A review on skin suits and sport garment aerodynamics: guidelines and state of the art

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Abstract

The present work describes and compares previous results in the field of garment aerodynamics combined with not published results coming from recent experiments conducted at the Norwegian University of Science and Technology (NTNU). A number of factors resulting from the combination of the athlete’s motion and posture, garment and aerodynamics are analyzed and their effect on the overall drag of the athlete is presented. Textiles with different patterns have been proven to be able to reduce the overall drag of the athletes.

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1. Introduction

The phenomenon of drag crisis has been known in the engineering field for decades and it has been used to solve a number of engineering problems such as vortex shedding instabilities \cite{1, 2} or to reduce the aerodynamic resistance on blunt structures \cite{3} at low Reynolds number however, its application to garment aerodynamics is quite recent. Research on garment aerodynamics has been constantly progressing from the first skin suit developed by Nike in 2000 which was the main outcome from the studies carried out by Brownlie \cite{4}. The aim of these studies was to find ways to improve athletic performance through a reduction in the aerodynamic drag on the athlete. A number of studies proved the

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efficiency of modern skin suits in terms of athletes’ performance [5-7]. Brownlie [4] suggested using segmented suits where each part of the body of an athlete was covered with fabrics of different performance attributes. Each of these fabrics interact with the incoming flow by changing the flow regime around the body from laminar to turbulent, consequently reducing the wake size, and thus the pressure drag. Brownlie [4] also introduced wind tunnel tests on cylindrical models in order to be able to compare and quantify the experimental results with the classical literature and existing knowledge [2, 8, 9]. Currently there are a large number of research studies addressing this aerodynamic phenomenon, and different aspects of the complex interaction between the air flow, garments and the body of an athlete have been independently analysed by different authors.

However, considering that the field of aerodynamic performance in high speed sport is quite diverse, covering a large number of variables and characteristics, such as textile type, garment fitting, garment stretching, air permeability, etc., the reported results are often difficult to interpret in a common context, and correlations and interdependencies are difficult to establish and quantify. This paper aims to highlight and analyse the main parameters influencing the aerodynamic efficiency of a skin suit worn in high-speed sports, giving some basic guidelines for the selection of comprising fabric(s) depending on the type of sport, the athlete’s speed, posture and body type. The analysis of existing results of the influence of fabric coating, inflow angle, body segment range of motion and fabric physical attributes (such as, for example, the air permeability, elastic deformation and porosity) combined with an overview of the different types of surface characteristics, such as roughness (macroroughness, microroughness and hairiness) is given. In addition new results on hysteresis, coating and the difference between macro and micro roughness are presented.

2. Garment aerodynamics and athletes, a complex system

2.1. Overview of the model

In sports where the main goal is to cover a defined distance in the lowest time possible, minimizing the drag is crucial. The drag force acting on an athlete can be generally expressed as 

\[ D = 0.5 A \rho C_D V^2 \]

where \( A \) [m²] is the frontal area, \( \rho \) [kg/m³] is the air density \( C_D \) [-] is the non-dimensional drag coefficient and \( V \) [m/s] is free stream velocity. Since the air density is dependent only on the atmospheric conditions, \( D \) can be considered as a function of \( V, C_D \) and \( A \), \( D = f(A, C_D, V) \).

Fig. 1. Factors that influence garment aerodynamics

The frontal area can be reduced either by optimizing the athlete’s posture or by using tight fitting suits when allowed by the regulations of the particular sport. Kyle [10] and Brownlie [4] noticed that loose garments increase the frontal area of the athlete and this could lead to an increase in drag of ca. 40%.
Kyle noticed that a suit two sizes too large could increase the drag by 3% on a cross-country skier. Tight skin suits are thus highly recommended in order to lower the drag. More interesting and complex is the drag reduction obtained with a reduction of the drag coefficient ($C_D$). The drag coefficient $C_D$ depends on a number of parameters that interact with each other and their combination can lead to an overall drag reduction for the athlete. As a first order approximation it can be stated that $C_D$ is a function of the shape, the motion and the surface $C_D = f(\text{shape}, \text{motion}, \text{surface})$ of the athlete. Shape and motion are typical quantities that depend on the athlete’s body (body size, body shape) and on the type of performance (posture, speed, vibrations, accelerations) while the surface can be modified using a garment able to modify the different parameters (surface structure, air permeability, coating, etc.) that compose the surface structure of the suit. However, the combination of the topological parameters that create the surface of the garment is linked to the motion and shape, and some garments could perform better than others depending on the different motion and shape conditions. In order to clearly understand how low drag suits are able to influence the flow around an athlete’s body, it is useful to isolate the different parameters that might play a role in the drag reduction and drag crisis process. As the drag crisis process is an unstable and nonlinear phenomenon, a number of factors can trigger or delay it and they might interact with each other to shift the critical Reynolds number ($Re_{crit}$), thereby influencing the drop in drag to either increase or decrease the typical drag coefficient recovery that happens at high $Re$. The type of athletic performance and thus the athlete’s motion, is able to influence a number of parameters. Amongst these parameters, the speed of the athlete is surely the most critical and it can be considered as the parameter that should be used in a first order approximation. A downhill skier will experience a much higher speed than a sprinter. Aside from the speed, in each sport where the ultimate goal is to cover a certain distance in the minimum time possible, the athlete’s posture and the techniques used can vary, affecting the angle of incidence between the body and the flow and adding local or global accelerations or vibrations. A typical example of local acceleration would be the change in local velocity experienced by the body limbs during a running race, while an example of global acceleration would be an increase in the speed of the athlete. Local vibrations can be experienced by alpine skiers as a result of repetitive impacts between skis and the snow.

2.2. Athlete posture and motion (shape and motion)

**Speed and size ($Re$)**: In aerodynamics, speed and size are often linked in a non-dimensional number called the Reynolds number $Re = LV/v$ where $L$ [m] is the characteristic length, $V$ [m/s] is the velocity and $v$ [m/s²] is the kinematic viscosity of the fluid. The $Re$ can be defined as the quotient between inertial and viscous forces and it is often used to characterize the different flow regimes, such as laminar or turbulent flow. Laminar flow occurs at low $Re$, where viscous forces are dominant, and is characterized by smooth, constant fluid motion while turbulent flow occurs at high $Re$ and is dominated by inertial forces, which tend to produce chaotic eddies and vortices. In bluff body aerodynamics and in particular in the aerodynamics of cylinders, the turbulent regime is characterized by a lower value of $C_D$ due to the shifting of the separation point towards the back side of the cylinder and thus a smaller wake and a lower pressure drag. The transitional state between laminar and turbulent flow is called critical. The $Re$ can also be used for model or flow scaling. However the assumption of similitude is only valid when the surface is smooth or scaled according to the characteristic length. When an absolute surface roughness $k$ is added to the model, the model size interacts with the roughness determining the relative roughness. The relative roughness can be defined as $r = k/L$ where $L$ [m] is the characteristic length of the model (in the case of a cylinder, the diameter) and $k$ is the roughness height. This means that the same textile would cause a higher critical $Re$ when $L$ is increased [11]. Previous experiments [4, 12, 13] show that larger models require a smoother textile to shift the transition to a lower speed.
Angle of incidence - Limiting the discussion to cylinder aerodynamics, it is known [14] that rough surfaces are able to reduce the drag when the cylinder model is placed almost perpendicular to the flow. However, for an angle of attack larger than 25 degrees, smoother surface give a lower drag [12]. Similar findings were shown by Chowdhury [15] while testing two different textiles for a cycling suit. Re_{crit} remains constant at different angles of attack[12].

Incoming flow acceleration - In many sports incoming flow velocity experienced by the athletes is not constant. Positive and negative accelerations are often present and they can reach high values especially on the body limbs. On the other hand, most of the wind tunnel tests regarding garment aerodynamics were carried out under the assumption of constant and stable incoming flow. In classical cylinder aerodynamics it has been predicted that the C_D-Re curve has a different shape for increasing and decreasing speed [16, 17] leading to a hysteretic cycle in the drag crisis process. The Re_{crit} for a decreasing speed test is lower than the critical Re for an increasing speed test. This behaviour has been confirmed by recent experiments carried out at NTNU on a cylindrical model (Fig. 3b). At NTNU, drag measurements have been made on periodically moving cylinders in cross-flow with the cylinders covered in different types of fabrics at a limited range of frequencies (0Hz to 1Hz) [18] . Compared to statically positioned vertical cylinders, oscillating cylinders show an increase in drag in the sub-critical region and similar C_D values in the post critical region. These results concur with previous reports in the literature [19]. The Re_{crit} seems not to be affected by the oscillations but further studies are needed in order to verify these results. Similar results were presented by D’Auteuil [20]who carried out experiments on a moving mannequin dressed with different suits at frequencies up to 1Hz to simulate a speed skater’s motion. The results show that the Re_{crit} is not affected by the motion but exclusively depends on the type of fabrics used in the suit.

Vibrations - In some sports vibrations can play a significant role. For example in downhill skiing the vibrations due to the interaction between skis and snow can be severe with loads in the order of 5g -30g and in a frequency range between 5Hz and 30Hz [21] at the ski boot. These vibrations are able to propagate throughout the body with resonance frequency ranges between 10 and 40 Hz for the ankle, 10 and 25 Hz for the knee, 10 and 20 Hz for the hip and 10 Hz for the spine [22]. Considering the human legs as cylinders [4] and knowing that the variation in the Strouhal number ($St=fD/V$, where f is the induced frequency [Hz], $D$ [m] is the cylinder diameter and $V$ [m/s] is the flow speed), which is associated with the changes in the flow structure, is about 0.2 over a large Reynolds number interval [23], Fig. 2 can be plotted. Fig. 2 demonstrates that there exists a large region where flow induced vibrations (FIV) and external vibrations (EV) are in the same range and it is well known from theory that the interaction between the natural instability of the wake and forced oscillation plays an important role with the flow properties depending strongly on $f_{FIV}/f_{EV}$. At values of $f_{FIV}/f_{EV}$ close to unity the changing relationship between these instabilities results in an abrupt change in the wake state and thus in drag and lift.

Shape - The body shape of an athlete might differ from athlete to athlete. However some studies showed that fabrics and garments tend to have similar behaviour both on the athlete body and on a
cylindrical model [4, 24]. Considering the body limbs not as circular cylinders but as irregular tapered oval cylinders, the form factor given by the tapering [25] (which lowers the $Re_{crit}$ due to three dimensional effects induced by the tapered shape) and by the oval form (which affects the $Re_{crit}$ depending on the angle of attack) play a role in determining the correct $Re_{crit}$ and drag drop. D’Auteuil [26] pointed out some limitations of modelling the human body as cylindrical elements. By measuring drag and surface pressure distribution on a full scale mannequin in a speed skating posture she showed that 3D flow effects and limb interaction affected the local limb flow transition and the $Re_{crit}$ of the limb segments.

2.3. Garments (surface structure)

Generic definition of textile roughness.- Brownlie [4] first carried out extensive studies on how different types of fabric with different surface roughness are able to trigger the drag crisis describing the roughness with an “integral” roughness parameter. Chowdhury [15, 27, 28] used a similar method to describe the surface structure. Some other authors estimated the surface roughness with a simplified parameter [7, 12, 13, 29, 30] that included only limited parameters of the surface topology. However, this type of analysis is often an incomplete and unsatisfactory way to describing surface topographies. Fuss [31] proposed the use of a skewness parameter instead of the mean roughness parameter as the main roughness indicator. Wieland et al. [32] proposed a wavelength-dependent roughness evaluation for the description of surface topographies in various characteristic roughness ranges segregating the overall roughness structure in macro-scale, meso-scale and micro-scale.

A simplified model of the method proposed by Wieland can be applied to textiles where the macrostructure can be represented by large modifications of the surface (like the dimples on a golf ball) and the microstructure can be represented by the roughness induced by the knitting or warping process. A third component is represented by the “fuzziness” induced by the type of yarn used. A balance of these components is able to influence the $Re_{crit}$ and the drag coefficient in the post critical area. Recent experiments carried out at NTNU in Trondheim on cylindrical models with different combinations of macroscale and microscale roughness on the surface show that a macroscale surface with no microscale is able to trigger the transition at low $Re$ keeping the $C_D$ low in the postcritical region (Fig. 3c). Similar results have been noted during the development of positively dimpled sprinting apparel utilized by some athletes at the 2012 London Olympic Games.

Yarn type and material - Frederik and Street [33] found that modern cross country ski suits have 10 to 16% less drag than the traditional woollen suits at speeds lower than 10m/s. Similar findings were shown by Van Ingen Schenau [34], in 1982 who noted that a wool suit has less drag than a lycra suit for speeds below 7m/s while, for higher speed, the Lycra®-containing suit has lower drag. Kyle [35] determined that a Lycra®-containing suit was able to reduce the drag of a cyclist by ca. 7%. Further experiments carried out by Brownlie [4, 36] showed that textiles are able to affect the flow transition on bluff bodies. However, if fabrics are coated and thus their surface is smooth, then the roughness will not be enough to induce to flow transition. Bardal [37] analyzed the effect of different yarn types with different cover factors and noticed that spun yarns create a “fuzzy” surface that flattens out the $C_D$-$Re$ curves, thereby reducing or even eliminating the critical region and thus increasing the drag at high $Re$. Bardal recommended using filament yarn rather than spun yarn in high performance suits.

Seam positioning.- Brownlie [4] pointed out that fabric seams can trigger early flow transition when placed in front of the flow separation point (45° to 60° from the front center of the cylinder). Chowdhury [27] replicated the experiments confirming these results and found that seam position at 45° triggered the flow separation earlier than any other configuration. Similarly a direct application of the early Brownlie
findings was the zig-zag strips applied to Dutch long track speed skating suits at the 1998 Olympic Games in Nagano.

**Fabric orientation** - Chowdhury [27] briefly analysed the effect of the fabric orientation of knitted fabrics on the relationship of $C_D$ to $Re$. Chowdhury placed fabric samples at three different orientations on a cylindrical model tested in a wind tunnel. He found out that flow transition occurred at the same time for all three orientation angles. In the transition regime of the flow, the effect of stitch orientation is clearly evident, showing that the orientation of the stitch has a small but possibly significant effect on $C_D$.

**Coating** - Fabrics used in modern sports garments will usually go through a printing process before the suit is manufactured. This process, involving sublimation with high pressure and temperature, will alter the topology of the surface and the air permeability to some degree. Little data is published on the effect of sublimation printing on polyester textiles, but wind tunnel measurements performed at NTNU (Fig. 3a) show that the process makes textiles considerably smoother. The effect may however be dependent on sublimation pressure and initial surface topology. For extreme speed sports like speed skiing where no premature flow transition is required, a polyurethane coating could be applied in order to reduce skin friction. Brownlie[4] performed wind tunnel tests of polyurethane coated fabrics that demonstrated a very high $Re_{crit}$ for the coated fabrics compared to uncoated fabrics.

**Stretching** - Recent studies carried out separately by Oggiano [38]and Moria [39]show that there is a direct correlation between the stretching of the fabric and the $Re_{crit}$. Both authors found a weak linear correlation between the stretching factor and the $Re_{crit}$. Bardal [40] concluded that the effect of fabric stretching was of no practical significance in the design of an alpine skiing suit. As an overall conclusion, stretching does not seem to play a major role in triggering the critical velocity.

**Air permeability** - Porosity and air permeability have been taken into considerations by a number of authors. Watanabe [41] found that textiles with high permeability had higher drag than textiles with low permeability at super critical speeds. The same findings were established by Holden [42] who explained the increase in drag by noting that porous materials create surface flapping and move the separation point forward in the model, leading to an increase in drag of ca. 5%. A third reason for an increase in drag is that the ventilation through porous fabrics traps the air inside the fabric and leads to an increase in the skier’s mass. This assumption have also been confirmed by Brownlie [4, 36] who suggested the use of coated fabrics in order to reduce the problem. However, more recent studies by Oggiano [38] and Bardal [43] show that there is no direct correlation between air permeability and drag in tight fit garments.

![Fig. 3](image-url) (a) $C_D$ - Re curve for a coated and non coated surface. (b) Hysteresis cycle obtained using dynamic measurements at 1000Hz. (c) Microroughness and macroroughness.
3. Conclusion

This paper has provided a general overview of the effect of various factors and provided new results regarding the hysteresis cycle, fabric coating and surface roughness on the complex aerodynamic relationship between athletes and performance apparel.

References


