the same for these two Reynolds numbers,  $Re = [10.3, 11.3] \times 10^4$ ,  $C_d = 0.6$ . Additionally, examining Figure 5.15, it can be seen that although the separation point of the flow for  $Re = 11.3 \times 10^4$  matches the separation location for the critical state, the width of the wake rapidly grows to match the wake width for  $Re = 10.3 \times 10^4$ .

All in all, with all of these results from the surface pressure coefficient and the separation point, one would expect the contribution to the drag coming from the pressure components for the case of  $Re = 11.3 \times 10^4$  to be lower than the one for the critical case. Given that the separation location is the same for  $Re = 11.3 \times 10^4$  and the critical case,  $Re = 9.3 \times 10^4$ ; and the fact that for  $Re = 11.3 \times 10^4$  there appears to be a slightly higher pressure in the backside of the cylinder.



**Figure 5.15:** Streamline  $\psi = 0$  for double layer cylinder with 10UL underlayer and smooth overlayer at  $Re = [6.2, 7.2, 8.2, 9.3, 10.3, 11.3, 12.4] \times 10^4$ .

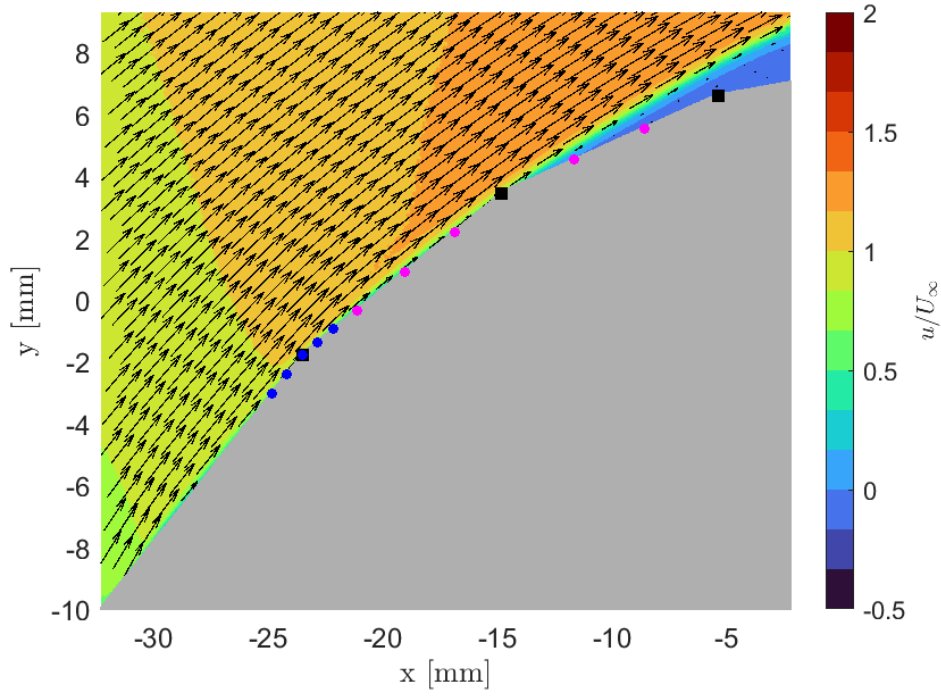
**Table 5.4:** Separation point angle  $\theta$  values for double-layer cylinder with 10UL underlayer and smooth overlayer at  $Re = [6.2, 7.2, 8.2, 9.3, 10.3, 11.3, 12.4] \times 10^4$ .

|                         | SM10 |     |     |     |      |      |      |
|-------------------------|------|-----|-----|-----|------|------|------|
| $Re \times 10^4 [-]$    | 6.2  | 7.2 | 8.2 | 9.3 | 10.3 | 11.3 | 12.4 |
| $\theta_{sep} [^\circ]$ | 80   | 80  | 81  | 117 | 114  | 117  | 105  |

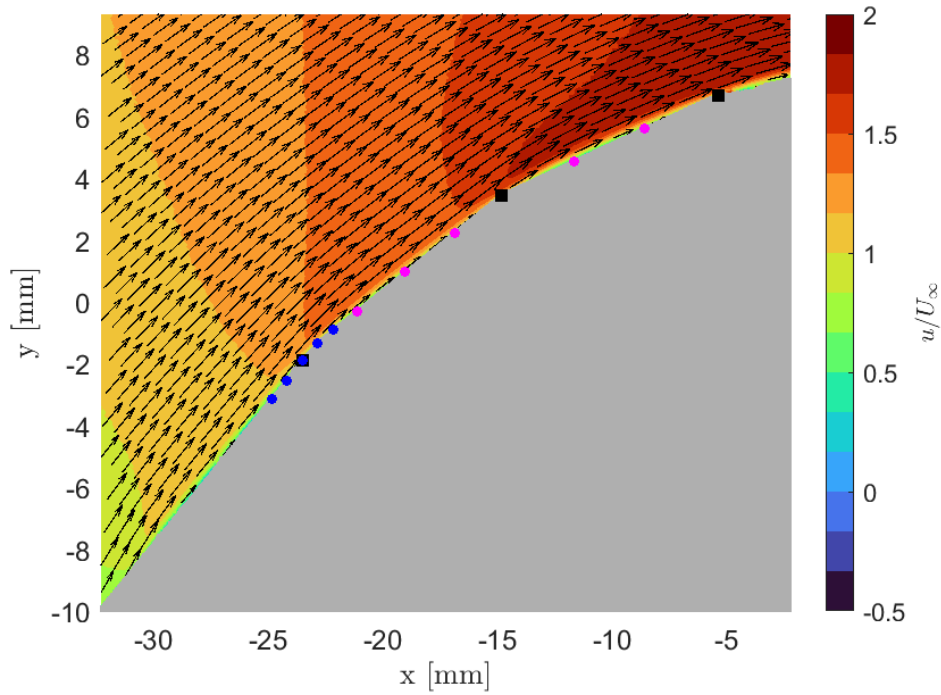
Next, the second PIV setup was used to capture a close-up of the flow around the cylinder's foreside, at  $Re = [7.2, 8.2, 9.3, 10.3] \times 10^4$ . Figures 5.16 and 5.17 show two normalized velocity fields for subcritical and critical Reynolds numbers  $Re = 8.2 \times 10^4$  and  $Re = 9.3 \times 10^4$ , respectively. The other two velocity fields are not displayed in this section and have been moved to the Appendix A.1.2.

Examining Figure 5.17, the lines from the velocity levels curve slightly towards the locations of the ribs. This indicates that the ribs are locations along the foreside of the cylinder that experience a localized acceleration of the flow. This is supported by the pressure distribution along the front of the cylinder as well, depicted by the oscillations of the pressure coefficient.

Similar to previous configurations, the cylinder has been probed and the boundary layer profiles for the normalized streamwise velocity components have been computed at specific locations along its surface. These locations are  $\theta = [62^\circ, 65^\circ, 68^\circ, 75^\circ, 79^\circ]$ , indicated by magenta markers in Figures 5.16 and 5.17. Similarly, the locations of the fabric ribs are indicated with a black square marker. Additionally, the boundary layer has been probed around a rib to determine what influence it plays in the development of the boundary layer; these locations are indicated with blue markers:  $\theta = [56.5^\circ, 57.5^\circ, 58.5^\circ, 59.5^\circ, 60.5^\circ]$ . Out of all of these probes,  $\theta = [56.5^\circ, 57.5^\circ]$  are locations upstream of the rib, and  $\theta = [59.5^\circ, 60.5^\circ]$  are locations downstream of the rib, with  $\theta = 58.5^\circ$  being a probe on the exact location on top of the rib; therefore, the blue boundary layer probe marker and the black marker of the rib are stacked on top of each other.



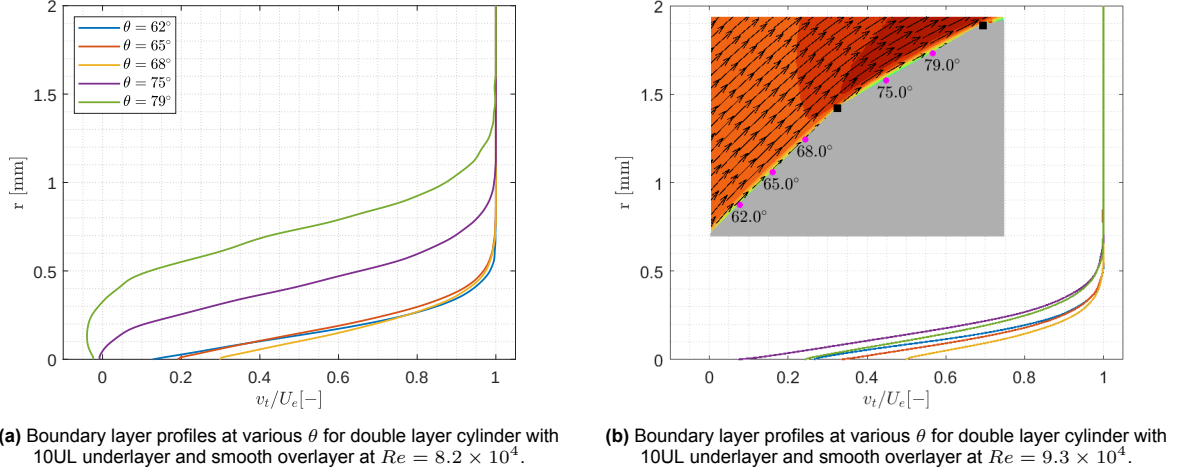
**Figure 5.16:** Close up of normalized velocity field around double layer cylinder with 10UL underlayer and smooth overlayer at  $Re = 8.2 \times 10^4$ .



**Figure 5.17:** Close up of normalized velocity field around double layer cylinder with 10UL underlayer and smooth overlayer at  $Re = 9.3 \times 10^4$ .

The boundary layer profiles over the surface of the cylinder (magenta markers) have been computed and are shown in Figure 5.18. Additionally, an inset plot is shown in Figure 5.18b to illustrate the location of the boundary layer probes. Note, that the legend of Figure 5.18a applies to Figure 5.18b

as well. Furthermore, the boundary layer parameters have been computed in these locations and are shown in Table 5.5.



**Figure 5.18:** Boundary layer profiles at various  $\theta$ , corresponding to the locations of the magenta markers in Figures 5.16 and 5.17, for double layer cylinder with 10UL underlayer and smooth overlayer at  $Re = 8.2 \times 10^4$  and  $Re = 9.3 \times 10^4$ .

**Table 5.5:** Boundary layer parameters for cylinder with the 10UL underlayer and smooth overlayer at  $Re = 8.2 \times 10^4$  and  $Re = 9.3 \times 10^4$  for increasing  $\theta$ , locations indicated by the magenta markers in Figures 5.16 and 5.17.

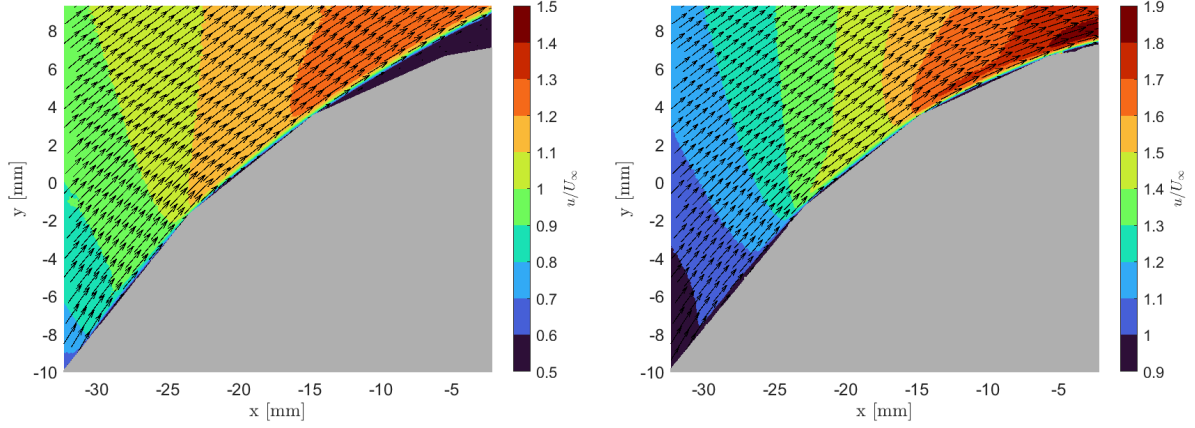
| $\theta$ [°] | $Re = 8.2 \times 10^4$ |                 |                 |         | $Re = 9.3 \times 10^4$ |                 |                 |         |
|--------------|------------------------|-----------------|-----------------|---------|------------------------|-----------------|-----------------|---------|
|              | $\delta_{99}$ [mm]     | $\delta^*$ [mm] | $\delta_m$ [mm] | $H$ [–] | $\delta_{99}$ [mm]     | $\delta^*$ [mm] | $\delta_m$ [mm] | $H$ [–] |
| 62           | 0.52                   | 0.16            | 0.07            | 2.15    | 0.42                   | 0.11            | 0.06            | 1.85    |
| 65           | 0.60                   | 0.17            | 0.08            | 2.04    | 0.44                   | 0.09            | 0.06            | 1.63    |
| 68           | 0.59                   | 0.14            | 0.08            | 1.76    | 0.42                   | 0.07            | 0.05            | 1.43    |
| 75           | 0.94                   | 0.43            | 0.11            | 3.92    | 0.55                   | 0.16            | 0.07            | 2.23    |
| 79           | 1.31                   | 0.76            | 0.11            | 6.75    | 0.54                   | 0.14            | 0.07            | 1.86    |

The general trend observed of the velocity profiles maintaining the steepness in locations before the separation point is maintained despite the oscillations of the pressure coefficient on the foreside of the cylinder. Then, once the separation point is reached, the boundary layer thickness parameters exhibit a rapid growth. Note that the separation point appears to slightly differ from the value obtained from the first setup ( $\theta_{sep} = 81^\circ$ ), in this case it appears that the separation point is closer to  $\theta = 77^\circ - 78^\circ$ . This discrepancy is likely due to the errors in the cylinder positioning from changing the setup. Furthermore, for the critical case, given the change in pressure distribution and a larger range of  $\theta$  on the foreside of the cylinder being exposed to a favorable pressure gradient, the boundary layer profiles are steep throughout all the probing locations.

Additionally, three separate probes have been placed in the same segment between two subsequent ribs,  $\theta = [62^\circ, 65^\circ, 68^\circ]$ . This allows studying the boundary layer development in between two ribs. As previously described, the air that flows over a rib experiences a small acceleration right before the rib and a slight deceleration after the rib. This implies that the air that has just flowed past a rib is moving slightly slower due to the geometric effect of the rib, in addition to it being slightly more prone to separation due to localized expansion. Conversely, as the air keeps flowing along the segment, the overall favorable pressure gradient on the foreside of the cylinder reverts the proneness to separation of the boundary layer by steepening the velocity profile. This is confirmed by the velocity profile at  $\theta = 68^\circ$  being steeper and fuller near the wall than at  $\theta = [62^\circ, 65^\circ]$ . Additionally, the shape factor gives an additional indication, as it peaks for  $\theta = 62^\circ$  and it diminishes along the segment.

Furthermore, another interesting observation is the fact that thickness parameters are the highest at the midpoint of the segment; this implies that the boundary layer height varies along the length of the

segment, with its peak located close to the segment midpoint. Ultimately, this results in the outer flow perceiving the cylinder as "slightly more rounded", as the width of the shear layer compensates for the geometric effect caused by the presence of the ribs. This effect can be more easily visualized by adjusting the colorbar limits and levels in the normalized velocity fields, as seen in Figure 5.19, note that the colorbar limits are not the same on the two fields shown:

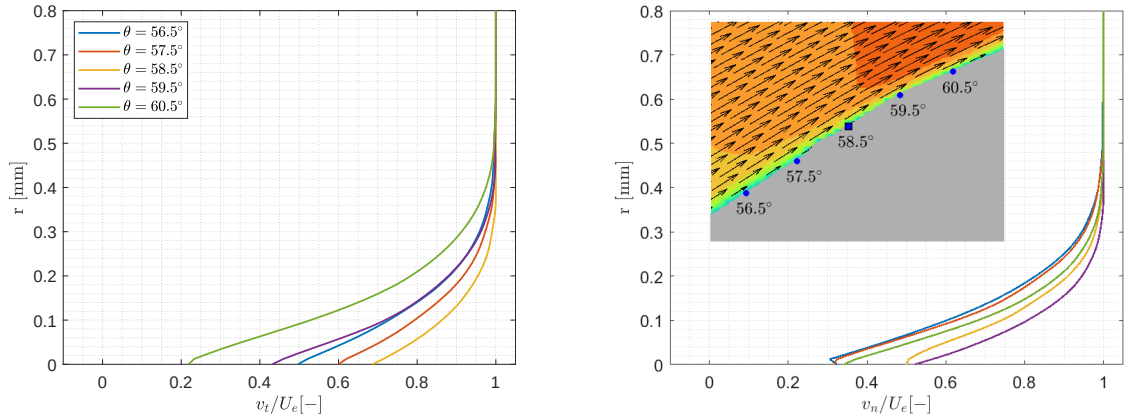


(a) Close up of normalized velocity field around double layer cylinder with 10UL underlayer and smooth overlayer at  $Re = 8.2 \times 10^4$ .

(b) Close up of normalized velocity field around double layer cylinder with 10UL underlayer and smooth overlayer at  $Re = 9.3 \times 10^4$ .

**Figure 5.19:** Close up of normalized velocity field with an adjusted colorbar around double layer cylinder with 10UL underlayer and smooth overlayer at  $Re = 8.2 \times 10^4$  and  $Re = 9.3 \times 10^4$ .

Next, the boundary layer profiles in locations near a rib (blue markers in Figures 5.16 and 5.17) have been computed and are shown in Figure 5.20. Note that the scale of the vertical axis is different from the one used for previous plots; this has been modified to make visualization clearer. Similarly, an inset plot is shown in Figure 5.20b to illustrate the location of the rib boundary layer probes. Note, that the legend of Figure 5.20a applies to Figure 5.20b as well. Similarly, the corresponding boundary layer parameters have been computed and are shown in Table 5.6.



(a) Boundary layer profiles around a rib for double layer cylinder with 10UL underlayer and smooth overlayer at  $Re = 8.2 \times 10^4$ .

(b) Boundary layer profiles around a rib for double layer cylinder with 10UL underlayer and smooth overlayer at  $Re = 9.3 \times 10^4$ .

**Figure 5.20:** Boundary layer profiles at various  $\theta$  around a rib with the 10UL underlayer and smooth overlayer at  $Re = 8.2 \times 10^4$  and  $Re = 9.3 \times 10^4$ .



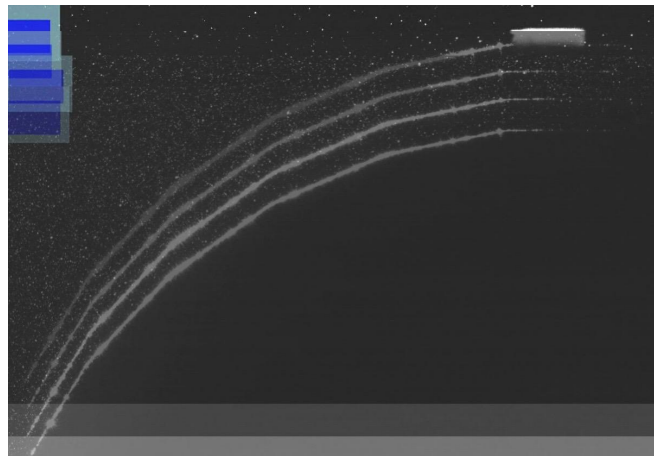
**Table 5.6:** Boundary layer parameters near the rib for cylinder with the 10UL underlayer and smooth overlayer at  $Re = 8.2 \times 10^4$  and  $Re = 9.3 \times 10^4$  for increasing  $\theta$  around a rib.

| $\theta$ [°] | $Re = 8.2 \times 10^4$ |                 |                 |         | $Re = 9.3 \times 10^4$ |                 |                 |         |
|--------------|------------------------|-----------------|-----------------|---------|------------------------|-----------------|-----------------|---------|
|              | $\delta_{99}$ [mm]     | $\delta^*$ [mm] | $\delta_m$ [mm] | $H$ [–] | $\delta_{99}$ [mm]     | $\delta^*$ [mm] | $\delta_m$ [mm] | $H$ [–] |
| 56.5         | 0.41                   | 0.07            | 0.05            | 1.41    | 0.42                   | 0.10            | 0.06            | 1.73    |
| 57.5         | 0.36                   | 0.05            | 0.04            | 1.30    | 0.42                   | 0.09            | 0.05            | 1.71    |
| 58.5         | 0.30                   | 0.03            | 0.03            | 1.22    | 0.34                   | 0.06            | 0.04            | 1.46    |
| 59.5         | 0.38                   | 0.07            | 0.05            | 1.49    | 0.30                   | 0.05            | 0.03            | 1.37    |
| 60.5         | 0.45                   | 0.12            | 0.06            | 1.90    | 0.36                   | 0.08            | 0.05            | 1.64    |

Analyzing the boundary layer profiles, there is a clear evolution of the velocity profile as the air flows over the rib. Taking  $\theta = 56.5^\circ$  as the initial profile, the subsequent probes exhibit a fuller velocity profile; this effect is due to the favorable pressure gradient before and at the location of the rib. Then, for the probes further downstream, the velocity profiles start losing fullness and steepness near the wall; this is due to the localized adverse pressure gradient after the rib. One clear difference between the subcritical and critical cases is the fact that for the subcritical case, the fullest and steepest velocity profile is located right at the rib  $\theta = 58.5^\circ$ , whereas for the critical case, the fullest profile is located at one probe downstream of the rib,  $\theta = 59.5^\circ$ . In terms of the boundary layer parameters, it can be observed that the location with the fullest boundary layer profile matches with the location with the lowest shape factor.

Additionally, regarding the formulated research questions, the question of whether fabric deformation is significant and whether it has an aerodynamic effect had been posed in Section 2.4. In order to determine if the fabrics undergo any type of deformation under the action of the airflow, snapshots of the raw data have been acquired at rest and at three different velocities. These pictures are compared by altering their transparency, overlaying them on top of one another, and vertically shifting so that each measured velocity can be discerned, shown in Figure 5.21. By doing this, the contour of the laser reflections on the fabric can be compared across different velocities. Figure 5.21 shows the four fabric contours:

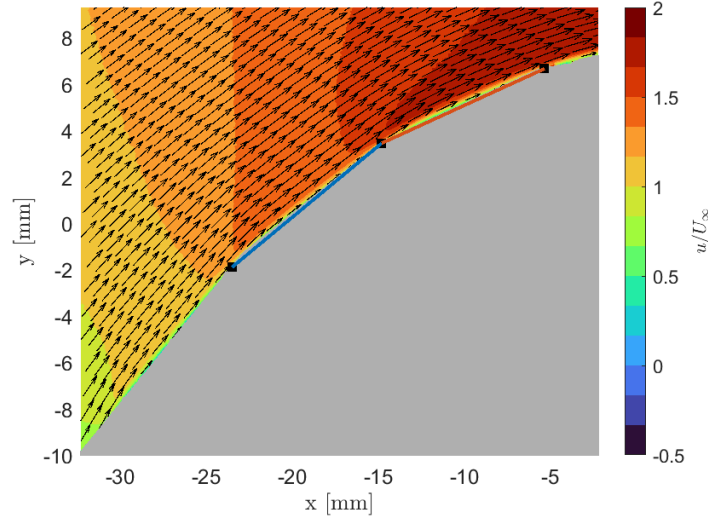
1. The top most fabric contour corresponds an airspeed of 0 m/s, the object present on the surface of the cylinder is a marker to denote the location of  $\theta = 90^\circ$ , not relevant for this comparison.
2. The second contour from the top corresponds to an airspeed of 10 m/s or a Reynolds of  $Re = 6.2 \times 10^4$ , subcritical regime for this configuration.
3. The third contour from the top corresponds to an airspeed of 15 m/s or a Reynolds of  $Re = 9.3 \times 10^4$ , critical regime for this configuration.
4. The bottom most contour corresponds to an airspeed of 20 m/s or a Reynolds of  $Re = 12.4 \times 10^4$ , supercritical regime for this configuration.

**Figure 5.21:** Vertically shifted outlines of the fabric outer contour for the SM10 configuration at different airspeeds.



Observing Figure 5.21, it can be seen that the fabric undergoes no significant deformation to the point that it would cause any alteration to the flow over the cylinder; this behavior is consistent across the subcritical, critical and supercritical regimes. These results were expected given the fact that the fabrics are quite tightly fitted. All in all, it can be concluded that no significant fabric deformation takes place.

Finally, according to the research questions formulated in Section 2.4, the question of whether porosity has any relevant effect in triggering the drag crisis for double-layer fabrics on cylinders had been formulated. In order to answer this question, the wall normal velocity component has been computed over the two surface segments in between the three marked ribs indicated in Figure 5.22:

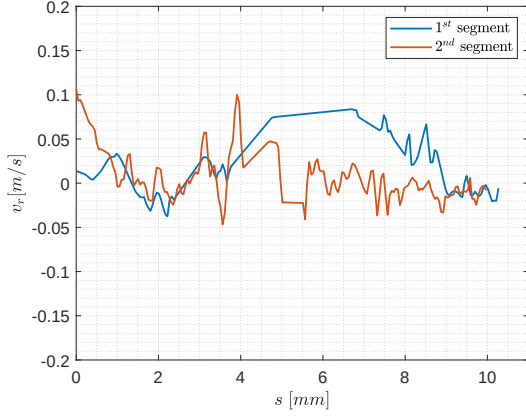


**Figure 5.22:** Locations of the cylinder segments over which the wall normal velocity has been computed for double layer cylinder with 10UL underlayer and smooth overlayer at  $Re = 9.3 \times 10^4$ .

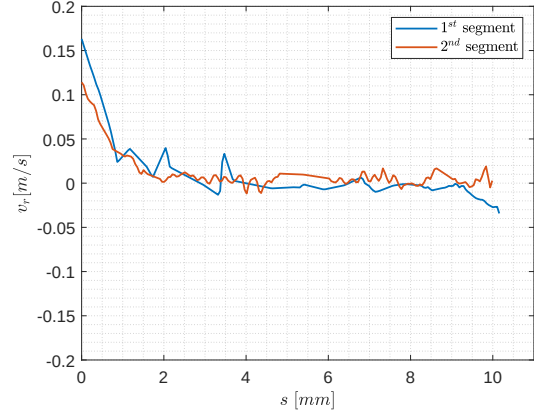
The values of the wall normal velocity component along these two segments have been computed for varying Reynolds numbers and are shown in Figure 5.23. Note that, unlike previous velocity profile computations, these results have not been normalized by any reference velocity, so the magnitudes shown in the  $y$  axis are the actual velocity magnitudes. Furthermore, another consideration is the fact that these velocity profiles are computed assuming that the PIV mask matches the location of the cylinder wall. In practice, there are small differences in the location of the cylinder boundary and the location of the mask, the mask covers a larger region in order to remove the undesirable fabric reflections.

Looking at the wall-normal velocity profiles shown in Figure 5.23, it can be first seen that the velocity magnitudes are overall small  $|v_r| < 0.2 \text{ m/s}$ . The radial velocity distributions appear to be consistent across different Reynolds numbers and segments. Though the velocity profiles appear to exhibit a large amount of uncertainty, this is due to the fact that, given the magnitude of the velocities that are being measured, the incurred error from the measurement techniques used is very significant relative to the velocity magnitude. Additionally, it seems that the measured velocities exhibit large deviations at both ends of the segment. This effect is a combination of the flow deviation due to the effect of the rib and the fact that the cylinder geometry changes due to the presence of the rib, seen in Figure 4.6, and thus the wall-normal and tangential vectors change accordingly. These changes in the cylinder surface are not captured by the mask outline, leading to inaccuracies in the periphery of the ribs.

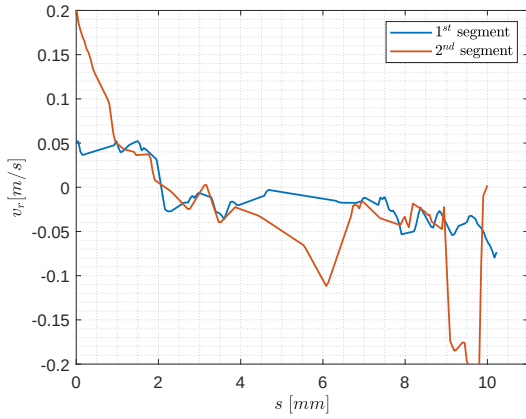
Regarding fabric porosity, findings from Oggiano [28] and Bardal [5] indicate that there is no direct correlation between air permeability and drag in tightly fit garments. All in all, given that the fabrics are tightly fitted and based on the wall-normal velocity distributions, it can be stated that porosity does not play a significant role in the tested configuration.



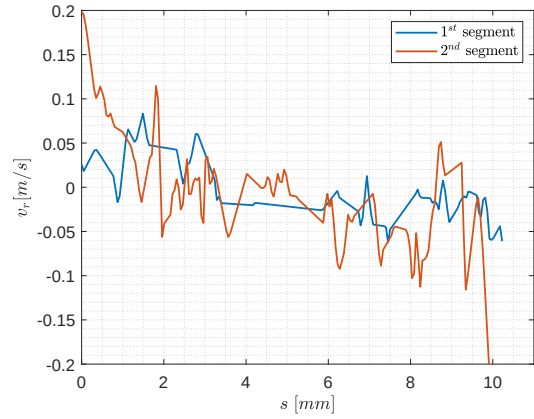
(a) Radial velocity profile over two different segments for double layer cylinder with 10UL underlayer and smooth overlayer at  $Re = 7.2 \times 10^4$ .



(b) Radial velocity profile over two different segments for double layer cylinder with 10UL underlayer and smooth overlayer at  $Re = 8.2 \times 10^4$ .



(c) Radial velocity profile over two different segments for double layer cylinder with 10UL underlayer and smooth overlayer at  $Re = 9.3 \times 10^4$ .



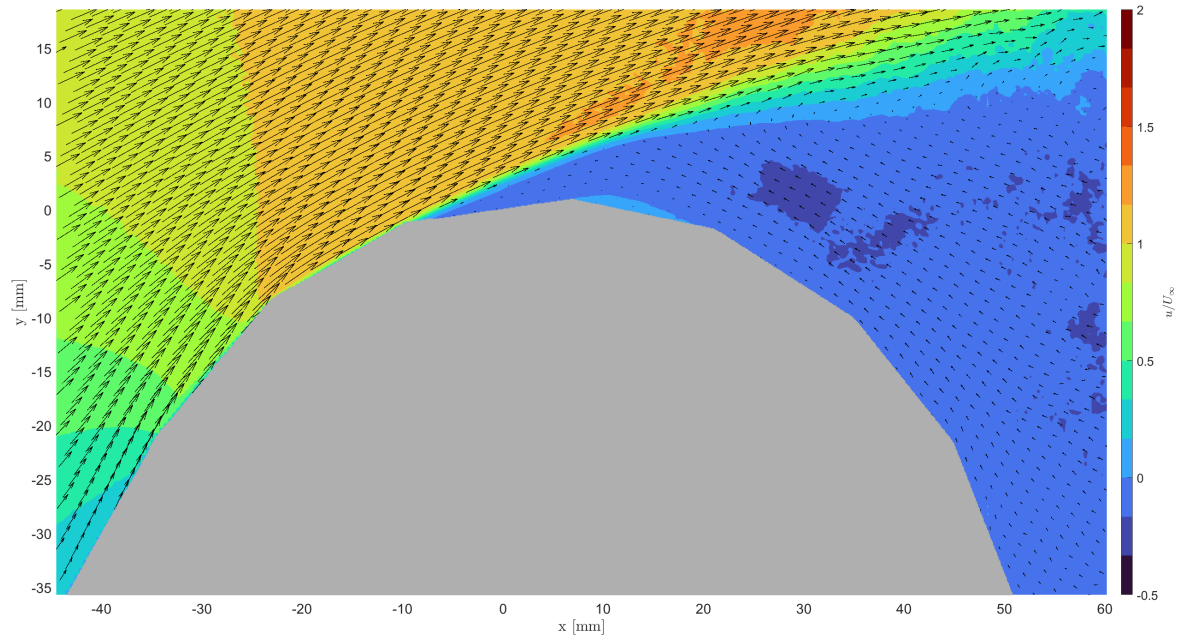
(d) Radial velocity profile over two different segments for double layer cylinder with 10UL underlayer and smooth overlayer at  $Re = 10.3 \times 10^4$ .

**Figure 5.23:** Radial velocity profiles over two different segments for double layer cylinder with 10UL underlayer and smooth overlayer at  $Re = [7.2, 8.2, 9.3, 10.3] \times 10^4$ .

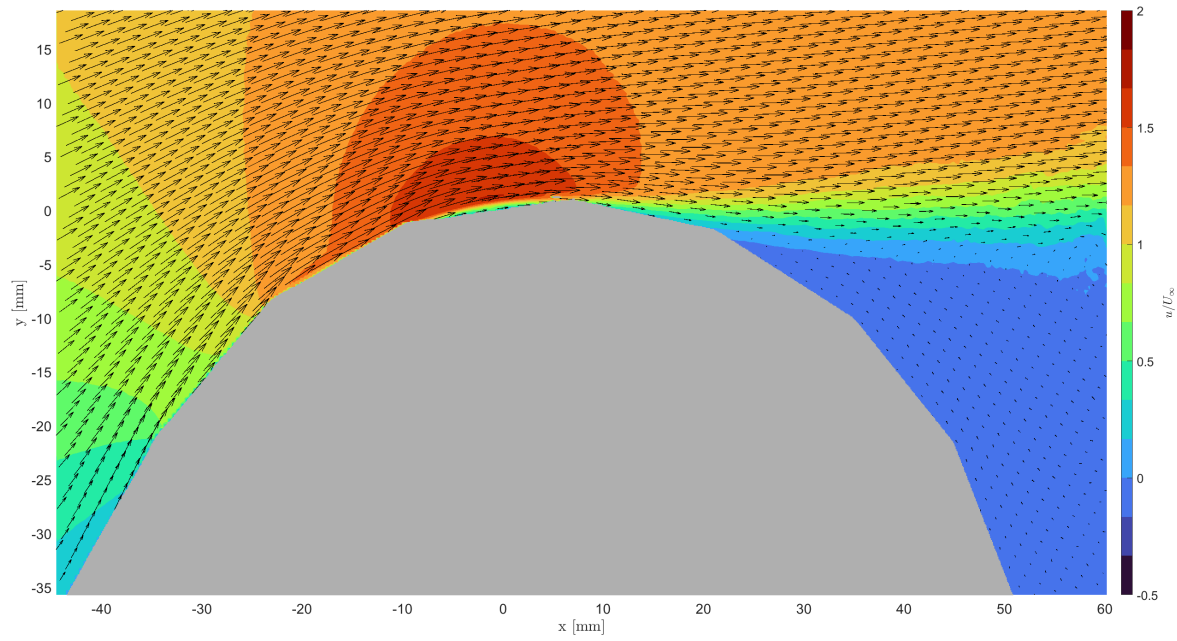
### SM20 Configuration

Figure 5.24 shows two time-averaged normalized velocity fields at subcritical and critical flow states, respectively. Similarly to the SM10 configuration, although the cylinder geometry has changed relative to the bare cylinder, the behavior in the subcritical regime is still similar to the baseline bare cylinder. This is characterized by an early separation, poor pressure recovery along the backside of the cylinder and a strong shear layer emanating from the separation point. On the other hand, Figure 5.24b shows the normalized velocity field at the critical Reynolds number for this configuration. Similar to previous configurations, once the drag crisis is triggered, the velocity fields experience a drastic change. Additionally, as expected, once the drag crisis is triggered, the flow separation point is moved massively downstream.

Figure 5.25 shows the pressure coefficient fields at the same Reynolds number as the aforementioned velocity fields. Similar to previous cases, the pressure distribution once the cylinder experiences the drag crisis changes drastically, resulting in a strong suction peak around  $\theta = 85^\circ - 90^\circ$ .

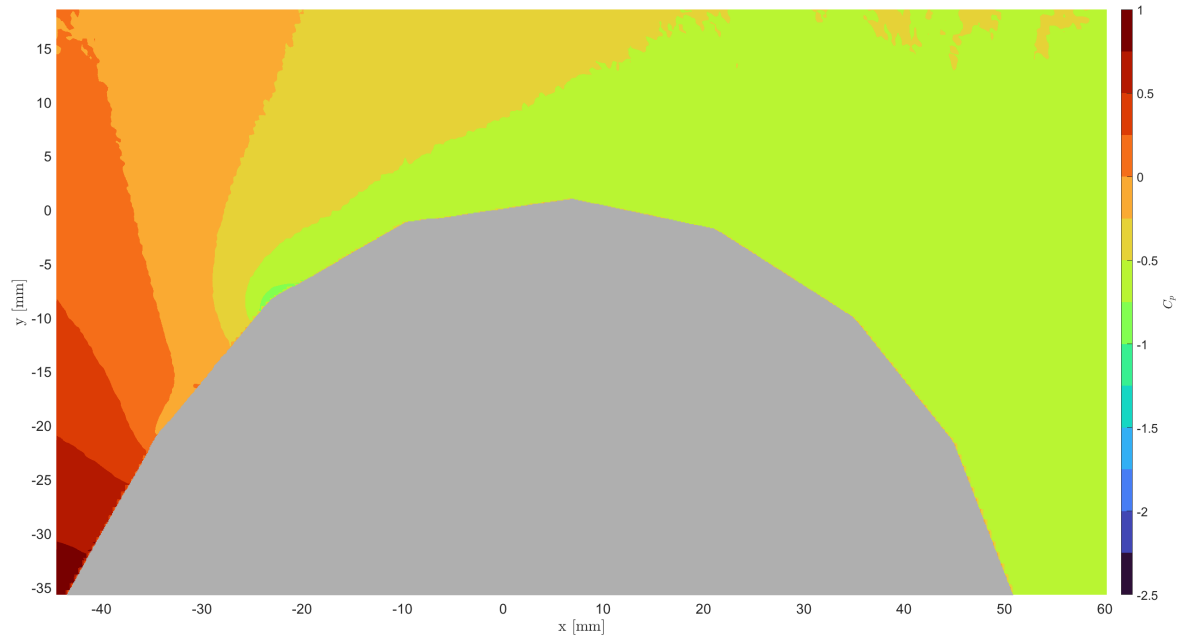


(a) normalized velocity field around double layer cylinder with 20UL underlayer and smooth overlayer at  $Re = 3.1 \times 10^4$ .

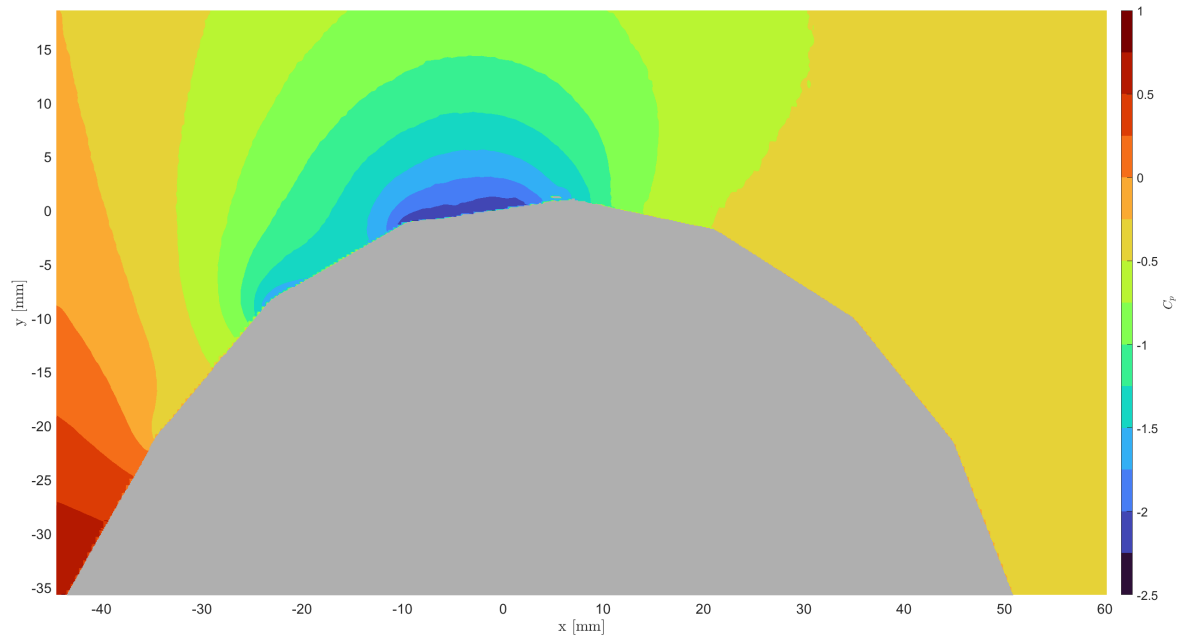


(b) normalized velocity field around double layer cylinder with 20UL underlayer and smooth overlayer at  $Re = 6.2 \times 10^4$ .

**Figure 5.24:** normalized velocity fields around double layer cylinder with 20UL underlayer and smooth overlayer at  $Re = 3.1 \times 10^4$  and  $Re = 6.2 \times 10^4$ .



(a) Pressure coefficient field around double layer cylinder with 20UL underlayer and smooth overlayer at  $Re = 3.1 \times 10^4$ .



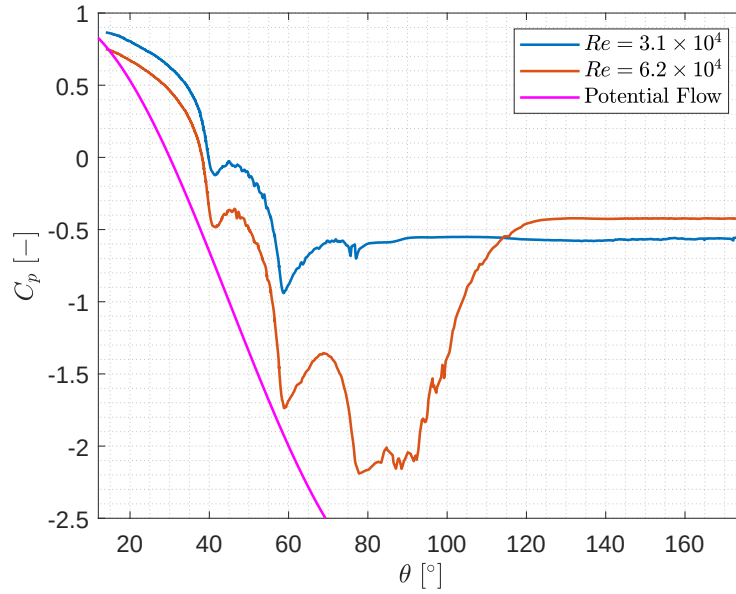
(b) Pressure coefficient field around double layer cylinder with 20UL underlayer and smooth overlayer at  $Re = 6.2 \times 10^4$ .

**Figure 5.25:** Pressure coefficient fields around double layer cylinder with 20UL underlayer and smooth overlayer at  $Re = 3.1 \times 10^4$  and  $Re = 6.2 \times 10^4$ .

Additionally, the pressure coefficient along the surface of the double layer fabric has been computed for this configuration and is shown in Figure 5.26. Similar to the previous double-layer case, the pressure coefficient exhibits oscillations over the foreside of the cylinder due to the presence of the ribs. In this case, as the ribs are spaced further apart, the frequency of the oscillations is lowered.

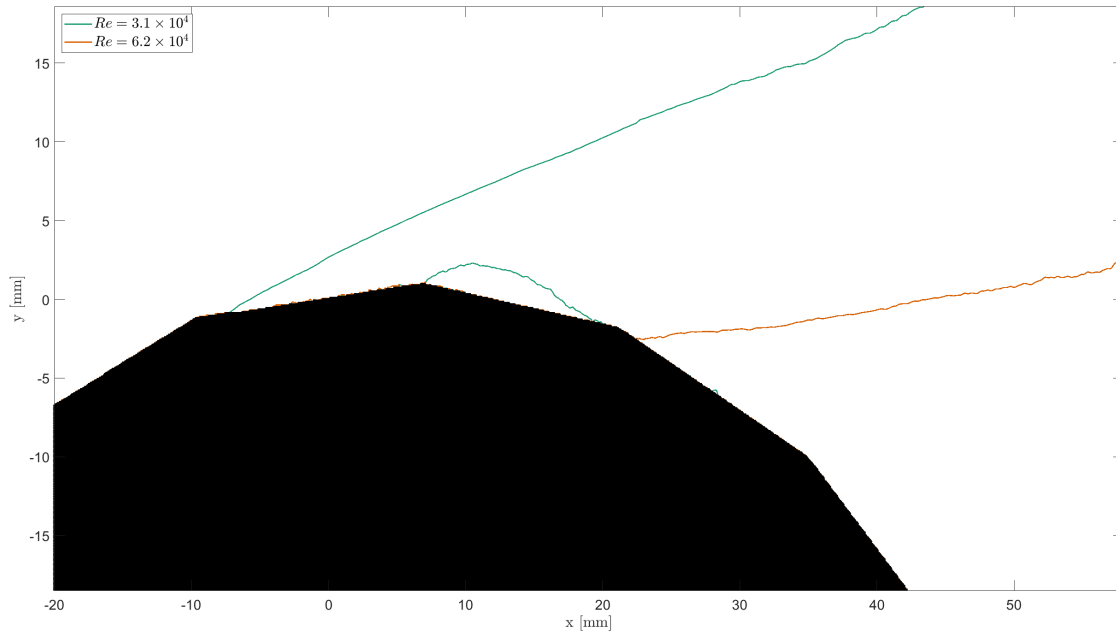
Furthermore, it can be seen that once the critical regime is reached, the pressure distribution around the cylinder undergoes a drastic change, as a much more intense suction peak is achieved around  $\theta = 85^\circ - 90^\circ$ . The delayed separation allows for a slight pressure recovery on the backside of the cylinder, resulting in a higher static pressure and a narrower wake. These two effects are the main

contributors to the drag reduction in the critical regime.



**Figure 5.26:** Pressure coefficient over double layer cylinder with 20UL underlayer and smooth overlayer vs  $\theta$  for  $Re = 3.1 \times 10^4$  and  $Re = 6.2 \times 10^4$ .

Next up, the separating streamline contour  $\psi = 0$  has been computed for this configuration at the Reynolds numbers of  $Re = 3.1 \times 10^4$  and  $Re = 6.2 \times 10^4$ . These contours cement the previously observed drag crisis behavior of postponed separation once the critical Reynolds number is achieved. For the subcritical case, the flow separates early, whereas for the case at higher airspeeds, the separation is greatly postponed. These plots allow for the accurate determination of the separation point and the azimuthal angle corresponding to the separation location is shown in Table 5.7.



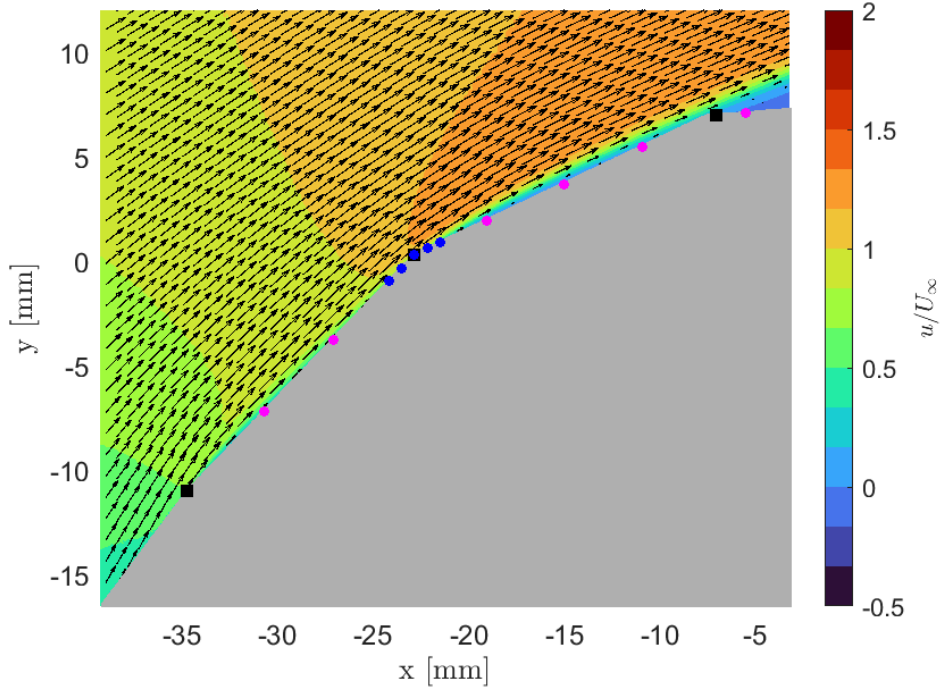
**Figure 5.27:** Streamline  $\psi = 0$  for double layer cylinder with 20UL underlayer and smooth overlayer at  $Re = 3.1 \times 10^4$  and  $Re = 6.2 \times 10^4$ .

**Table 5.7:** Separation point angle  $\theta$  values for double-layer cylinder with 20UL underlayer and smooth overlayer at  $Re = 3.1 \times 10^4$  and  $Re = 6.2 \times 10^4$ .

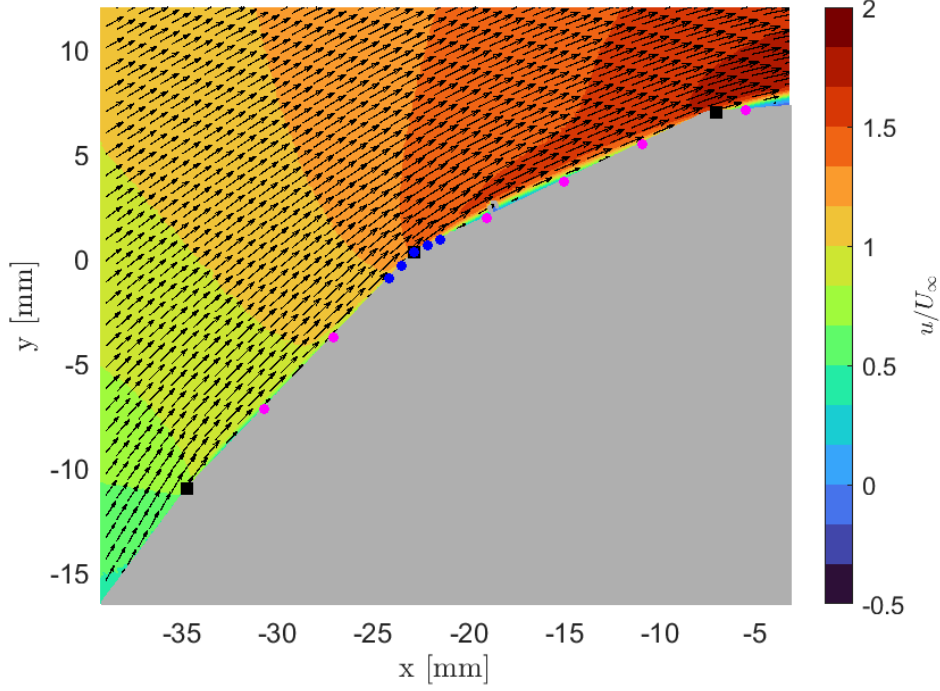
| $Re \times 10^4$ [-] | SM20 |     |
|----------------------|------|-----|
|                      | 3.1  | 6.2 |
| $\theta_{sep}$ [°]   | 81   | 120 |

Next up, the second PIV setup was employed to capture a higher resolution image of the field for the Reynolds numbers of  $Re = 3.1 \times 10^4$  and  $Re = 6.2 \times 10^4$ . The two streamwise normalized velocity fields are shown in Figures 5.28 and 5.29. Similarly to the other double-layer configuration, the flow behavior of experiencing acceleration and deceleration near the ribs is maintained. Additionally, the differences between the two velocity fields highlight how the flow is accelerated on the foreside of the cylinder once the drag crisis is reached.

In this case, the boundary layer has been probed at the locations of  $\theta = [47^\circ, 53^\circ, 65^\circ, 70.5^\circ, 76^\circ, 83^\circ]$ , indicated by the magenta markers in Figures 5.28 and 5.29. On the same note, boundary layer probes have been placed in the region neighboring the rib, at  $\theta = [57.5^\circ, 58.5^\circ, 59.5^\circ, 60.5^\circ, 61.5^\circ]$ , indicated by blue markers; with  $\theta = 59.5^\circ$  matching the location of the rib.



**Figure 5.28:** Close up of normalized velocity field around double layer cylinder with 20UL underlayer and smooth overlayer at  $Re = 3.1 \times 10^4$ .



**Figure 5.29:** Close up of normalized velocity field around double layer cylinder with 20UL underlayer and smooth overlayer at  $Re = 6.2 \times 10^4$ .

The boundary layer profiles over the surface of the cylinder (magenta markers) have been computed and are shown in Figure 5.30. Additionally, the boundary layer parameters have been computed in these locations and are shown in Table 5.8.

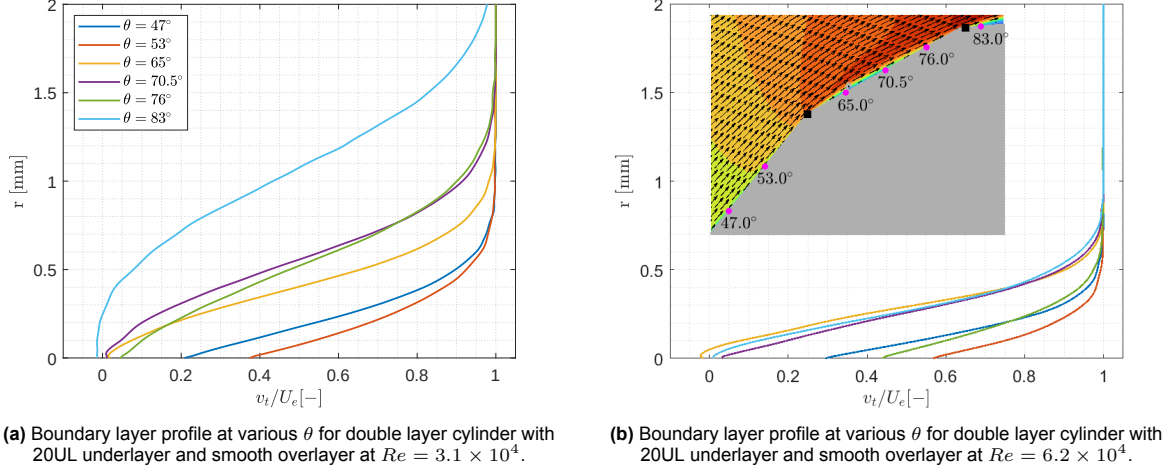
Once again, the tangential velocity profiles maintain the steepness near the wall in probing locations before flow separation, and as the separation point approaches, the velocity gradient at the wall decreases, resulting in a less full boundary layer. For these profiles, three different segments have been probed. The locations of the probes for the first two values of  $\theta$  belong to the same segment.  $\theta = 47^\circ$  is close to the midpoint of that segment and because of that, the boundary layer thickness parameters,  $\delta_{99}$ ,  $\delta^*$  and  $\delta_m$  are thicker than for  $\theta = 53^\circ$ . Additionally, the shape factor is also decreasing from  $\theta = 47^\circ \rightarrow 53^\circ$ , which is also in concordance with the fact that the shape factor tends to reduce along the length of the segment due to the overall favorable pressure gradient present on the foreside of the cylinder.

The three subsequent values for  $\theta = [65^\circ, 70.5^\circ, 76^\circ]$  belong to the second segment. On the one hand, for the subcritical case, based on the pressure distribution depicted in Figure 5.26, it is clear that the pressure gradient is no longer favorable for this segment. For  $\theta = 65^\circ \rightarrow 70.5^\circ$ , the pressure gradient is adverse in the beginning of the oscillation in the  $C_p - \theta$  curve. For that reason, the boundary layer loses some fullness during this first evolution. Then, the pressure gradient is mostly null, so the profile remains similar. On the other hand, for the critical case, the pressure gradient around  $\theta = 65^\circ$  is adverse, as depicted by Figure 5.26, as the air flows away from the rib. For this reason, the velocity profile at  $\theta = 65^\circ$  is at its emptiest, but as the flow remains attached, the flow on the foreside of the cylinder is overall still favorable. Therefore, for subsequent probes the velocity profile becomes progressively fuller.

Finally, the last probing location is at  $\theta = 83^\circ$ , the flow for the subcritical case has detached and already separated, as the velocity slope on the wall is vertical. On the other hand, for the subcritical case, the flow has just flowed past a rib, leading to an emptier velocity profile as the divergent flow after a rib causes an adverse pressure gradient. Finally, one interesting observation is the fact that the velocity profiles in the first probe after a rib for the subsequent segments in the critical case,  $\theta = [65^\circ, 83^\circ]$  are quite closely matched in terms of their parameters and profile shape.



In terms of the boundary layer parameters, the thickness parameters and the shape factors evolve similarly within the same segment, probes  $\theta = [65^\circ, 70.5^\circ, 76^\circ]$ , with the last and first probe having a smaller thickness value and the middle one having the largest thickness value across all parameters. When it comes to the shape factor, a small distinction between the subcritical and the supercritical cases can be made. For the supercritical case, the shape factor is the largest in the first location along a segment and steadily decreases:  $\theta = [65^\circ, 70.5^\circ, 76^\circ]$  with  $H = [3.64, 2.74, 1.51]$ , whereas for the subcritical case, the shape factor is at its largest in the second probing location, in the middle of the segment.



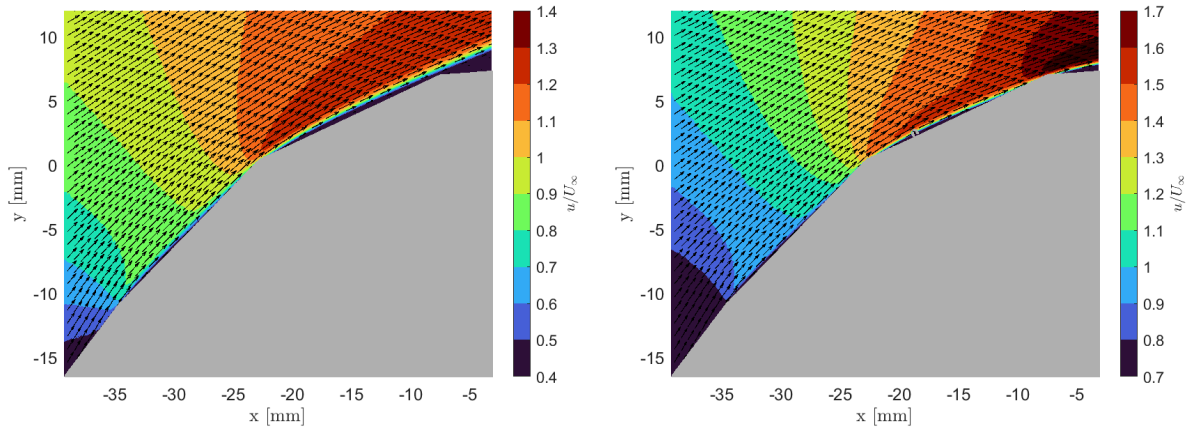
**Figure 5.30:** Boundary layer profiles at various  $\theta$  for a bare cylinder at  $Re = 3.1 \times 10^4$  and  $Re = 6.2 \times 10^4$ .

**Table 5.8:** Boundary layer parameters for cylinder with the 20UL underlayer and smooth overlayer at  $Re = 3.1 \times 10^4$  and  $Re = 6.2 \times 10^4$  for increasing  $\theta$ .

| $\theta$ [°] | $Re = 3.1 \times 10^4$ |                 |                 |         |  | $Re = 6.2 \times 10^4$ |                 |                 |         |
|--------------|------------------------|-----------------|-----------------|---------|--|------------------------|-----------------|-----------------|---------|
|              | $\delta_{99}$ [mm]     | $\delta^*$ [mm] | $\delta_m$ [mm] | $H$ [-] |  | $\delta_{99}$ [mm]     | $\delta^*$ [mm] | $\delta_m$ [mm] | $H$ [-] |
| 47           | 0.80                   | 0.22            | 0.11            | 1.93    |  | 0.56                   | 0.12            | 0.07            | 1.74    |
| 53           | 0.79                   | 0.16            | 0.10            | 1.55    |  | 0.48                   | 0.07            | 0.05            | 1.33    |
| 65           | 1.06                   | 0.42            | 0.13            | 3.19    |  | 0.69                   | 0.30            | 0.08            | 3.64    |
| 70.5         | 1.36                   | 0.57            | 0.17            | 3.42    |  | 0.73                   | 0.27            | 0.10            | 2.74    |
| 76           | 1.39                   | 0.54            | 0.19            | 2.82    |  | 0.59                   | 0.12            | 0.08            | 1.51    |
| 83           | 2.14                   | 1.10            | 0.24            | 4.67    |  | 0.76                   | 0.29            | 0.10            | 3.01    |

Similarly to the SM10 configuration, this SM20 configuration also experiences the boundary later being the thickest at the midpoint of each segment, thus adjusting the overall shape of the configuration to a slightly rounder shape, as shown in Figure 5.31.



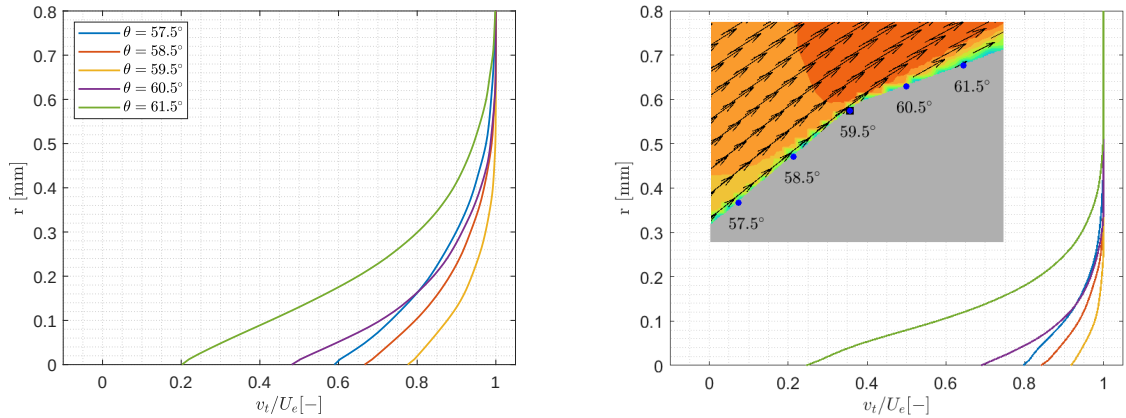


(a) Close up of normalized velocity field around double layer cylinder with 20UL underlayer and smooth overlayer at  $Re = 3.1 \times 10^4$ .

(b) Close up of normalized velocity field around double layer cylinder with 20UL underlayer and smooth overlayer at  $Re = 6.2 \times 10^4$ .

**Figure 5.31:** Close up of normalized velocity field with an adjusted colorbar around double layer cylinder with 20UL underlayer and smooth overlayer at  $Re = 3.1 \times 10^4$  and  $Re = 6.2 \times 10^4$ .

Next, the boundary layer profiles neighboring a rib (blue markers) have been computed and are shown in Figure 5.32; note that the  $y$ -axis has been rescaled for the boundary layer profiles near the ribs, and their respective boundary layer parameters are computed and displayed in Table 5.9.



(a) Boundary layer profiles at various  $\theta$  around a rib for double layer cylinder with 20UL underlayer and smooth overlayer at  $Re = 3.1 \times 10^4$ .

(b) Boundary layer profiles at various  $\theta$  around a rib for double layer cylinder with 20UL underlayer and smooth overlayer at  $Re = 6.2 \times 10^4$ .

**Figure 5.32:** Boundary layer profiles at various  $\theta$  around a rib for double layer cylinder with 20UL underlayer and smooth overlayer at  $Re = 3.1 \times 10^4$  and  $Re = 6.2 \times 10^4$ .

**Table 5.9:** Boundary layer parameters around a rib for cylinder with the 20UL underlayer and smooth overlayer at  $Re = 3.1 \times 10^4$  and  $Re = 6.2 \times 10^4$  for increasing  $\theta$ .

| $\theta$ [°] | $Re = 3.1 \times 10^4$ |                 |                 |         | $Re = 6.2 \times 10^4$ |                 |                 |         |
|--------------|------------------------|-----------------|-----------------|---------|------------------------|-----------------|-----------------|---------|
|              | $\delta_{99}$ [mm]     | $\delta^*$ [mm] | $\delta_m$ [mm] | $H$ [-] | $\delta_{99}$ [mm]     | $\delta^*$ [mm] | $\delta_m$ [mm] | $H$ [-] |
| 57.5         | 0.62                   | 0.08            | 0.06            | 1.29    | 0.31                   | 0.02            | 0.02            | 1.13    |
| 58.5         | 0.50                   | 0.06            | 0.05            | 1.23    | 0.23                   | 0.02            | 0.01            | 1.10    |
| 59.5         | 0.38                   | 0.03            | 0.03            | 1.14    | 0.15                   | 0.01            | 0.01            | 1.05    |
| 60.5         | 0.53                   | 0.08            | 0.06            | 1.40    | 0.27                   | 0.03            | 0.02            | 1.20    |
| 61.5         | 0.68                   | 0.17            | 0.09            | 1.89    | 0.42                   | 0.10            | 0.06            | 1.85    |

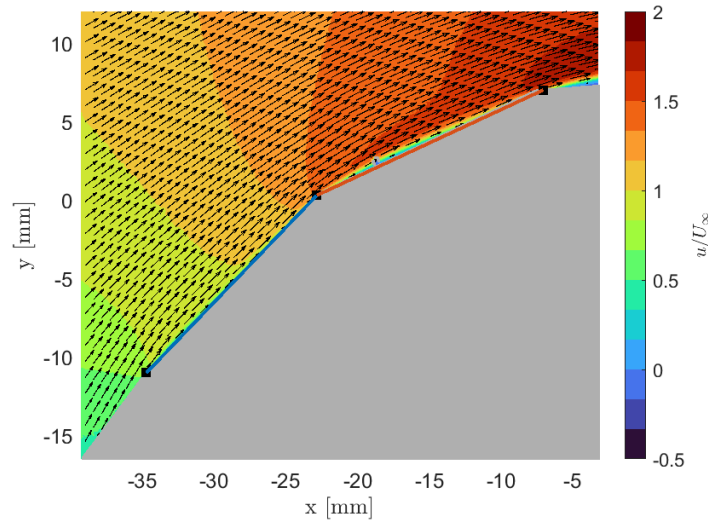
Analyzing the boundary layer profiles, there is a progression of the boundary layer profile as the air

flows over the rib. Starting from the upstream most probe, as the air starts flowing onto the rib, the boundary layer profile experiences an increase in fullness thanks to a localized favorable pressure gradient; this is caused by the acceleration due to the convergence of the air before the rib. Then, the boundary layer reaches its fullest point right at the location of the rib and then the air divergence begins. This results in a localized adverse pressure gradient that decreases the steepness of the profiles.

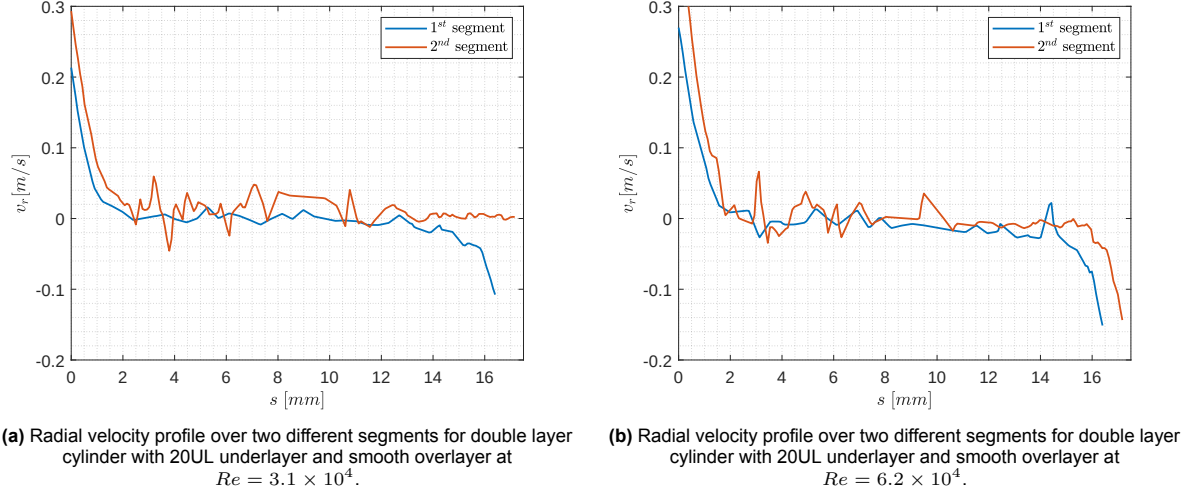
Overall, the main difference between the boundary layer profiles between the subcritical and the critical cases is the steepness of the velocity profiles due to the difference in overall favorable pressure gradient caused by the cylinder. But in terms of the progression of both boundary layers, within each regime, that is maintained.

In terms of the boundary layer parameters, it can be observed that as the air incurs on the rib, the thicknesses diminish. And once the air has flowed past the rib, the thicknesses start increasing again. Similarly, the relative variation of the shape factor gives an indication of whether the pressure gradient is favorable or adverse. When the shape factor decreases from probe to probe, the pressure gradient is favorable.

Finally, the radial component of the flow along the two segments between the three rib location markers has been computed, indicated in Figure 5.33. The obtained results are shown in Figure 5.34 and closely match the results obtained for configuration SM10, Figure 5.23. The same degree of uncertainty in the wall-normal velocity is observed, this is again due to the magnitude of the velocities that are being measured and the error present within the measurement techniques. Additionally, the deviations present at the ends of the segments are present as well, and these are explained by the fact that the flow experiences deflections due to the presence of the rib and the fact that the cylinder mask is not fully able to capture the angles of the fabric/cylinder boundary around the ribs, resulting in inaccuracies in the calculation of the wall-normal velocities around the ribs. This leads to the conclusion, for the two double-layer fabric configurations tested, no significant contribution can be assigned to fabric porosity.

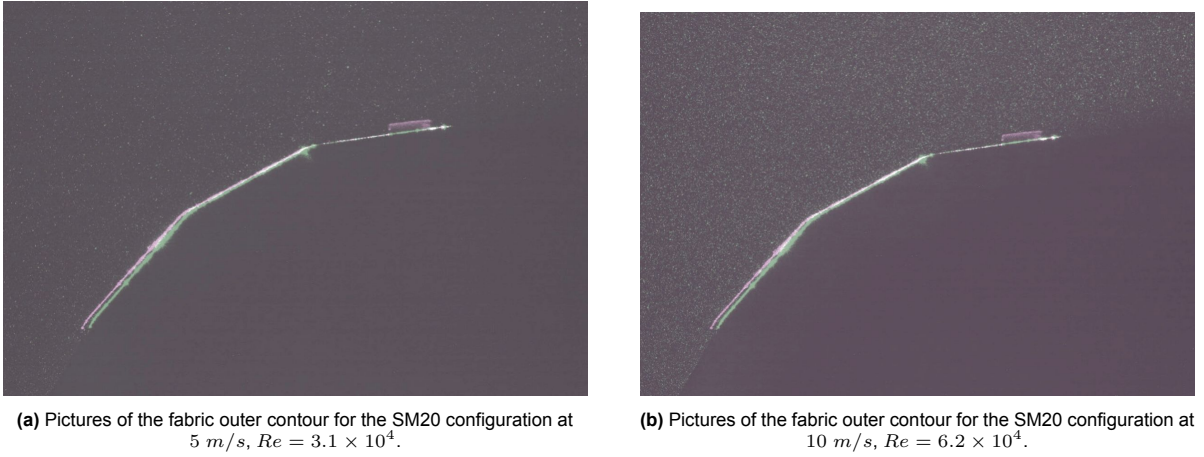


**Figure 5.33:** Locations of the cylinder segments over which the wall normal velocity has been computed for double layer cylinder with 10UL underlayer and smooth overlayer at  $Re = 9.3 \times 10^4$ .



**Figure 5.34:** Radial velocity profiles over two different segments for double layer cylinder with 20UL underlayer and smooth overlayer at  $Re = 3.1 \times 10^4$  and  $Re = 6.2 \times 10^4$ .

Finally, in order to determine the significance of fabric deformation, the outlines of the cylinder are compared at different airspeeds to the fabric contour with the wind off. Figure 5.35 shows the comparison of the outlines, the magenta outline is the fabric with the wind off and the green contour is the fabric outline with the wind tunnel running. It can be seen in both cases that the fabric undergoes a slight deformation at both velocities, for low values of  $\theta$ , relative to the image of the fabric outline with still air. This deformation could just be a small displacement due to the action of the airflow generating drag and pushing the cylinder slightly. All in all, it can be observed that there is no significant deformation from the subcritical to the critical case. Therefore, regarding the formulated research question, fabric deformation does not play a role in the triggering of the drag crisis, nor does it have an effect on its behavior.



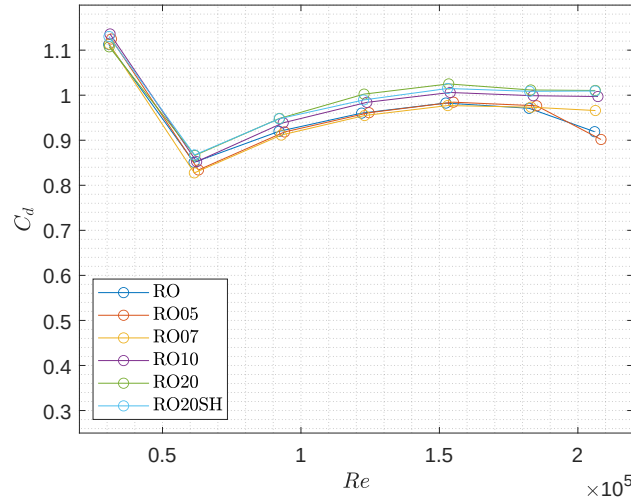
**Figure 5.35:** Pictures of the fabric outer contour for the SM20 configuration at different airspeeds.

### 5.2.2. Varying Underlayer + Rough Overlayer

The cylinder was fitted with a set of different double layer fabric configurations. The top smooth overlayer previously employed has been swapped for the rough overlayer presented in Section 4.1.2. The underlayer sets have been the same ones previously used.

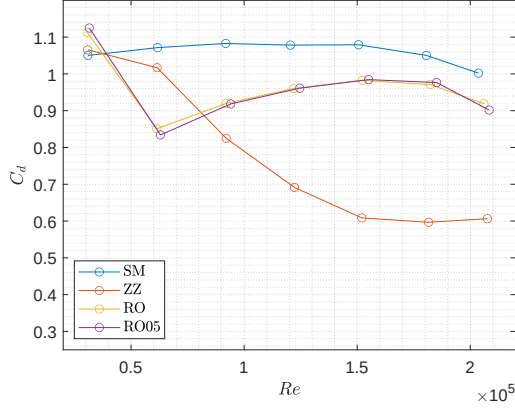
### Balance Results

The balance measurements were acquired for all of the double-layer combinations involving the rough overlayer. The result for all of the measurements is shown in Figure 5.36. Examining the  $C_d - Re$  plot, it is clear that any fabric combination using the rough overlayer as the outer fabric exhibited virtually the same behavior. This was expected as the height maps for the double-layer fabrics did not reveal any significant differences in the height profiles of the fabric configurations.

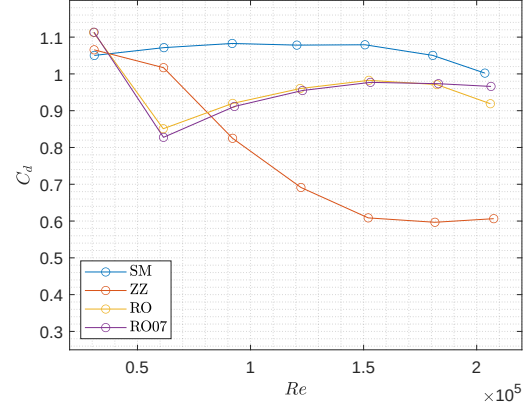


**Figure 5.36:** Comparison between double fabric configuration with the varying underlayer and rough overlayer.

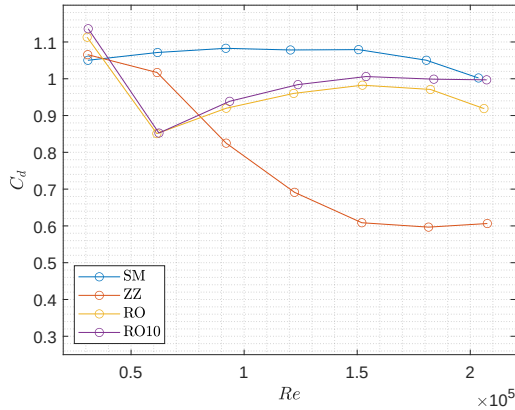
The critical Reynolds number across all configurations with the rough overlayer is around  $Re_{crit} = 6.1 \times 10^4$ ; on the other hand, the minimal drag coefficient ranges from  $C_{d,min} = 0.83 - 0.87$  with no clear pattern or correlation. One phenomenon that stands out is the unexpected drop observed in the supercritical regime for  $Re > 2 \times 10^5$ , particularly for the configurations RO and RO05, being just the rough overlayer alone and the rough overlayer with 05UL underlayer. This effect is not observed across any of the other configurations, nor has it been recreated anywhere in previous studies or in the literature. Looking into this effect, it turns out that the cause of this reduction in the measured force was an experimental error that had been made during the first balance measurement runs. Checking the test matrix for the measurement campaign, the configurations that exhibit this behavior are towards the beginning before the balance was fully fixed down. This leads to the conclusion that the drop in the measured force was due to a faulty measurement on the balance.



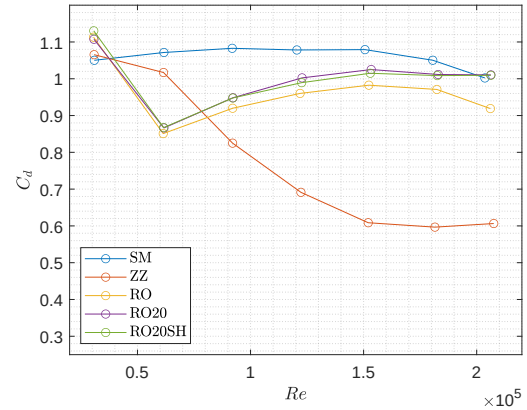
(a) Double fabric configuration with the 5 mm spacing underlayer and the rough overlayer.



(b) Double fabric configuration with the 7 mm spacing underlayer and the rough overlayer.



(c) Double fabric configuration with the 10 mm spacing underlayer and the rough overlayer.



(d) Double fabric configuration with the 20 mm spacing underlayer and the rough overlayer.

**Figure 5.37:** Double fabric configuration with the varying underlayer and rough overlayer.

Furthermore, each of the double layer configurations is compared to other reference fabrics such as just the rough overlayer, the bare cylinder and a cylinder with a zig-zag strip. It can be seen that the RO05 and RO07 are more closely matched to the overlayer alone, and the configurations employing a larger rib spacing result in a slighter higher drag coefficient, especially in the supercritical regime. All in all, given the limited drag reduction potential of the double layer fabric configurations involving the rough overlayer, this set of configurations will not be studied with PIV.

## 5.3. Single Fabric Configurations

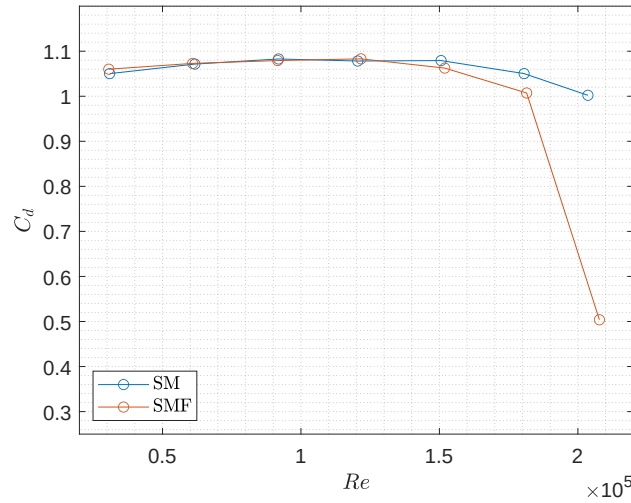
In this section, after having studied the relevant configurations for the double-layer cases, each of the fabrics used to make up the relevant configurations will be studied individually. This is done to determine the effects on the flow of each individual fabric. By uncovering the individual effects of each fabric, it could help understand how the double-layer fabrics trigger the drag crisis and how different parameters alter the behavior of the drag crisis.

### 5.3.1. Smooth Overlayer

This configuration adds the smooth overlayer as a single fabric configuration. The added roughness provided by the smooth overlayer will lower the  $Re_{crit}$ , thus making the cylinder reach the critical regime within the region of measurement.

### Balance Results

The  $Re_{crit}$  is determined with the aid of balance measurements, the  $C_d - Re$  curve is shown in Figure 5.38:



**Figure 5.38:** Drag coefficient against Reynolds number for the cylinder with the smooth overlayer compared to the bare cylinder.

For most of the region of measurement, the cylinder remains in the subcritical regime; it is only around  $Re = 18.4 \times 10^4$  that there is a slight decrease in the drag coefficient, indicating the beginning of the critical regime. This is followed by a very large drop in the drag coefficient for Reynolds number a of  $Re_{crit} = 20.9 \times 10^4$ . When the Reynolds number reaches this critical value, the drag coefficient also reaches its minimum  $C_{d,min} = 0.5$ .

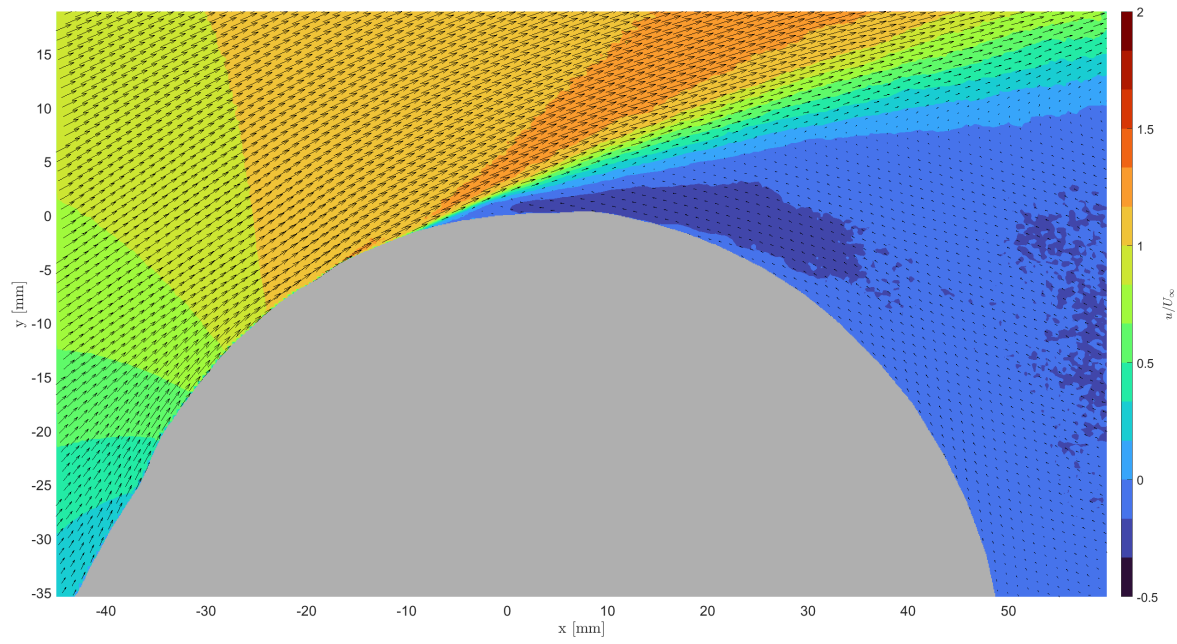
### PIV Results

For this configuration, PIV measurements are performed to study what occurs during the crisis phenomenon. Therefore, PIV measurements have been acquired for  $Re = [9.3, 18.4, 20.9] \times 10^4$ . The normalized velocity field, in the subcritical regime ( $Re = 9.3 \times 10^4$ ), maintains great resemblance to the fields shown in the previous Bare Cylinder Section 5.1.2, due to the fact that the flow regime is well within the subcritical regime; for that reason, those velocity and pressure fields are shown in the Appendix Section A.1.4 in Figures A.35 and A.38.

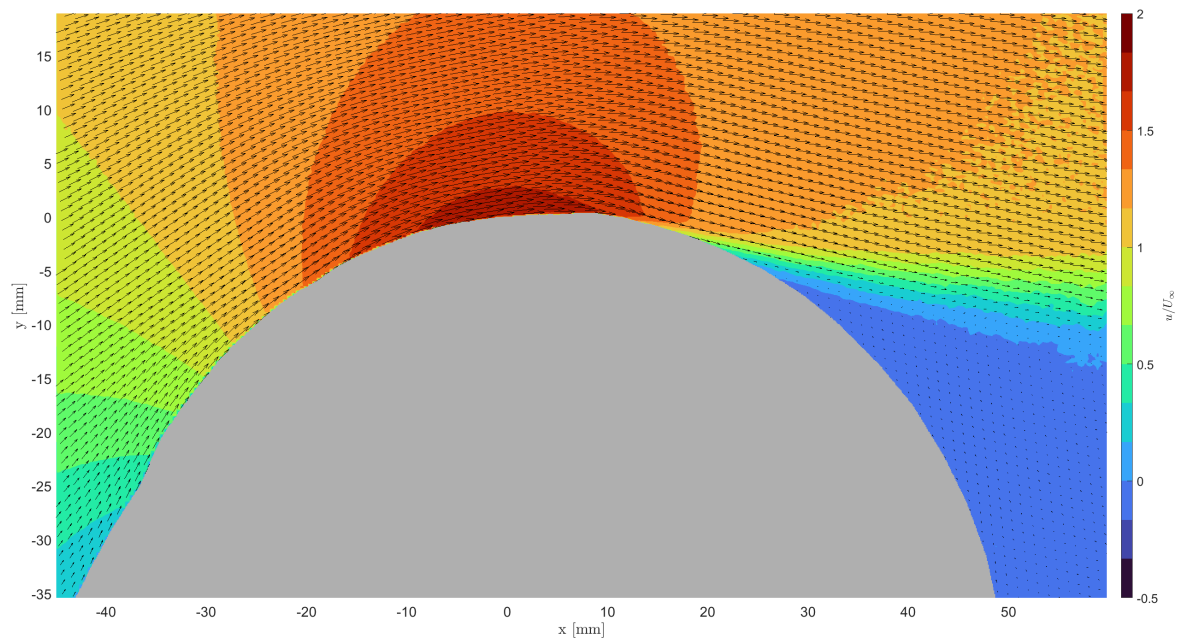
For larger Reynolds numbers approaching the critical regime, the velocity and pressure fields vary slightly. For the case of  $Re = 18.4 \times 10^4$ , shown in Figure 5.39a, the width of the wake is reduced slightly relative to the subcritical cases. This results in the slight reduction of the drag coefficient.

Further increases in the Reynolds number past the critical Reynolds number trigger the drag crisis. This results in drastically different velocity field, shown in Figure 5.39b. Additionally, it can be observed that the flow separation point is drastically shifted downstream, resulting in much faster flowing air over  $\theta = 90^\circ$ ; this in turn generates a large drop in pressure at the same location, shown in Figures 5.41 and 5.40, setting the suction slightly before  $\theta = 90^\circ$ . Additionally, because of the shift downstream of the separation point, there is a significant reduction in the width of the wake. Added to the fact that there is a slight pressure recovery after the peak suction, leading to a slightly higher pressure on the backside of the cylinder. These two factors combined result in a drastic reduction in pressure drag.



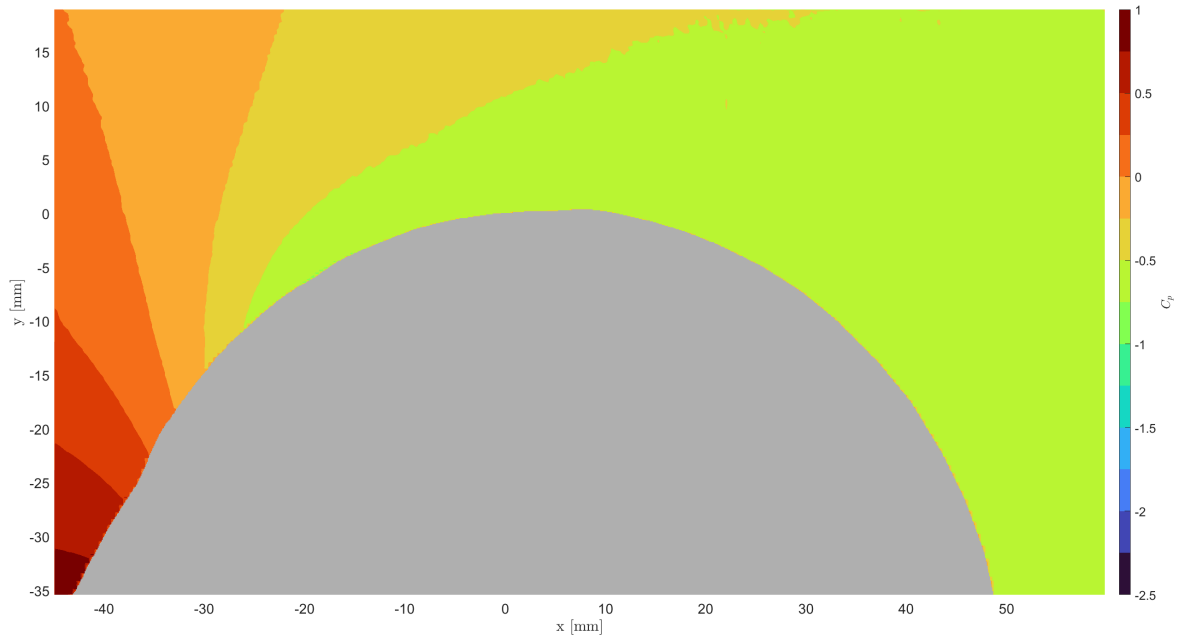


(a) normalized velocity field around cylinder with the smooth overlayer for  $Re = 18.4 \times 10^4$ .

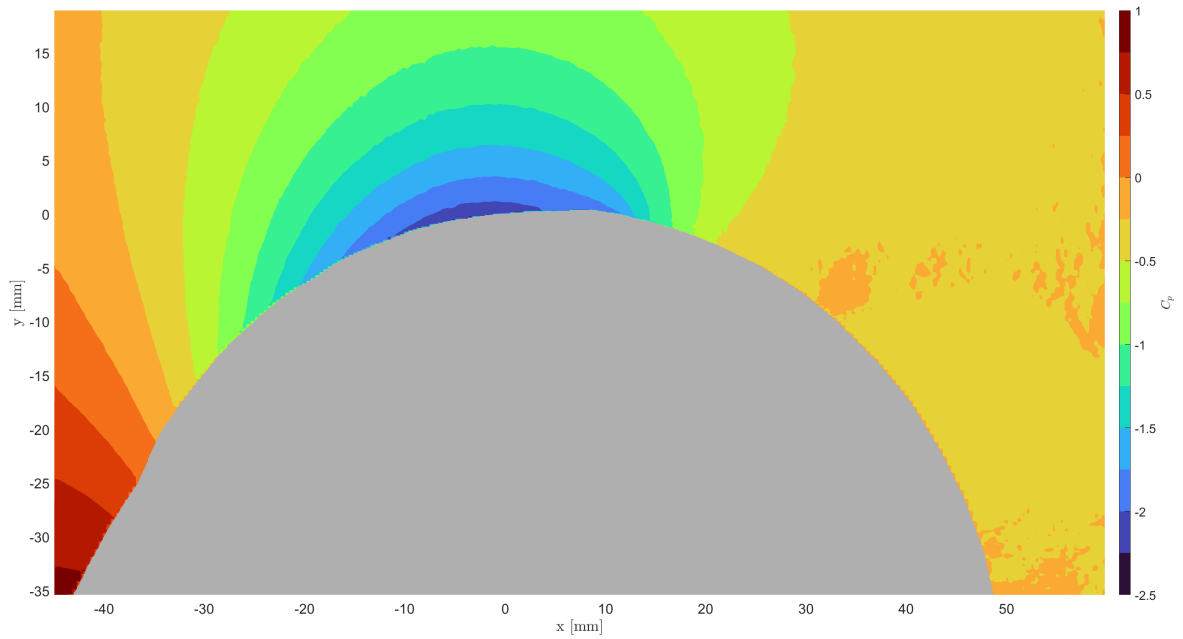


(b) normalized velocity field around cylinder with the smooth overlayer for  $Re = 20.9 \times 10^4$ .

**Figure 5.39:** normalized velocity fields around the cylinder with the smooth overlayer for  $Re = 18.4 \times 10^4$  and  $Re = 20.9 \times 10^4$ .



(a) Pressure coefficient field around cylinder with the smooth overlayer for  $Re = 18.4 \times 10^4$ .

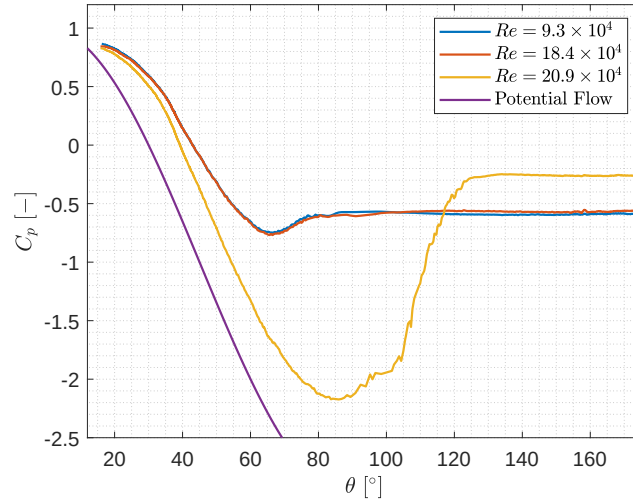


(b) Pressure coefficient field around cylinder with the smooth overlayer for  $Re = 20.9 \times 10^4$ .

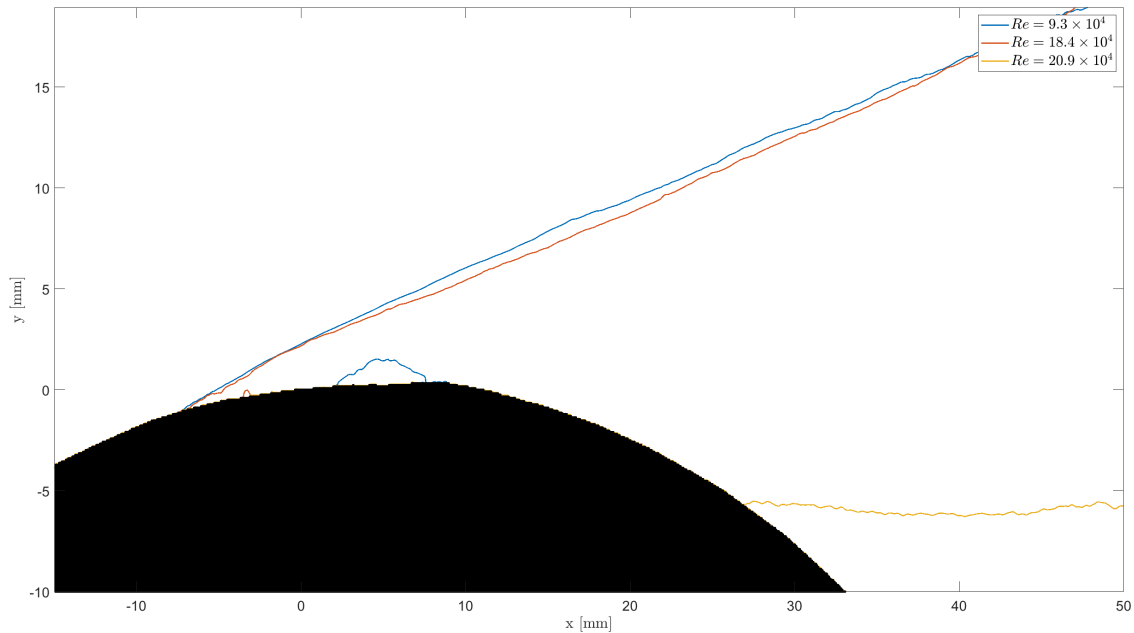
**Figure 5.40:** Pressure coefficient fields around the cylinder with the smooth overlayer for  $Re = 18.4 \times 10^4$  and  $Re = 20.9 \times 10^4$ .

Additionally, the pressure coefficient over the surface of the cylinder with the smooth overlayer has been computed and the  $C_p - \theta$  curve is obtained. It can be seen that the flow in the critical regime achieves a much stronger suction peak. Furthermore, examining the separating streamline for different Reynolds numbers shown in Figure 5.42, it can be seen that for the subcritical and precritical cases the separation points lie around  $\theta = 81^\circ$  and  $\theta = 82^\circ$ , respectively. Whilst for the critical case, the separation point is located around  $\theta = 127^\circ$ . Overall, for the subcritical cases, the pressure distribution over the surface of the cylinder is pretty much identical to the bare cylinder baseline.





**Figure 5.41:** Pressure coefficient over cylinder surface vs  $\theta$  with smooth overlayer for  $Re = [9.3, 18.4, 20.9] \times 10^4$ .

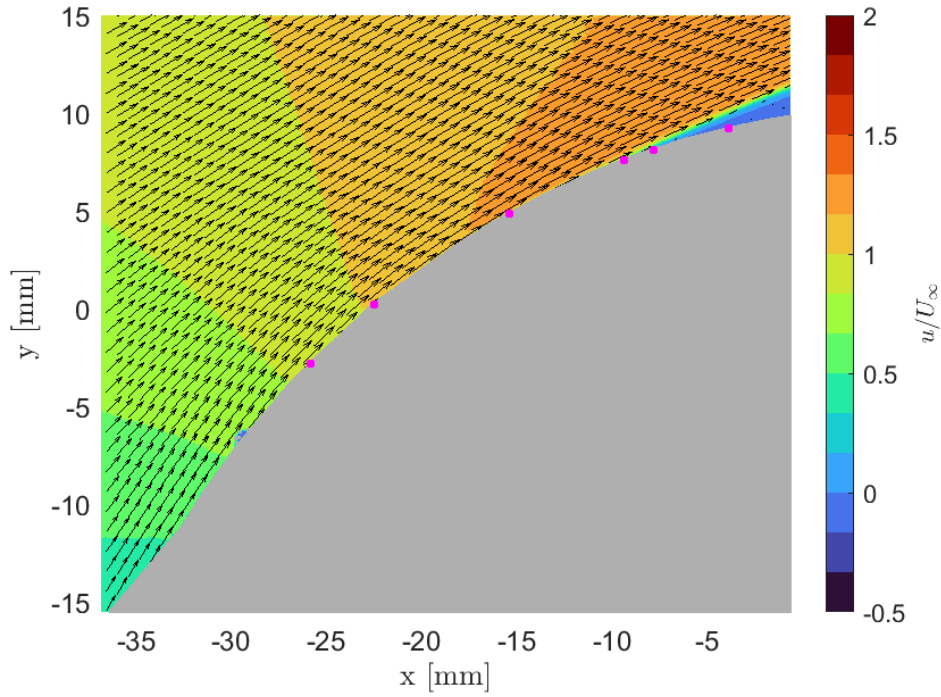


**Figure 5.42:** Streamline  $\psi = 0$  for cylinder with smooth overlayer at  $Re = 3.1 \times 10^4$  and  $Re = 6.2 \times 10^4$ .

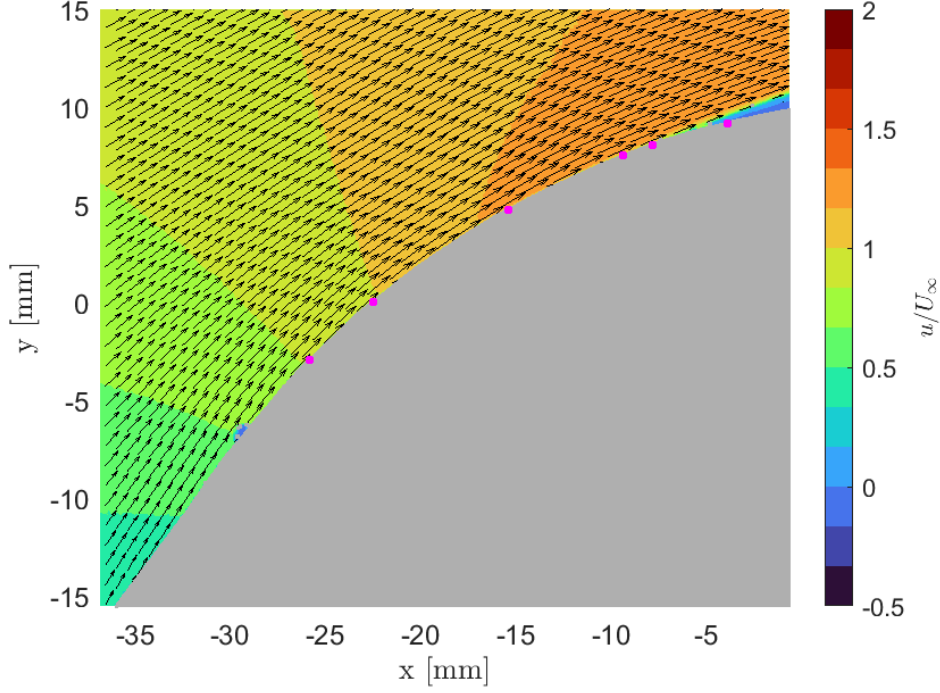
Now, taking a more detailed look into the boundary layer development for this configuration using the second setup. Close-ups of the velocity fields have been computed for the normalized velocity field. At varying  $\theta$ , note that the angles in this configuration have changed slightly due to the presence of a small reflection present around  $\theta = 50^\circ$ . For this reason, the angles in which the boundary layer profiles have been computed are:  $\theta = [55^\circ, 70^\circ, 78^\circ, 80^\circ, 85^\circ]$ . One important remark is that the masking is consistent across different Reynolds numbers as long as the configuration is the same, that is to say that all smooth overlayer cases share the same mask and vice versa. On the other hand, the masks between different configurations present slight differences due to the test subjects having different amounts of reflections and other surface elements such as fabric hairs. All in all, this results in the wall-normal distance used to describe the boundary layer profile being slightly inconsistent across configurations.

Looking at the close-up of the flow over the cylinder with the smooth overlayer at  $Re = 20.9 \times 10^4$ ,

Figure 5.44, and comparing it to the zoomed-out field for the same configuration, Figure 5.39b, one clear thing stands out, and that is the slight separation and shear layer present in Figure 5.44 around  $x = -5 \text{ mm}$  that appears to be missing from Figure 5.39b. Initially, both configurations were assumed to be equal, resulting in the exact same flow regime, but inspecting the processed and raw PIV data, it can be concluded that the two configurations had slightly different Reynolds numbers, subcritical for Figure 5.44 and critical for Figure 5.39b. This is further confirmed by the outlines of the contours on the foreside of the cylinder being the same between Figures 5.43 and 5.44. Opposed to the velocity contours having a noticeable difference between Figures 5.39a and 5.39b. One possible explanation for this phenomenon could be an error in the tunnel settings during the experimental campaign, as the measurements shown in Figures 5.39b 5.44 are taken separately with different setups.

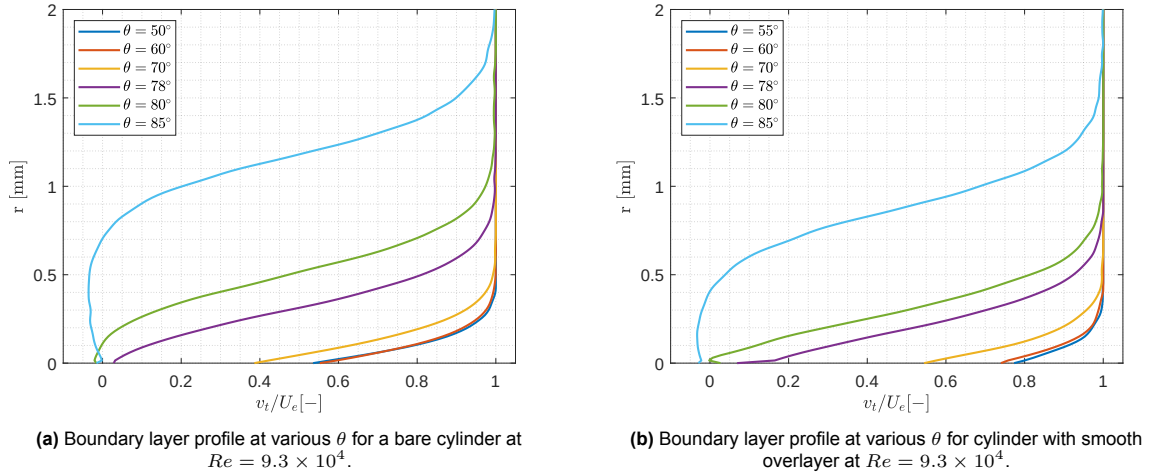


**Figure 5.43:** Close up of normalized velocity field around cylinder with the smooth overlay for  $Re = 18.4 \times 10^4$ .



**Figure 5.44:** Close up of normalized velocity field around cylinder with the smooth overlayer for  $Re = 20.9 \times 10^4$ .

Similarly, the analysis of the boundary layer has been performed for this configuration at all three measured Reynolds numbers:  $Re = [9.3, 18.4, 20.9] \times 10^4$ . Figure 5.45 shows a comparison between the boundary layer profiles for the bare cylinder and the cylinder with the smooth overlayer for the same Reynolds number.



**Figure 5.45:** Comparison of boundary layer profiles at various  $\theta$  between bare smooth cylinder and cylinder with smooth overlayer at  $Re = 9.3 \times 10^4$ .

Looking at the boundary layer profiles, it can be determined what effect surface roughness has on the development of the boundary layer on the foreside of the cylinder. Overall, for low values of  $\theta \leq 70^\circ$ , the boundary layer appears to be very similar to the bare cylinder configuration in terms of thickness and velocity profile gradient. This is explained by the fact that for these values of  $\theta$  there is a favorable pressure gradient for both cases that maintains near-wall momentum. The profiles change slightly for larger values  $\theta$ , for the configuration with the smooth overlayer. Although the adverse pressure gradient

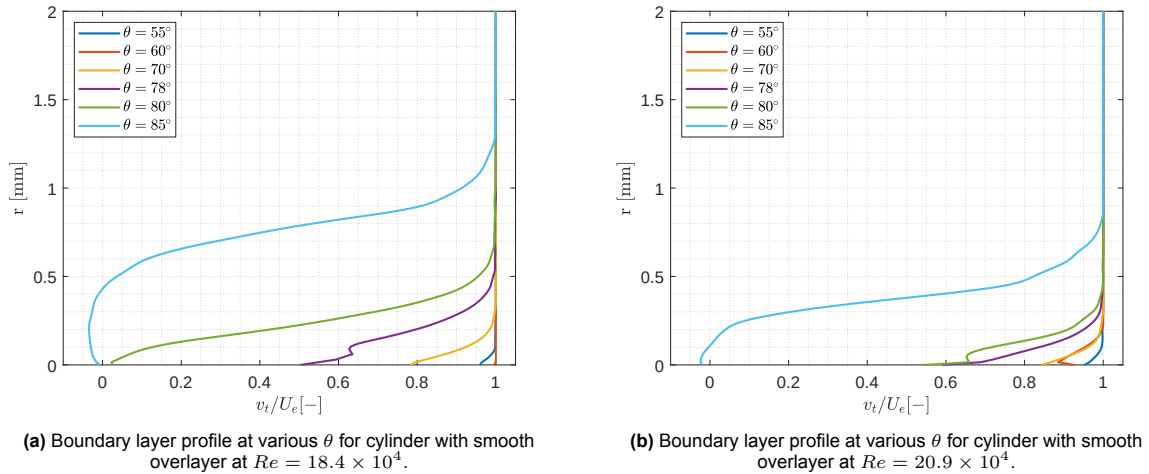
is similar to the bare cylinder case, as shown in Figures 5.3 and 5.41, the velocity profiles appear to be steeper near the wall. This indicates a larger degree of mixing caused by the surface roughness leading to momentum being transferred from higher parts of the boundary layer to the near-wall region. This mixing aids the velocity recovery, increases the resistance of the boundary layer to the adverse pressure gradient, and ultimately results in a reduction of the boundary layer thickness.

**Table 5.10:** Boundary layer parameters for a bare cylinder and a cylinder with the smooth overlayer at  $Re = 9.3 \times 10^4$  for varying  $\theta$ .

| $\theta$ [°] | Bare Cylinder      |                 |                 |         | Smooth Overlayer   |                 |                 |         |
|--------------|--------------------|-----------------|-----------------|---------|--------------------|-----------------|-----------------|---------|
|              | $\delta_{99}$ [mm] | $\delta^*$ [mm] | $\delta_m$ [mm] | $H$ [–] | $\delta_{99}$ [mm] | $\delta^*$ [mm] | $\delta_m$ [mm] | $H$ [–] |
| 50           | 0.34               | 0.05            | 0.04            | 1.36    | —                  | —               | —               | —       |
| 55           | —                  | —               | —               | —       | 0.27               | 0.02            | 0.02            | 1.15    |
| 60           | 0.37               | 0.05            | 0.04            | 1.34    | 0.32               | 0.03            | 0.02            | 1.18    |
| 70           | 0.47               | 0.10            | 0.06            | 1.56    | 0.40               | 0.06            | 0.05            | 1.35    |
| 78           | 0.85               | 0.33            | 0.11            | 3.03    | 0.72               | 0.22            | 0.10            | 2.20    |
| 80           | 1.13               | 0.53            | 0.12            | 4.40    | 0.88               | 0.33            | 0.11            | 3.01    |
| 85           | 1.85               | 1.21            | 0.11            | 10.71   | 1.55               | 0.91            | 0.12            | 7.40    |

Table 5.10 shows a comparison of the boundary layer parameters between a bare cylinder and a cylinder with the smooth overlayer at  $Re = 9.3 \times 10^4$ . One general trend can be observed, and it is that the thicknesses for the configuration with the smooth overlayer are smaller than for the bare cylinder. Not only that, but also the reduced shape factors at the same  $\theta$  indicate a fuller boundary layer near the wall, hence a steeper velocity profile, as previously stated.

Furthermore, the boundary layer profiles have been computed for the cylinder with the smooth overlayer at the other two remaining Reynolds numbers,  $Re = 18.4 \times 10^4$  and  $Re = 20.9 \times 10^4$ , shown in Figure 5.46.



**Figure 5.46:** Boundary layer profiles at various  $\theta$  for cylinder with smooth overlayer at  $Re = 18.4 \times 10^4$  and  $Re = 20.9 \times 10^4$ .

Overall, it appears that the quality of the results for these two sets of boundary layer probes is quite unsatisfactory. For the subcritical case, for the lower azimuth angles,  $\theta \leq 78^\circ$ , the boundary layer profiles exhibit a weird behavior. Similarly, for the critical case, the overall thicknesses of the boundary layer are diminished, which is an expected effect due to the more favorable pressure gradient on the foreside of the cylinder, but the same problem regarding the quality of the results is still present.

**Table 5.11:** Boundary layer parameters for a cylinder with the smooth overlayer at  $Re = 18.4 \times 10^4$  and  $Re = 20.9 \times 10^4$  for varying  $\theta$ .

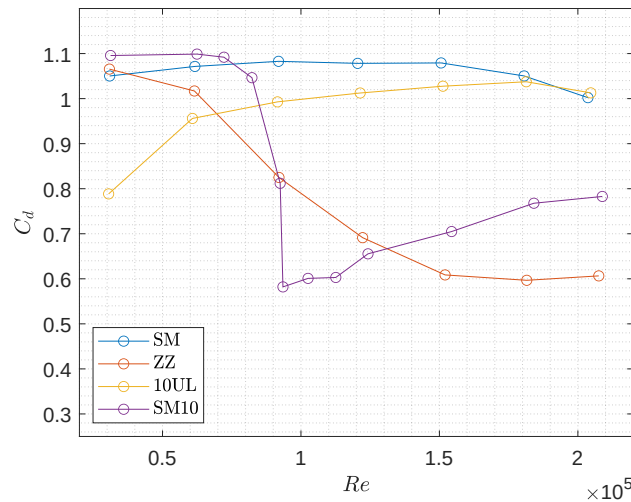
| $\theta$ [°] | $Re = 18.4 \times 10^4$ |                 |                 |         | $Re = 20.9 \times 10^4$ |                 |                 |         |
|--------------|-------------------------|-----------------|-----------------|---------|-------------------------|-----------------|-----------------|---------|
|              | $\delta_{99}$ [mm]      | $\delta^*$ [mm] | $\delta_m$ [mm] | $H$ [–] | $\delta_{99}$ [mm]      | $\delta^*$ [mm] | $\delta_m$ [mm] | $H$ [–] |
| 55           | 0.06                    | 0.002           | 0.002           | 1.03    | 0.07                    | 0.002           | 0.002           | 1.03    |
| 60           | —                       | —               | —               | —       | 0.17                    | 0.01            | 0.01            | 1.08    |
| 70           | 0.23                    | 0.02            | 0.02            | 1.15    | 0.18                    | 0.01            | 0.01            | 1.10    |
| 78           | 0.47                    | 0.09            | 0.06            | 1.43    | 0.29                    | 0.04            | 0.03            | 1.26    |
| 80           | 0.63                    | 0.24            | 0.08            | 3.21    | 0.37                    | 0.06            | 0.04            | 1.36    |
| 85           | 1.23                    | 0.80            | 0.08            | 10.36   | 0.78                    | 0.40            | 0.07            | 5.84    |

### 5.3.2. 10UL Underlayer

This configuration adds the underlayer with 10 mm spacing as a single fabric configuration. The effect of the exposed ribs on the flow will be studied.

#### Balance Results

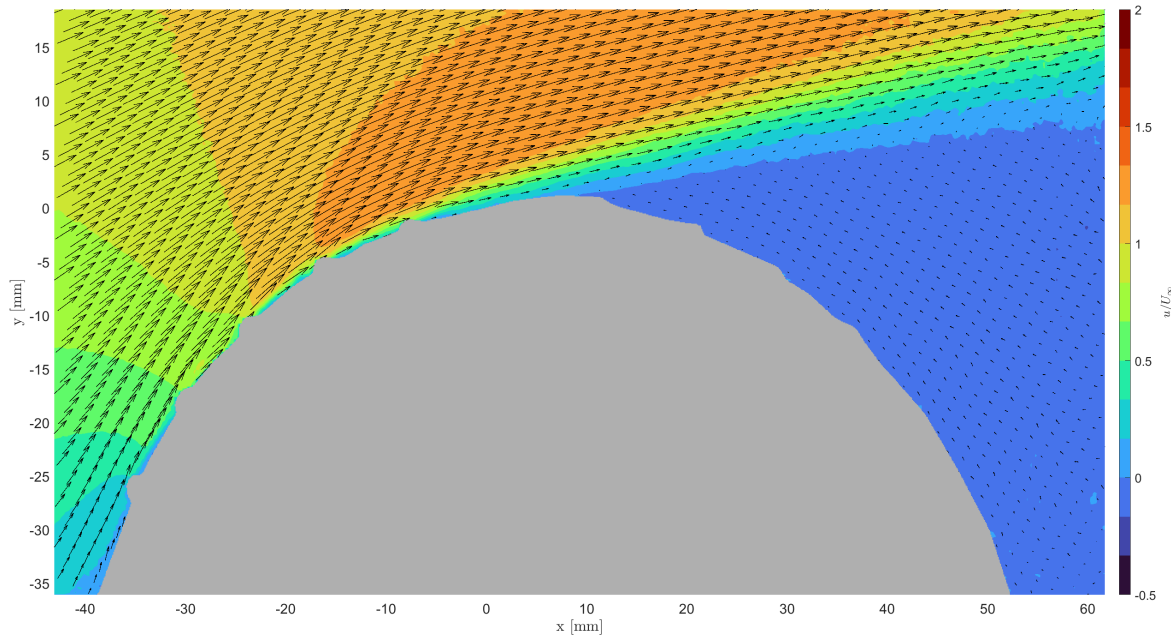
Figure 5.47 shows the  $C_d - Re$  curve for the 10UL fabric as a single fabric configuration compared to the smooth cylinder, the reference zigzag strip and the double-layer fabric configuration with this underlayer and the smooth overlayer.

**Figure 5.47:** Drag coefficient against Reynolds number for the cylinder with the smooth overlayer compared to the bare cylinder.

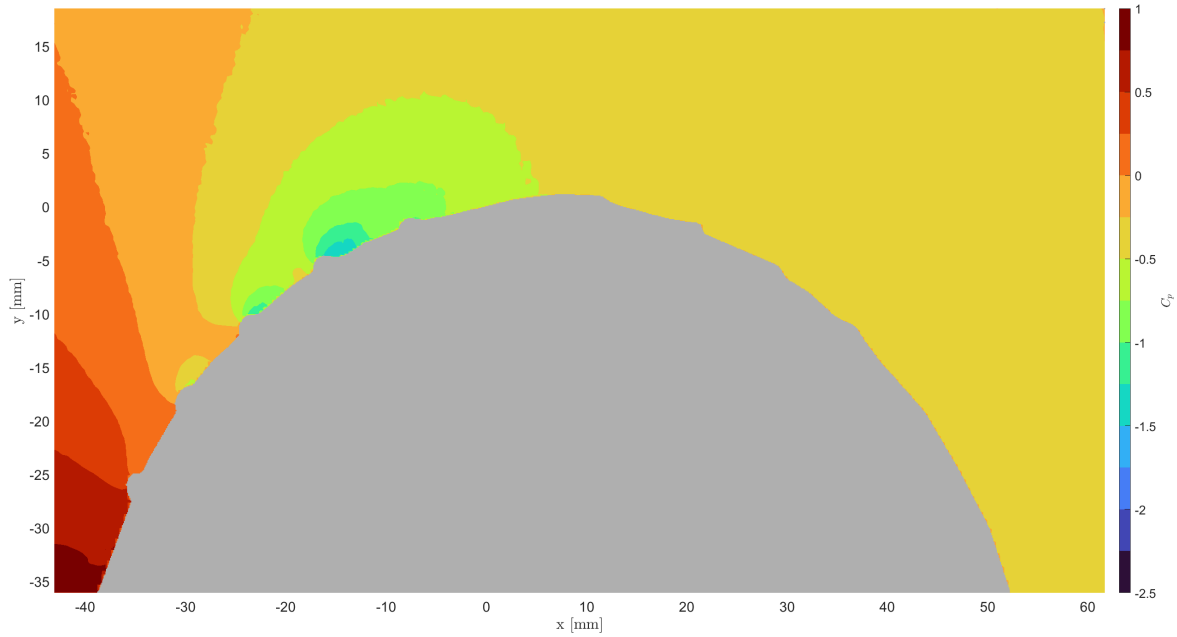
Examining the  $C_d - Re$  curve, it appears that the whole measurement range is located in the supercritical regime for the 10UL as a single fabric. Therefore, it will be assumed that the first measurement point will be the critical case, though in reality, it could be slightly lower, both in terms of  $C_{d,min}$  and  $Re_{crit}$ . Therefore, for 10UL the  $C_{d,min} = 0.79$  and  $Re_{crit} = 3.1 \times 10^4$ .

#### PIV Results

For this configuration, the chosen Reynolds number to study the 10UL as a single fabric is the Reynolds number that triggers the drag crisis for the SM10 configuration,  $Re = 9.3 \times 10^4$ , with the aim of determining how the exact same flow conditions would behave around that configuration if the smooth overlayer were to be removed. Figure 5.48 shows the normalized streamwise velocity field and the pressure coefficient field for this single fabric configuration.



(a) normalized velocity field around cylinder with the 10UL underlayer for  $Re = 9.3 \times 10^4$ .



(b) Pressure coefficient field around cylinder with the 10UL underlayer for  $Re = 9.3 \times 10^4$ .

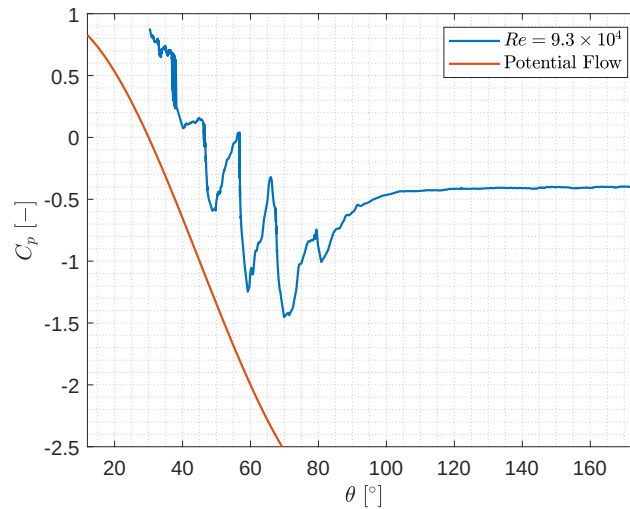
**Figure 5.48:** Normalized velocity and pressure coefficient fields around the cylinder with the 10UL underlayer for  $Re = 9.3 \times 10^4$ .

Examining the velocity and pressure coefficient fields, it can be seen that the ribs act as small steps placed along the surface of the cylinder. Two subsequent ribs effectively create a cavity on the surface of the cylinder. In the double-layer configurations, the air remained attached as it flowed past a rib on the foreside of the cylinder. Because of that, the diverging geometric effect after the rib caused the air to slow down, resulting in a rise in static pressure, and thus, a localized adverse pressure gradient. In the single underlayer case, a small separation is generated after the rib, resulting in recirculation after a rib; this results in a localized area of low pressure. In terms of pressure, this is the exact opposite effect, as the static pressure in the region drops due to the flow separation, rather than increasing because of the air slowing down. Conversely, on the foreside of the ribs, the flow stagnates on the base of the rib

causing a sudden spike in static pressure; this causes the foreside of the rib to behave like a spoiler or a forward-facing step, deflecting the air upwards.

In terms of pressure gradient, an interesting phenomenon occurs: the air that is leaving the tip of the rib tends to flow tangentially to the surface of the cylinder, thus creating the cavity in the base of the backside of the rib. This results in a pressure gradient in the radial direction,  $\frac{\partial p}{\partial r} > 0$ , this pressure gradient acts on the flow leaving the tip of the rib, effectively pulling it downwards toward the surface of the cylinder, like a backward facing step. This causes air to flow into the cavity; once this occurs, the air that is inside the cavity experiences a significant adverse pressure gradient as there is a low pressure zone at the back of the upstream rib and a high pressure zone on the foreside of the second rib, as the flow experiences a small stagnation.

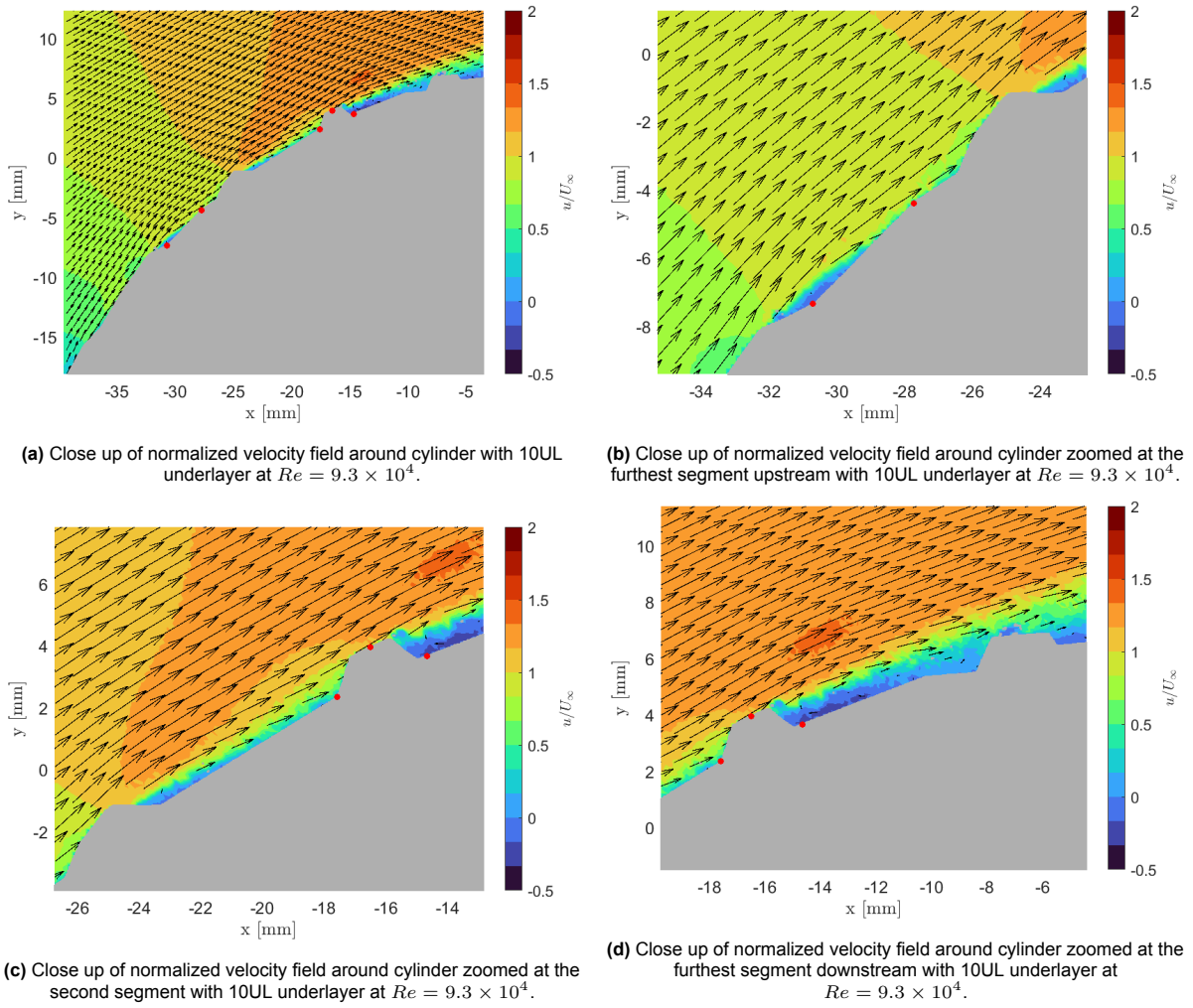
This pressure distribution can be better examined as it is shown in Figure 5.49. Compared to the double-layer cases, it is clear that the oscillations on the pressure coefficient are sharper and steeper, meaning that the pressure gradients are generally more intense. In overall terms, it can be observed that the suction peak at peak around  $\theta = 80^\circ$  is quite weak, for the double-layer cases, as the flow remained attached a stronger suction peak could be observed for subcritical, critical and supercritical flow regimes.



**Figure 5.49:** Pressure coefficient over cylinder surface vs  $\theta$  with 10UL underlayer for  $Re = 9.3 \times 10^4$ .

Additionally, the second PIV setup has been utilized to capture a higher resolution of the image field for  $Re = 9.3 \times 10^4$ . A close-up of the normalized velocity field is provided at different locations of the domain. This is done so the flow behavior around ribs at different  $\theta$  can be studied. Additionally, the boundary layer has been probed at certain locations,  $\theta = [47^\circ, 52^\circ, 67^\circ, 68.5^\circ, 71^\circ]$ , and the velocity profiles are shown in Figure 5.51.



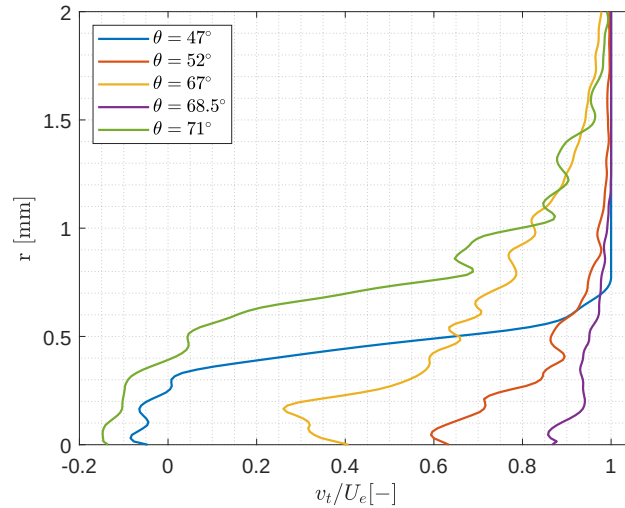


**Figure 5.50:** Close up and zoom-ins of normalized velocity fields around cylinder with 10UL underlayer at  $Re = 9.3 \times 10^4$ .

Looking at the zoomed-in snapshots of the time-averaged normalized velocity field, it is clear that the angle of the segment relative to the freestream flow has a significant effect on how the external flow fills the cavity and on the size of the recirculation bubble on the backside of the upstream rib.

Examining Figure 5.50d, this is the segment that is most easily filled by the external flow. Due to the location of the segment upstream on the foreside of the cylinder, this results in the relative angle between the segment and the freestream flow to be significant, allowing the freestream flow to push on the external flow and thus fill the cavity, resulting in a small separation. For the next segment, the angle is slightly more shallow and, as a result, the outer flow struggles a bit more filling the cavity. Finally, for the third segment, the angle becomes the shallowest and the external flow is effectively unable to fill the cavity, resulting in the space between those two ribs to have very slow-moving air.





**Figure 5.51:** Boundary layer profile at various  $\theta$  for cylinder with 10UL underlayer at  $Re = 9.3 \times 10^4$ .

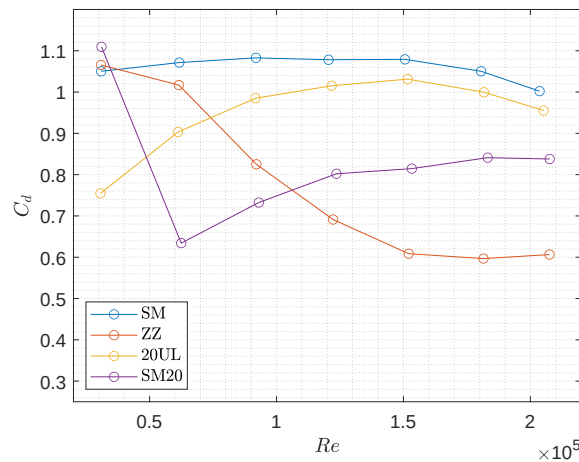
Examining the boundary layer profiles, it is clear that for the locations in the backside of a rib  $\theta = 47^\circ$  and  $\theta = 71^\circ$ , there is a small amount of backflow in the near-wall region indicating the appearance of a recirculation bubble. Additionally, out of the two locations, the downstream one,  $\theta = 71^\circ$  has a larger velocity deficit, caused by the fact that for that segment, the outer flow is unable to recover as easily as for the other probe. For the probe at  $\theta = 52^\circ$ , the outer flow has managed to flow into the cavity resulting in a fuller velocity profile. On the other hand, for the probe at  $\theta = 67^\circ$  right on the foreside of a rib, it can be seen that the velocity profile has lost some fullness likely due to the adverse pressure gradient present within the cavity.

### 5.3.3. 20UL Underlayer

For this configuration, the underlayer with 20 mm spacing is the subject of the study as a single fabric.

#### Balance Results

Figure 5.52 shows the  $C_d - Re$  curve for the 20UL fabric compared to the reference fabrics as well as its double-layer counterpart.



**Figure 5.52:** Drag coefficient against Reynolds number for the cylinder with the 10UL underlayer compared to other reference measurements.

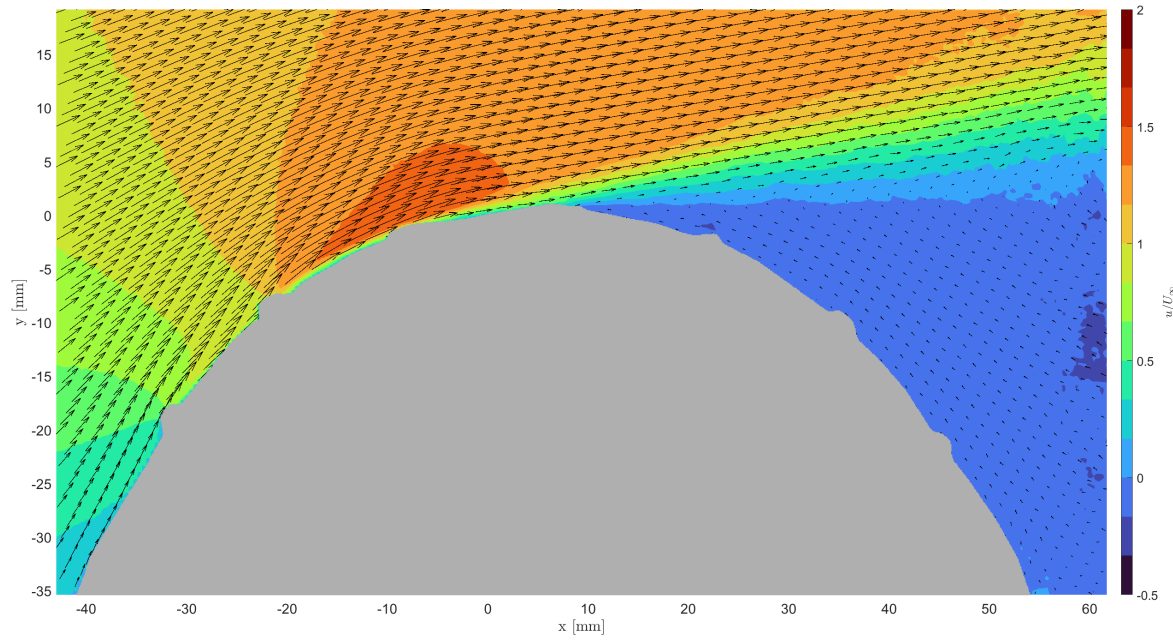
Similar for the 10UL configuration, it appears that the entire measurement range is located in the supercritical regime. Therefore, measurement at the lowest Reynolds number will be taken as the critical point, with a  $Re_{crit} = 3.1 \times 10^4$  and a  $C_{d,min} = 0.75$ . The minimum drag coefficient is slightly smaller than for the 10UL configuration.

#### PIV results

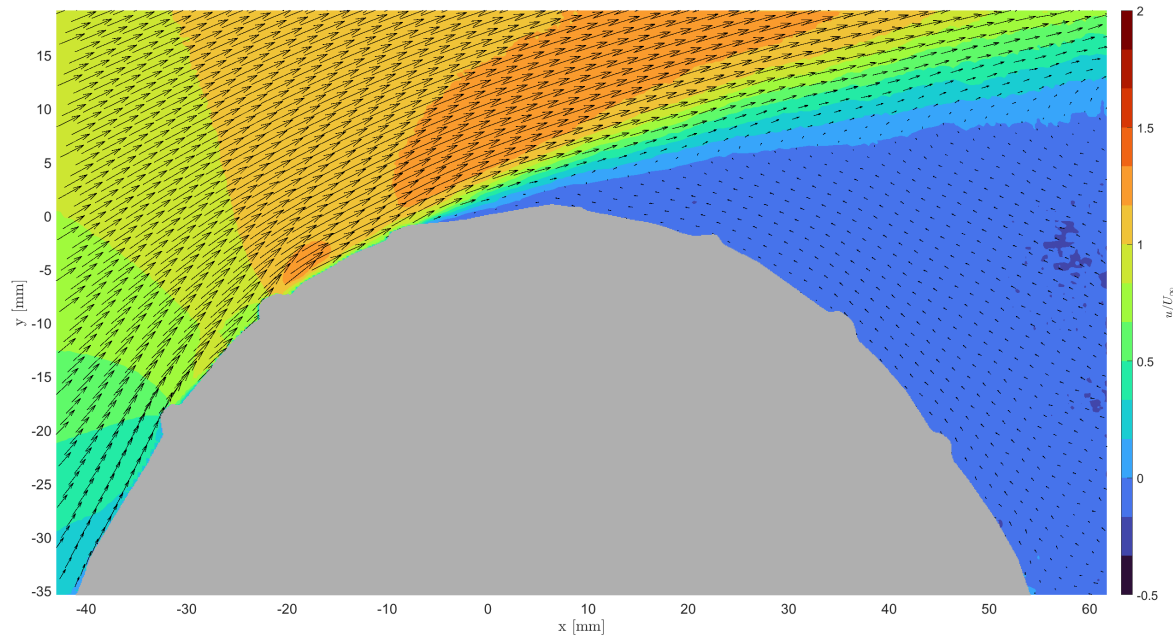
For the 20UL underlayer configuration, the chosen Reynolds numbers under which the PIV measurements were obtained have been  $Re = [3.1, 6.2, 9.3] \times 10^4$ . Figure 5.53 shows two normalized velocity fields for the Reynolds numbers of  $Re = 3.1 \times 10^4$  and  $Re = 9.3 \times 10^4$ . Additionally, Figure 5.54 shows the pressure coefficient fields for the same Reynolds numbers. The remaining configuration has been left out and is shown in the Appendix A.1.6.

The overall behavior of the flow remains consistent with the 10UL configuration. The air flows into a rib and it slows down and stagnates, resulting in an increased static pressure. Then, as it flows over the rib, it experiences an acceleration due to there being an increased pressure at the foreside of the rib. Right after flowing over a rib, the backside of the rib acts as a backwards-facing step, resulting in a small separation point behind the rib, and an area of low static pressure. This is the exact same behavior for the flow as for configuration 10UL.

Furthermore, analyzing the differences in the two different Reynolds numbers, it appears that the configuration with the lower Reynolds number is the one with the stronger suction peak and higher peak velocity, and it is also the measurement in which the flow stays attached a little better, as depicted by the angle of the shear layer emanating from the separation point. This is coherent with the known information as this is the supercritical regime and lower Reynolds numbers approach the critical regime, which corresponds to the case in which the separation point moves the furthest downstream and the velocity and suction peak are the strongest.

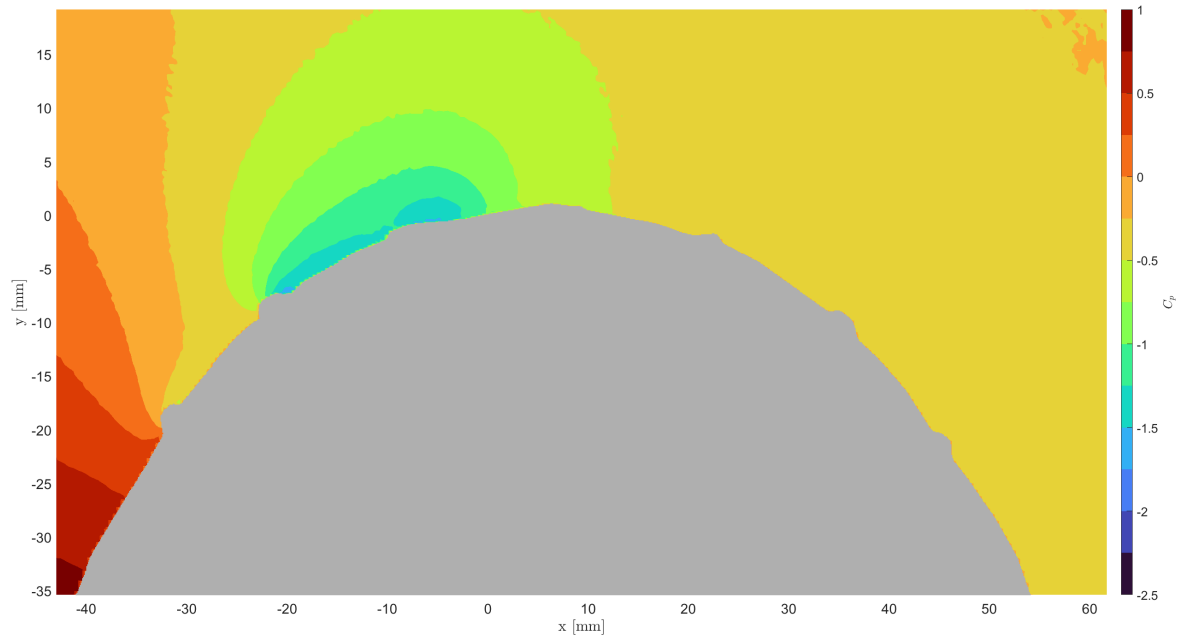


(a) normalized velocity field around cylinder with the 20UL underlayer for  $Re = 3.1 \times 10^4$ .

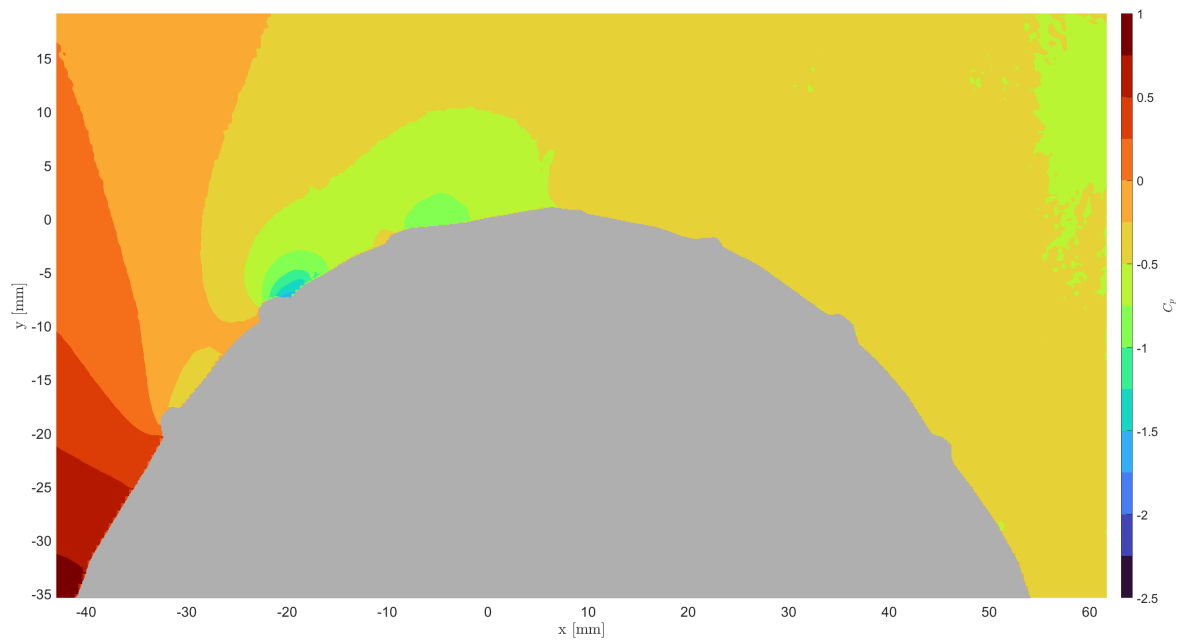


(b) normalized velocity field around cylinder with the 20UL underlayer for  $Re = 9.3 \times 10^4$ .

**Figure 5.53:** normalized velocity fields around the cylinder with the 20UL underlayer for  $Re = 3.1 \times 10^4$  and  $Re = 9.3 \times 10^4$ .



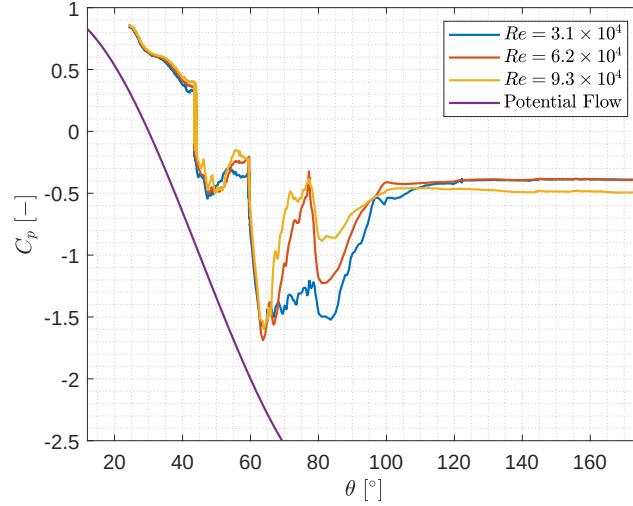
(a) Pressure coefficient field around cylinder with the 20UL underlayer for  $Re = 3.1 \times 10^4$ .



(b) Pressure coefficient field around cylinder with the 20UL underlayer for  $Re = 9.3 \times 10^4$ .

**Figure 5.54:** Pressure coefficient fields around the cylinder with the 20UL underlayer for  $Re = 3.1 \times 10^4$  and  $Re = 9.3 \times 10^4$ .

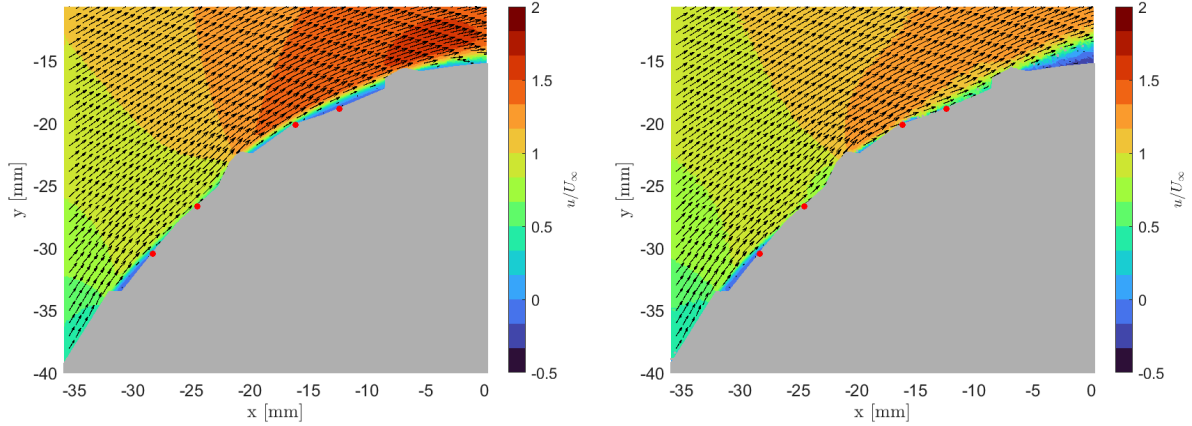
The pressure distributions along the surface of the cylinder have been computed and they are shown for all three Reynolds numbers in Figure 5.55:



**Figure 5.55:** Pressure coefficient over cylinder surface vs  $\theta$  with 20UL underlayer for  $Re = [3.1, 6.2, 9.3] \times 10^4$ .

Once again, with larger rib spacing, the frequency of the pressure oscillations on the foreside of the cylinder decreases, as the ribs are the elements responsible for the localized changes of static pressure along the surface of the cylinder. The pressure distribution for  $Re = 3.1 \times 10^4$  stands out because the pressure remains low for  $70^\circ \leq \theta \leq 90^\circ$ , as the flow remains attached to the cylinder in that region.

Additionally, the second PIV setup has been utilized to capture a set of images that allow for the resolution of the velocity field with a greater degree of spatial accuracy. The normalized velocity fields for  $Re = 3.1 \times 10^4$  and  $Re = 9.3 \times 10^4$  are shown in Figure 5.56.



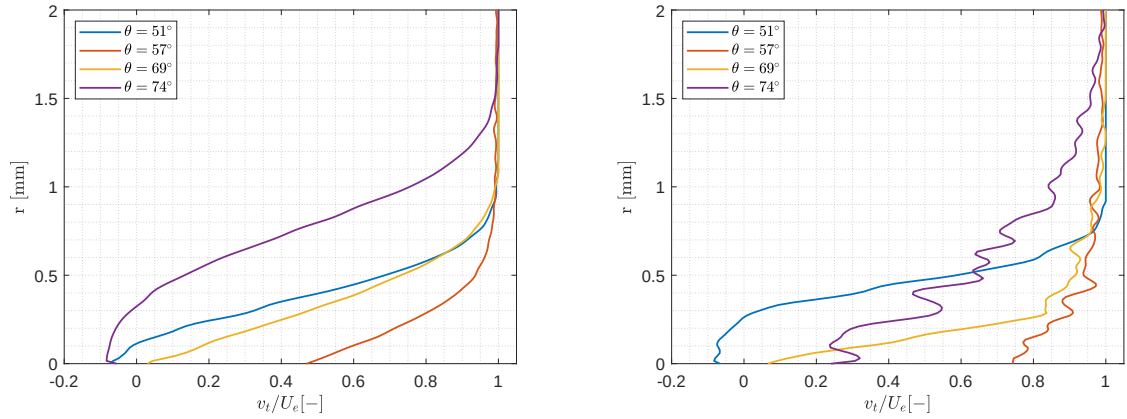
**(a)** Close up of normalized velocity field around double layer cylinder with 20UL underlayer at  $Re = 3.1 \times 10^4$ .

**(b)** Close up of normalized velocity field around double layer cylinder with 20UL underlayer at  $Re = 9.3 \times 10^4$ .

**Figure 5.56:** Close up of normalized velocity fields around double layer cylinder with 20UL underlayer at  $Re = 3.1 \times 10^4$  and  $Re = 9.3 \times 10^4$ .

The effects of the Reynolds number can be observed, as the same configuration has been measured with PIV across different flow conditions. In this instance, the case in which the drag is lower is for the flow field shown in Figure 5.53a. In this flow field, it can be observed that for the second segment between the ribs, the outer flow is not incurring into the cavity, resulting in an isolated recirculation within the cavity. Conversely, as the Reynolds number is increased, the outer flow gains streamwise momentum, resulting in the incursion of the outer flow into the cavity. This, in turn, results in the flow stagnating against the foreside of the rib and the rib causing an upward deflection of the flow leading to the onset of separation.

Additionally, the boundary layer has been proved at the locations indicated with magenta markers in Figure 5.56, corresponding to  $\theta = [51^\circ, 57^\circ, 69^\circ, 74^\circ]$ . The velocity profiles are shown in Figure 5.57:



(a) Boundary layer profile at various  $\theta$  for cylinder 20UL underlayer at  $Re = 3.1 \times 10^4$ .

(b) Boundary layer profile at various  $\theta$  for cylinder 20UL underlayer at  $Re = 9.3 \times 10^4$ .

**Figure 5.57:** Boundary layer profiles at various  $\theta$  for cylinder 20UL underlayer at  $Re = 3.1 \times 10^4$  and  $Re = 9.3 \times 10^4$ .

For the first segment,  $\theta = 51^\circ \rightarrow 57^\circ$ , the first probe captures a bit of the recirculation bubble, as the velocity at the wall is negative. For the next probe, along the same segment, the outer flow has incurred in the cavity resulting in an injection of momentum, thus the boundary layer has become fuller and the recirculation bubble has been closed further upstream.

Conversely, for the second segment,  $\theta = 69^\circ \rightarrow 74^\circ$ , in the case for the lower Reynolds number, the recirculation appears for the probe at  $\theta = 74^\circ$ , but conversely is not observed on the probe at  $\theta = 69^\circ$ , this is likely a slight misrepresentation of the results, as looking at the velocity fields, the recirculation bubble is clearly there. Therefore, it leads to the conclusion that the mask is intruding in the cavity too far, thus resulting in loss of information of the flow in that particular region. Whereas, for the critical value, the probe located at  $\theta = 74^\circ$  does not indicate any recirculation, as the bubble has been closed because of the incursion of the outer flow.

# 6

## Conclusion

Once concluded the analysis and discussion of the experimental results, it is relevant to provide answers to the posed research question exposed in Section 2.4 based on the obtained results.

### 6.1. Main Research Question

**What is the mechanism responsible for the drag crisis behavior of cylinders with double-layer fabrics?**

Throughout Chapter 5, the flow fields around cylinders with different fabric configurations have been presented and examined. Based on the flow development along the foreside of the cylinders with double-layer fabrics, it can be stated that the localized favorable and adverse pressure gradients that appear due to the geometric effect of the ribs are the main driving mechanism of the trigger for the drag crisis. As the rib interferes with the flow, a localized flow convergence results in an acceleration and a pressure drop, which causes a favorable pressure gradient. Once the air flows past the rib, the flow experiences a divergence and thus a slow-down and an increase in static pressure.

These repeated favorable and adverse pressure gradients aid in the development of the boundary layer through the seeding of instabilities introduced by the adverse pressure gradients, effectively causing it to transition earlier than the case for a smooth cylinder or even a cylinder with roughness. Therefore, the onset of the crisis can be triggered at a lower Reynolds number. Additionally, the presence of the rib generates a small radial component of the velocity, which aids the boundary layer in maintaining its momentum in the near-wall region through advection from the higher momentum external flow, preventing an early flow separation.

The overlayer plays the role of acting as a pseudo impermeable layer that smoothens out the sharp step of the rib, resulting in the gradual change of geometry that allows for these flow phenomena to occur. Additionally, a small amount of roughness on the smooth overlayer enhances mixing in the near wall region and makes the overall flow more resistant to separation.

In the context of sport aerodynamics, these findings are particularly interesting, as the addition of an underlayer allows for the optimization of the drag coefficient of the studied body part for a specific Reynolds number. This has been shown in Section 5.2.1, the relation of the underlayer spacing and the critical Reynolds number.

### 6.2. Secondary Research Questions

**Does fabric deformation have an effect on the drag crisis behavior?**

In order to determine the extent and significance of fabric deformation, the raw PIV images have been compared for different wind speeds and configurations.

The images with the comparison of different configurations and different airspeeds are shown in Figures 5.21 & 5.35. Based on this comparison, no relevant fabric deformation is captured, and the fabric outlines present the same geometry in both subcritical, critical and supercritical regimes. Therefore, it can be confidently stated that fabric deformation is not a relevant factor in the drag crisis behavior.

**Is fabric porosity significant enough that it would affect the flow around the cylinder, influencing the triggering mechanism for the drag crisis?**

In order to determine the relevance of fabric porosity, the wall normal/radial velocity profiles along segments in between two ribs have been computed for the studied double layer configurations. The wall normal velocity profiles are shown in Figures 5.23 & 5.34. As seen in these velocity profiles, in the regions neighboring the rib at both ends of the segment, there is a significant component of the radial velocity. This is due to the fact that the ribs cause the aforementioned convergence and divergence effect on the flow, resulting in some radial components at the end of the segments. The reason why these components are being measured rather than the actual velocity component through the fabric is that the PIV masking cannot be done flush with the cylinder boundaries due to the presence of fabric reflections. Furthermore, in the central part of the segment, the velocity profiles are on average null.

All in all, based on these results and other findings from Oggiano [28] and Bardal [5], it can be stated that the effect of fabric porosity does not play a significant role in the behavior of the drag crisis for cylinders with double layer fabrics.

**How is the drag crisis influenced by the height and spacing between the ribs of the underlayer?**

It has not been possible to study the effect of rib height in isolation in this thesis, due to the unavailability of underlayers varying in rib height whilst maintaining the same rib spacing. Though, with the findings obtained from the study of the SM10 and SM20 configurations, some hypotheses can be made regarding the effect of varying rib height. With increasing rib height, the localized flow convergence and divergence effects are strengthened as the disturbance on the flow along the surface of the cylinder is directly related to the height of the ribs. As such, with an increased intensity of the favorable and adverse pressure gradients, the drag crisis will likely occur at a lower critical Reynolds number due to an earlier transition from laminar to turbulent flow along the foreside of the cylinder.

On the other hand, the effect of fabric spacing for a similar rib height has been determined through the study of the SM10 and SM20 configurations. Based on the balance results from the SM10 and SM20 configurations, it is clear that increasing rib spacing will promote a much earlier drag crisis, as seen in the  $C_d - Re$  curves. The same phenomenon is also observed when comparing the SM05 and SM07 configurations. As previously stated, the adverse pressure gradients seed instabilities in the flow, if left to develop, these instabilities will trigger laminar to turbulent transition. For that reason, when the rib spacing is increased, the region for instability development/growth is increased and thus the drag crisis is triggered at a lower Reynolds number due to an earlier transition.

**What are the differences in the flow fields between the underlayer alone and the double-layer fabric?**

As seen in the last section of Chapter 5, if the overlayer is removed, the ribbed fabric has a totally different effect on the flow. Given that there is no overlayer to smoothen out the fabric ribs, the sharp ribs become a very localized disturbance on the surface of the cylinder. The ribs effectively become discrete steps along the surface of the cylinder, these elements cause localized stagnations and separations on their fore and backside respectively, effectively acting as a forward and backward facing step. Furthermore, for higher azimuthal locations, the ribs can cause a much earlier flow separation from the cylinder due to the flow stagnating at the front of the rib and failing to reattach past the rib, thus leading the rib to behave like a spoiler.



## 6.3. Considerations and Recommendations for Future Work

Based on the carried out research and the gained insight from it, some considerations and recommendations can be formulated as guidelines for future work or future developments of this thesis.

### **Research into shape effects as opposed to the double layer fabric construction.**

Based on the drag crisis trigger mechanism studied in this thesis project, there is no indication, a priori, that this effect could not be achieved with a single fabric that replicated the effect of the overlayer plus underlayer combination. This would completely eliminate the need for a two layer fabric construction, thus simplifying and streamlining the usage of the fabrics in order to achieve aerodynamic gains. Furthermore, throughout the experimental campaign, it was noted that the two layers of fabrics can be a bit challenging to set on the cylinder/body part, especially if the overlayer is a tight fit. The hypothesized single fabric with the combined effects would completely eliminate this issue in addition to avoiding wrinkles and other issues in the underlayer fabrics that might result in reduced aerodynamic performance.

In order to achieve this, a single fabric would need to be constructed such that, when it is laid over the cylinder, it would recreate the geometry achieved with the double fabric construction.

### **Effect of rib height**

As previously mentioned, the effect of rib height has not been explicitly measured, and although some educated hypotheses have been formulated, they still need to be verified. For future developments of this thesis project, it would be interesting to obtain underlayers of the same rib spacing but vastly different rib heights. Then, by studying the double layer construction with varying rib heights, the effect of rib height on the flow will be able to be studied and analyzed, as there already exist studies in the literature regarding the  $C_D - Re$  curves.

### **Unsteady flows and cylinder inclination**

In this thesis, the model has been studied in a steady manner without any consideration of flow in the axial direction of the cylinder, perpendicular to the  $x - y$  plane. This cross-plane flow component would result in a three-dimensional flow and the effects of such flow were not in the scope of this thesis project. However, in real-world applications, as these fabrics could be employed as garments on suits for high-performance athletes, such flow scenarios with cross-plane components will definitely appear as a result of athlete movement, of changing external conditions.

Additionally, the effect of unsteady flow has not been considered, either by a varying yaw angle of the outer flow or an oscillating outer velocity magnitude. These flow scenarios are appropriate, given that the intended use for these types of fabrics would be in the limbs of the athletes, locations where the flow would experience oscillations in both yaw and magnitude as the athlete moves.

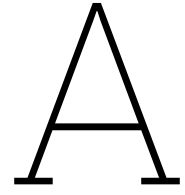
The operation of the double layer fabrics in these flow conditions is unknown, there will likely be hysteresis effects in the flow and in the drag as the tunnel outlet conditions are varied.

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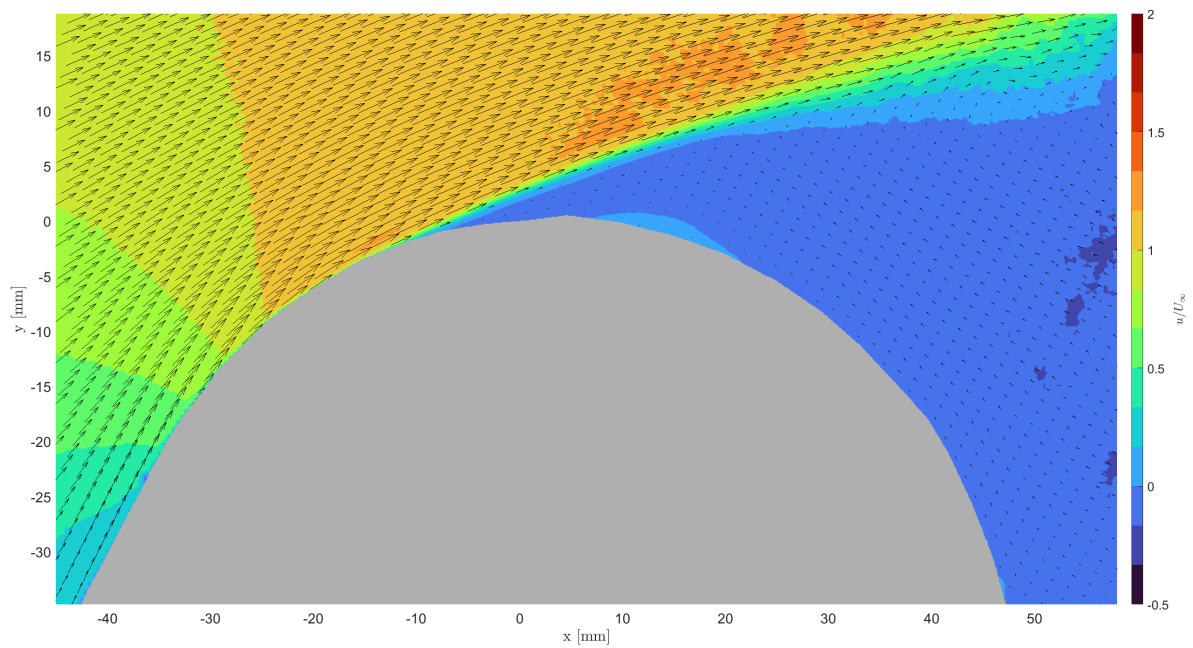
# Appendix

This appendix chapter is a compilation of all the flow contours analyzed for this thesis project. They are separated by the distinct configurations and the fields displayed are the normalized velocity field, the pressure field and the close-up normalized velocity field obtained from setup 2.

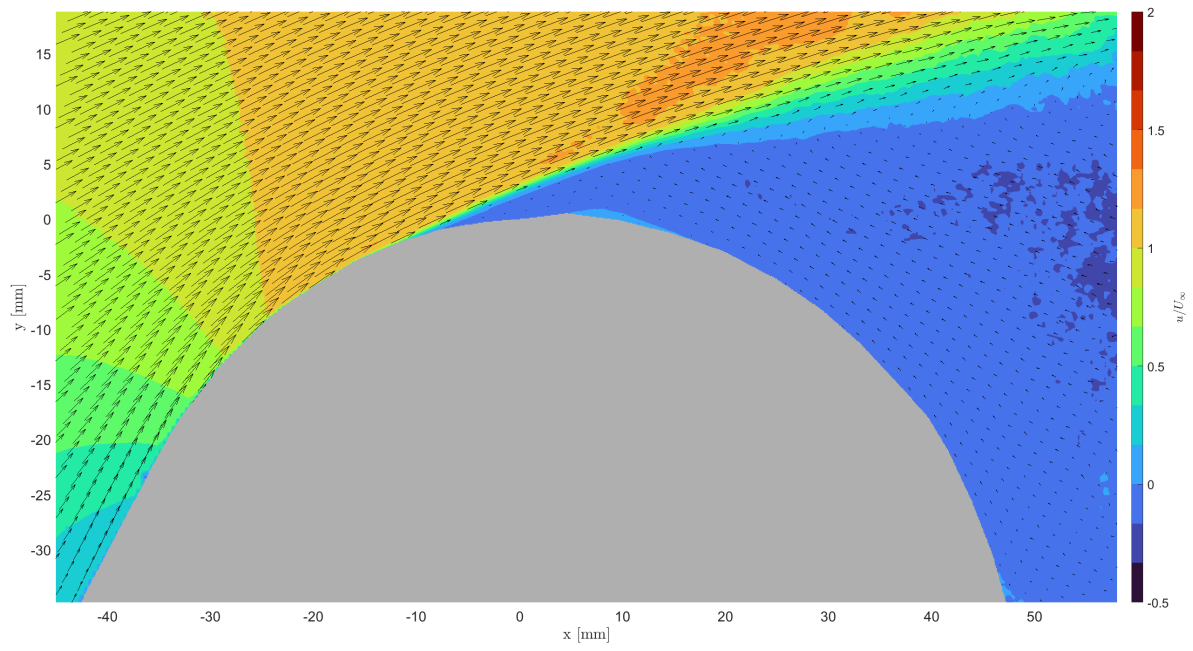
## A.1. Results

### A.1.1. Bare Cylinder

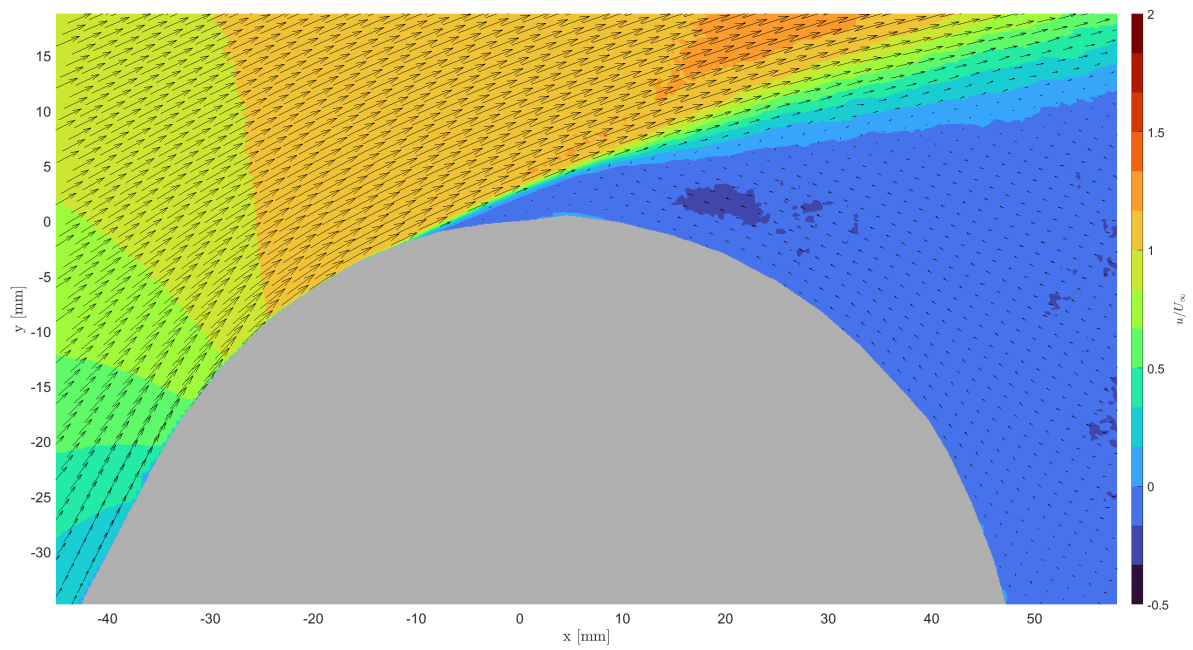
#### Velocity Fields



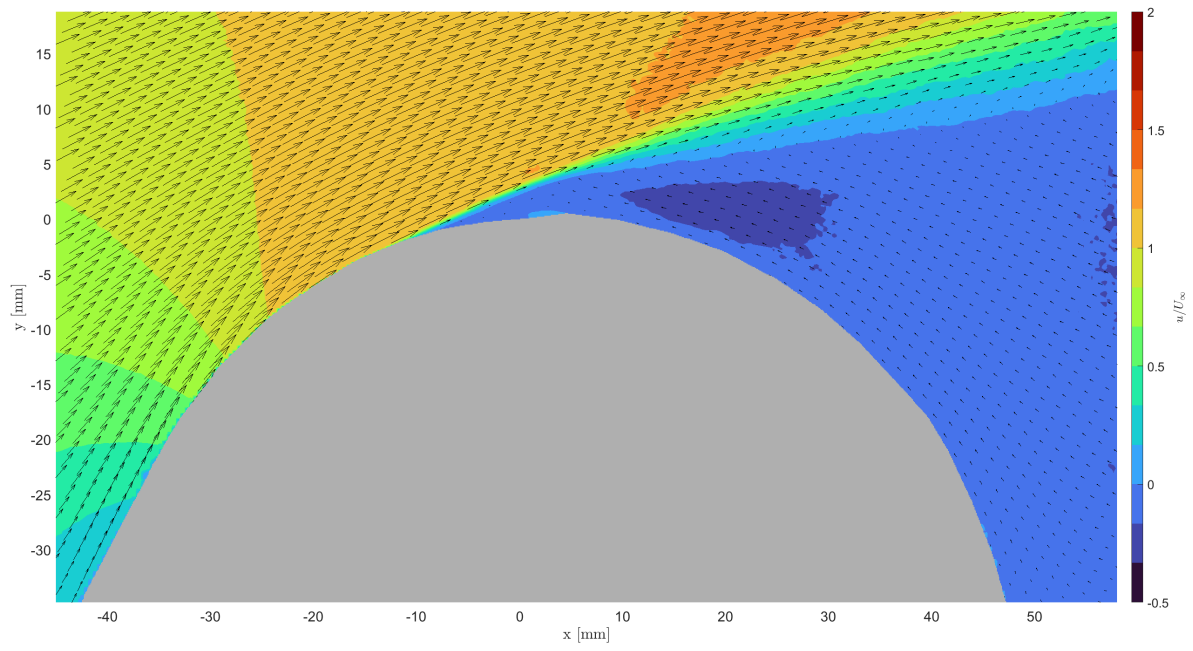
**Figure A.1:** Normalized velocity field around bare cylinder for  $Re = 3.1 \times 10^4$ .



**Figure A.2:** Normalized velocity field around bare cylinder for  $Re = 6.2 \times 10^4$ .

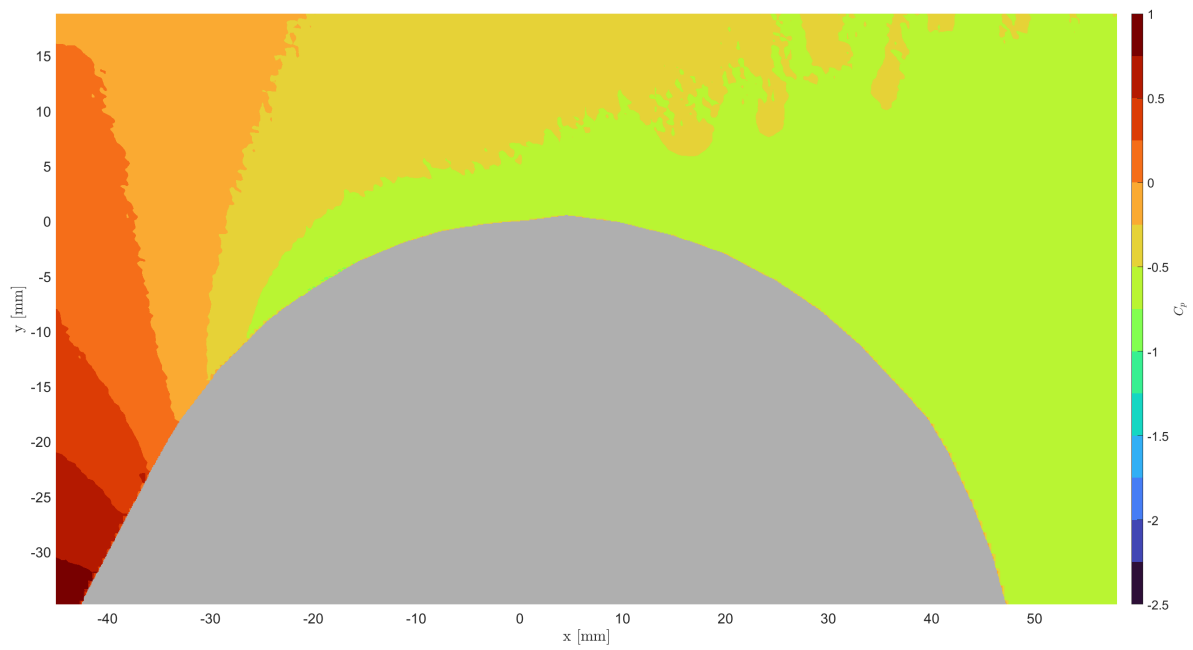


**Figure A.3:** Normalized velocity field around bare cylinder for  $Re = 9.3 \times 10^4$ .

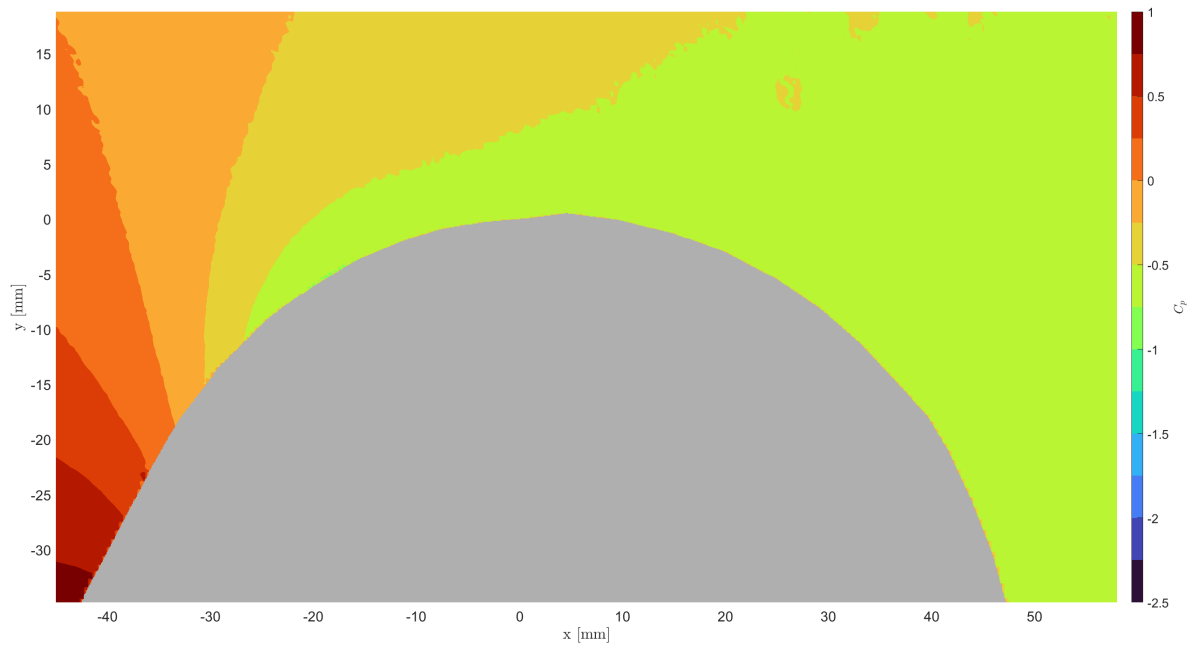


**Figure A.4:** Normalized velocity field around bare cylinder for  $Re = 12.4 \times 10^4$ .

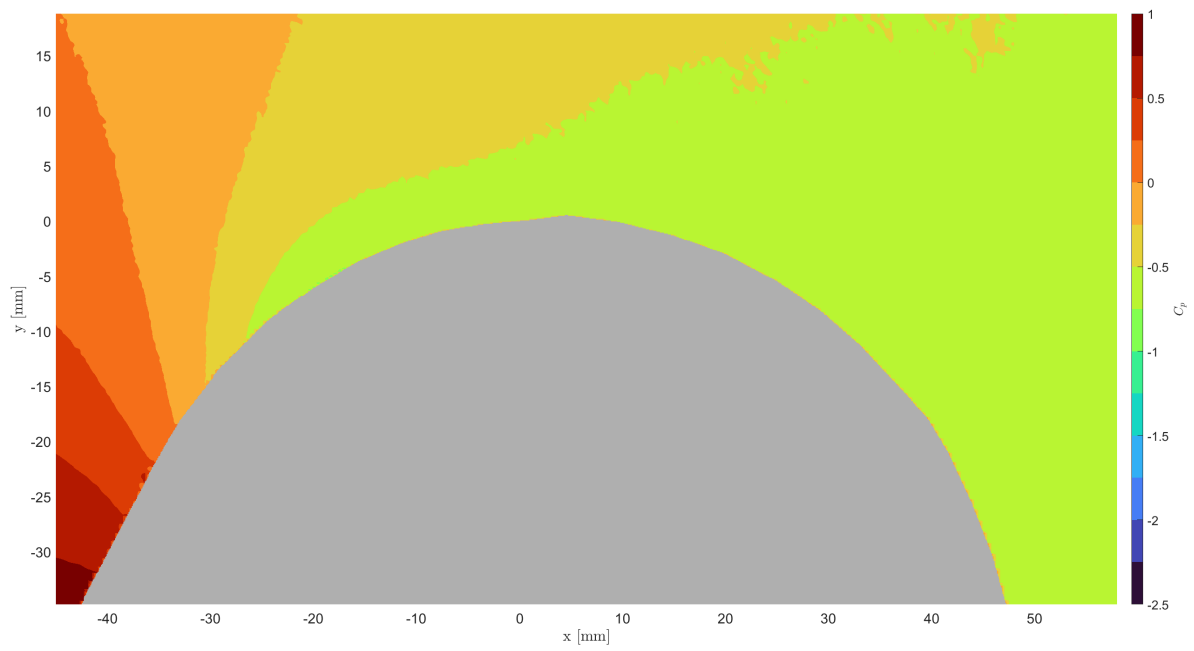
### Pressure Coefficient Fields



**Figure A.5:** Pressure coefficient field around bare cylinder for  $Re = 3.1 \times 10^4$ .

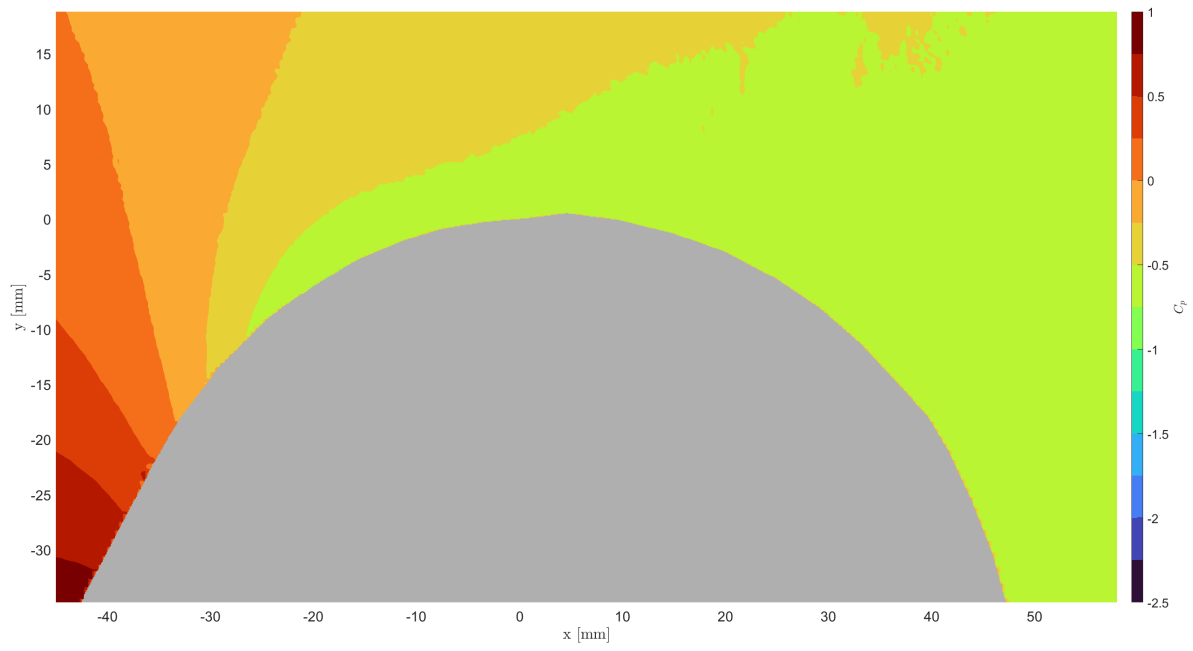


**Figure A.6:** Pressure coefficient field around bare cylinder for  $Re = 6.2 \times 10^4$ .



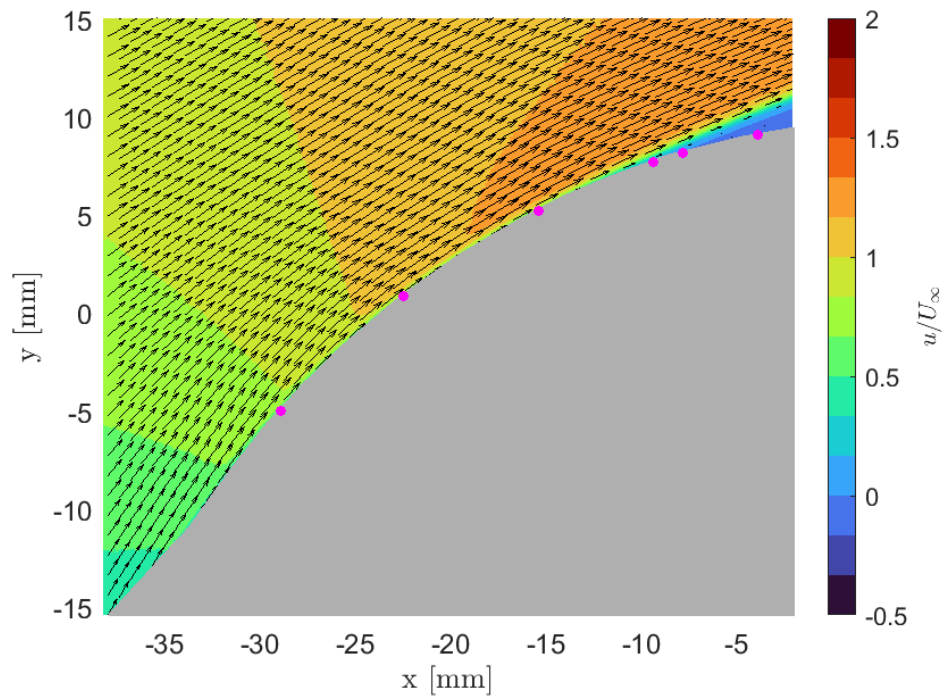
**Figure A.7:** Pressure coefficient field around bare cylinder for  $Re = 9.3 \times 10^4$ .



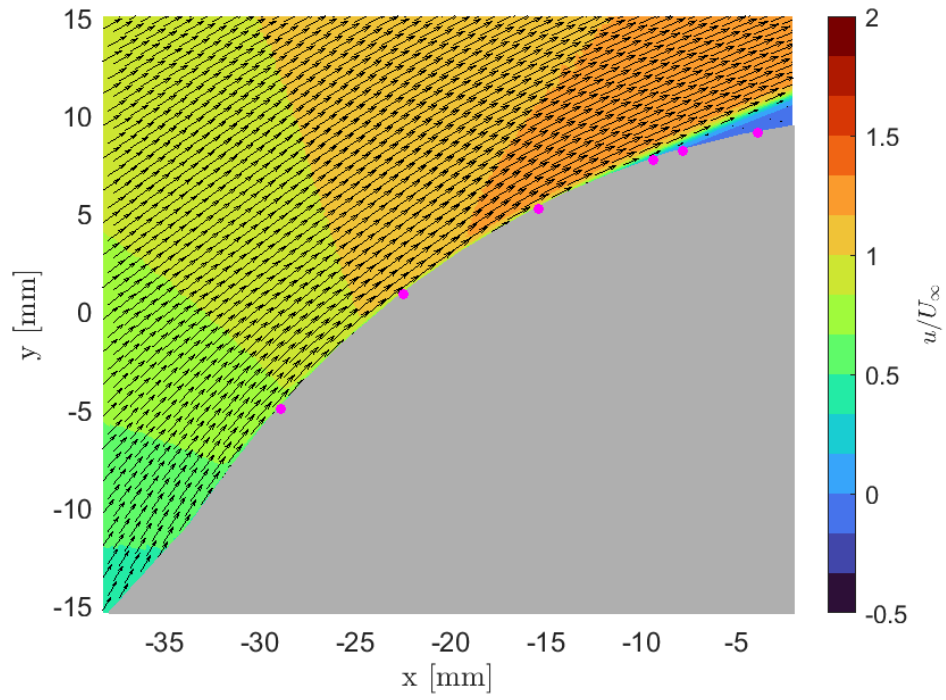


**Figure A.8:** Pressure coefficient field around bare cylinder for  $Re = 12.4 \times 10^4$ .

### Velocity Fields Setup 2



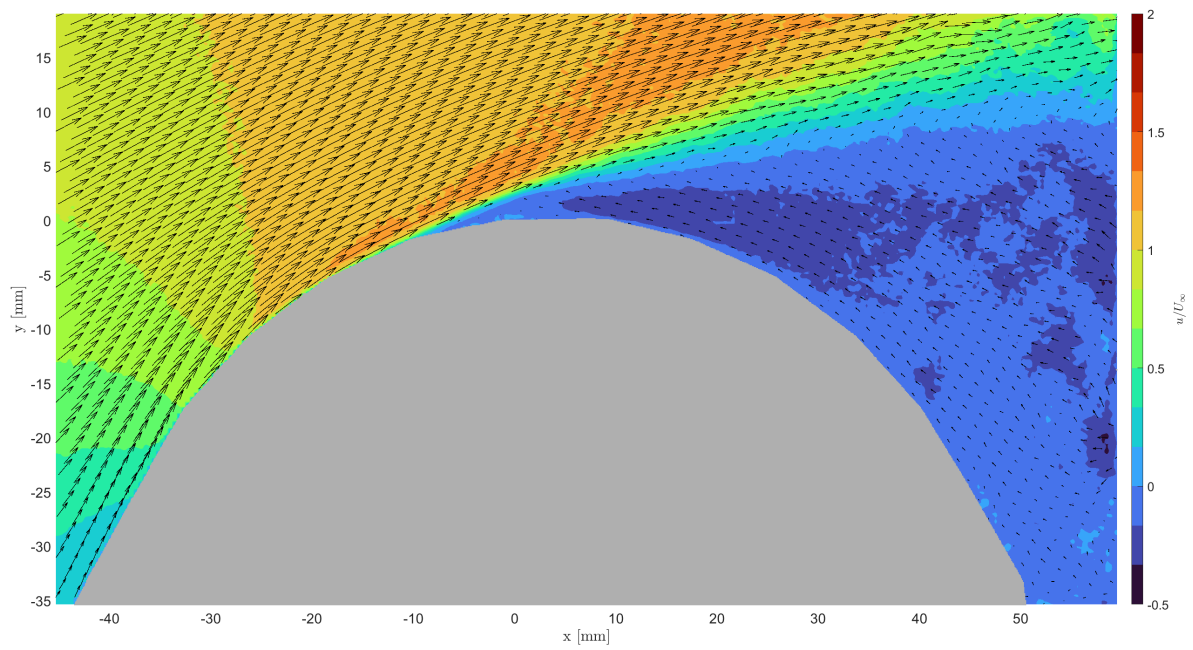
**Figure A.9:** Close up of normalized velocity field around bare cylinder for  $Re = 6.2 \times 10^4$ .



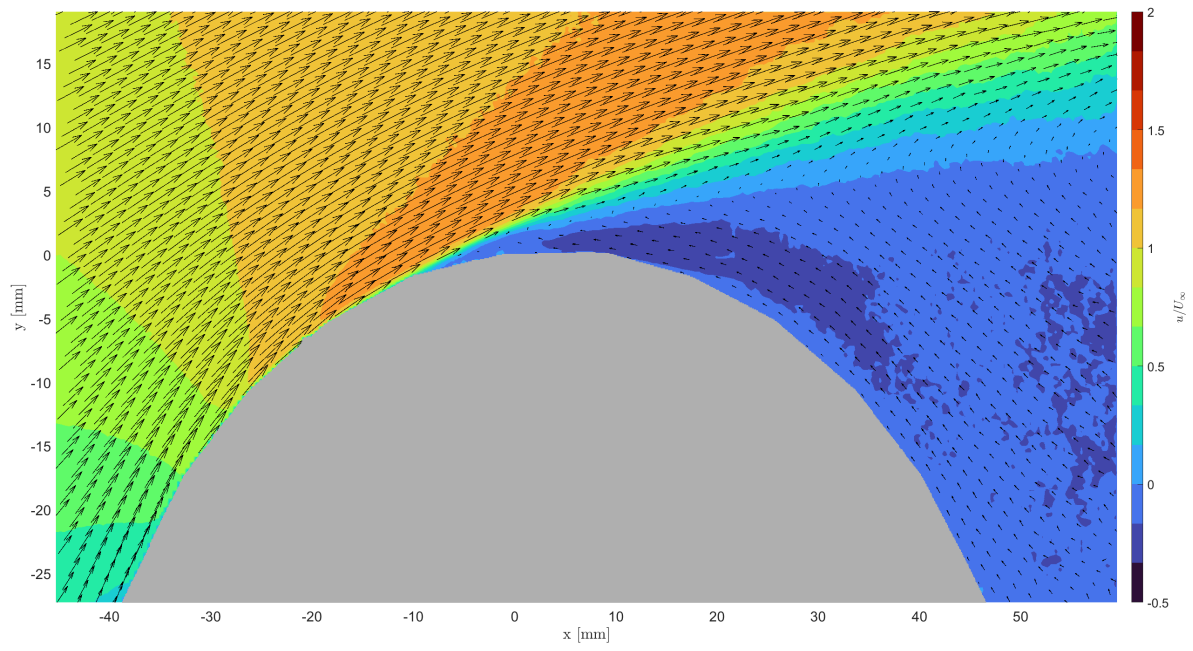
**Figure A.10:** Close up of normalized velocity field around bare cylinder for  $Re = 9.3 \times 10^4$ .

### A.1.2. SM10 Configuration

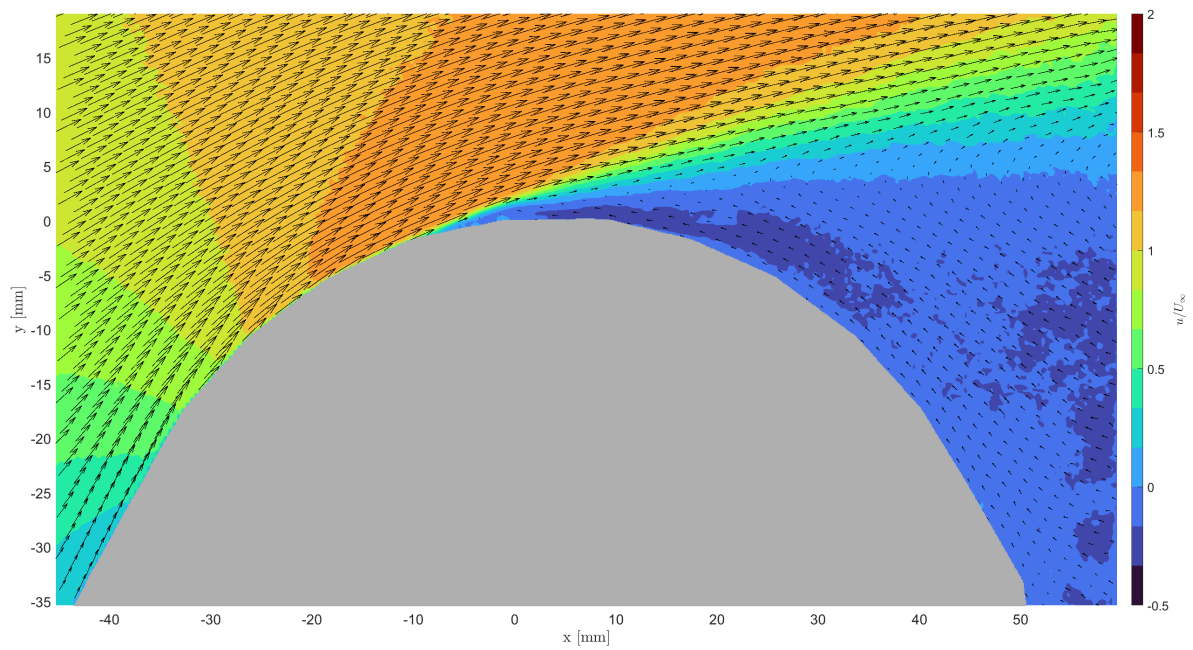
#### Velocity Fields



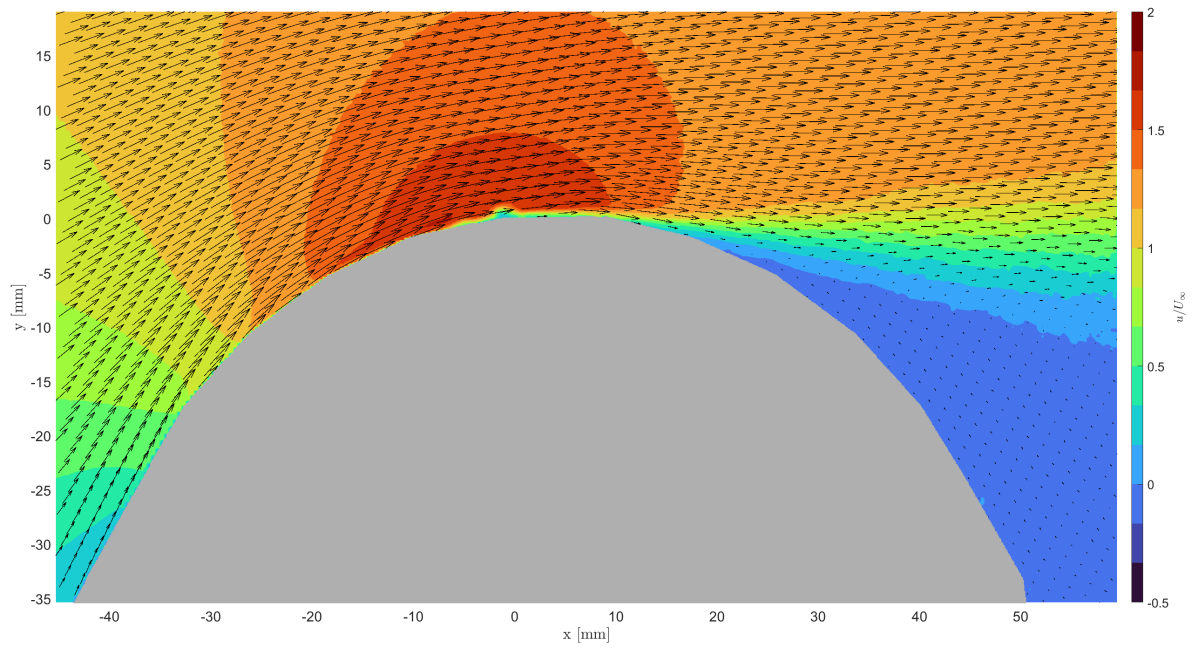
**Figure A.11:** Normalized velocity field around cylinder with double layer fabric with smooth overlayer and 10UL underlayer at  $Re = 6.2 \times 10^4$ .



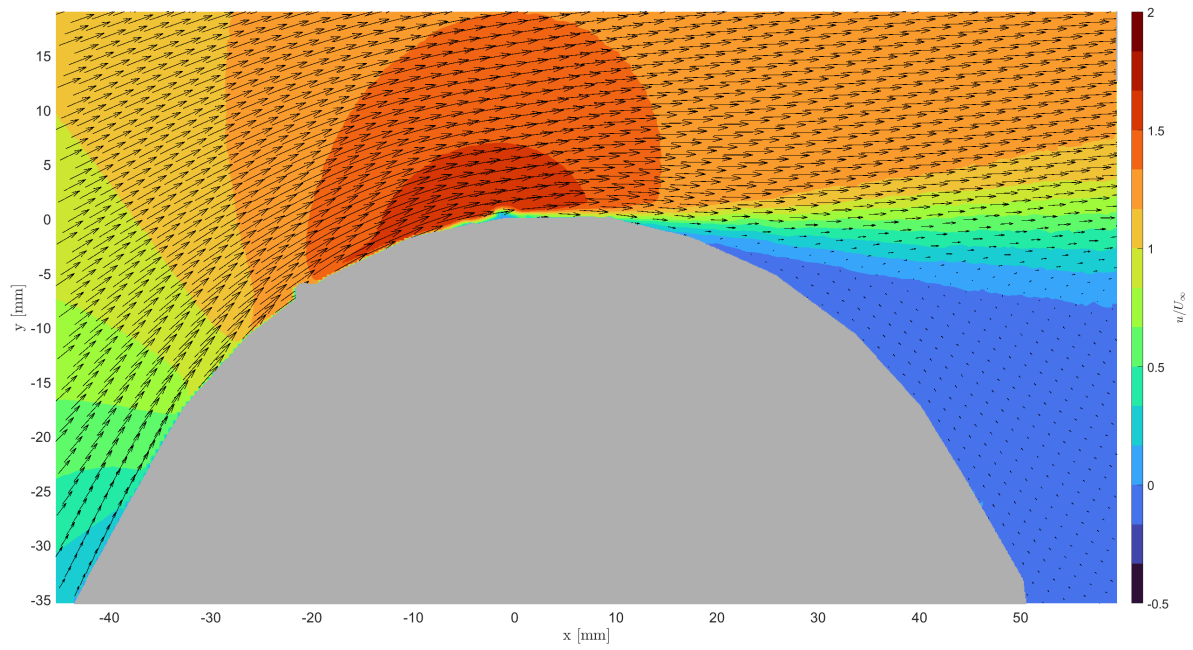
**Figure A.12:** Normalized velocity field around cylinder with double layer fabric with smooth overlayer and 10UL underlayer at  $Re = 7.2 \times 10^4$ .



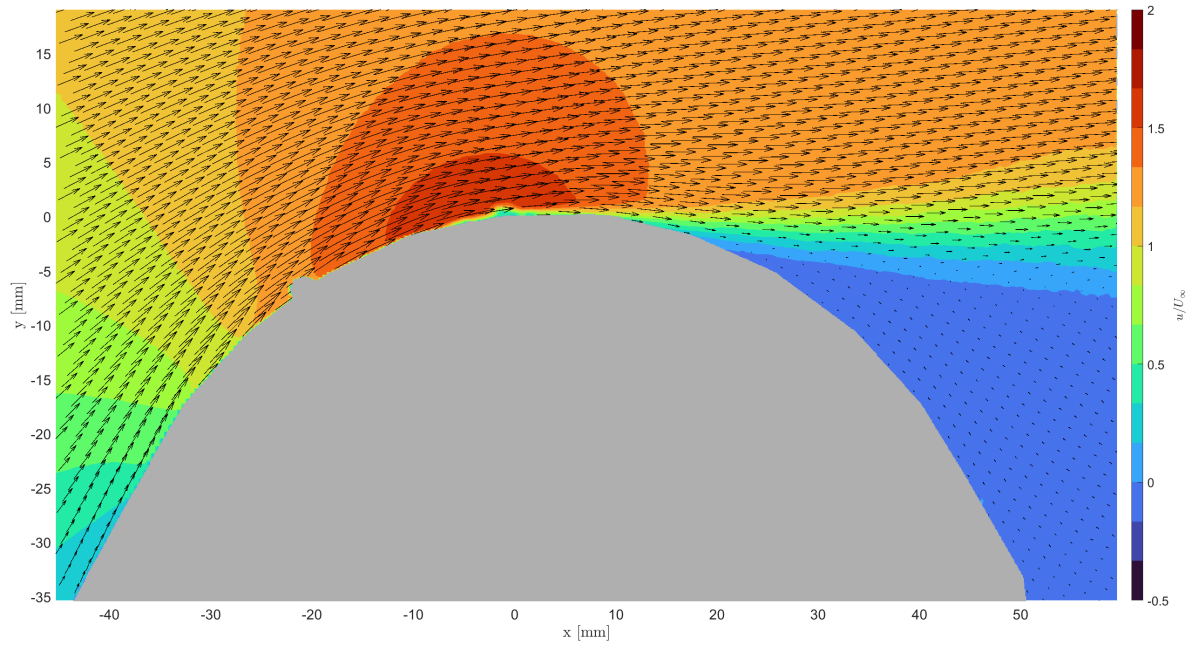
**Figure A.13:** Normalized velocity field around cylinder with double layer fabric with smooth overlayer and 10UL underlayer at  $Re = 8.2 \times 10^4$ .



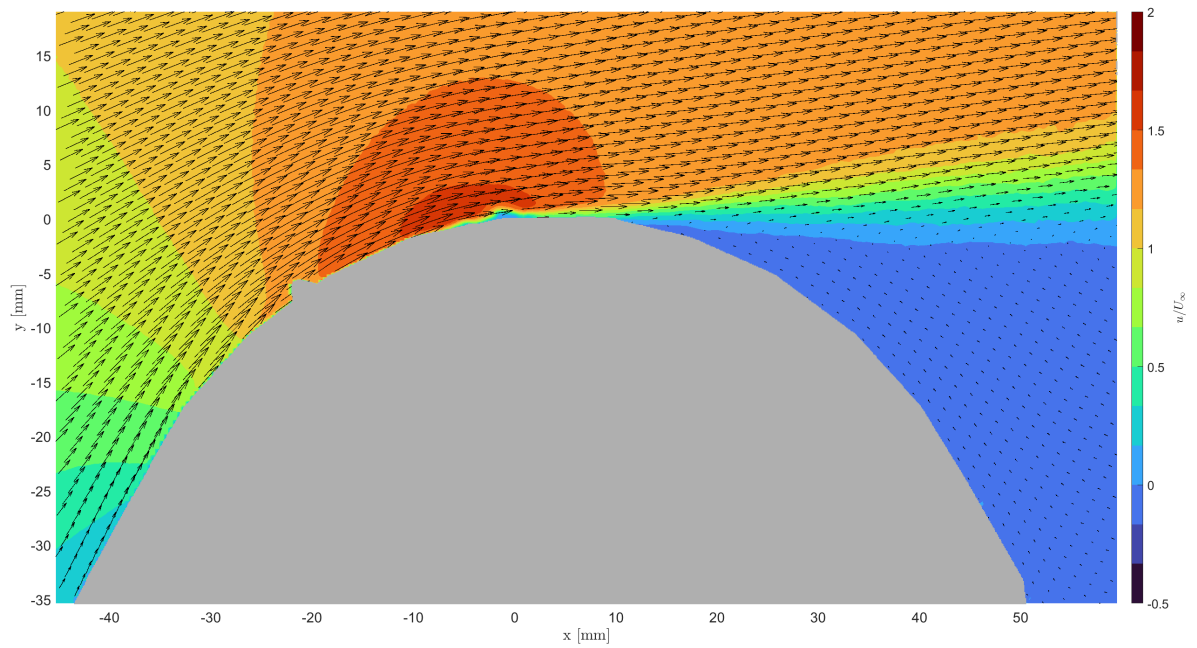
**Figure A.14:** Normalized velocity field around cylinder with double layer fabric with smooth overlayer and 10UL underlayer at  $Re = 9.3 \times 10^4$ .



**Figure A.15:** Normalized velocity field around cylinder with double layer fabric with smooth overlayer and 10UL underlayer at  $Re = 10.3 \times 10^4$ .

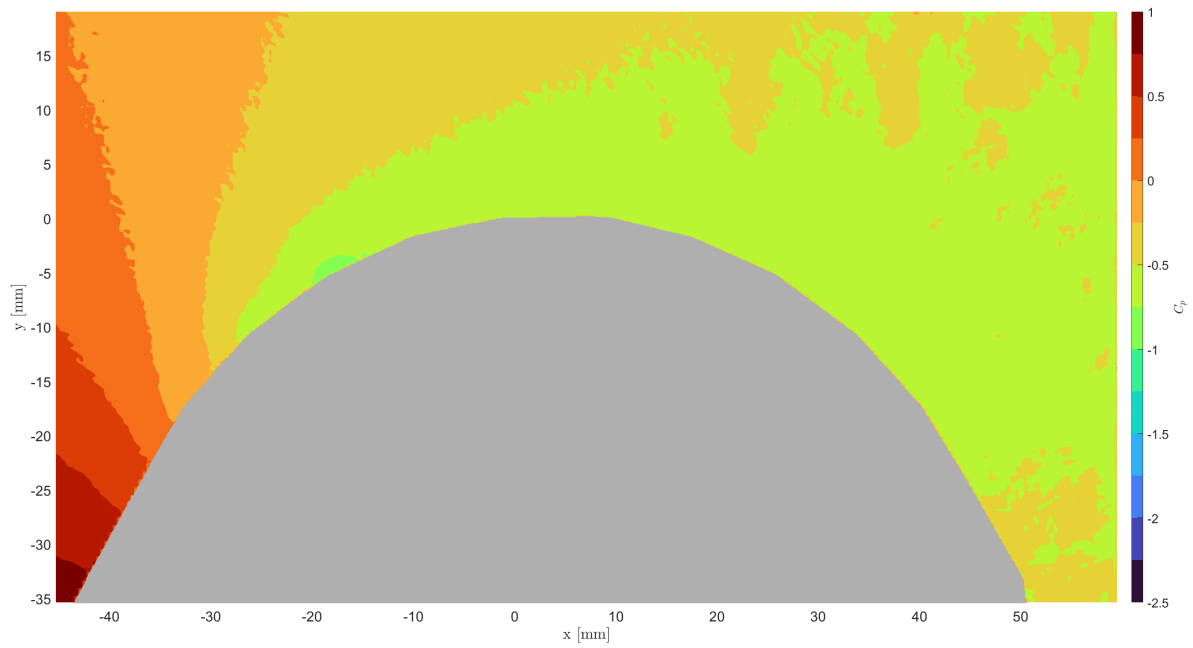


**Figure A.16:** Normalized velocity field around cylinder with double layer fabric with smooth overlay and 10UL underlayer at  $Re = 11.3 \times 10^4$ .

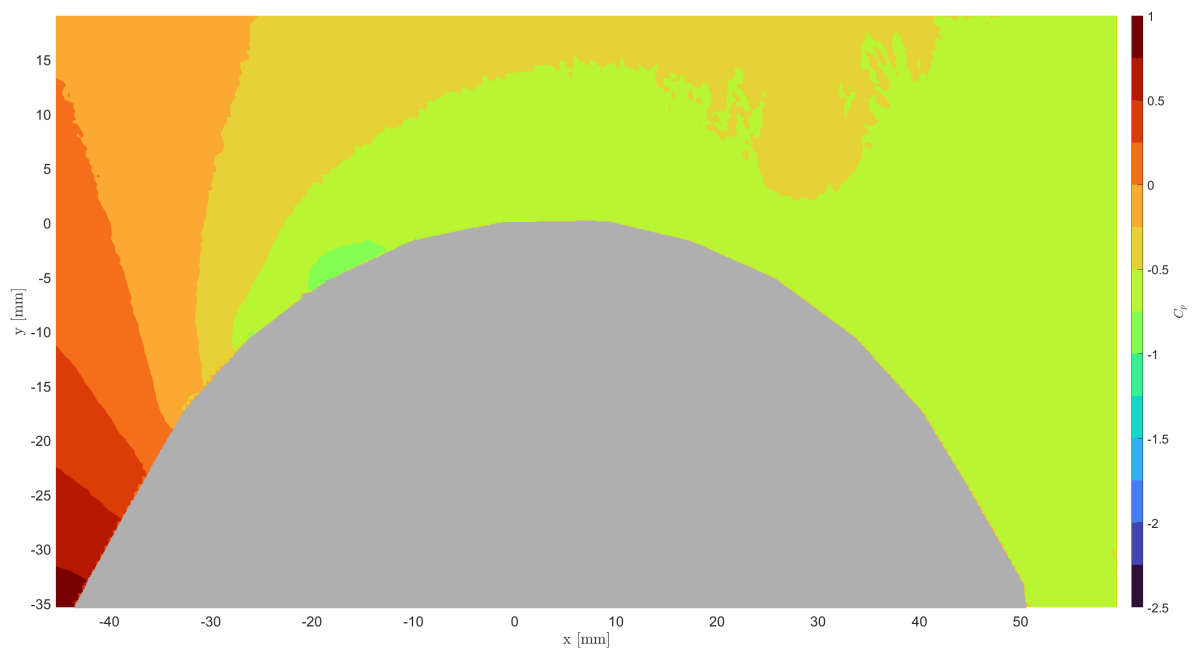


**Figure A.17:** Normalized velocity field around cylinder with double layer fabric with smooth overlay and 10UL underlayer at  $Re = 12.4 \times 10^4$ .

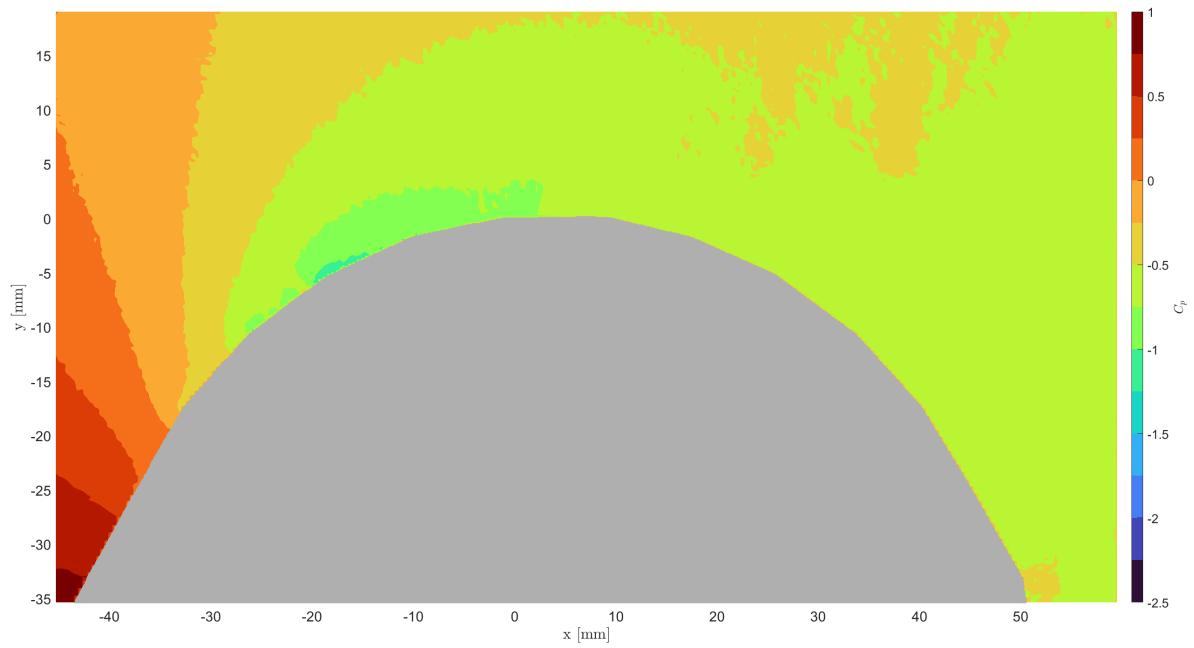
## Pressure Coefficient Fields



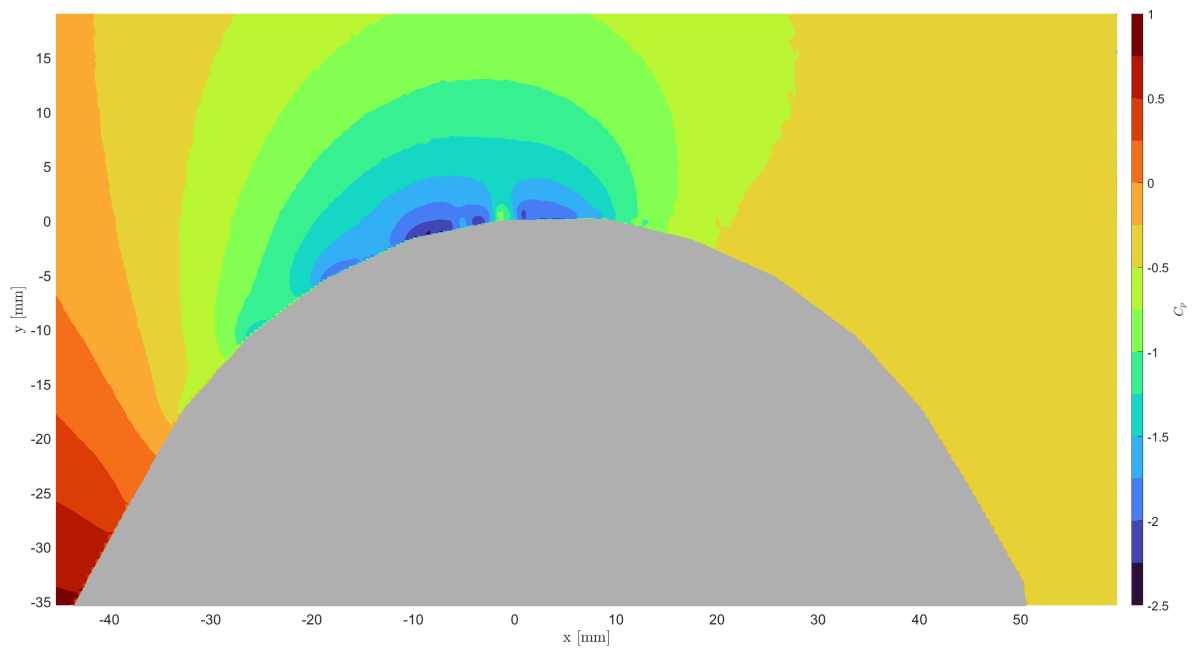
**Figure A.18:** Pressure coefficient field around cylinder with double layer fabric with smooth overlayer and 10UL underlayer at  $Re = 6.2 \times 10^4$ .



**Figure A.19:** Pressure coefficient field around cylinder with double layer fabric with smooth overlayer and 10UL underlayer at  $Re = 7.2 \times 10^4$ .

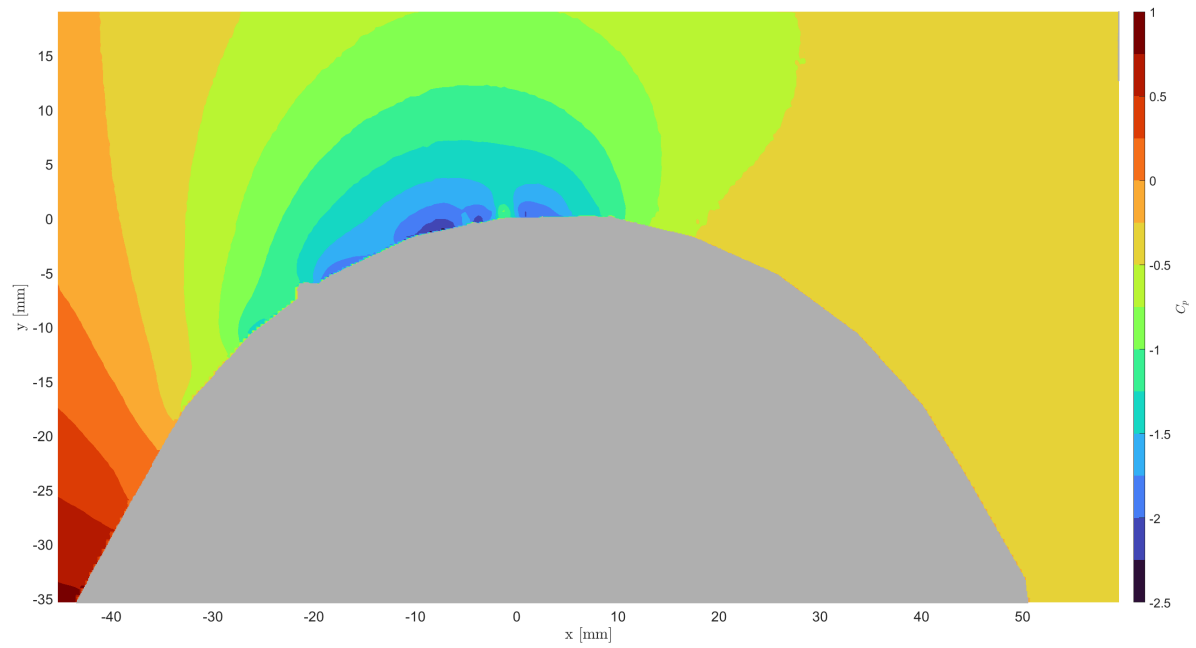


**Figure A.20:** Pressure coefficient field around cylinder with double layer fabric with smooth overlayer and 10UL underlayer at  $Re = 8.2 \times 10^4$ .

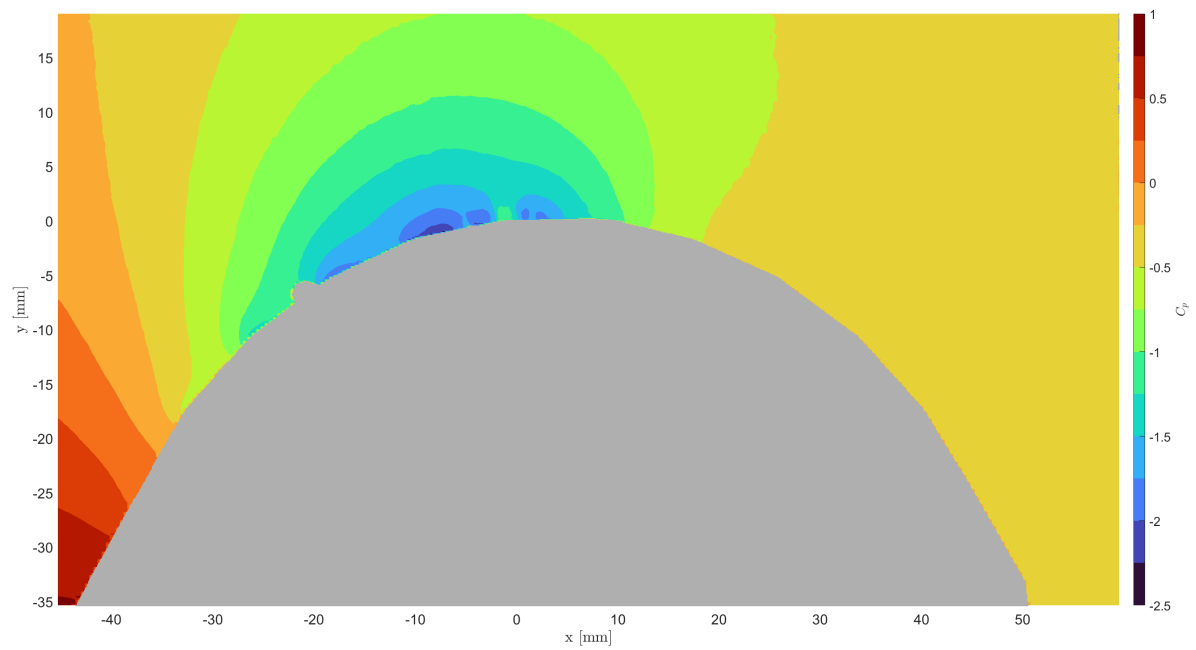


**Figure A.21:** Pressure coefficient field around cylinder with double layer fabric with smooth overlayer and 10UL underlayer at  $Re = 9.3 \times 10^4$ .



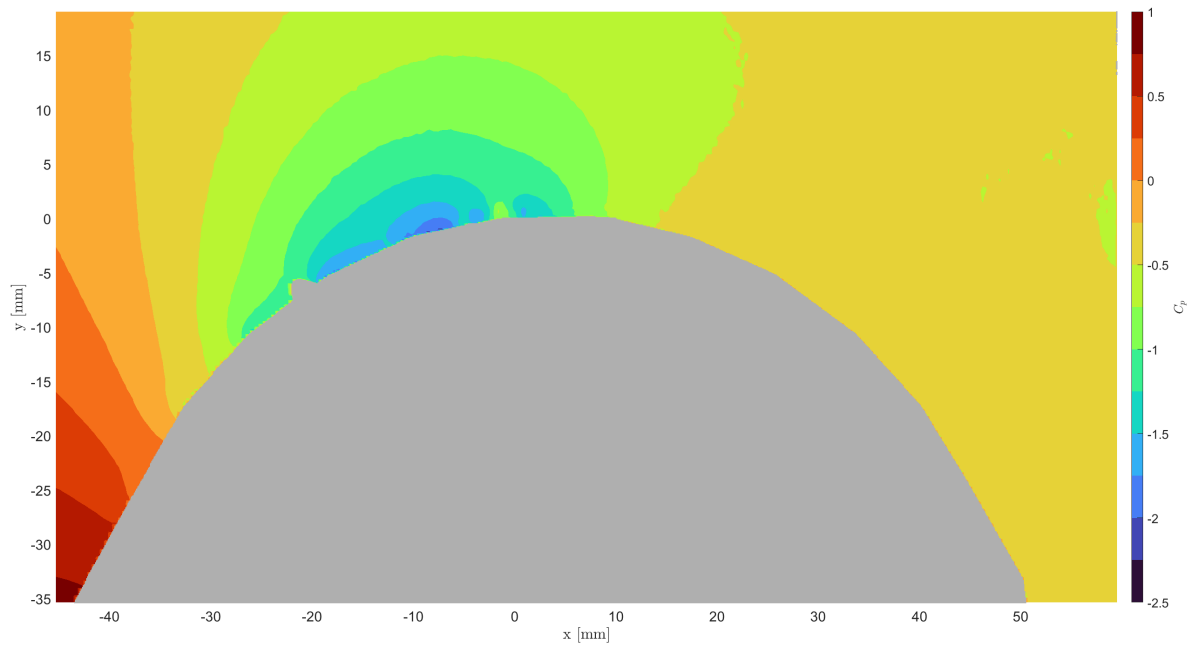


**Figure A.22:** Pressure coefficient field around cylinder with double layer fabric with smooth overlayer and 10UL underlayer at  $Re = 10.3 \times 10^4$ .



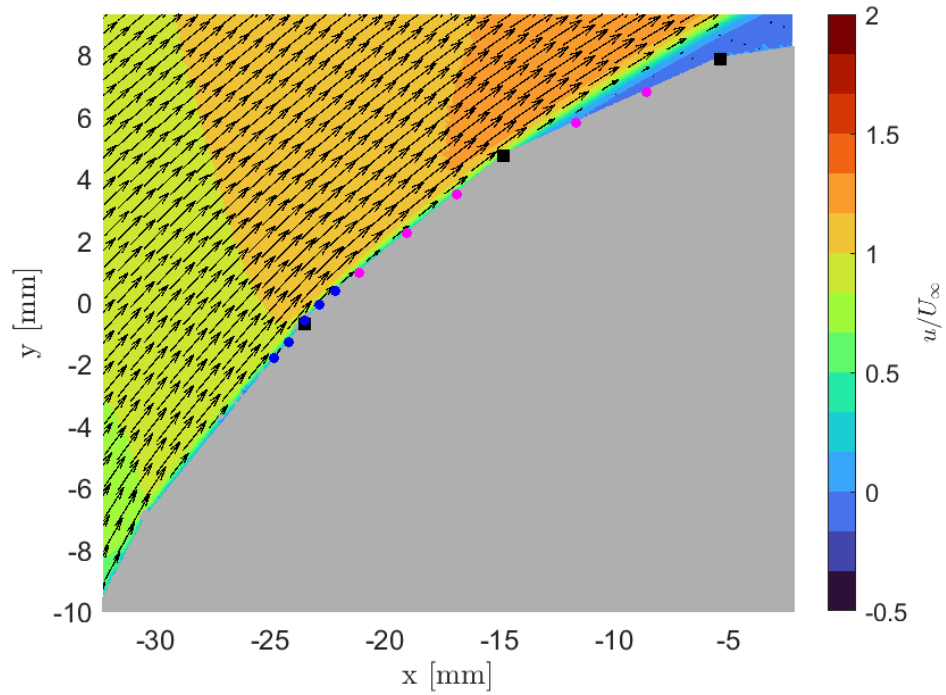
**Figure A.23:** Pressure coefficient field around cylinder with double layer fabric with smooth overlayer and 10UL underlayer at  $Re = 11.3 \times 10^4$ .



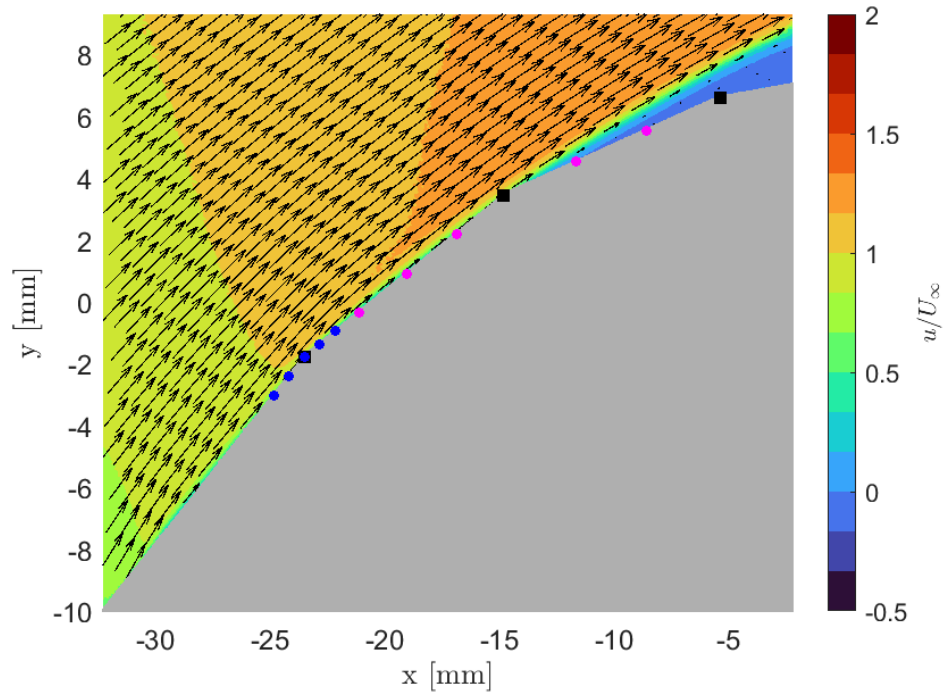


**Figure A.24:** Pressure coefficient field around cylinder with double layer fabric with smooth overlayer and 10UL underlayer at  $Re = 12.4 \times 10^4$ .

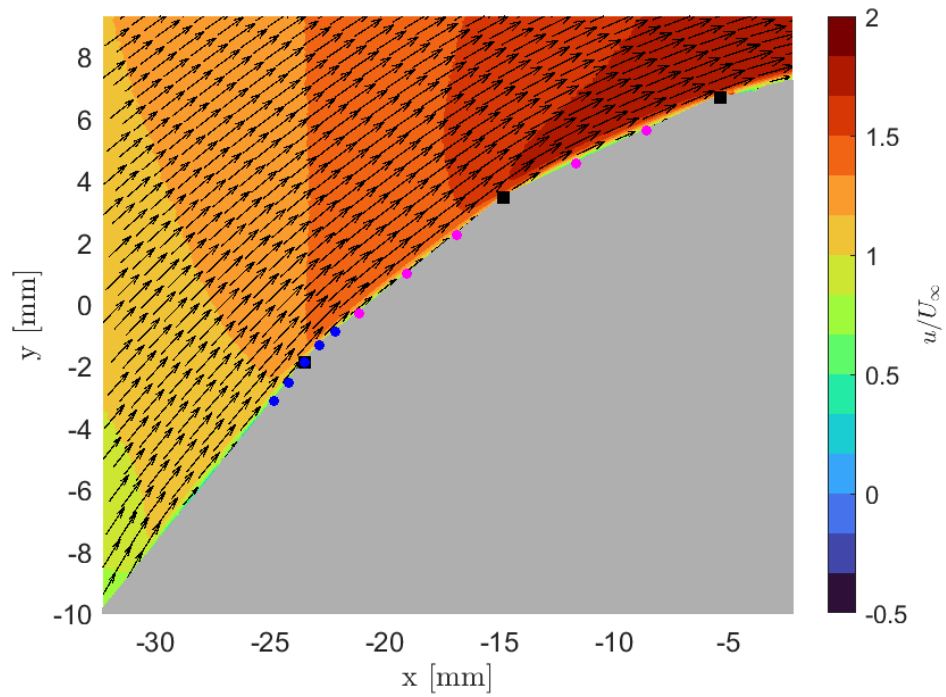
### Velocity Fields Setup 2



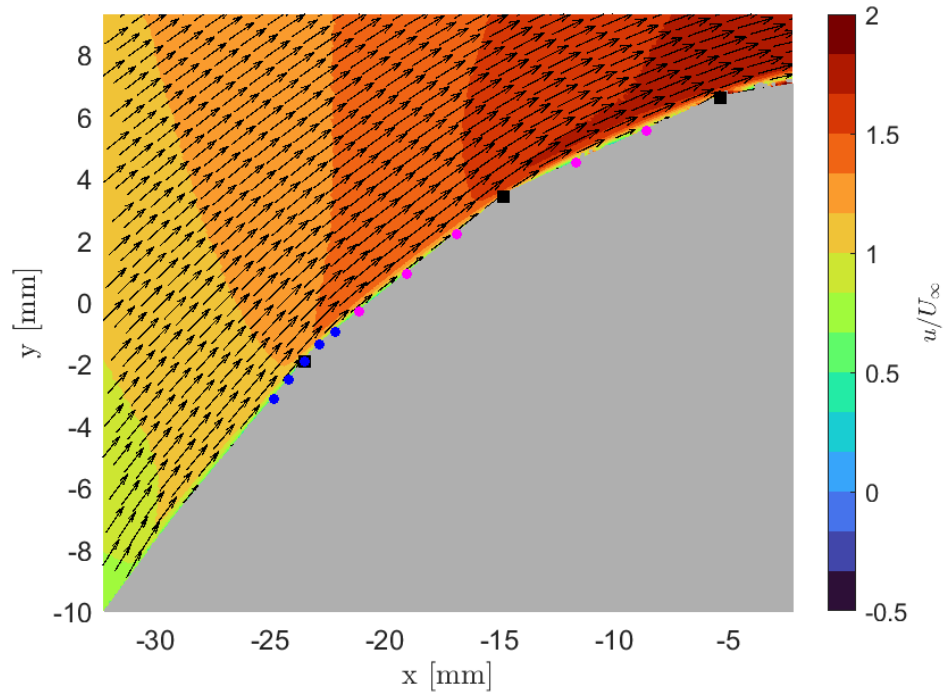
**Figure A.25:** Close up of normalized velocity field around cylinder with double layer fabric with smooth overlayer and 10UL underlayer at  $Re = 7.2 \times 10^4$ .



**Figure A.26:** Close up of normalized velocity field around cylinder with double layer fabric with smooth overlayer and 10UL underlayer at  $Re = 8.2 \times 10^4$ .



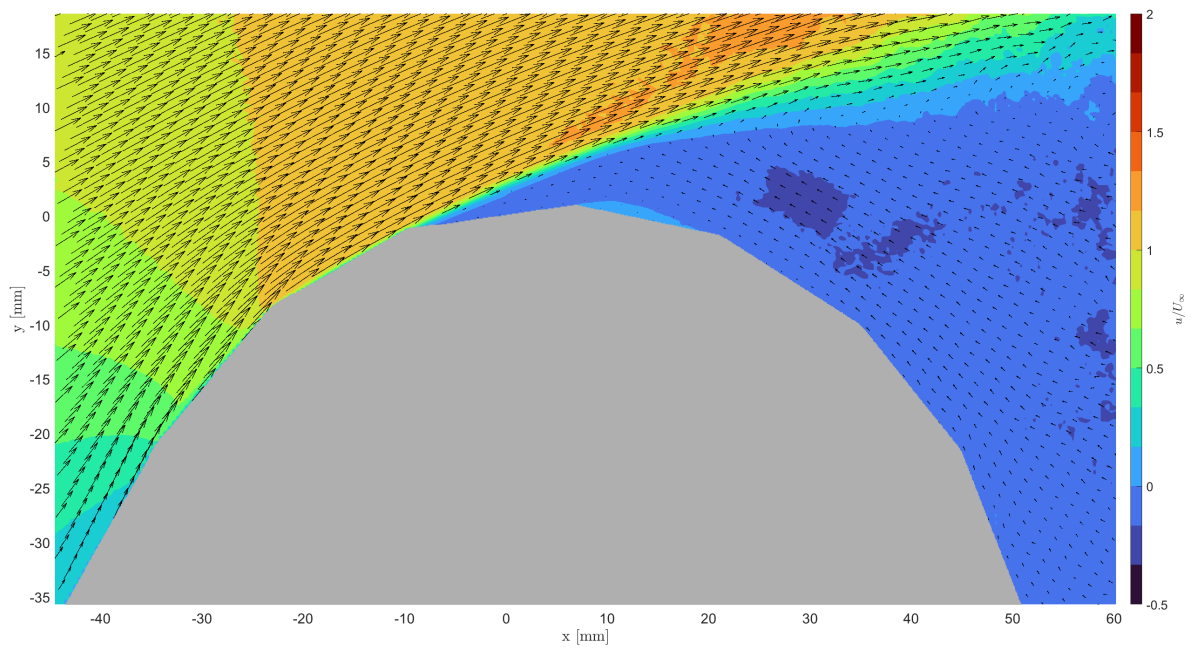
**Figure A.27:** Close up of normalized velocity field around cylinder with double layer fabric with smooth overlayer and 10UL underlayer at  $Re = 9.3 \times 10^4$ .



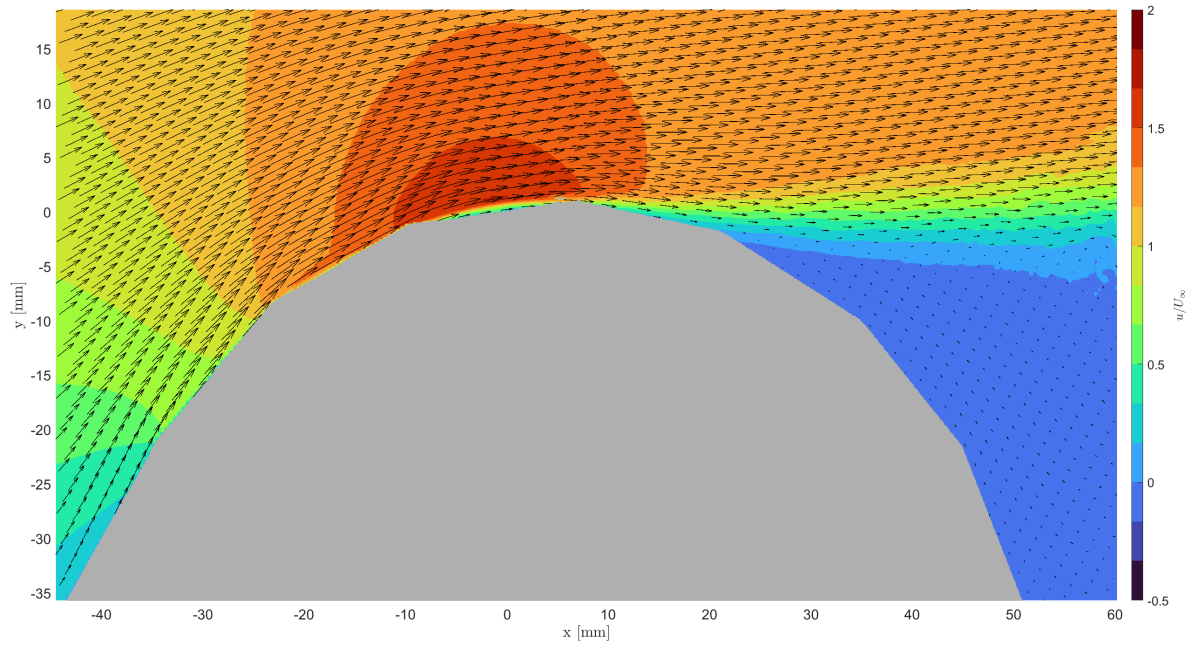
**Figure A.28:** Close up of normalized velocity field around cylinder with double layer fabric with smooth overlayer and 10UL underlayer at  $Re = 10.3 \times 10^4$ .

### A.1.3. SM20 Configuration

#### Velocity Fields

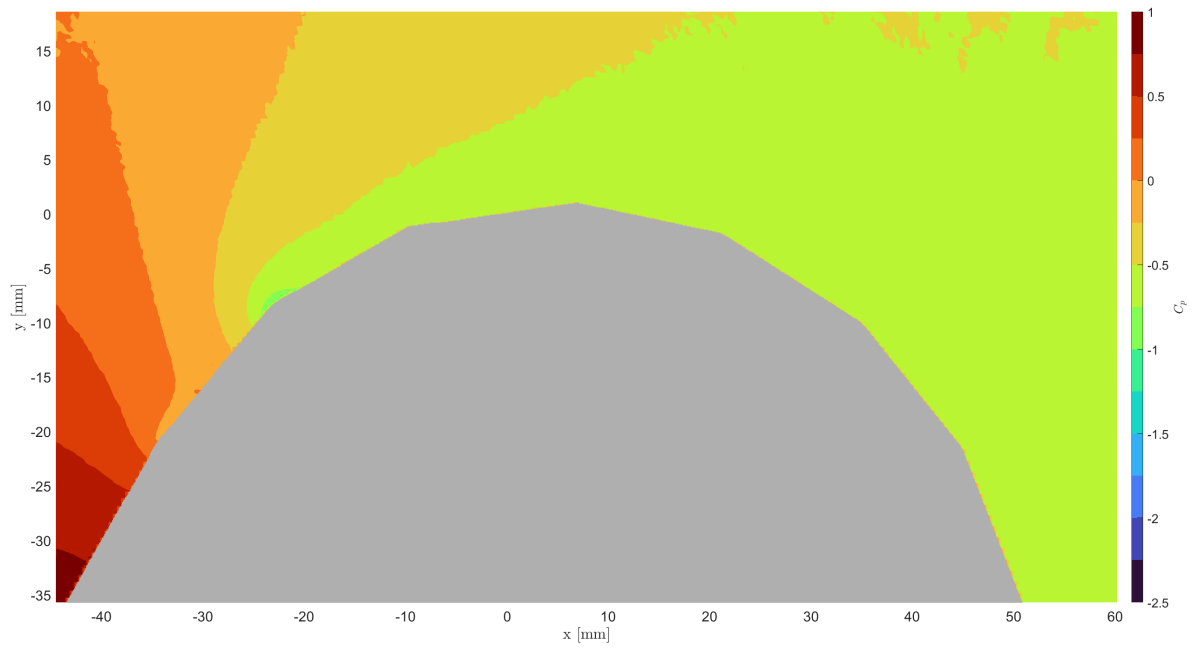


**Figure A.29:** Normalized velocity field around cylinder with double layer fabric with smooth overlayer and 20UL underlayer at  $Re = 3.1 \times 10^4$ .

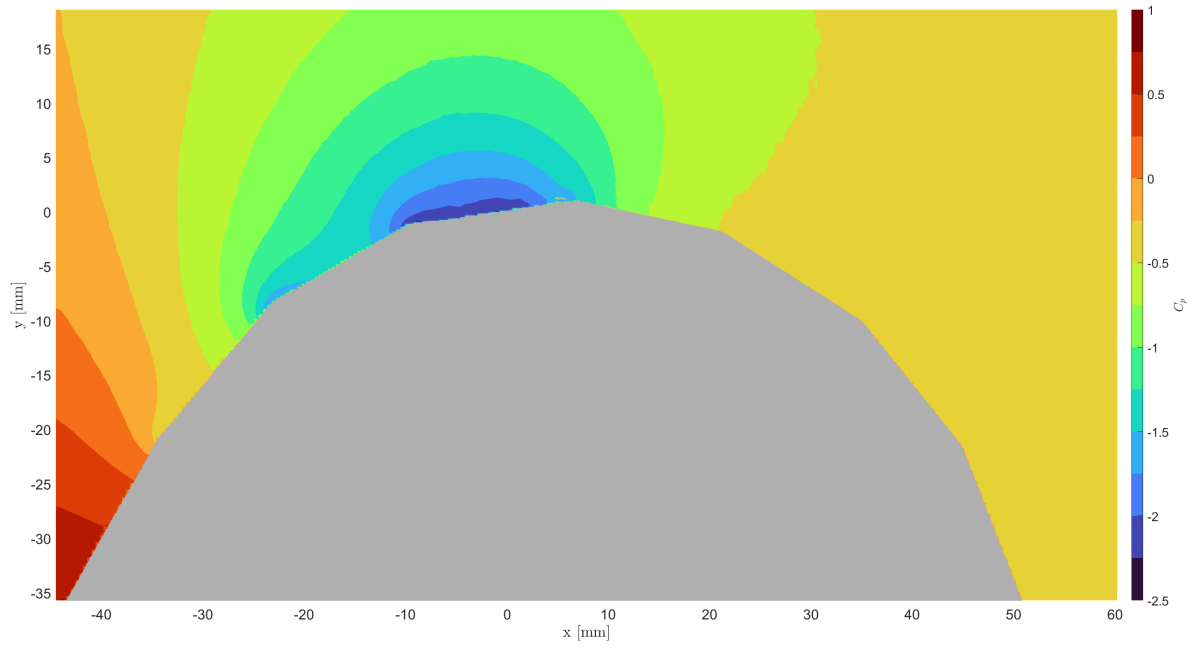


**Figure A.30:** Normalized velocity field around cylinder with double layer fabric with smooth overlayer and 20UL underlayer at  $Re = 6.2 \times 10^4$ .

### Pressure Coefficient Fields

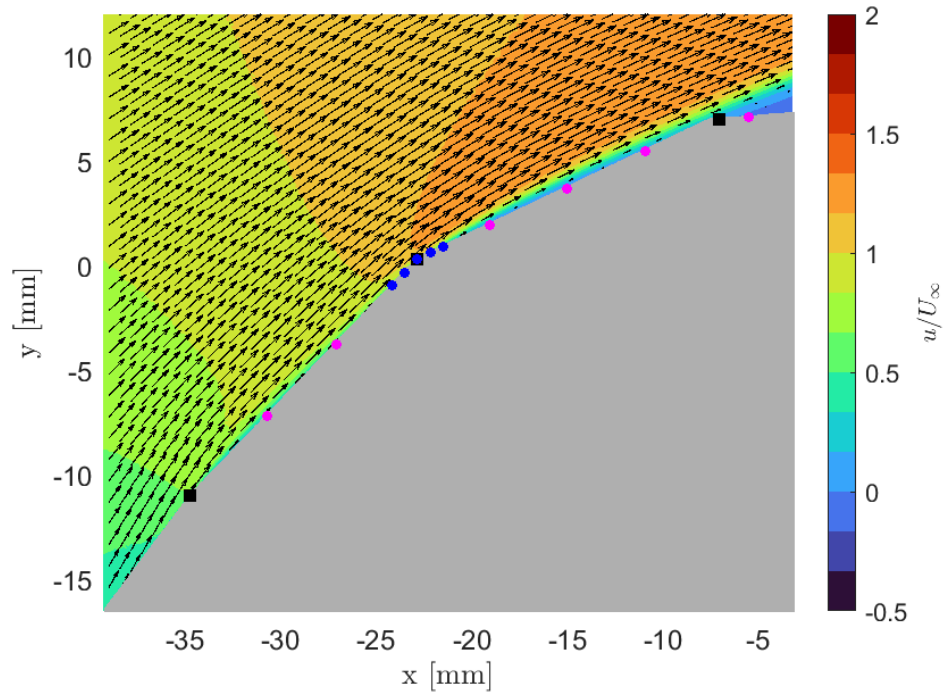


**Figure A.31:** Pressure Coefficient field around cylinder with double layer fabric with smooth overlayer and 20UL underlayer at  $Re = 3.1 \times 10^4$ .

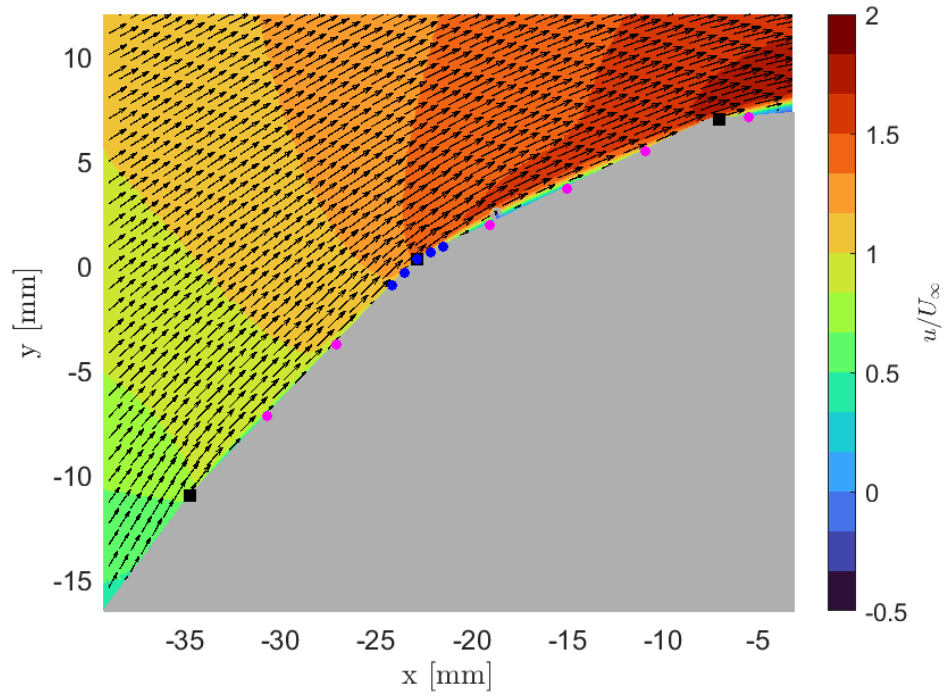


**Figure A.32:** Pressure Coefficient field around cylinder with double layer fabric with smooth overlayer and 20UL underlayer at  $Re = 6.2 \times 10^4$ .

### Velocity Fields Setup 2



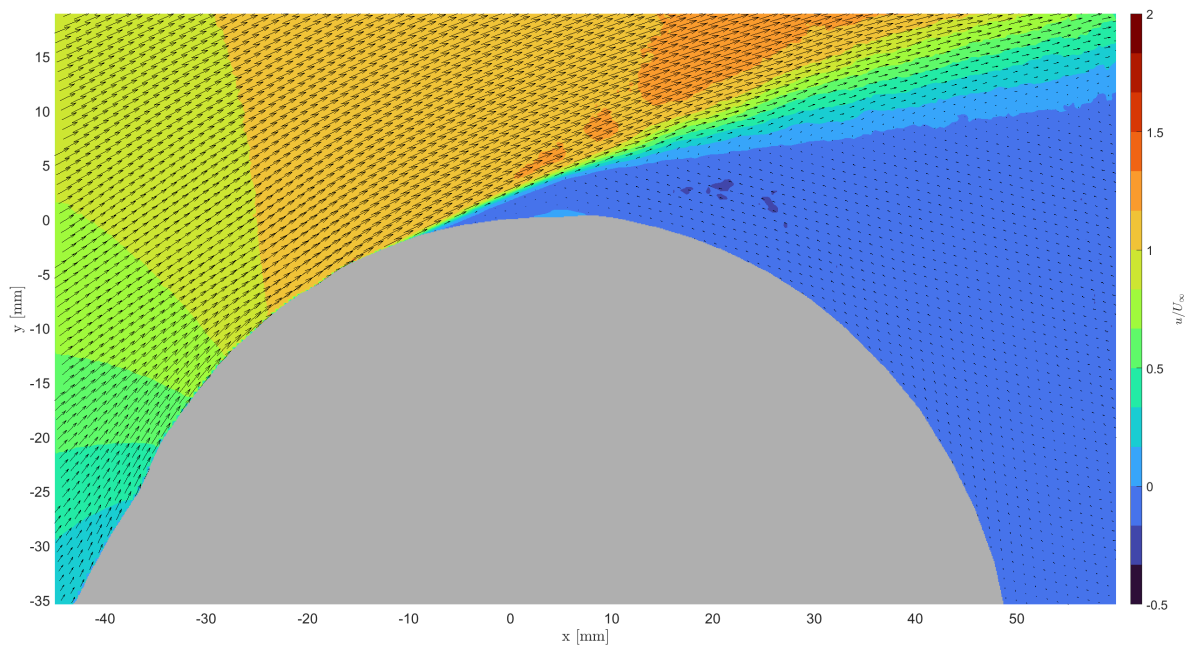
**Figure A.33:** Close up of normalized velocity field around cylinder with double layer fabric with smooth overlayer and 20UL underlayer at  $Re = 3.1 \times 10^4$ .



**Figure A.34:** Close up of normalized velocity field around cylinder with double layer fabric with smooth overlayer and 20UL underlayer at  $Re = 6.2 \times 10^4$ .

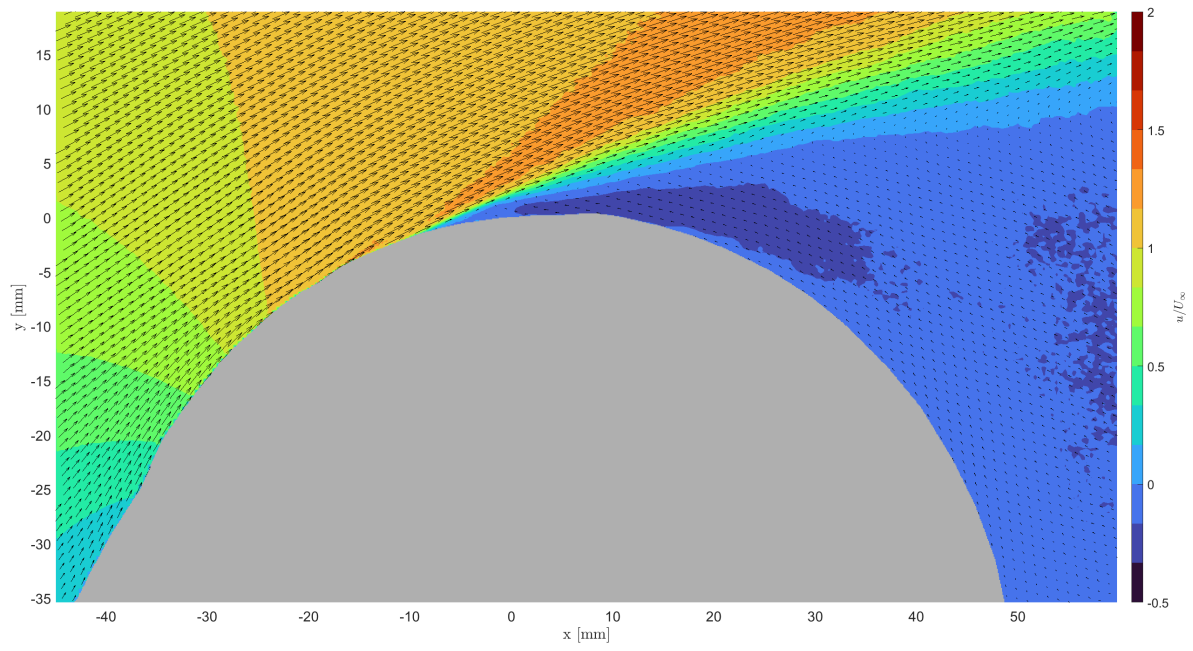
#### A.1.4. Smooth Overlayer

##### Velocity Fields

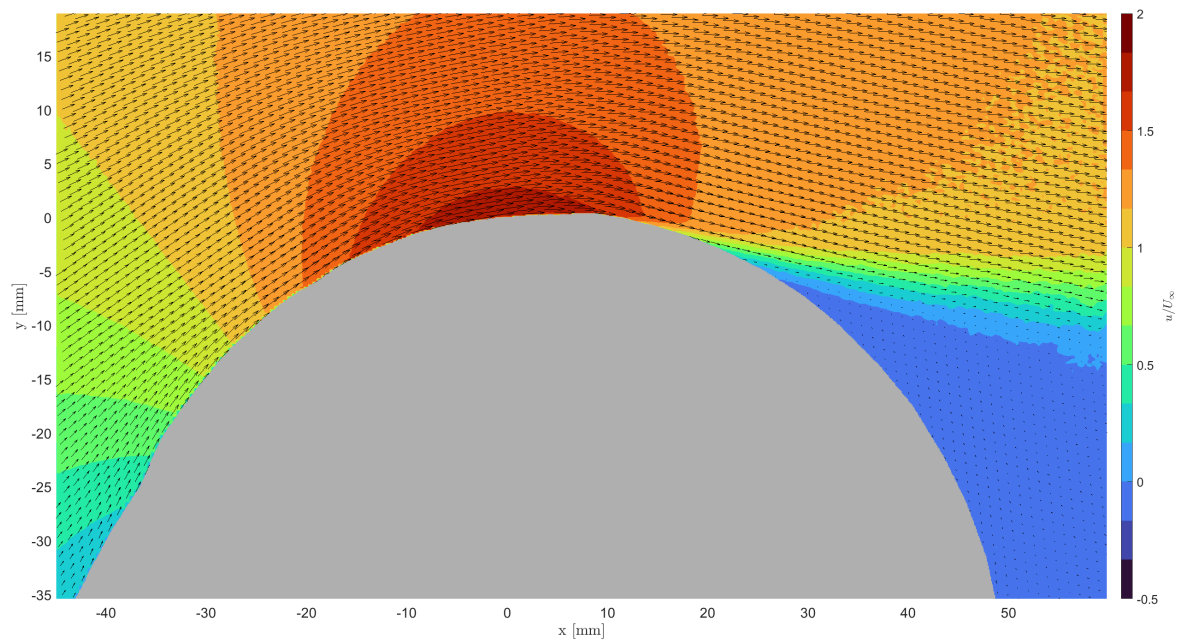


**Figure A.35:** Normalized velocity field around cylinder with smooth overlayer for  $Re = 9.3 \times 10^4$ .



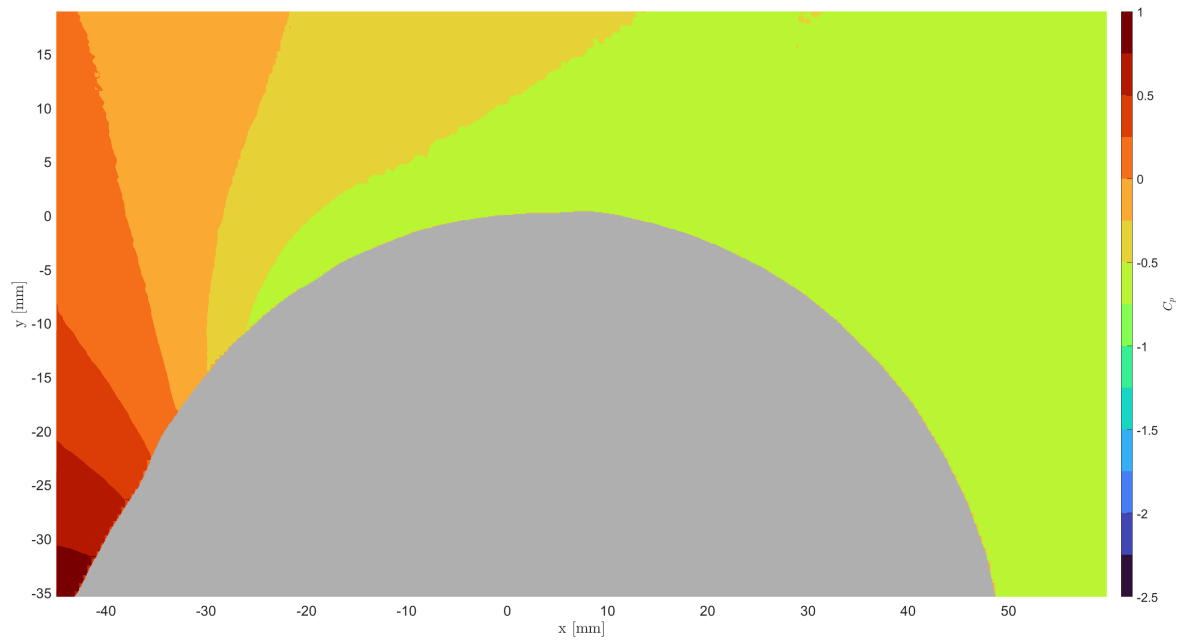


**Figure A.36:** Normalized velocity field around cylinder with smooth overlayer for  $Re = 18.4 \times 10^4$ .

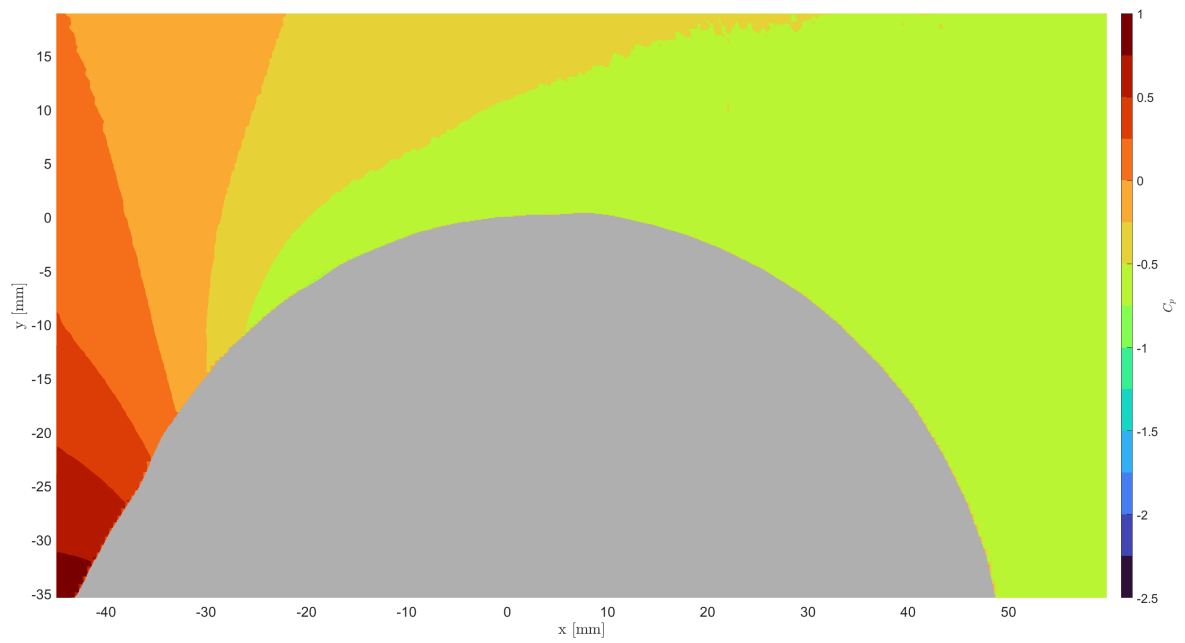


**Figure A.37:** Normalized velocity field around cylinder with smooth overlayer for  $Re = 20.9 \times 10^4$ .

## Pressure Coefficient Fields

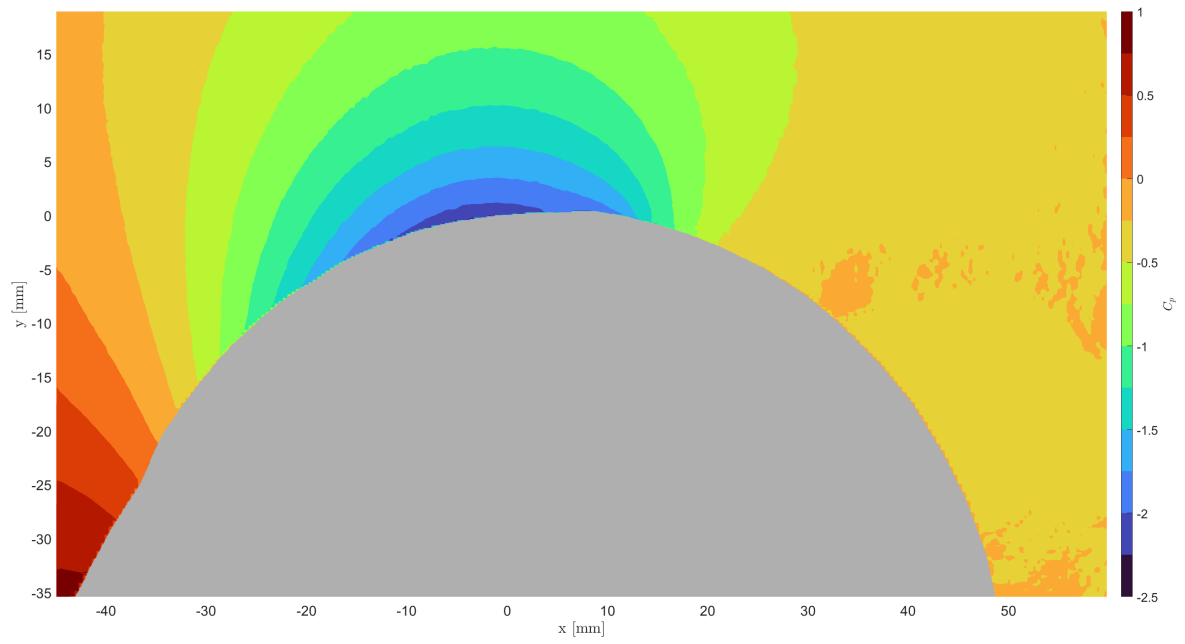


**Figure A.38:** Pressure coefficient field around cylinder with smooth overlayer for  $Re = 9.3 \times 10^4$ .



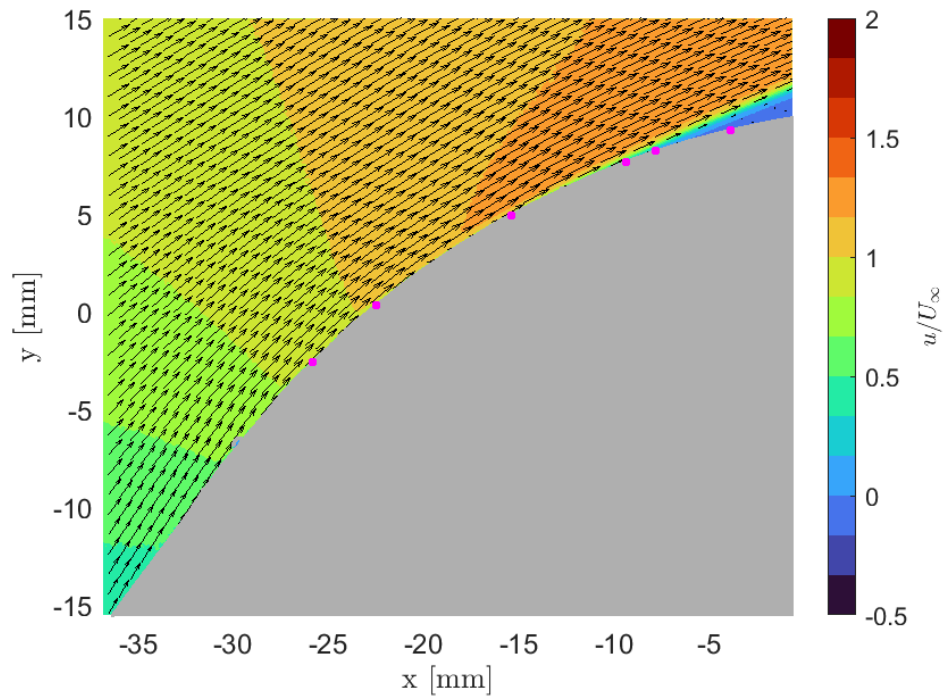
**Figure A.39:** Pressure coefficient field around cylinder with smooth overlayer for  $Re = 18.4 \times 10^4$ .



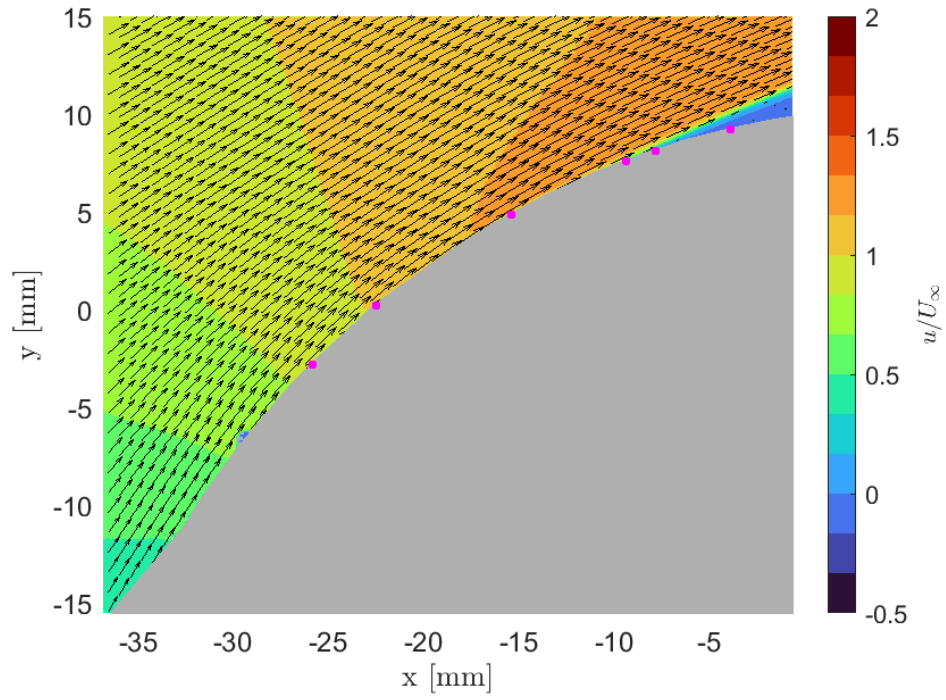


**Figure A.40:** Pressure coefficient field around cylinder with smooth overlayer for  $Re = 20.9 \times 10^4$ .

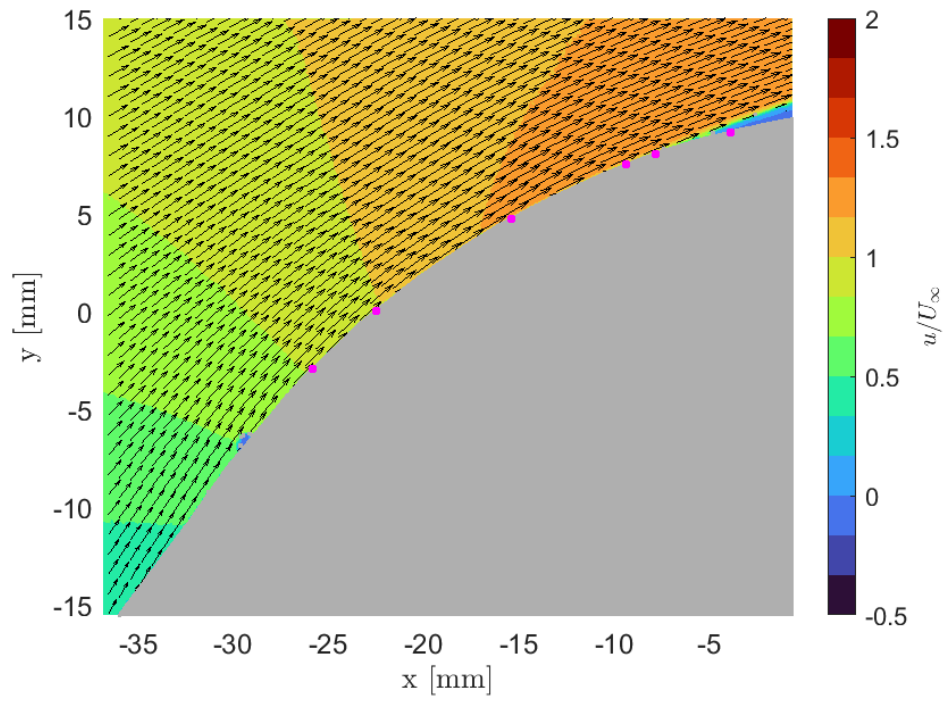
### Velocity Fields Setup 2



**Figure A.41:** Close up of normalized velocity field around cylinder with smooth overlayer for  $Re = 9.3 \times 10^4$ .



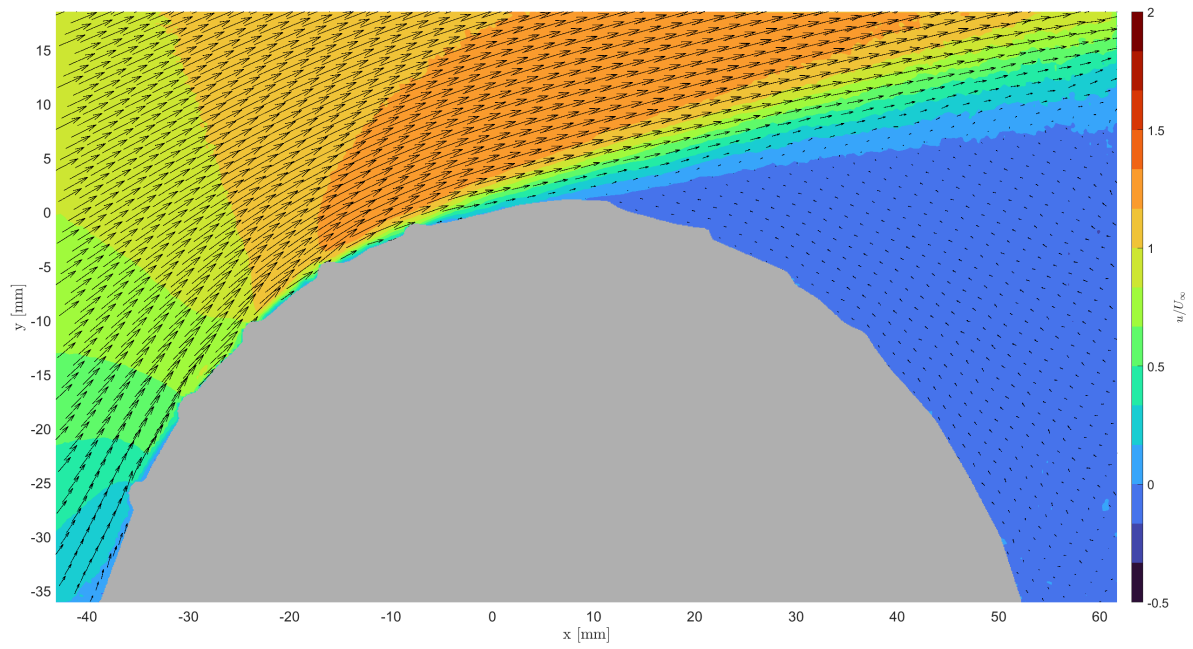
**Figure A.42:** Close up of normalized velocity field around cylinder with smooth overlayer for  $Re = 18.4 \times 10^4$ .



**Figure A.43:** Close up of normalized velocity field around cylinder with smooth overlayer for  $Re = 20.9 \times 10^4$ .

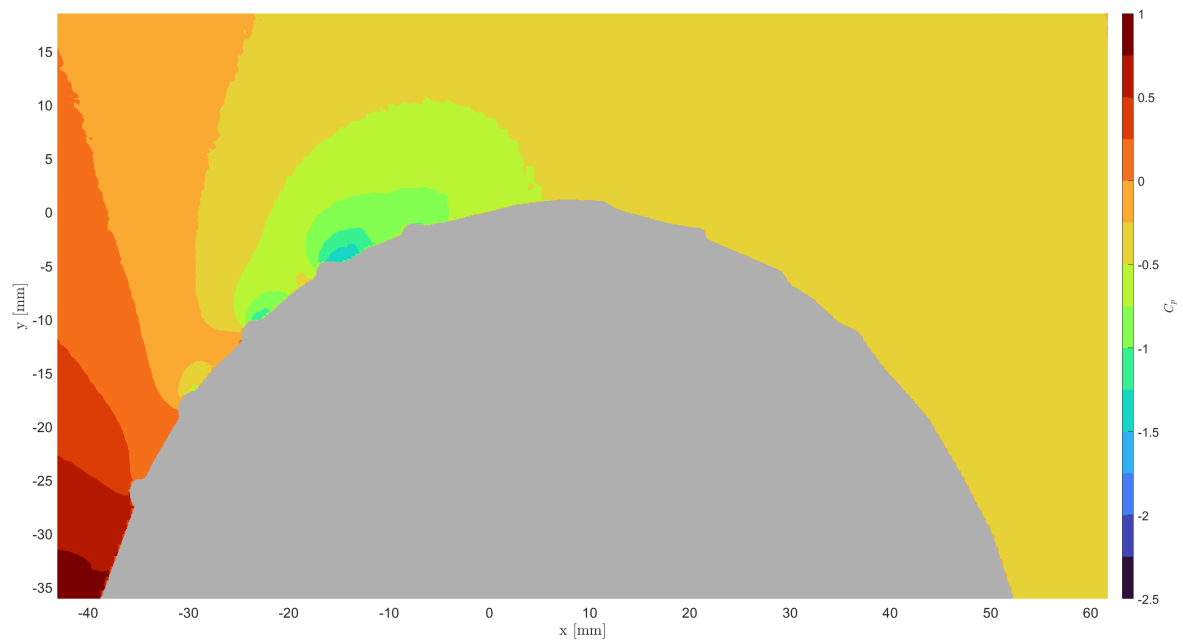
### A.1.5. 10UL Underlayer

#### Velocity Fields



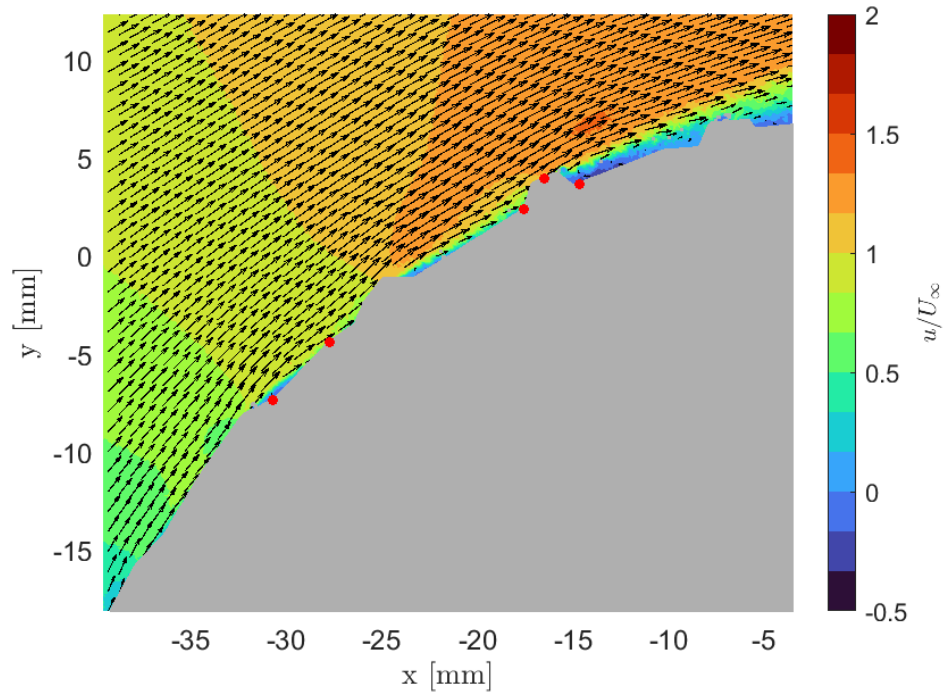
**Figure A.44:** Normalized velocity field around cylinder with 10UL underlayer for  $Re = 9.3 \times 10^4$ .

#### Pressure Coefficient Fields



**Figure A.45:** Pressure coefficient field around cylinder with 10UL underlayer for  $Re = 9.3 \times 10^4$ .

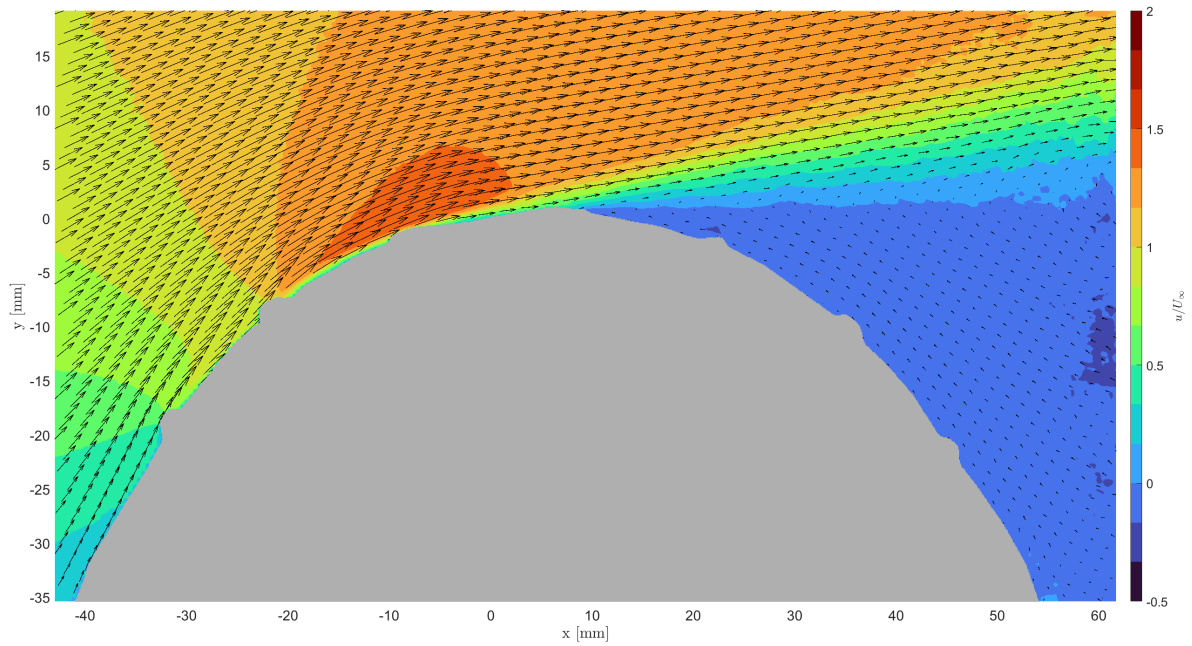
### Velocity Fields Setup 2



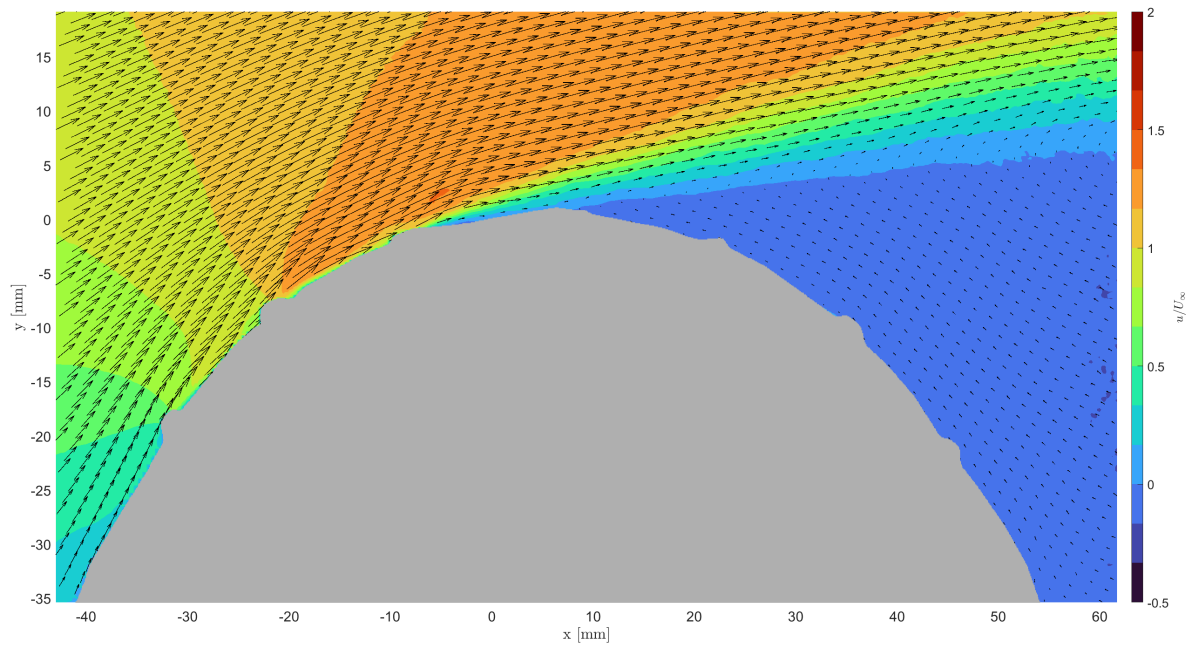
**Figure A.46:** Close up of normalized velocity field around cylinder with 10UL underlayer for  $Re = 9.3 \times 10^4$ .

### A.1.6. 10UL Underlayer

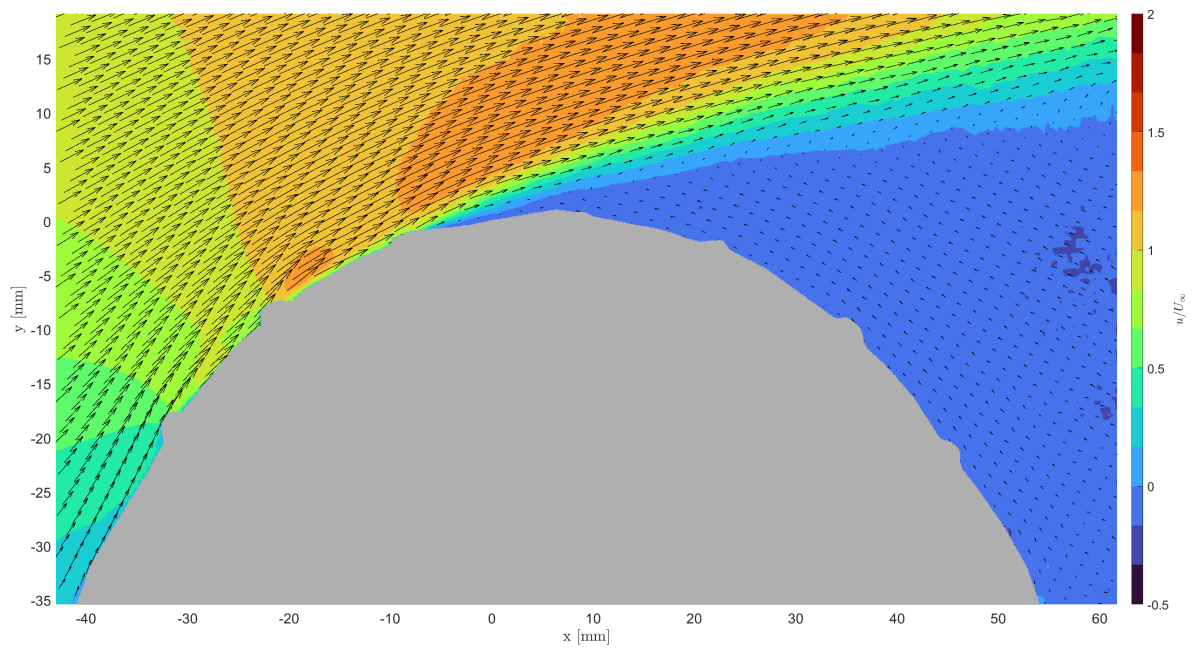
#### Velocity Fields



**Figure A.47:** Normalized velocity field around cylinder with 20UL underlayer for  $Re = 3.1 \times 10^4$ .

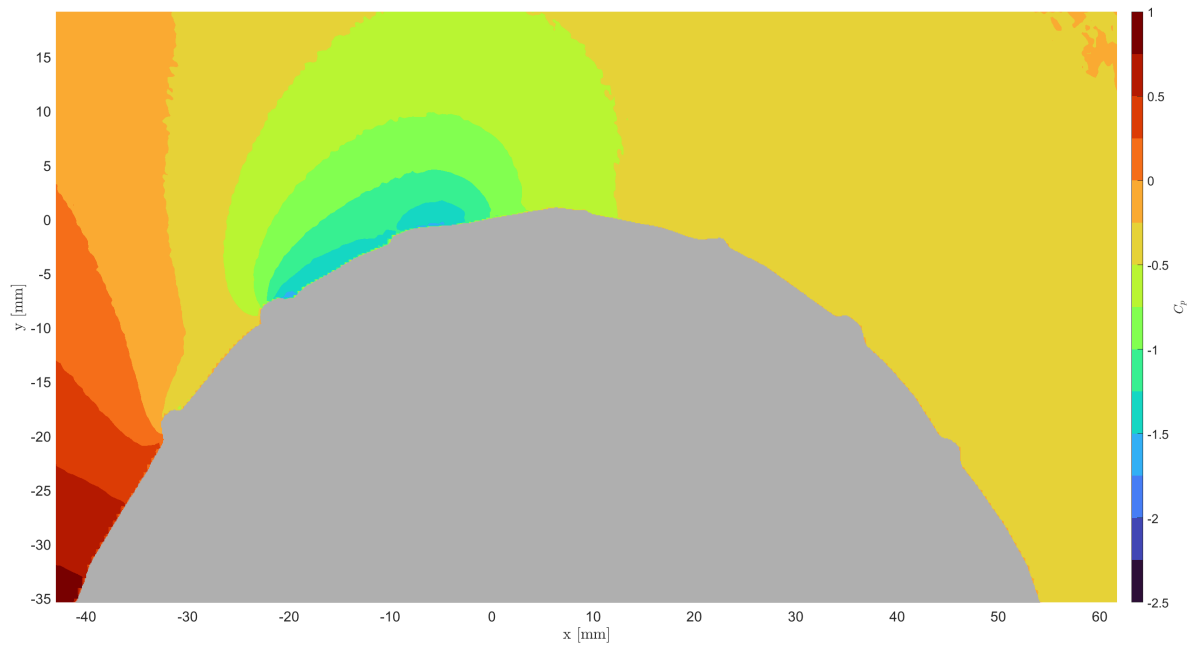


**Figure A.48:** Normalized velocity field around cylinder with 20UL underlayer for  $Re = 6.2 \times 10^4$ .

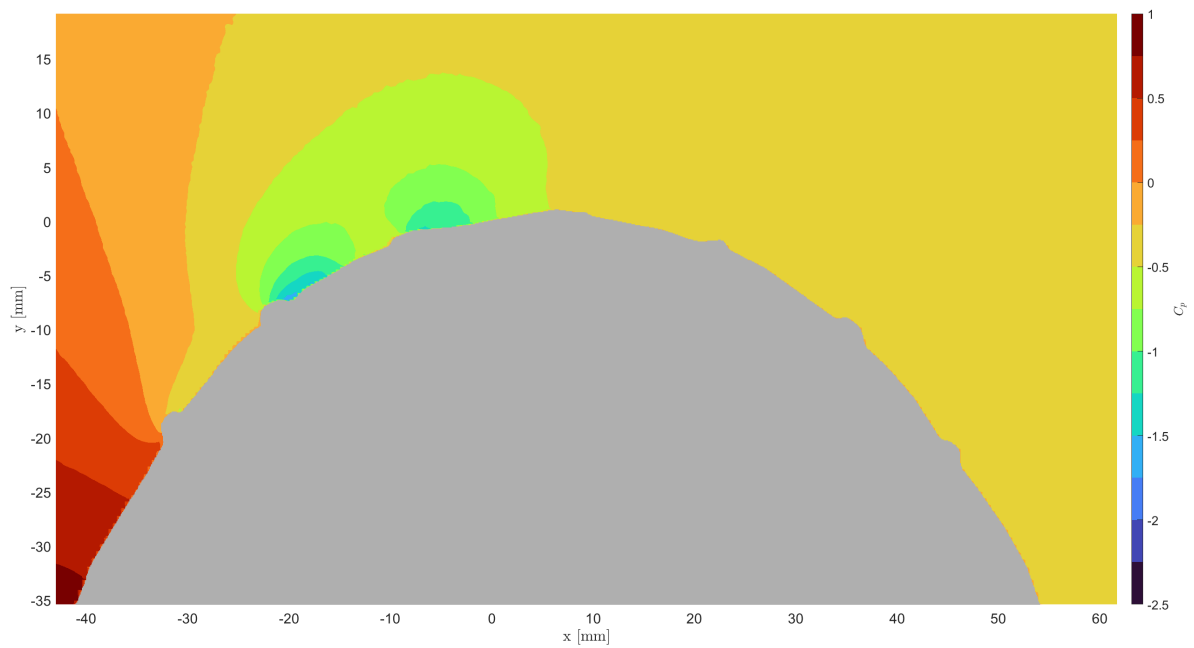


**Figure A.49:** Normalized velocity field around cylinder with 20UL underlayer for  $Re = 9.3 \times 10^4$ .

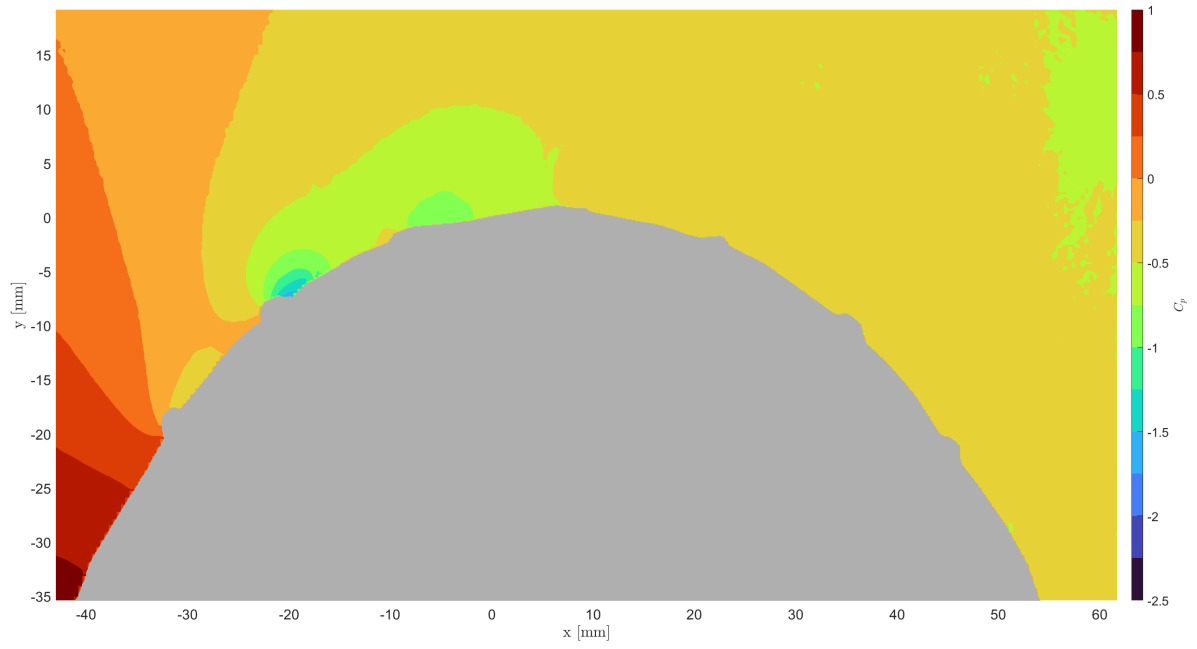
## Pressure Coefficient Fields



**Figure A.50:** Pressure Coefficient field around cylinder with 20UL underlayer for  $Re = 3.1 \times 10^4$ .

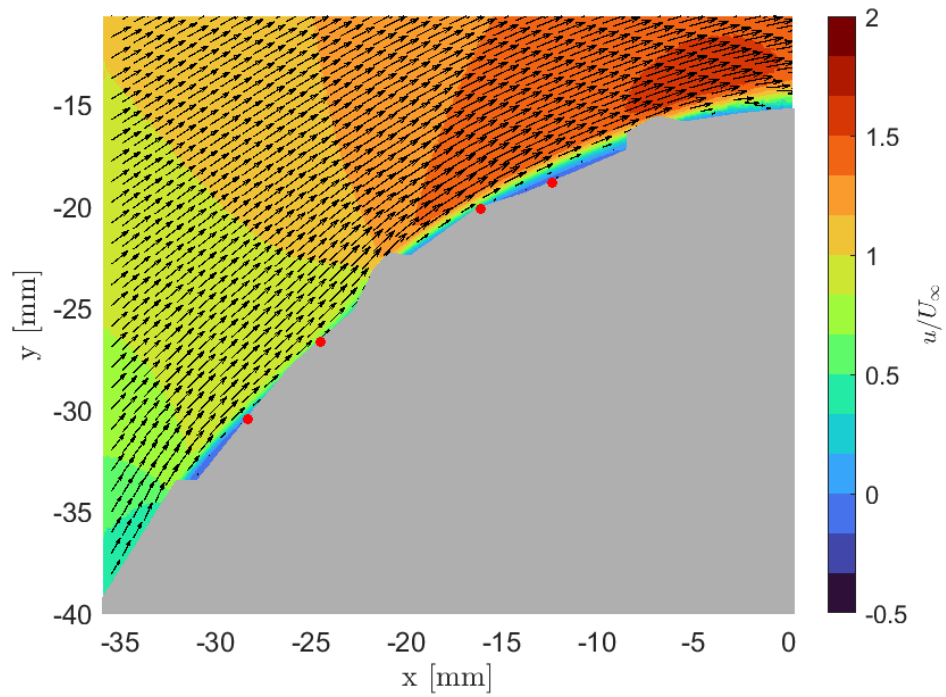


**Figure A.51:** Pressure Coefficient field around cylinder with 20UL underlayer for  $Re = 6.2 \times 10^4$ .



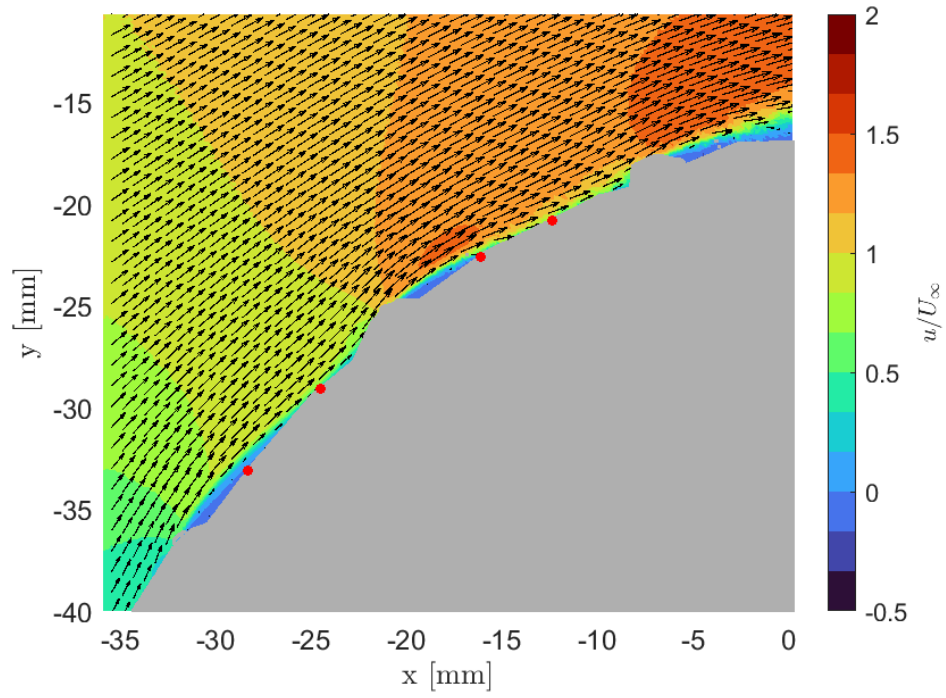
**Figure A.52:** Pressure Coefficient field around cylinder with 20UL underlayer for  $Re = 9.3 \times 10^4$ .

### Velocity Fields Setup 2

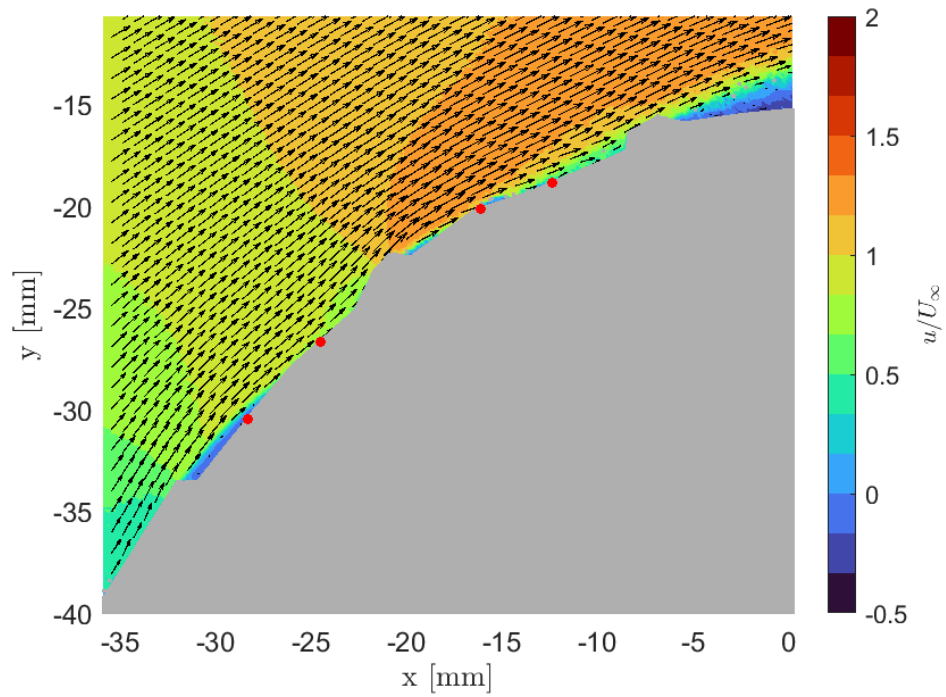


**Figure A.53:** Close up of normalized velocity field around cylinder with 20UL underlayer for  $Re = 3.1 \times 10^4$ .





**Figure A.54:** Close up of normalized velocity field around cylinder with 20UL underlayer for  $Re = 6.2 \times 10^4$ .



**Figure A.55:** Close up of normalized velocity field around cylinder with 20UL underlayer for  $Re = 9.3 \times 10^4$ .