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REDUCING THE ATHLETE'S AERODYNAMIC RESISTANCE

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Abstract. This paper presents an experimental investigation into the effect of surface roughness on athletes legs and arms. Because of their cylindrical shape, arms and legs of an athlete can be approximately studied as flow over circular bodies. The variation of roughness has been obtained using three different textiles and changing the diameter of the cylinder. To evaluate the results, three more textiles have been tested on a 20cm diameter cylinder. Two of them are utilized in two alpine suits used by the Norwegian alpine ski team and one is from a ski suit produced by Eschler. All the results have been compared with a cylinder with a smooth surface. The critical Reynolds number for a significant drop in the drag coefficient decreases by increasing surface roughness.

Keywords: aerodynamics, bluff bodies, cylinder, drag, roughness, sport

1. Introduction

In many sports aerodynamic resistance ($drag - D$) is of primary importance for the athlete's performance - e.g. in speed-skating where D is about 80 % of the physical forces acting against the athlete's speed; and in a ski-jumper's in-run where the velocity at take-off is determined on 60 % by the ski/snow friction and in 40 % by D.

Estimates using these figures show that a speed-skater will reduce his lap-time by one tenth of a second per cent reduced D, and that a ski-jumper can increase significantly the velocity at take-off by a modest reduction in D.

D can be defined as:

$$D = \frac{1}{2} c_d A V^2 \ . \qquad (1.1)$$

The drag D is proportional to the square of the velocity V, where $c_d A$ is the product of the drag coefficient and a characteristic cross-sectional area – and is an important parameter to evaluate and work on to minimize.

One can work on this parameter either by 1) reducing and 'streamlining' the body, and/or 2) by manipulating the flow close to the body such that flow separation from the body is delayed – producing a smaller wake zone and thereby less drag force.

The athletes themselves normally have no quantitative feedback on how effectivelly their body posture and equipment minimize D. The wind tunnel equipped with instrumentation for the measurement of physical forces represents an efficient way of quantitatively optimizing body posture and aerodynamically develop clothing and equipment for the athletes.

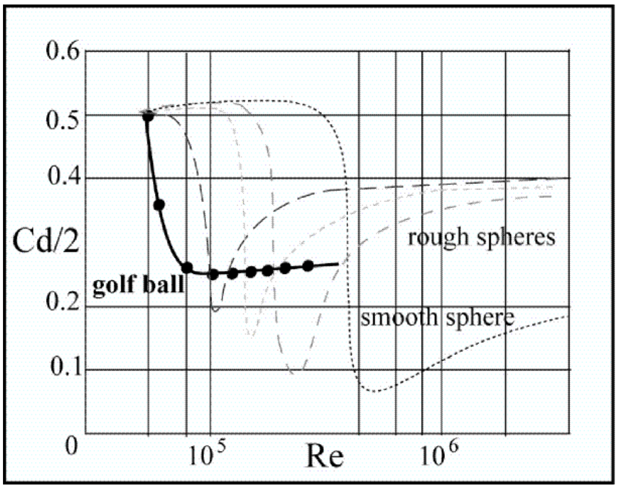

Figure 1. Variation of c_d with Reynolds number for smooth and rough sphere and golf ball [5]

For a speed-skater the leg, from the skate and up to the knee, represents about 1/3 of the skater's total air resistance. By tripping the airflow boundary layer on the leg, using certain material textures, separation can be delayed and the leg's D significantly reduced.

Working on body postures for ski-jumpers (in-run) resulted in an increased speed of 1 km/h at take-off for the Norwegian national team (in average). In the experiments carried out it has been chosen to focus the attention on the reduction of drag in legs and arms using different textiles with different surface roughnesses (or dimples).

Using the approximation that legs and arms are cylindrically shaped, the textiles have been tested on cylinders with different diameters.

For smooth cylinders in a cross flow the critical Reynolds number (when transition occurs and the drag coefficient falls) is around $3 \cdot 10^5$. The introduction of surface roughness on the cylinder surface can shift the transition to lower Reynolds numbers.

Increasing the roughness parameter induces a reduction in the value of the critical Reynolds number and decreases the drop in c_d. That has been shown by Achenbach

[2] for spheres and by Bearman and Harvey [5] for cylinders. From Achenbach's experiments [2], for the post-critical regime, to increase the roughness on a sphere means increasing the drag coefficient if it is compared with a smooth surface sphere (see Figure 1).

Flows around spheres and cylinders are very similar so it can be expected that the results carried on from the experiments performed will be close to the results of what Achenbach [2] and Bearman-Harvey found [3, 5]. The objective is to obtain the same drag reduction for a cylinder as obtained for a golf ball (Figure 1) by covering the cylinder surface with testiles of different textures thereby varying the roughness coefficient.

This will permit an estimation of the drag reduction in the cylindrical parts of the athlete's body.

2. **Effect of transition and separation**

The total drag can be split in two different parts. One part of the drag is due to skin

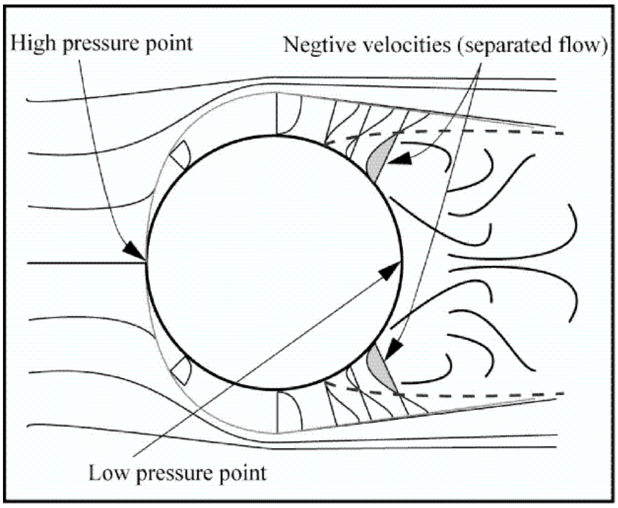

Figure 2. Flow around cylinder

friction and is called friction drag and the other part is due to the difference between the high pressure in the front part of the body (close to the stagnation point) and the low pressure in the rear region (separated region) and is called pressure drag:

$$c_{dTOT} = c_{dFRICTION} + c_{dPRESSURE} \, . \tag{2.1}$$

The relative contributions of friction and pressure drag depend on the body shape, especially its thickness. The cylinder is a bluff body and most of the drag, even with a rough surface, will be contributed by the pressure drag.

For cylinders (and in general for bluff bodies) the transition from laminar to turbulent flow increases the skin friction because of the Reynolds stress but, on the other hand, the pressure drag decreases by a large margin by moving the separation point to the back of the cylinder and diminishing the width of the wake.

3. Experimental setup

3.1. **Wind tunnel.** For the experiments, the wind tunnel of NTNU (Norwegian University of Science and Technology) in Trondheim has been used (Figure 3). The con-

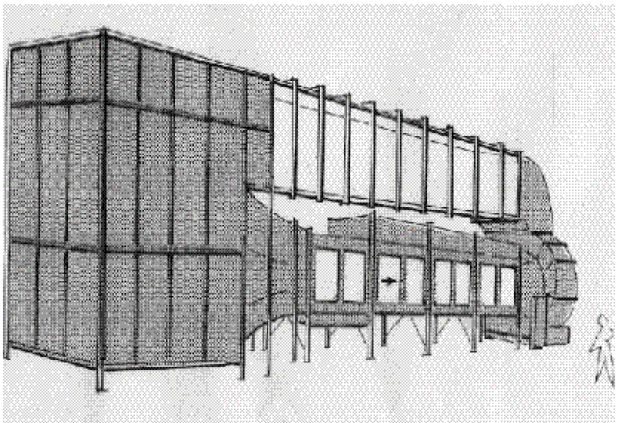

Figure 3. Wind tunnel

traction ratio is 1 : 4.23, and the test section of the wind tunnel is 12.5 m long, 1.8 m high, and 2.7 m wide. The wind tunnel is equipped with a 220 KW fan that can produce a variation of speed between $0 - 30$ m/s.

3.2. **Cylinder position in the wind tunnel.** The cylinder is mounted as shown in Figure 4 and it is connected to a balance positioned under the wind tunnel floor. The cylinder is mounted in the wind tunnel on a support and two dummy cylinders are connected to the wall but not to the balance to reduce the finite cylinder length effect.

This solution permits a comparison of the results with an infinitely long cylinder. The cylinder length is 120 cm (for all the 3 cases: 11 cm, 20 cm, 31 cm diameter.)

3.3. **Six component balance.** The balance (Carl Schenck AG) used is a six component balance capable of measuring the three forces and the three momentums around the three axes. Variations of forces and momentum are measured using strain gauges glued to the balance body.

The voltage outputs are measured by a LabVIEW based PC program.

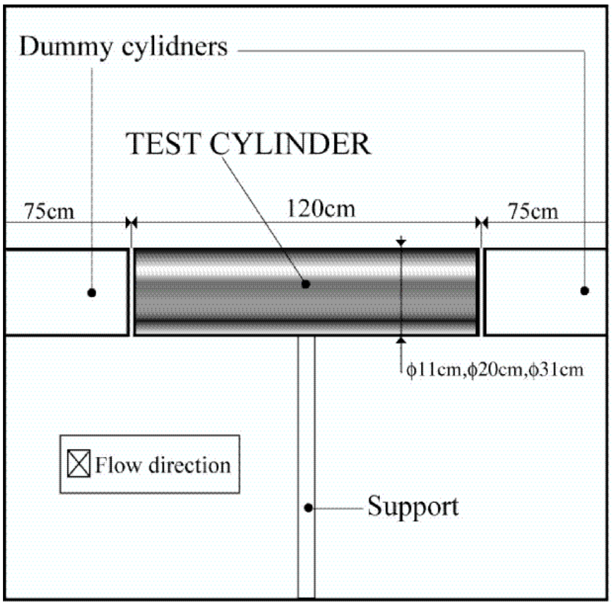

Figure 4. Cylinder in the wind tunnel

3.4. **Textiles.** The following chapter shows the different textiles used to change the surface roughness on the cylinders. Each of the five textiles has a different surface roughness (Table 1).

Different roughness has been obtained by manufacturing each textile in a different way and with a different pattern (See Table 1).

The roughness factor for each textile was found using an electronic microscope with a magnification factor of $20X$. Based on structure width and depth a surface parameter can be defined as:

$$k_{surface} = \sqrt{w \cdot d}\ . \qquad (3.1)$$

Only for the black textile it has been chosen to use a different surface because of the different structure of this textile. The black textile presents in fact an inner-seam and an outer-seam. The roughness calculated is the average between inner and outer roughness

$$k_{surfaceTOT} = \frac{k_{inner} + k_{outer}}{2}\ . \qquad (3.2)$$

Figure 5 represents five pictures of the textiles. The first three (1), (2) ,(3) are obtained using a magnification factor of $4X$.

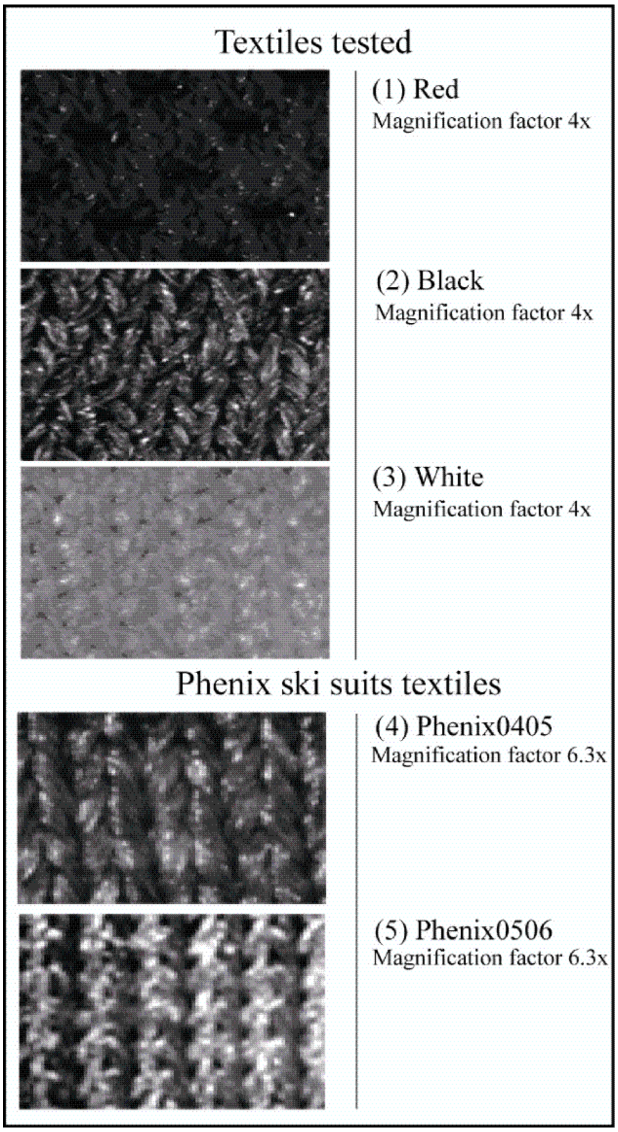

Figure 5. The five different textiles used

The red textile is the roughest and some dimples are present in the structure. The black structure presents a roughness parameter k between the red and the white textile. Some dimples are present also in the black textile structure but it is not possible to localize them in the picture shown.

Table 1. Roughness parameters of the different textiles used

		k	r
11 cm Red	(1)	642	$5.84E-03$
11 cm Black	(2)	386	$3.51E-03$
20 cm Red	(1)	642	$3.21E-03$
20 cm Black	(2)	386	$1.93E-03$
31 cm Red	(1)	642	$2.07E-03$
31 cm Black	(2)	386	$1.25E-03$
11 cm White	(3)	108	$9.82E-04$
20 cm White	(3)	108	$5.40E-04$
31 cm White	(3)	108	$3.48E-04$
20 cm 0405	(4)	273	$1.37E-03$
20 cm 0506	(5)	335	$1.68E-03$

Figures 5(4) and 5(5) show the pictures obtained with a magnification factor of 6.3 of the two textiles used in the alpine suits.

The roughness parameter k is a surface length scale that will influence the flow close to the cylinder surface.

The surface curvature (given by the cylinder diameter) determines the pressure gradient that influences the flow separation conditions. Then combining these two parameters in a dimensionless roughness coefficient r:

$$r = \frac{k}{Diam} \, . \tag{3.3}$$

4. **Results**

4.1. $c_d - \mathrm{Re}$ **curves.** The four curves in Figure 6 represent the $c_d - \mathrm{Re}$ curves for the 11 cm diameter cylinder. The transition for the black ($r = 3.51 \cdot 10^{-3}$) and the red ($r = 5.84 \cdot 10^{-3}$) textiles occurs at a lower Reynolds number than for the smooth cylinder and for the white ($r = 9.82 \cdot 10^{-4}$) material.

The results are in accordance with the literature: increasing the roughness, the transition to turbulence occurs at a lower Reynolds numbers which means that it is possible to reduce the drag by about 40 %. Over a certain Reynolds number range the white textile has a $c_d - \mathrm{Re}$ curve similar to the $c_d - \mathrm{Re}$ curve for the smooth cylinder.

Choosing the correct material for the correct speed enables a drag coefficient reduction of about $40 - 45$ %.

Comparing the 20 cm diameter cylinder results (Figure 7) with the same graph for the 11 cm diameter (Figure 6) it is easy to recognize the same trend (increased roughness means shifting the transition to lower Reynolds numbers).

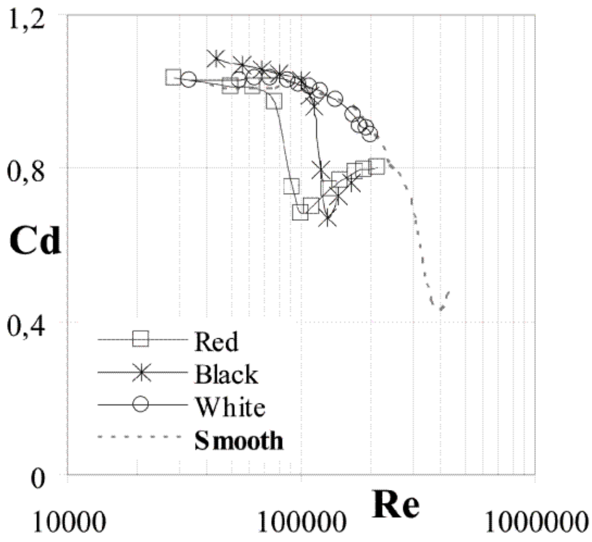

Figure 6. 11 *cm* cylinder

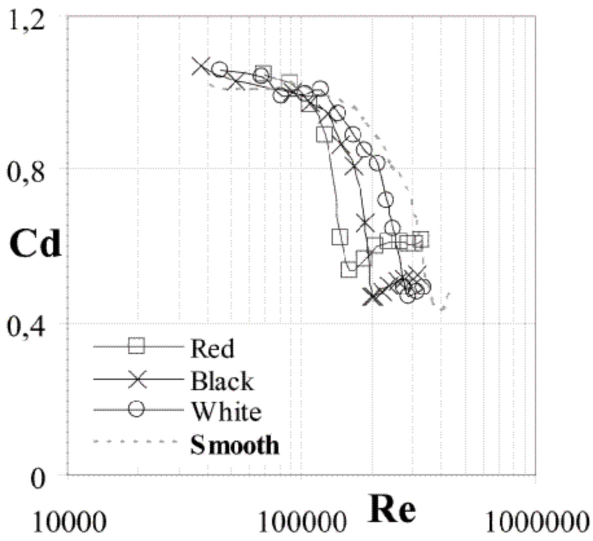

Figure 7. 20 *cm* cylinder

Until a certain Reynolds number ($\mathrm{Re} = 1.75 \cdot 10^5$), the red textile ($r = 3.21 \cdot 10^{-3}$) minimizes the drag coefficient most. Between $\mathrm{Re} = 1.85 \cdot 10^5$ and $\mathrm{Re} = 2.7 \cdot 10^5$ the black ($r = 1.93 \cdot 10^{-3}$) and for a $\mathrm{Re} > 2.7 \cdot 10^5$ the white textile ($r = 5.4 \cdot 10^{-4}$) produces the lowest drag coefficient.

Increasing the Reynolds number ($\mathrm{Re} > 3.2 \cdot 10^5$), the cylinder with the red textile has a c_d higher than the c_d measured for the smooth cylinder.

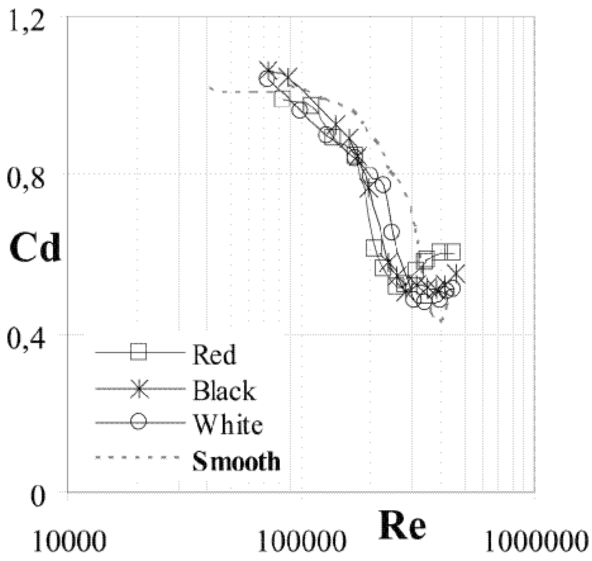

Figure 8. 31 *cm* cylinder

The $c_d - \mathrm{Re}$ curves trend for the 31 *cm* diameter cylinder is comparable to the tendency shown in Figure 6 and Figure 7 for the 11 *cm* and 20 *cm* diameter cylinders.

For the lower Reynolds number region the cylinder dressed with the red textile ($r = 2.07 \cdot 10^{-3}$) is the one with the lowest c_d, for the middle region the black textile ($r = 1.25 \cdot 10^{-3}$) minimizes the drag coefficient and for high Reynolds numbers the material that minimizes the drag coefficient more than the others is the white textile ($r = 3.48 \cdot 10^{-4}$).

It is also easy to see that now the drag coefficient reduction is about 20 – 30 % which is less than the 40 – 45 % found for the other cylinders (11 *cm* and 20 *cm* diameter).

4.2. **Roughness coefficient correlation.** The correlation between the roughness parameter r and the trend of the $c_d - \mathrm{Re}$ curves has been analyzed defining a specific Reynolds number Re_{trans}.

This specific Reynolds number has been chosen to give an approximate description of where transition occurs.

Defining Re_{trans} as the Reynolds number where the c_d curve has gone through half its drop, Re_{trans} can be correlated with the roughness coefficient r (Figure 9), and the results can be expressed by the correlation

$$r = A + B \ln(\mathrm{Re}_{trans}), \tag{4.1}$$

where the best fit for our limited data base is for $A = 0.0594$, $B = -0.0048$.

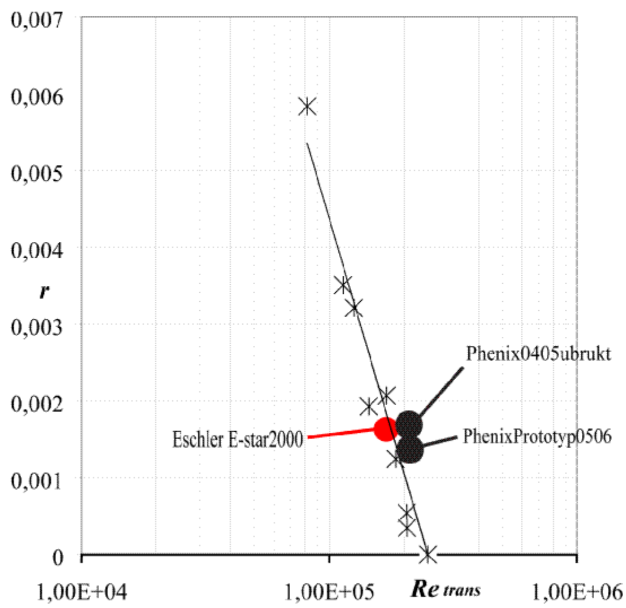

Figure 9. Correlation between r and Re_{trans}. The 3 round marks present in the Figure relate to the data acquired for 3 textiles from 2 different ski suits used by the Norwegian national team and one from a new suit produced by Eschler

5. Conclusions

Experiments carried out on cylinders dressed with different textiles show that the introduction of surface roughness (dimples) cause the critical regime to occur at lower Reynolds numbers than for smooth cylinders. For increasing roughness, the experiments show that transition occurs at lower Reynolds numbers.

An explicit correlation between the roughness factor r and the typical Reynolds number Re_{trans} has been suggested. The results for drag reduction presented here can be used for choosing the right textiles when designing suits for athletes, thereby reducing the athlete's aerodynamic resistance.

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