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Pilot study concerning approaches to reduce the friction losses in pressure tunnels of high head hydropower plants

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Für den Inhalt und die Schlussfolgerungen ist ausschliesslich der Autor dieses Berichts verantwortlich.

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Zusammenfassung

Hydraulische Reibungsverluste im Triebwassersystem von Hochdruck-Wasserkraftwerken verringern deren Wirkungsgrad massgeblich. Diese Verluste betragen meist um 5 bis 10% der Brutto-Fallhöhe und nehmen mit der Zeit oft zu, wodurch die Energieproduktion weiter eingeschränkt wird. Aus hydraulischer Sicht lassen sich diese Verluste verringern, sofern die Strömungsgeschwindigkeit im Stollen reduziert wird – indem beispielweise der Tunneldurchmesser vergrössert oder ein Parallel-Stollen ausgebrochen wird – oder durch eine Verringerung der Oberflächenrauheit mittels Auskleidungen und Anstichen. Die vorliegende Pilotstudie konzentriert sich auf letztgenannte Massnahme, und stellt sowohl die genannten klassischen Massnahme als auch innovative Ansätze aus der Biologie und Medizin vor. Daraus lassen sich unter Umstände neue Möglichkeiten zur Reduktion der Reibungsverluste im Triebwassersystem von Hochdruck-Wasserkraftwerken ableiten.

Herkömmliche Massnahmen konzentrieren sich – sofern von einer Verringerung der Fliessgeschwindigkeit abgesehen wird – meist auf eine Glättung der Stollenoberfläche, entweder mittels Unterhalt bzw. Reinigung, oder durch den Einbau einer glatten Auskleidung. Gleichzeitig zeigen Erfahrungen aus anderen Disziplinen, dass eine bestimmte Oberflächenstruktur die hydraulische Wandschubspannung im Vergleich zur vollkommen glatten Oberfläche verringert. Beispiele dazu liefert die Natur, insbesondere die Mikrostruktur der Haut von Haifischen, die Beschaffenheit einzelner Pflanzenblätter oder Insektenflügel. Die Mikrostruktur der Oberfläche, teils mit hydrophoben Eigenschaften, schützt vor Verunreinigung und verringert Reibungsverluste bei der Fortbewegung. Nach ausgiebiger Forschung nutzt heute die Industrie Werkstoffe mit ähnlichen Eigenschaften, meist in der Textilbranche und im Schiffsbau. Eine Einführung solcher Oberflächen in der Wasserkraft scheint verheissungsvoll und effizient, sofern möglich und rentabel. Gleichzeitig stellt die Applikation der erwähnten Beschichtungen grosse Herausforderung bezüglich der grossflächigen Produktion und der Dauerhaftigkeit. Die Autoren versuchen im Rahmen der vorliegenden Pilotstudie einen ersten Schritt in diese verheissungsvolle Richtung zu machen, indem Literatur zum Thema aufgezeigt wird, mit dem Fokus auf eine Anwendung im Bereich der Wasserkraft. Eine Stellungnahe von Experten aus Wasserkraft, Betreibern von Kraftwerken und Fachpersonen der Beschichtungstechnik rundet den Bericht ab.

Resumé

Les pertes de charge par frottement représentent une contribution importante au manque d'efficacité des aménagements hydroélectriques. Ces pertes représentent généralement de 5 à 10% de la charge brute de dimensionnement. Elles ont tendance s'accroitre avec le temps entrainant une exploitation moins efficace réduisant la production d'énergie par l'aménagement. D'un point de vue hydraulique, les pertes par frottement peuvent être limitées en réduisant la vitesse de l'écoulement ; i.e. soit en augmentant le diamètre de la conduite ou en réalisant une conduite en parallèle, ou en agissant sur la rugosité de la paroi de la conduite en plaçant de la peinture ou un revêtement. Ce travail s'intéresse à cette dernière solution et explore diverses solutions, traditionnelles ou innovantes, trouvées dans différents domaines d'étude comme la biologie ou la médecine. Ceci pourrait entrainer de nouvelles perspectives dans la réduction du frottement dans les conduites des aménagements hydroélectriques à haute chute.

Les solutions traditionnelles utilisent le lissage des parois de conduite, soit en enlevant le mauvais matériau ou en recouvrant les parois avec un revêtement lisse. Ces mesures ont longtemps été utilisées pour assurer une résistance au frottement minimum. Cependant, des scientifiques ont trouvé que, paradoxalement, une surface avec une certaine microstructure peut entraîner une plus petite tension de cisaillement à la surface qu'une paroi lisse avec un même matériau. Cette conclusion a été faite après d'importantes recherches sur la peau des requins nageant à grande vitesse, les feuilles des plantes et des ailes d'insectes. En effet, dans certains cas, une microstructure alliée avec des propriétés hydrophobiques protège de l'encrassement et réduit les forces de frottement. Toutes ces observations ont inspirées le dimensionnement de multiples matériaux ayant diverses applications dans l'industrie tels que des revêtements hydrophobes ou des films microstructurés. Ces solutions semblent prometteuses dans le cas d'une doublure du revêtement de parois de conduite dans des aménagements hydroélectriques. Cependant, il y a encore beaucoup de questions sans réponses quant à l'application, l'efficacité et la maintenance qui nécessitent d'autres recherches. Dans ce travail, les auteurs réalisent un premier pas dans cette direction.

Abstract

Friction losses represent an important contribution to the lack of efficiency of hydropower systems. These losses typically represent 5 to 10 % of the gross head at the design stage and tend to increase with time, leading to a less efficient system and, therefore, to less energy produced. From a hydraulic perspective, approaches to reduce the friction losses pass by reducing the flow velocity – i.e. increasing the tunnel diameter or providing a parallel-tunnel – or acting on the wall roughness by lining and painting. The present work focuses on the latter approach and investigates both traditional and innovative solutions found in different areas, such as biology and medicine, which might give a new perspective in friction reduction in tunnels of high head hydropower plants.

Traditional solutions typically focus on smoothing the tunnel walls, either by cleaning fouling material or lining the walls with smooth coatings, a measure long believed to provide the minimum frictional resistance. However, scientists have paradoxically found that a surface with a given microstructure may lead to lower wall shear stress than a smooth surface of the same material. This conclusion was drawn after extensive research on the skin of fast swimming sharks, plant leaves and insect wings, where a microstructure, in some cases allied with hydrophobic properties, were seen to protect against biofouling and to reduce friction drag. These observations have been inspiring the design of multiple materials, namely hydrophobic coatings and microstructured films, with diverse applications in industry. The solution where the tunnel walls are lined with a microstructured pattern seems promising for hydropower applications; however, there are still many open questions regarding the application, efficiency and maintenance of this solution that need further investigation. The authors intend to do a first step in that direction.

1 Introduction

This study investigates approaches to reduce friction losses in tunnels of high head hydropower plants, in order to improve the efficiency of the entire pressure system. It summarizes the solutions traditionally applied in industry to reduce friction drag, as well as innovative methods found in literature that could give a new insight in friction reduction in hydropower applications.

Friction drag reduction is a topic of interest in several areas, namely in aerospace, oil and marine transportation, biology and medicine. In commercial aircrafts, the skin friction represents about to 50 % of the total drag (Bechert et al. 1997, Stenzel et al. 2011), whereas in the marine transportation industry that value can raise up to 70 % of the total drag in a cargo ship (Fukuda et al. 2000). In the hydropower industry, the head loss due to friction at the design stage typically reaches 5 to 10 % of the gross head. However, with time, several factors contribute to an increase of the friction losses in the system, such as operation above the original design capacity, degradation of the tunnel walls, leaking and fouling induced problems (degradation of the wall surface and increase of the wall roughness). Therefore, less energy is produced as a consequence of increased friction drag. To overcome these issues, traditional solutions include cleaning and lining the existing pressure tunnels, typically with very smooth lining materials. In fact, results from numerous investigations (Nikuradse 1933, Colebrook 1939, Schlichting 1979, among others) have shown that smooth surface has the smallest flow resistance compared with the other surface structures (rough).

However, various observations in nature indicate that the assumption of minimum friction drag being given by very smooth surfaces should be reanalysed. The skin of fast swimming sharks is covered by small dermal denticles that are shaped like small ribs (riblets) and are seen to protect against biofouling and to reduce drag experienced by sharks as they swim. Plant leaves have a microscopic structure composed by hydrophobic components - wax crystals, allied with a microscopic roughness, causing effective water repellency, self-cleaning and drag reduction (Barthlott and Neinhuis 1997, Wagner et al. 2003, Bhushan and Jung 2008, Dean and Bhushan 2010, Bixler et al. 2014). Motivated by these and other similar observations, scientists have shown that a turbulent boundary layer on a surface exhibiting longitudinal ribs can develop a lower shear stress than that on a smooth surface (Walsh and Lindemann 1984, Nitschke 1984, Bechert et al. 1997, 1997a, Lee and Lee 2001). This inspired, for instance, the design of low-drag swim suits textured with riblet microstructures (Krieger 2004, Matthews 2008). Furthermore, recent advances in material and biomimetic sciences have enabled the design of artificial structures imitating superhydrophobic proprieties of plant surfaces and insect wings, which motivated the development of coating materials with several applications in industry.

The greatest challenge nowadays deals with the optimization, manufacturing and application of these solutions in large scale industrial demands. To the author's knowledge, there are no studies available where similar innovative solutions were tested in hydropower pressure tunnels. Therefore, the present study aims at exploring the potential of these new insights in the reduction of friction drag in pressure tunnels of high head hydropower plants.

After this introduction, fundamental considerations on friction drag reduction are presented in section 2, together with a summary of the traditional methods and innovative solutions to reduce skin drag. In section 3 are presented the opinions given by specialists in the hydropower industry regarding solutions to reduce drag and their application. Finally, in section 4 are summarized the main conclusions of this study.

2 Friction drag reduction

2.1 Fundamental considerations

Friction or viscous drag is related to the relative motion of fluid layers, due to attraction between the molecules of the fluid, and to the interaction between the fluid and the surface parallel to the flow. The friction forces are associated with the fluid viscosity: fluids with higher viscosity exhibit therefore higher drag due to higher attraction between fluid layers, increasing thus the skin friction (Schlichting 1979).

In laminar flows, the motion of the fluid particles is translatory. The fluid resistance is due to viscous shear of the fluid particles moving in parallel paths with different velocities. Particles moving along the pipe walls are subjected to viscous shear from other particles which adhere to the walls. In turbulent flows, which are the most common in practical applications, in addition to viscous drag there is drag due to cross-flow, i.e., flow perpendicular to the main flow direction, and due to fluid particles following irregular paths. In pipe flows, laminar regime occurs for Reynolds numbers Re < 2000, whereas turbulent regime occurs for Re > 4000, where Re is the Reynolds number, defined as Re = UD/ν, where U is the mean flow velocity, D is the pipe diameter and ν is the fluid kinematic viscosity. In the transition region (2000 < Re < 4000), laminar flow switches easily to turbulent flow when a trigger exists (Pope 2000).

The frictional resistance in pipes can be traduced by the empirical Darcy-Weisbach expression

$$f = \frac{h_f}{L}\frac{2gD}{U^2}$$

(1)

where f is the friction coefficient, h_f is the head loss due to friction, L is the pipe length, and g the acceleration due to gravity. This expression states that the head loss h_f is proportional to the pipe length and to the square of the flow velocity and inversely proportional to the pipe diameter, the friction factor being the coefficient of proportionality. Given that the head loss h_f expresses the pressure loss Δp as the height of a column of fluid, $\Delta p = \rho g h_f$, where ρ is the fluid density, the above expression (1) is equivalent to

$$f = \frac{\Delta p}{\rho L}\frac{2D}{U^2}$$

(2)

where the friction factor f can be evaluated directly by measuring the pressure drop between two sections of a pipe flow. To reduce the head losses in a pipe flow it is thus possible to act in three parameters: U, D and f.

2.2 Traditional solutions

The decision to act in the tunnel of an existing hydropower plant is typically related to leaking problems or structural integrity, rather than acting solely in the tunnel hydraulic efficiency. However, the traditional interventions to rehabilitate and to refurbish existing tunnels have in general positive effects in reducing the head losses, since the measures usually include cleaning the inner surface and replacing old and damaged lining materials. In unlined tunnels constructed by the drill and blast method, lining the walls with concrete, paving the invert or removing rock protrusions have natural benefits in drag reduction (ASCE 2007). In lined

tunnels, the replacement of the old deteriorated lining materials by smooth new lining, for instance epoxy based paints typically with low friction coefficients, is beneficial for the friction losses. However, when the structural integrity of the tunnel cannot be ensured with minor rehabilitation, lining with steel or fibreglass to reinforce the tunnel structure, or replacing the existing penstock, are frequent measures where drag reduction is an extra advantage. The traditional measures to reduce friction are summarized below, where examples of real applications are given, highlighting the motivation, methods and benefits associated to each particular situation.

2.2.1 Cleaning

Cleaning the tunnel inner walls is an effective solution to remove attached fouling materials. Fouling can be biologic or inorganic and it damages the tunnel walls, increases the wall roughness and the head losses, with an associated reduction of flow carrying capacity (Barton et al. 2008, Andrewartha et al. 2008, 2010, 2011, Bixler et al. 2014). The effect of biofilms on near wall flows has been studied extensively (Schultz and Swain 2000, Andrewartha et al. 2010). Schultz and Swain (1999) studied the influence of marine biofilms on turbulent boundary layer structure and found that, depending on the biofilm thickness and morphology, an increase of 68 % of the skin friction occurs for slime films with average thickness 350 µm and an increase in 190 % occurs for filamentous green algae with mean thickness of 310 µm, when compared with smooth surface. Some authors suggest that the viscoelastic nature of biofilms causes additional energy dissipation mechanisms (Picologlou et al. 1980, Stoodley et al. 1998).

Although effective, cleaning is a short term solution since the fouling tends to build up again after some time (Mirza et al. 2001). Cleaning methods depend on the characteristics of the wall and typically include high-pressure water jet, wire brushing, hydrogen peroxide, flame and high-pressure soda blasting.
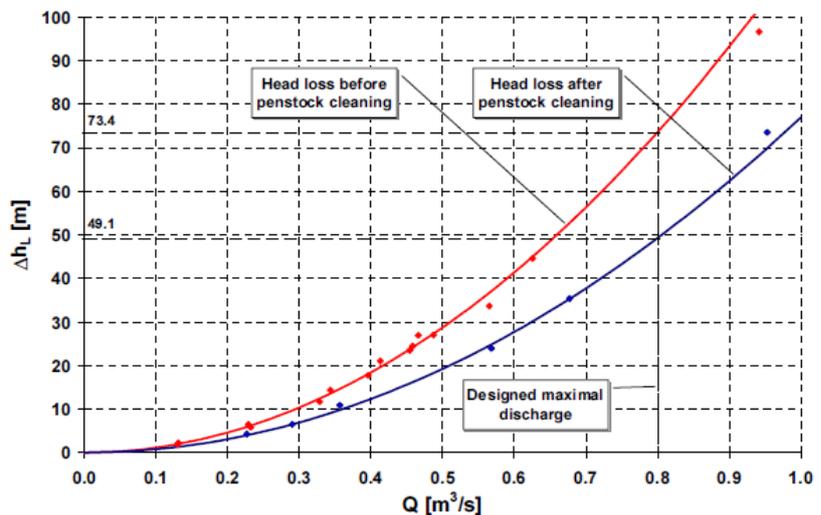
Fig. 2 – Head losses before and after penstock cleaning

Figure 1 – Incrustation that developed in the inner surface of Sapuncica penstock, Macedonia. Head losses measured at the penstock before and after cleaning (adapted from Ševčík and Krejčí 2010).

Case history – Sapuncica. The hydropower plant Sapuncica, Macedonia, is equipped with a steel penstock 2 km long and diameter of 0.5 to 0.6 m, and an installed capacity of 2.91 MW. In a performance evaluation test it was observed that the system was having significant

friction losses, about 20 % of the gross head. After inspection, it was detected the presence of incrustations in the penstock walls resulting from the reaction between the steel walls and the highly oxygen-saturated water. The incrustation was removed by an abrasive cleaning tool, leading to head losses of 12 % of the gross head (head loss relative reduction of 33 %) (Ševčík and Krejčí 2010).

Case history – Tasmanian hydroelectric schemes. Three pipelines in Tasmanian hydroelectric schemes (Poatina, Wilmot and Terraleah Hilltop), were cleaned with high-pressure water jet to remove biofilm attached in the inner walls. A general benefit in the decrease of the head losses was observed for all pipelines, except in Poatina penstock. This was related to the poor conditions of the existing lining of coal-tar enamel, which was further replaced (see section 2.2.2) (Barton et al. 2008, Andrewartha et al. 2011).

2.2.2   Lining/relining

Lining the tunnel inner wall provides protection for the wall material and plays a role on the performance and longevity of the tunnel. Many different lining/coating materials are available and the use of a specific material type will be dependent on the project specific needs. Some coatings not only improve surface roughness but can also prevent fouling. The constant innovation in the lining technology gives nowadays a wide range of solutions. Newer liners have also longer life expectancies and limit costly maintenance or repair expenses. Nevertheless, the cost of lining a meter of tunnel is often two to three times the cost of excavating the tunnel (Best Practice Catalogue 2011).

Case history – Bersimis. The intake concrete tunnel at Bersimis-1 generating station in Quebec, Canada, is a 12 km long horseshoe section tunnel with mean diameter of 9.45 m, and initial installed capacity of 912 MW. Power losses estimated in 39 MW/year were related to the development of slime in the tunnel walls. Other factors contributing to head losses are cracks in the concrete, irregular surface of the slime, construction joints, among other defects. A study was developed to evaluate the benefits of cleaning and lining the tunnel walls with a protective material that could both reduce the friction losses and minimize the development of slime at the walls. Several coating materials were tested, being selected a polymer modified cement-based mortar with thickness 2 to 3 mm to cover uniformly the concrete surface. Finite-element modelling was used to estimate the head losses and indicated that these would be around 8 % of the gross head for the maximum flow rate (head loss relative reduction of 20 %). The cost of this intervention was estimated in $10 to $11 million dollars, the cost of material being estimated in $2.0 to $2.5 million dollars (Mirza et al. 2001).

Case history – Kingston Mills. Kingston Mills Generating Station in Ontario, Canada, has two steel penstocks 67 m long, one with diameter of 1.8 m (P1) and the other with diameter of 2.4 m (P2), and total installed capacity of 1.8 MW. An inspection in early 1990s has revealed that the thickness of the walls were near the minimum safe due to corrosion. Besides wall thickening, there was also the concern of zebra mussel fouling. Penstock P1 was lined with a latex-based primer and topcoat of thickness 0.20 to 0.25 mm and P2 was lined with an epoxy primer with added solids to fill any small irregularities caused by corrosion. The effect of lining P1 increased the output in 11.6 % (600 to 670 kW), whereas lining P2 produced a benefit of order 1 to 2 %, this fact being attributed to the initial oversize of penstock P2. No information on costs was found (Steel Penstock-Coating and Lining Rehabilitation 2000).

Case history – El Dorado. El Dorado steel penstock in California, USA, is 1.2 km long with diameter ranging from 0.76 m to 1.37 m with 21 MW of installed capacity. Corrosion was thickening the penstock walls so it was decided to line the walls with 100 % solids polyurethane. The material was applied in two coats to a total dry film thickness of 1.3 to 2 mm. Application of the polyurethane was accomplished with a spin spray mechanism. The

final project cost was near $1.6 million dollars. Head loss relative reduction due to new lining was near 39 %, which represents a power increase of about 3.3 % per year. The project has a 12-year payback for a life extension estimate of 30 years (Steel Penstock-Coating and Lining Rehabilitation 2000).

Case history – Poatina. The hydropower plant Poatina in Tasmania, Australia, has a steel penstock 1.7 km long and 3 m diameter. During the cleaning operations (see section 2.2.1) it was observed that the existing anti-corrosion coat of coal-tar enamel was in poor conditions, influencing the performance of the system (Barton et al. 2008). This was removed and replaced by epoxy-based painting. The refurbishing operations took 5 months, with costs of around $10.4 million dollars. Although great benefits in drag reduction are expected, no quantification was found in the literature.

2.2.3   Additional penstock

To provide an additional penstock to the existing system is not a common solution to reduce friction losses due to high costs associated. However, depending on the flow demand, the layout of the existing system and operation flexibility, this might be an advantageous solution since it requires minimal service interruption.

Case history – Moccasin. The Moccasin hydroelectric project in California, USA, is a system where downstream of the pressure tunnel is a trifurcation where two of the three branches are connected to two steel penstocks (Figure 2). Increased flows and demands for water delivery have resulted in relatively high head losses in the system (about 11 % of the gross head). The system operating flexibility was also a concern. To address these issues, the addition of a third steel penstock to the existing system was considered by taking advantage of the third branch of the trifurcation. This solution would reduce the existing head losses in about 40 %, which corresponds to a 5 % increase in power output at maximum flow (Gass 2001).
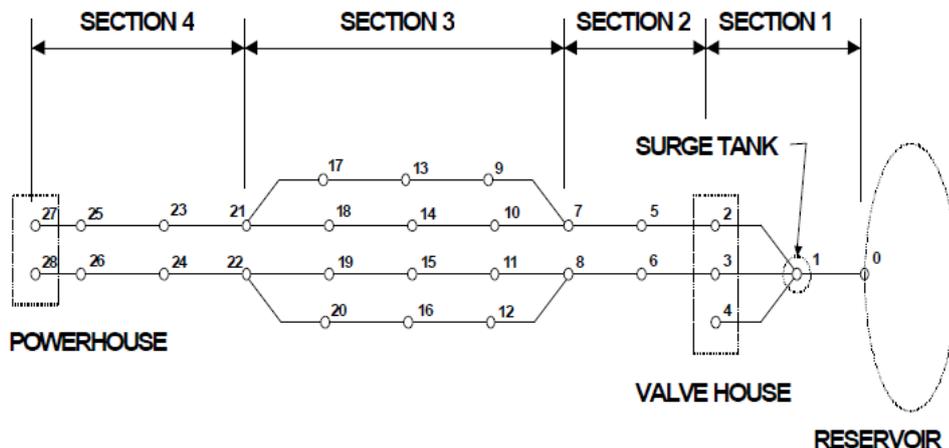
Figure 2 – Layout of the Moccasin hydroelectric power system (extracted from Gass 2001).

2.3   Innovative solutions

Inspired by the capacity of preventing biofouling and drag reduction observed in organisms in nature, where a certain roughness in the surface has proved to be effective, in some cases allied to hydrophobic properties, biomimetic sciences have tried to replicate the effects of such surfaces to use in industrial applications. After an extensive search in literature, innovative solutions inspired by nature can be organized by: shark-skin inspired riblets, superhydrophobic surfaces and superhydrophilic surfaces.

Riblets inspired by the micro-roughness texture found in the skin of fast swimming sharks are seen to influence the position and the interaction between streamwise vortices generated in turbulent flows, as well as the interaction between vortices and the wall surface. Experiments with riblets aligned in the streamwise flow direction have shown that these microstructures can reduce drag in external and internal flows, an effect proved more effective in turbulent than in laminar flows (Bixler and Bhushan 2013). In external flows, drag reductions up to 14 % were measured with straight riblets (Neumann and Dinkelacker 1991, Ali and Al-Fatlawie 2011), whereas experiments with sinusoidal riblets in a wind tunnel have revealed drag reductions up to 19 % (Ali and Al-Fatlawie 2011) relatively to smooth surface. Although limited data is available for internal flows, results from Reidy and Anderson (1988) revealed drag reductions up to 28 % in a pipe of 15 cm of diameter lined with riblet structures, whereas experiments in micro-sized pipes have shown drag reductions up to 9 % (Rohr et al. 1992).

Superhydrophobic surfaces are accomplished by combining low surface energy, i.e., a surface that repels water, with micro-roughness. A surface with such characteristics provides low fluid friction in the laminar flow range, which results from the formation of an air layer between water and surface (Shirtcliffe et al. 2009). This property is governed by the air-layer sustainability and depends on the surface energy or the fluid flow rate. Once the air layer is removed, fluid friction on the surface increases markedly because of its own surface roughness (Sakai et al. 2012). Therefore, low fluid friction is difficult to obtain on superhydrophobic surfaces under large flow velocities in the turbulent flow range. However, recent experiments from Bixler and Bhushan (2013), where micro-sized pipes were lined with optimized riblet structures and coated with a nanostructured material, revealed drag reductions up to 34 % in the turbulent flow regime.

Superhydrophilic surfaces strongly attract water molecules, forming a permanent layer of water at the wall surface. By creating a water-water interface, higher slip length is obtained and, hence, less drag is promoted than the one observed in water-surface interface. To our knowledge, only one study has been performed on the effect of hydrophilic surfaces in reducing friction drag, where drag reductions up to 5 % were reported (Sakai et al. 2012).

2.3.1   Shark-skin inspired riblets

Riblets are microstructures aligned in the streamwise direction of the flow. The mechanism for friction drag reduction is related to the capacity of these structures to affect the position, size and interaction between streamwise vortices generated in the flow. In turbulent flows, the strong exchange of momentum is produced by high speed flow lumps approaching the surface ("sweeps") and by low speed flow moving away from the surface ("ejections") into the high speed regions of the flow (Bechert 1997a). By impeding the spanwise motion of streamwise vortices during sweep events, the interaction of neighbour vortices is reduced as well as shear stress and momentum transfer. Furthermore, with an optimized distance between riblets, the vortices can be pined in the peaks and detached from the skin, which could reduce the pulse exchange near the skin, reducing the friction resistance (Bechert et al. 1997, Fish 1998, Lee and Lee 2001).

The effectiveness and the optimization of the riblets geometry strongly depends on the flow characteristics. For a given flow velocity, or for a narrow range of flow velocities, if the spacing between riblets is larger than the average streamwise vortex diameter, vortices can allocate in the valleys between riblets and interact with a higher wetted surface area (Figure 3b). Ideally, vortices should be kept above the riblets tips (Figure 3a), this being the area exposed to high-shear stresses. By keeping the vortices above the riblet tips, cross-stream velocity fluctuations inside the valleys are much lower than the ones in flat plate (Lee and Lee 2001).

The most thorough riblet characterization has been completed for symmetrical two-dimensional riblets with sawtooth, scalloped (semi-circular) and blade cross sections (Figure 4). Alternative riblet geometries have, in general, shown no increased benefit. Three-dimensional riblets, which include segmented two-dimensional riblets as well as shark-skin mouldings and replicas, have also been studied (Bechert et al. 1997, 1997a, Jung and Bhushan 2010, Bixler and Bushan 2013).

The riblet geometry can be characterized by non-dimensional parameters allowing the comparison between studies using different flow conditions. Normalization accounts for the change in size of vortex diameter, which is the critical value to which riblets must be matched. Typical non-dimensional vortex diameters are in the order of $d^+ = 20$ to 50 (Kim et al. 1987, cited in Ali and Al-Fatlawie 2011), defined as $d^+ = du^*/v$, where d is the vortex diameter and u^* is the wall shear stress velocity. Similarly, non-dimensionalized spacing between riblets, s^+, is defined as $s^+ = su^*/v$, where s is the riblet spacing, and the non-dimensional riblet height, h^+, is given by $h^+ = hu^*/v$.

Experiments have been carried out with various surface materials and in air, oil and water. Under the same non-dimensionalized flow conditions, riblet arrays sharing characteristic dimension ratios show similar performance whether they are made of different materials, are tested in different fluids or fabricated at a different scale (Dean and Bhushan 2010). In general, values of s^+ near 15 have shown the maximum drag reduction for various riblets geometries, which is between one-third and one-half of the width of the streamwise vortices. Sawtooth riblets made of vinyl film are the most commonly used in laboratory experiments. Stenzel et al. (2011) recently proposed a new method for the production of a painting coat reproducing microstructured riblets for application on large surfaces.

| Drag decreasing case (U_o = 3 m/s) | Drag-increasing case (U_o = 5 m/s) | U_o = 3 m/s (flat plate) | U_o = 5 m/s (flat plate) |
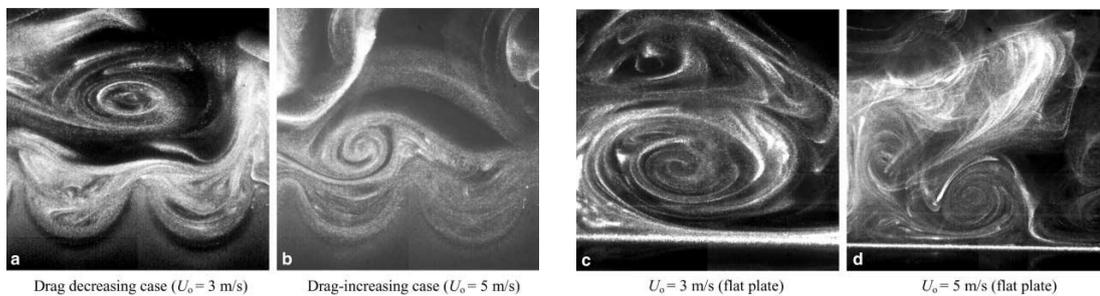
Figure 3 – Turbulent flow visualization of streamwise vortices in a vertical cross section over riblet surface (a,b) and over a flat plate (c,d) (extracted from Lee and Lee 2001).
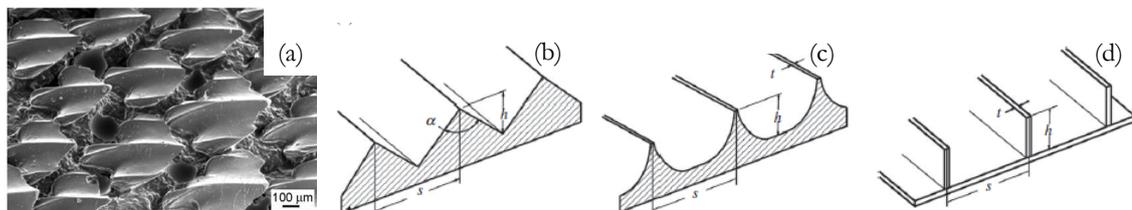
Figure 4 – Riblet structures. Riblets in shark skin (a), sawtooth (b), scalloped (c) and blade (d) (extracted from Jung and Bhushan 2010 (a) and Dean and Bushan 2010 (b,c,d)).

Ribblets in industrial applications – Aircraft. Bechert et al. (1997) reported that riblets with optimized geometry and properly manufactured can reduce turbulent skin friction drag up to 8 % in an aircraft covered up to 70 % with these microscopically small structures. In such conditions, drag and fuel consumption reductions up to 3 % can be achieved.

Ribblets in industrial applications – Swimsuit. The low drag swimsuit developed by Speedo – Fastskin LZR Racer, is textured with riblets that mimic the denticles of shark skin. Speedo claims that Fastskin swimsuits reduce drag up to 4 %. The efficiency in reducing drag by these suits lead to great discussion among expert since it is not clear whether it acts in reducing the skin or pressure drag (Krieger 2004, Matthews 2008).

Table 1 summarizes the results in drag reduction obtained in several experiments using riblet structures.

Table 1 – Summary of the tested riblet structures and maximum drag reductions measured.

Riblet type	s^+	h^+	Maximum drag reduction	Flow tipe	Reference
Sawtooth	10 - 15	10 - 15	8 %	Air (external)	Walsh and Lindemann (1984)
			28 %	Water (internal)	Reidy and Anderson (1988)
			8 %	Water (external)	Reidy and Anderson (1988)
			7 %	Water (internal)	Liu *et al.* (1990)
			13 %	Water (external)	Neumann and Dinkelacker (1991)
			9 %	Water (internal)	Rohr *et al.* (1992)
			5 %	Oil (external)	Bechert *et al.* (1997)
Scalloped	16	0.7 s^+	8 %	Oil (external)	Bechert *et al.* (1997)
Blade	16	0.5 s^+	10 %	Oil (external)	Bechert *et al.* (1997)
Trapezoidal	15 - 20	0.5 s^+	8 %	Oil (external)	Bechert *et al.* (1997)
			6 %	Wind (external)	Stenzel *et al.* (2011)
Rectangular (straight)	-	-	14 %	Air (external)	Ali and Al-Fatlawie (2011)
Rectangular (sinusoidal)	-	-	19 %	Air (external)	Ali and Al-Fatlawie (2011)
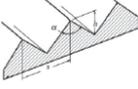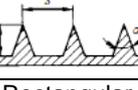
Challenges. One of the main challenges is the fabrication and application of riblets. There is a commercial manufacturer of vinyl riblet films whose products have been widely used in laboratory studies (Nitschke 1984, Liu et al. 1990; Rohr et al. 1992, Bechert et al. 1997, among others). There is an interesting method to create riblet like structure inside pipelines through a scratching technique (reported in Bechert et al. 1997 and in Dean and Bhushan 2010, with the indication that drag reduction up to 10 % was measured) that should be better explored. Microscale manufacturing techniques are experiencing a great development nowadays, but are not yet well fitted for large-scale application owing to the associated costs.

If application is intended for flows with a wide range of velocities, the benefit that can be achieved from riblets has to be calculated very carefully before attempts are made to apply riblets to such surfaces, since the efficiency of these structures is strongly related to the flow characteristics.

2.3.2   Superhydrophobic surfaces

Superhydrophobic surfaces are achieved by combining hydrophobicity with surface roughness. This feature was first observed in plant leaves: some plant leaves when put under water displayed a silvery shine layer (Figure 5), due to air trapped between the surface structures. Microscopic techniques have revealed micro roughness in the surface of plant leaves which minimizes the contact area between water and leaf. As the attraction between fluid and surface is decreased, also decreases the fluid drag. The superhydrophobic mechanism therefore requires air "trapped" between the nanostructures on the surface (Watanabe et al. 1999, Shirtcliffe et al. 2009).

This phenomenon has gained significant interest with regard to drag reduction and the prevention of biofouling. Experiments in internal flows in very small-sized hydrophobic pipes (Watanabe et al. 1999, Shirtcliffe et al. 2009) have shown friction drag reduction of about 14 % in the laminar and transition region. However, when Reynolds number started to increase, no benefit in drag reduction was observed. This is believed to be related to the air trapped in the porous surface, i.e., for higher flow rates the air film cannot be sustained, leading to the increase of fluid drag.

Jung and Bhushan (2010) and recently Bixler and Bhushan (2013) have measured drag reduction in micro-sized pipes lined with riblet structures coated with hydrophobic material (nanostructured coating of silica), as well as surfaces textured with shark skin replica. The results of the experimental measurements on shark skin replica showed a reduction of pressure drop up to 30 % in turbulent flow, relative to smooth surface, whereas drag reduction of 34 % was measured in the pipe lined with coated riblets, indicating that properly sized riblets combined with an appropriate nanostructured coating gives the maximum drag reduction for turbulent flows.
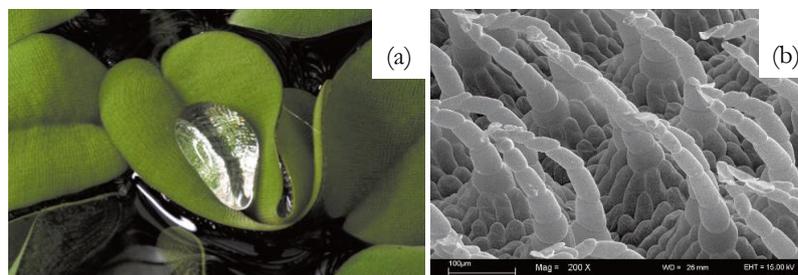
Figure 1 – Surface of the water fern salvinia leaf. Water droplet in the leaf (a) and detail of the leaf rough-ness structure (b) (extracted from Cerman et al. 2009).

Superhydrophobic surfaces in industrial applications. Many researchers have focused on fabricating water repellent films, which are potentially suitable for various practical applications: protecting satellite antennas, buildings, traffic signs and roofs against adhesion of snow, as well as increasing the performance of automobiles, ships and aircrafts by reducing friction drag (Nakajima et al. 2001).

Challenges. In turbulent flows, the air film between water and the superhydrophobic surface cannot be sustained, leading water to adhere to the wall increasing the wetted area and thus the friction drag. However, the solution tested by Bixler and Bhushan (2013), where riblet structures are allied to water repellent properties, seems promising in reducing drag in turbulent flows. This solution should be further investigated, with the ultimate aim of applying in hydropower tunnels. Manufacturing techniques have to be explored in order to achieve an economic solution for large scale applications.

2.3.3   Superhydrophilic surfaces

A hydrophilic surface strongly attracts the water molecules. The creation of a highly hydrophilic surface of titanium dioxide by UV illumination (photoinduced hydrophilicity) was reported by Wang et al. (1997). The antifogging and self-cleaning properties of such surface have led the development of titanium dioxide coatings for several industrial applications (Fujishima et al. 2000). Highly hydrophilic surface is expected to be advantageous for decreasing fluid friction for large flow velocity if the slipping boundary switches from a solid-liquid to a liquid–liquid interface (Sakai et al. 2012).

Sakai et al. (2012) studied the effect of a photoinduced hydrophilic surface in fluid drag in a small-sized pipe (diameter of 10 mm). It was observed that laminar flow regime was maintained in the range Re = 4000-6000 after UV illumination, suggesting that a highly hydrophilic titanium dioxide surface reduced the fluid friction, to a maximum of 5 % for Re = 6000. They compared hydrophilic with hydrophobic surfaces, observing that in the latter the fluid drag increased markedly for Re > 4000 (transition and turbulent flow), this being related to the air-layer removal and resultant bubble generation.

Challenges. Similarly to the previous innovative solutions, hydrophilic surfaces should be further investigated in order to clarify and control their effect in drag reduction. Durability and maintenance issues, together with manufacturing and application techniques should be also addressed in future studies.

2.4   Summary table

The Table 2 indicates a summary of the described traditional solutions, whereas the Table 3 gives an overview on the innovative methods.

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Table 2 – Summary of traditional solutions.

	Solutions	Example	Methods	Benefits	Cost	Advantages	Disadvantages
Traditional	**Cleaning** $f\downarrow$ $D\uparrow$	*Sapuncica, Macedonia*	Removal of incrustations that developed in steel tunnel	**Head loss reduction 33 %** (from 18 % to 12 % H_b)	not found	**Maintain the tunnel** if in good structural conditions Can be performed at the **same time of other interventions** in the system	**Short term duration**; incrustations and biofouling eventually build up again after some time **System shutdown** (time?) **Disposal of the removed material** has to be considered in advance
		Poatina Wilmot Terraleah Hilltop HPP's in Tasmania	Removal of biofouling in tunnels already lined with protective materials	**Head loss reduction 25 %** (if original lining was in good conditions)	not found		
	Lining $f\downarrow$	*Bersimis-1, Canada*	Lining with polymer modified cement-based mortar (thickness 2 to 3 mm), after cleaning to remove slime substance attached in the concrete walls	**Head loss reduction 20 %** (from 10 % to 8 % H_b) **Increased capacity 39 MW/y**	$ 10 - 11 million ($30/m^2) (not included power losses during shutdown period)	Multi-purpose linings: - **Reduce fouling** in the wall surface - **Protect the wall material** (concrete or steel) against aggressive agents - **Smooth finishing** - **Long term duration**	**System shutdown** (ex: 5 months to line 1.7km Poatina tunnel) **Disposal of the removed material** has to be considered in advance **Cost**

Table 2 – Summary of traditional solutions (continued).

Traditional	**Lining** $f\downarrow$	*Kingston Mills, Canada*	Lining P1 with a latex-based primer and topcoat (thickness 0.2 to 0.25 mm)and P2 with an epoxy primer with added solids, after cleaning	**Increased capacity 11.6 %** P1 (600 to 670 kW) **Increased capacity 1 – 2 %** P2	not found		
		El Dorado, USA	Lining with 100 % solids polyurethane (thickness 1.3 to 2 mm)	**Head loss reduction 39 %** **Increased capacity 3.3 %**. (12-year payback time, life extension ~ 30 years)	$ 1.6 million ($409/m^2)		
		Poatina, Tasmania	Removal of old lining (coal tar enamel) and replacement with new epoxy-based painting	**Head loss reduction** (not quantified)	$ 10.4 million ($650/m^2) (inc. power losses during shutdown?)		
	Additional tunnel $f\downarrow$ $D\uparrow$	*Moccasin HPP, USA*	Add a third steel tunnel to the existing system	**Head loss reduction of 43 %** (from 11 % to 6.3 % H_b) **Increased capacity in 5 %.**	not found	**Take advantage of the original layout**; existing system was designed to accommodate a 3rd tunnel **Minimal service interruption** **Operating flexibility**	**Cost**

Table 3 – Overview on innovative methods.

	Solutions	Example	Methods	Benefits (relative to smooth surface)	Challenges
Innovative	**Shark-skin inspired riblets** *friction drag reduction by acting in the cross-flow*	*Aircraft*	Cover ~70 % of the surface with **trapezoidal** shaped **grooves** with 0.1 mm of spacing and height	**Drag reduction up to 8 %** **Fuel** consumption **reduction of 3 %** (*Bechert et al. 1997*)	Effectiveness is strongly **dependent on the flow velocity**, does not work in a varying flow range (a given **riblet geometry** only works for a **fixed flow condition**)
		Aircraft wing and torpedo-shaped specimen	Application of a **microstructured paint** (**trapezoidal** shaped **grooves**), combining application, embossing, and curing in one single process *Air flow, Re= 1.6x10^6*	**Drag reduction up to 6 %** (wing) **Drag reduction up to 5 %** (torpedo) (*Stenzel et al. 2011*)	It was not tested in pipes with diameter > 5cm **Cost** Pre-fabricated films: Manufacturing and application; **difficult to apply in curved surfaces** (with the actual manufacturing mechanisms)
		Flat plate	Covered with straight riblets and sinusoidal riblets (**rectangular** shaped **grooves**) *Air flow, Re = 4.9x10^5*	**Drag reduction up to 14 %** (straight) **Drag reduction up to 19 %** (sinusoidal) (*Ali and Al-Fatlawie 2011*)	Ensure **adhesion** of the riblet film to the surface? Does it work with **high pressure flow?**
		Internal flow in a pipe	Cover the pipe walls with sawtooth riblets made of vinyl film *Water flow*	**Drag reduction up to 9 %** (*Rohr et al 1992*) **Drag reduction up to 28 %** (*Reidy and Anderson 1988*)	On site **Surface scratching? How to perform? Would it be effective to produce riblets?**

Table 3 – Overview on innovative methods (continued).

Innovative	**Shark-skin inspired riblets** *friction drag reduction by acting in the cross-flow*	*Swimsuit*	Surface textured with riblet pattern (Speedo abandoned riblets and turned its focus to minimizing form drag)	**Drag reduction up to 4 %** (*Matthews 2008*)	
	Superhydrophobic surface *friction drag reduction by minimizing the contact area between water and surface* *(air-water interface)*	*Internal flow in a micro-sized pipe* *(3.4 mm x 0.7 mm)*	Combination of **hydrophobic** surface with hierarchical rough **micro-structure** The practical slipping boundary for liquid flow becomes an **air–water** interface.	**Drag reduction up to 30 %** **Reduces biofouling** (*Bixler and Bhushan 2013*)	**Cost** **Depends on the flow rate**; once the **air layer is removed**, **fluid friction** on the surface **increases markedly** because of its own surface roughness Does it work in **"normal"-sized pipes?**
	Superhydrophilic surface *friction drag reduction by minimizing the contact area between water and surface* (water-water interface)	*Small-sized pipe* *(ϕ = 10mm)*	Surface lined with TiO_2 (90nm) and subject to UV illumination -> hydrophilic effect *Water flow, tested range* *$4000<Re<6000$*	**Drag reduction up to 5 %** (*Sakai et al 2012*) Fluid remains in the laminar regime in the range $4000<Re<6000$	Does it work with **high pressure flow?** **Manufacturing and application in a real scale model?** **Maintenance? Is this resistant?**

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3 Feedback from experts

3.1 Experts

The following experts (HPP operators, industry related to surface applications and scientists) provided their feedback to the present report (chapters 1 and 2):

- Prof. Dr. Eugen Brühwiler (EB), Structural Maintenance and Safety Laboratory, EPFL
- Prof. Dr. Anton J. Schleiss (AS), Hydraulic Constructions Laboratory, EPFL
- Michael Zbinden (MZ), Produktingenieur Korrosions- & Brandschutz, Sika Schweiz AG
- Nicola-V. Bretz (NB), HYDRO Exploitation SA, Sion
- Andres Fankhauser (AF), Kraftwerke Oberhasli AG, Innertkirchen

3.2 Questions asked

The Authors of the report submitted the following catalogue of questions to the experts:

1. Do you consider head loss (i.e. friction) reduction along headrace tunnels as a substantial interest of hydropower plant owners?
2. Do you have experience with head loss reduction measures focusing on the traditional solutions (e.g. lining)?
3. Are you aware of innovative solutions to reduce head losses? Have you ever applied such solutions?
4. Can you quantify the critical investment sum to apply such measures (e.g. 1 m of head loss reduction in a specific headrace tunnel would generate N CHF/annum additional profit)?
5. Which risks are linked to such measures (e.g. aging, damaging of turbine)?
6. Do you think it is feasible to line the tunnel concrete surface with a film with a structured surface? Would it be resistant to emptying operations? How would adhesion be ensured? How much time do you think would be required to fix/glue the film to the tunnel surfaces? Which problems could emerge?
7. Do you think it is feasible to scratch the concrete surfaces (small depth, some mm) to produce a requested roughness structure (for instance streamwise ribs)? Any idea of how to perform this? How much time would it take? Would this compromise the long-term structural integrity of the tunnel? Which problems could emerge?
8. Is it promising to further investigate such friction reducing techniques, for instance with physical model tests or prototype applications? Would you recommend to collaborate with a manufacturer of constructional material?
9. Do you have any other inputs or comments to the topic?

3.3 Feedback

The experts provided the following feedback to the questions asked by the Authors of the report:

1. Do you consider head loss (i.e. friction) reduction along headrace tunnels as a substantial interest of hydropower plant owners?

AS: Yes, since head losses in waterway systems of high-head storage power plants are in the range of 10 – 15 % of the gross head. Furthermore, the optimization of the diameter of tunnels and shafts has been done in Switzerland typically 50-60 years ago. If the optimizations would be done today, higher diameters would result since material and labour cost decreased and energy cost rather increased. Further, reduced head losses would allow to increase the installed capacity of a power plant (rehabilitated/refurbished or additional turbines), which increases operation flexibility for storage power plants.

EB: It seems that this is really a relevant topic.

MZ: Following our (Sika) experience, dam owners have an interest in this topic, given that the loss reduction is directly linked to the efficiency and power generation of a power plant.

NB: Yes, of course. By reducing head loss, we can increase the power and therefore the energy production.

AF: Substantial interest for head loss reduction exists (experience of KWO) mainly in the context of older plants (constructed before the 1960s and 70s). Newer plants are built considering the new excavation methods (ventilation and equipment require bigger excavation cross sections) and costs to reduce the existing friction are rather high compared to the effects. Additionally, the plants are seldom used in its full design capacity which means that effective existing losses due to friction are not really considerable.

2. Do you have experience with head loss reduction measures focusing on the traditional solutions (e.g. lining)?

AS: Yes I was involved in the rehabilitation of several pressure tunnels as for example pressure tunnel Handeck-Kapf of KWO (new parallel tunnel).

MZ: We (Sika) have experience linked to the subject. In 2012, the tailrace channel of HPP Emosson, which is made of precast concrete slabs, had to be refurbished due to abrasion of the concrete reducing its discharge capacity. The goal was to provide again the initial discharge capacity. This goal was achieved by applying a suitable Sika system, re-profiling the uneven surface and providing a smooth and resistant surface.

NB: Not exactly experience, but it has been many times discussed in various studies (concrete lining for rough rock, exchange of pipes with better roughness coefficient…).

AF: In order to reduce friction losses the following projects have been realized by KWO: (a) 1974 – 1978: applying shot concrete on the head race tunnel of Handeck 2 plant. Originally this tunnel was built by means of explosives without any lining. By adding the new power plant Handeck 3 additional flow through the existing system required the friction reduction. (b) 2002-2007: Realizing a parallel head race tunnel between Handeck and the surge chamber Chapf reduced the head losses by 10 %. The decision to build a new tunnel was mainly driven by the advantage of minimizing the production losses in the existing system during the construction period. (c) 2011-2016: Realizing a parallel penstock (connected to the existing system) and building an

additional power cavern in Innertkirchen reduces the losses due to friction and generates a power increase of 150 MW. (d) 2013-2016: Realizing a parallel headrace tunnel, penstock (connected to the existing system) and building an additional power cavern in Handeck reduces the losses due to friction and generates a power increase of 90 MW. Together with the project above (i.e. aspect c) the head loss reduction amounts to 70 GWh/a. (e) Regularly, the existing penstocks are retreated by anti-corrosion materials which reduces the friction losses.

3. Are you aware of innovative solutions to reduce head losses? Have you ever applied such solutions?

AS: Yes I'm aware of solutions in biology (biofilms and special surfaces) and vessel design (also special surfaces and boundary layer modification). Nevertheless there was until now no attempt to adapt such solutions to pressure tunnels and shafts of hydropower plants.

AF: We are aware of the existence of innovative solutions. But we never applied such solutions.

4. Can you quantify the critical investment sum to apply such measures (e.g. 1 m of head loss reduction in a specific headrace tunnel would generate N CHF/annum additional profit)?

AS: Normally long head race tunnels are combined with high-head storage power plants which generate mainly peak energy. Any head loss reduction increases therefore proportionally the yearly generation and consequently to the yearly income by energy selling. Based on peak energy prize scenario the critical investment for a certain ROI can be computed.

NB: No, unfortunately. It seems difficult to quantify because of the too many parameters to deal with.

AF: The actual prize of the kWh of around 5 cents is very low and is not very favourable for big investments. The KWO benchmarks to separate interesting projects from not interesting projects are 5 cents for additional kWh, 1 CHF for additional kW. Depending on the amount of kWh/a that can be saved, the additional installed MW, the production losses due to the construction period and the amortisation period which can be taken into account, the allowable investment can be calculated.

5. Which risks are linked to such measures (e.g. aging, damaging of turbine)?

AS: If a kind of surface coating is used the risk is that this material is detached by turbulence and dynamic uplift as well as external rock water pressure.

EB: Not qualified to answer this question. Detached coating material depending on its type may be transported to turbines and produce significant damages especially in Pelton turbines. PVC type coating and biofilms may not represent such risk.

NB: Production loss during implementation of measures, durability of measures against friction because of suspended load (sometimes severe…), crushing during headrace tunnel emptying.

AF: The major risks we can identify by using the described innovative solutions are: (a) missing long time experience, (b) production losses during longer construction period, (c) short amortisation period (end of concession) and (d) very low power prices (CHF/kWh).

6. Do you think it is feasible to line the tunnel concrete surface with a film with a structured surface? Would it be resistant to emptying operations? How would adhesion be ensured? How much time do you think would be required to fix/glue the film to the tunnel surfaces? Which problems could emerge?

AS: Yes but a special apparatus would have to be developed which can clean the tunnel surface and coat the material on it efficiently that means very fast. The cohesion of the material would have to be very high in order to avoid buckling of the material during emptying. Since in concrete linings always cracks exist, the adhesion of the material would have to be such that the acting external pressure on the coating material at these cracks can be bridged without pop-put, tensile failure and detachment. If a tight material would be found which can resist to this external water pressure loading (may be high due to elevation of ground water table in rock), it would have also the huge advantage to decrease water losses due to seepage out of the tunnel. Nevertheless to have a coating material with a certain permeability would avoid the risk of overloading due to external pressure. The adhesion would have to be ensured by a very fast binding high-resistant glue which works even in humid environment. This would be one of the main challenges besides finding the good friction reducing material. As mentioned, the lining should be fast in order to avoid an emptying of the tunnel during more than 3 months, which may be considered a period during summer where the power plant do not operate due to very low peak energy prices. In principal, a tunnel could be lined in several steps i.e. during several periods of 2 to 3 months. Nevertheless, the installation of the contractor would have been erected several times which increase the costs. As an estimate and a goal a machine would have to be developed which can clean, prepare and line about 100 m tunnel per day (24 h). This would allow to line a roughly 10 km during 3 months.

EB: (1) A film with a structured surface could maybe obtained with quartz particles mixed in and applied with rapid-hardening epoxy resin. Surface preparation (cleaning) and application could be rationalized but would need something like 12 h for a certain length … Problems: to achieve sufficient adherence everywhere (since one weak spot could be the initiation of a major delamination/peeling off process of the film. (2) One could imagine working on the existing concrete surface: removing the weak particles at the very surface and then apply a hardening agent on the concrete surface anchoring itself in the near-surface pores of concrete to form a tough skin … to be invented/developed/tested (I am not aware of such a technique for concrete).

MZ: We (Sika) identify some challenges to be solved, with the major concerns linked to: (1) how can be achieved that the orientation of the ingredients of such a film is appropriate in order to minimize the friction? We think that the application method of such a film does not allow for the latter, as our experience with iron mica applications indicates. If renovation works are conducted, they remain visible given that the orientation of the ingredients can't be affected by the application method. Thus, we think that the surface structure should be generated after the application by using adequate machines or tools. (2) The lifespan of such a particular surface structure seems limited, especially if the conveyed water contains abrasive materials resulting from glacial polish. Even mechanically highly resistant coatings suffer from glacial polish products. The ingredients providing the requested surface structure must thus be highly resistant against abrasion.

NB: Perhaps during construction of the tunnel. It doesn't seem to be easy to achieve. It must be resistant to emptying operations, otherwise it could be damaged or lost. The question how to ensure the adhesion is relevant, but we can't answer. Regarding the time needed to fix/glue the film to the tunnel surfaces: The less, the better… when production stop is linked with operations in tunnel. Or as affordable as possible. In existing tunnels, you'll first to clean/wash the surface and they're many obstacles such as grouting pipes, drainage valves, bad concrete surface (with holes or merging stones or any other damage). Overlapping of the film and fixing it could be a problem too.

AF: In this point we see two major problems: (a) the walls of tunnels in operation are coated with deposits and have to be cleaned before applying a new lining, this may be a long and costly operation. (b) The applied film must resist the water pressure in the rock foundation in the case of emptying operations, or allow the drainage into the empty tunnel.

7. Do you think it is feasible to scratch the concrete surfaces (small depth, some mm) to produce a requested roughness structure (for instance streamwise ribs)? Any idea of how to perform this? How much time would it take? Would this compromise the long-term structural integrity of the tunnel? Which problems could emerge?

AS: I do not see a solution where the tunnel surface would have to be scratched. Normally the concrete in pressure tunnel is of quite low quality and it is practical not possible to scratch a precise surface pattern since looser granulates would detach. Furthermore, the tunnel lining is often already damaged locally. It has to be kept in mind that concrete is rather a conglomerate that a homogenous material. Thus – for me – solution of scratching concrete surface is not promising and the focus should be on a coating with a flexible, PVC like material glued to the surface. The surface would have to be cleaned with high water pressure (Kärcher type).

EB: Please read my response to question 6.

MZ: Some years ago we initiated a project in which a wood-type surface pattern should be generated on the freshly applied film by using an air jet. We intended to produce a surface similar to that of cast-in-place concrete using formwork. However, we dismissed the project because of several difficulties and an extraordinary application complexity.

NB: Yes, why not! We don't have a precise idea on how to perform the latter, but we could try hydro-jet, micro-picking or laser. As for the time request: as less as possible! This would not compromise the long-term structural integrity of the tunnel, but it depends on the quality of the concrete. Aging could be the main challenge: how will the surface behave through the years? Particularly if important suspended load is transported in the water. Additionally, mussels could populate the surface. Will the surface deteriorate faster so that cavitation problems appear?

AF: Technically and statically it's possible to scratch the concrete surfaces. In order to reduce the costs of such operations the scratching has to be performed mechanically (by machines). And this – we think – could be the problem, because of the irregularities of the tunnel sections.

8. Is it promising to further investigate such friction reducing techniques, for instance with physical model tests or prototype applications? Would you recommend to collaborate with a manufacturer of constructional material?

AS: Technically applicable friction reducing techniques with focus on coating are worth to be investigated due to the high potential. First laboratory test under near prototype conditions (real concrete surfaces and gluing procedure) should be conducted. Then a prototype stretch could be tested before going into the development of a high speed coating machine together with a contractor (potential of brevet/licence).

EB: the financial gain from friction reduction will probably justify some investment to investigate novel techniques.

MZ: As a specialist for surface coating on concrete and steel we (Sika) are interested in your study and partially in potential results.

NB: It depends on the financial gain.

AF: Considering the statements above we see a potential interest limited to the cases of regularly lined tunnels with constant cross sections.

9. Do you have any other inputs or comments to the topic?

MZ: Practice shows that often persons without particular formation apply such surface coatings, on site as well as in workshops. The system should thus also be easy to apply, beside the aforementioned requirements. Finally, the cost-efficiency consideration has to be positive.

NB: In the Alps we are dealing almost with "dirty" water (suspended load) through the headrace tunnels and pipes, this could compromise the innovative solutions.

4 Summary

The present report gives an overview on traditional and innovative techniques to reduce friction losses based on a comprehensive literature research. It covers various areas of knowledge, with the ultimate aim of providing new perspectives for solutions to apply in pressure tunnels of high head hydropower plants.

The traditional solutions found in literature are primarily related to rehabilitation or refurbishment of existing tunnels, motivated by issues as structural integrity, poor conditions of the lining materials, water demand and leaking problems, being the tunnel hydraulic efficiency typically a secondary concern. Nevertheless, significant benefits in the head loss reduction do arise from these solutions. In some reported examples head losses can be reduced to values below 10 % of the gross head. The common solutions found can be divided in: (i) cleaning, (ii) lining, (iii) adding a tunnel to the existing system, and (iv) increasing the diameter of the existing gallery. Although effective, cleaning the tunnel walls is always a short term solution since the fouling materials tend to build up after some time, as well as the eventual deposit of particles transported in suspension by the flow. Together with the cleaning operations, lining the tunnel walls requires the shutdown of the hydropower system, usually for long periods, which leads to postponing these solutions for situations of extreme necessity. The solution of adding a supplementary tunnel to the existing system or increasing the area of the current tunnel is not always possible, mainly due to the high costs associated. However, it might be an advantageous solution since it provides operating flexibility and requires minimal service interruption.

On the other hand, innovative solutions to reduce friction losses, mostly inspired by observations in nature, are being developed and tested in various areas. The solutions found can be organized as: (i) shark-skin inspired riblets, (ii) superhydrophobic surface and (iii) superhydrophilic surface. The microstructures shaped like small ribs found in the skin of fast swimming sharks were investigated due to their properties in avoiding biofouling and promoting drag reduction. It was found that these structures influence the position and the interaction between streamwise vortices generated in turbulent flows, as well as the interaction between vortices and the wall surface. Riblets aligned in the streamwise flow direction, and after geometry optimization, have shown drag reduction in external and internal flows, an effect proved more effective in turbulent than in laminar flows. Although limited data is available for internal flows, the maximum drag reduction reported is of 28 % for water flow in a pipe with diameter of 15 cm lined with riblet structures. Lining the walls of a headrace tunnel with a riblet microstructure is thus a promising solution, with considerable challenges associated.

Experiments in microsized pipes have shown that superhydrophobic surfaces, accomplished by combining a surface with microroughness and hydrophobic materials, provide low fluid friction in the laminar flow range, which results from the formation of an air layer between water and surface. This property is governed by the air-layer sustainability and depends on the surface energy or the fluid flow rate. Therefore, low fluid friction is difficult to obtain on superhydrophobic surfaces under large flow velocities in the turbulent flow range. However, experiments with optimized riblet structures and coated with a nanostructured material, revealed drag reductions around 30 % in the turbulent flow regime. The main challenge of this solution deals with manufacturing such a complex surface at reasonable costs and for large scale demands.

Instead of repelling the water molecules, superhydrophilic surfaces strongly attract them, forming a permanent layer of water at the wall surface. By creating a water-water interface, higher slip length is obtained and, hence, less drag is promoted than the one observed in water-surface interface. To our knowledge, only one study has been performed on the effect of hydrophilic surfaces in reducing friction drag, where drag reductions up to 5 % were reported. Similarly to the previous innovative solutions, hydrophilic surfaces should be further investigated in order to clarify and control their effect in drag reduction. Durability and maintenance issues, together with manufacturing and application techniques should be also addressed in future studies.

Many questions emerged when considering applying innovative solutions that have never been considered or tested before in hydropower systems. To discuss and to clarify some of the questions, the authors decided to contact experts in the hydropower industry and from material sciences to have their feedback, particularly on the microstructured surface solution.

Based on the feedback provided, it became clear that the topic of friction reduction is indeed relevant for the hydropower industry, with the prospect of increasing power generation and, therefore, energy production. Some of the experts have experience in the application of traditional solutions to reduce the friction losses, as a consequence of the rehabilitation and refurbishment of existing systems. The majority is aware of the existence of innovative solutions and, depending on the gain of extra energy produced, some consider interesting the investment in innovative solutions. The general concerns pointed out in the application of such solutions include the lack of experience in using those methods, ensuring the adhesion of an eventual microstructured film in the concrete walls, the durability against friction of suspended load and resistance during tunnel emptying operations, the consequences of eventual detached material in the turbines, how much time the interventions for implementing the solution would take, and how much would be the production losses during that period.

For the solution of fixing a microstructured film in the tunnel walls, the experts gave the following indications: the potential materials should be cohesive enough to avoid buckling during emptying operations and ensure perfect adhesion to the concrete walls, which is a great challenge given the common cracks present in the tunnel walls. External water pressure issue should also be addressed, where a porous material could possibly remediate this situation; application should be as fast as possible to minimize shutdown period and corresponding production losses and cleaning of the tunnel before film application has to be considered which makes the process longer and more costly.

The idea of scratching the concrete to promote a given microroughness is seen with contradictory opinions. While some say it is possible but still requires attention, others defend that the quality of the concrete in pressure tunnels is low and therefore is not possible to scratch a precise surface pattern due to detachment of loose granulates and due to irregularities in the concrete. Further research and testing is thus needed in order to answer to the questions associated with these promising innovative methods. All the contacted experts believe that the study of this topic is very relevant since the gain from reducing the friction losses might justify the investment.

5 Symbols

Symbol	*Definition*
d	vortex diameter
D	pipe diameter
f	friction coefficient
g	acceleration due to gravity
h	riblet height
h_b	gross head
h_f	head loss due to friction
L	pipe length
p	pressure
Re	Reynolds number
s	spacing between riblets
u^*	wall shear stress velocity
U	mean flow velocity
Δp	pressure loss
ν	fluid kinematic viscosity
ρ	fluid density
a^+	non-dimensional generic variable a ($a^+ = au^*/\nu$)

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