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The Application of a Thin Liquid Film at the Outlet of a Tesla Turbine

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Abstract— A Tesla turbine has a different approach in producing torque than a bladed turbine. Frictional forces applied by the working fluid onto a disk make the rotor spin and torque is produced. The advantage in such design is that, no object hinders the flow path of a fluid element and particle laden flows can be used to operate the turbine. Therefore, condensation within the turbine is possible. Condensation is necessary to reduce the rising fluid velocity towards the outlet which accounts for high energetic losses, and decrease the turbine efficiency. In this article, the utilization and maintaining of a thin liquid condensate film at the outlet of a Tesla turbine gap is investigated. Therefore, a developed analytic model is compared to a numeric simulation. The outcome of both, simulation and analytic solution is, that the film can be maintained if the radial gas velocity is sufficient.

Keywords— ***Tesla turbine, Friction turbine, Turbine efficiency, Film condensation, Laminar thin film, Computational Fluid Dynamics.***

I. INTRODUCTION

A Tesla turbine has a different approach to produce torque than a conventional, bladed turbine. The torque is produced by frictional forces applied to a disk surface. Imagine a fluid that flows adjacent to a surface which is not fixed (i.e. it can move in any direction). The surface is dragged along with the flow due to the adhesion of the fluid on the surface. The resulting drag is depended on and the fluid viscosity. The same principle applies in a Tesla turbine where the surface is a disk which can rotate. In accordance to Tesla's patent, the turbine consists of several disks, which are arranged plane parallel on a shaft. The gap between these disks,is dependent on the viscosity of the working fluid entering the gap with a high tangential velocity at the outer perimeter. The fluid continues its way on a spiralling path towards the outlet located at the centre of the disks. Due to frictional forces caused by the viscosity of the working fluid, the rotor starts spinning and atorque is produced[1]. Fig. 1,shows the original drawing from the patent application of Tesla. It is possible to seethe rotor and the outlet in the centre of the disks. Furthermore, the original Tesla design has two inlet valves, allowing the turbine to rotate in different directions. The turbine was never a commercial success and isregarded as a "lost invention" nowadays.

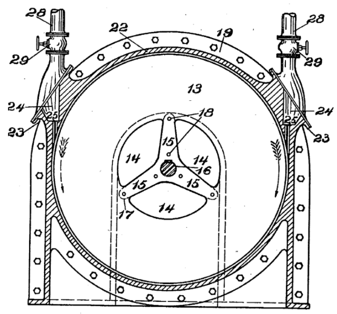

Fig. 1.

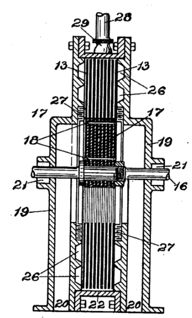

Fig. 2.

Fig. 1original drawing of Nikola Tesla's turbine [1]

One reason for the commercial failure is the claimed low turbine efficiency.The reason for this claim is the outlet design and the resulting high energetic losses due to the rising velocities at the outlet [2, 3].But the advantages of the turbine design are apparent. The simple design implies for low production costs and the use of simple manufacturing processes. The high surface area of the diskmakes this turbine type suited to heat transfer processes and the gap between the disk without any obstacles allows the usage of particle laden flows. The rising velocities and energetic losses towards the outlet are a continuity problem. The specific volume of the working fluid increases (due to expansion) on the way to the outlet and the through-flow area is reduced as the radius decreases. To overcome this, the specific volume needs to be reduced.If the conditions at the outlet are such that the working fluid condenses, the volume flow of the gas phase would decrease dramatically due to the lower specific volume of the liquid phase and thus, the velocities decrease. Assuming film condensation, a closed, thin liquid film develops on the disk surface and is pushed by the gas flow towards the outlet. Within this article, a simple model is presented to calculate the film thickness on a Tesla turbine disk. The model is then compared to a computational fluid dynamic simulation.

The first closed theory about film condensation was presented by Nusselt. He calculated the thickness and heat transfer in a water film on a vertical plate under the influence of gravity [4]. Later, these models have been refined and transferred to tubular and turbulent flows [5].Stein researched the behaviour of a thin liquid film on the surface of a Tesla turbine disk. He used a Volume of Fluid model to simulate a water film and showed, that the length of the film in radial direction is essential, since the rising centrifugal forces can disrupt the film[6]. A more recent investigation on the behaviour of a liquid film at the outlet of a friction turbine gap has been carried out by Meller:He tried to model the laminar film condensation process in a friction turbine gap and showed that a fluid film can be maintained in the outlet area [7]. Besides the flow field, there is few literature about condensation in Tesla turbines, whereas the flow between two parallel rotating disks from the centre to the outer perimeter is widely discussed in the scientific literature. Two systems of importance can be identified. The first is a single rotating disk, surrounded by a gaseous fluid which must condense onto the disk surface. Heat transfer values and film thicknesses have been given by Beckett et al., Kahn and Shevchuk[8–10]. The second system is made of two parallel disks, rotating at either the same or different angular speed. Due to the rotation and the centrifugal force, the saturated steam is pushed toward the outer perimeter and a condensate film develops on the cooled disc surface. Such a system has been investigated by Al Assadi et aland Shevchuck[11, 12].

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II. LAMINAR THIN FILM CONDENSATION

Hereafter, a simplified model for the forming of a thin liquid film on a rotating disk is presented. The laminarfluid film should be thin and present in the outlet area of the friction turbine. The thin liquid film at the outlet region is governed by the gas flow in radial direction and the centrifugal force opposing the gas flow. To prevent the spreading of the film across the disk, due to the rotation of it, the balance between the centrifugal force, catapulting the film towards the outer disk perimeter and the applied drag from the gaseous working fluid, pushing it towards the outlet,must be considered. If the drag force of the gas flow is higher than the centrifugal force, the fluid film is flushed towards the outlet. On the contrary, if the centrifugal force prevails, the film starts spreading all over the disc. For the application in a Tesla turbine the fluid film must be very thin due to the small gap width and the influence of the centrifugal force caused by the tangential velocity of the gas flow. Furthermore, if a thin film is used, it underlies the impact of the centrifugal force caused by the disk and not the gas flow due to the film thickness. If the film thickness is high, two cases are possible. Firstly, the centrifugal force dominates and droplets will be torn off the film or the film is disrupted and catapulted towards the gap inlet.Secondly, if the film thickness on both sides of the disk is in such range that the fluid films unite, the turbine clogs since no throughflow in the gap is present. The force balance of a fluid element in the liquid film at the liquid-gas phase interface is presented in equation 1.

$$\frac{\partial \tau}{\partial y} = r\omega_D^2\rho_L \tag{1}$$

In this equation τ is the shear stress on the fluid element coming from the gas flow, r is the radius, ω_D is the rotation rate of the disk and $\rho_L$is the density of the fluid film. The coupling of the gas flow and the liquid film is realized at the liquid-gas interface by equation 2.

$$\eta_G \frac{\partial w_{y=\delta}}{\partial y} = \eta_L \frac{\partial c_{r\,y=\delta}}{\partial y} \tag{2}$$

Here, w is the film velocity and c_r is the gas velocity in radial direction. With the energy equation, the film thickness can be determined with equation 3.

$$\delta(r) = \sqrt[3]{\frac{3Ja_L v_L v_G b r}{\mathrm{Pr_L}(2\frac{\eta_G}{\eta_L}c_r(r) - Re_L\omega_D b)}} \tag{3}$$

In equation 3, Ja is the Jakob number, Pr the Prandtl number and Re the Reynolds number of the thin film. Within the brackets of the denominator of equation 3, the interface velocity w_δ is present. If the interface velocity is zero or higher the film is maintained or flushed towards the outlet of the gap at the centre of the disk. If the interface velocity is below zero, no drag is applied to the film, the centrifugal forces prevail and the film is thrown towards the outer disk perimeter. In the following figure, the film thickness is plotted for a rotation rate of 3000 rpm. The straight line indicates a rising interface velocity over the film length. Here, at the beginning, the interface velocity is low, allowing the formation of a bulge. At the end the interface velocity rises and thus, the film thickness decreases. The dashed, dotted and dashed-dotted lines represents a constant interface velocity. Here, the film thickness rises towards the end due to the proportional lower interface velocity.

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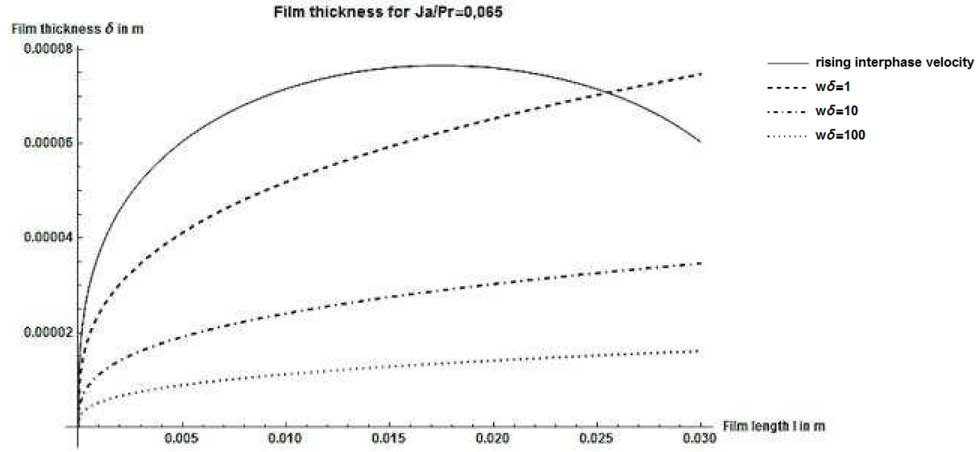

Fig.2: film thickness for different interface velocities at constant Ja/Pr number

From figure 2, it can be concluded, that the filmthickness calculated according to equation (3) is in the range of 1 and 10 µm and thus, a thin liquid film at the outlet of a Tesla turbine gap can be maintained without blocking the gap.. A constant interface velocity inducess a rise of the film thickness towards the end of the film wheras a rising interface velocity induces a decrease. For Tesla turbine application the film length can be considered short due to the impact of the centrifugal velocity. Therefore, the rise in interface velocity is not significant and a constant interface velocity can be assumed.

Numeric Simulation

The model presented in II is compared to the results of a computational fluid dynamic simulation. For the simulation, the commercial simulation program Star CCM+ in version 11.04.012 was used. The model dimensions have been taken from an existing Tesla turbine prototype examined at the Technical University of Applied Sciences Wildau. The 2.2 kW turbine had been examined with superheated and saturated steam and showed a turbine efficiency of 0.3 for saturated and 0.7 for superheated steam [13, 14]. The disk diameter is 0.175 m and the gap width is 0.5 mm. The thin liquid film is applied at the outlet of the turbine gap element (Fig 3, left light blue) and has a length of 10 mm. Three cases have been simulated with different inlet velocities. In all three cases the rotation rate of the disk has been set to 750 rpm.The used working fluid was steam at saturation conditions at 1 MPa and 180 °C. The inlet velocity was set to 15, 45 and 60 m s^{-1}.

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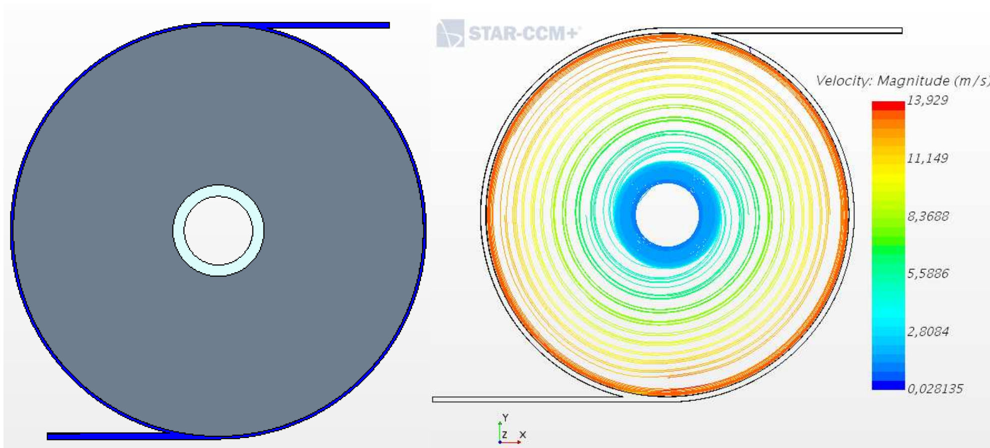

Fig.3: left, simulation model, grey the disk, dark blue the inlet and light blue the liquid film; right, streamline plot of the velocity

The mesh consists of approximately 1.5 Million cells and the predominant mesh type is a hexahedron element due to the benefits in accuracy and calculation time. For the simulation, the $k-\varepsilon$ turbulence model was used since it is a prerequisite of the implemented thin film model. The advantage of the implemented thin film model is that it can simulate film stripping, condensation and evaporation.The implemented model is not able to simulate the forming of a liquid film and thus, an initial film of the thickness 1 µm needs to be given. An alternative would be to use the implemented Volume of Fluid model. Here, the liquid phase must be modelled separately. Due to restrictions in memory and calculation time, the memory efficient thin film model was used. Christo Ananth et al. [14] proposed a principle in which another NN yield input control law was created for an under incited quad rotor UAV which uses the regular limitations of the under incited framework to create virtual control contributions to ensure the UAV tracks a craved direction. Utilizing the versatile back venturing method, every one of the six DOF are effectively followed utilizing just four control inputs while within the sight of un demonstrated flow and limited unsettling influences. Elements and speed vectors were thought to be inaccessible, along these lines a NN eyewitness was intended to recoup the limitless states. At that point, a novel NN virtual control structure which permitted the craved translational speeds to be controlled utilizing the pitch and the move of the UAV. At long last, a NN was used in the figuring of the real control inputs for the UAV dynamic framework. Utilizing Lyapunov systems, it was demonstrated that the estimation blunders of each NN, the spectator, Virtual controller, and the position, introduction, and speed following mistakes were all SGUUB while unwinding the partition Principle.

III. Results

In the following, the results of the simulation and the analytic model are presented. To compare the results, the non-dimensional flow figure is introduced. It is the ratio of the radial velocity of the gas flow and the disk velocity at the outer perimeter.

$$\boldsymbol{\varphi} = \frac{c_r(r)}{r_1 \omega_D} \qquad (4)$$

In the following picture, the film thickness of the 15 m s^{-1} inlet velocity case is shown. The maximum film thickness of the analytic solution is 2.2 µm whereas in the simulation it is 1.44 µm. From the numeric simulation, it can be seen, that a bulge forms at the beginning of the film (grey dotted line) and that the film thickness rises towards the outlet. Here, the impact of the centrifugal force is present. Despite of the bulge at the outlet on the right-hand

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side (reddish area) which comes from an uneven low filed, the film thickness seems even distributed along the circumference (fig. 4 right).

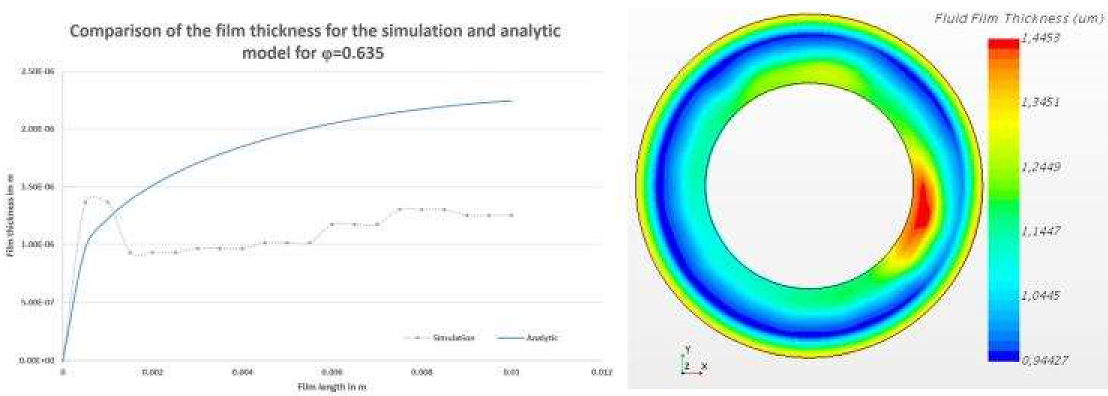

Fig.4: left: film thickness comparison of the 15 m s^{-1} simulation with the analytic model, right; contour plot of the filmthickness

Figure 2 showed, that with rising velocities the film thickness decreases. In Fig. 5 the outcomes of the 45 m s^{-1} simulation are presented. The final film thickness of the simulation is 1.61 µm and 1.59 µm for the analytic solution,which shows the reduction in film thickness. In the simulation, the bulge at the beginning of the film is still present and another bulge at the end of the film develops.

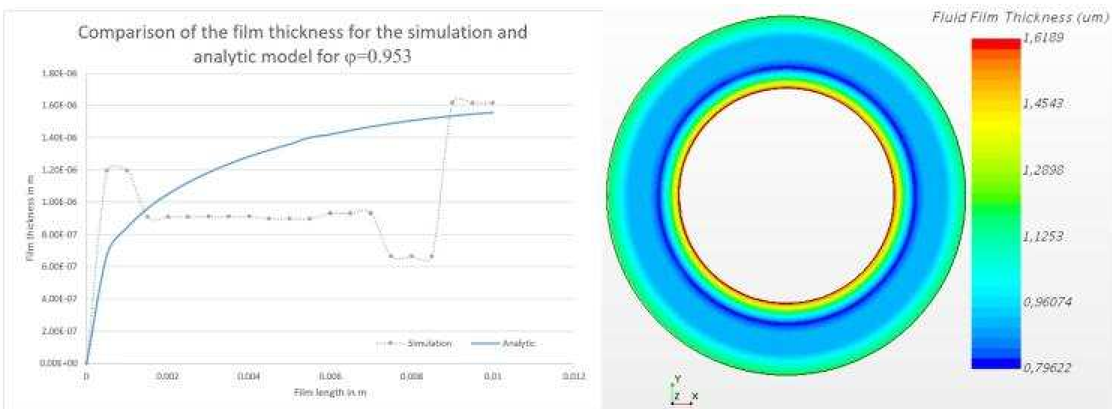

Fig.5: left: film thickness comparison of the 45 m s-1 simulation with the analytic model, right; contour plot of the film thickness

By rising the velocity up to 60 m s^{-1} the film becomes thinner and the bulge at the beginning is significantly reduced. The bulge at the end is still present. the film thickness of the simulation is 1.6 µm and the analytic solution shows a film thickness of 1.41 µm.

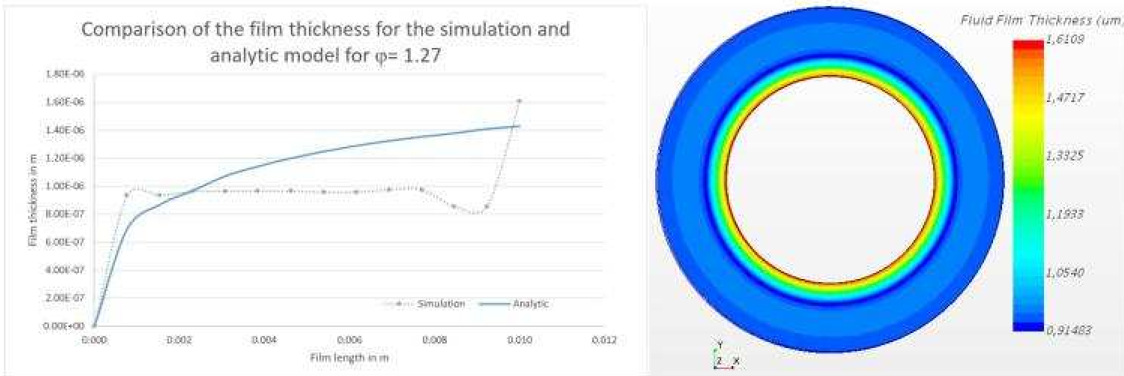

Fig.6: left: film thickness comparison of the 60 m s-1 simulation with the analytic model, right; contour plot of the film thickness

IV. Discussion

From the results above, the analytic model does not fit the simulation well. The reasons are manifold. A reason for the bulge at the beginning of the film is a low interface velocity, which allows the formation of a bulge since the velocity is not high enough to push the fluid film towards the outlet. Here, the analytic model fails to predict the development of the bulge. Within the 45 and 60 m s^{-1} simulation a bulge at the end of the of the film is present. The fluid is pushed towards the outlet and at the edge of the disk, due to the adhesion of the film to the disk, the fluid is impounded and the bulge develops. At higher velocities it is likely, that droplets will be ripped of the film (film stripping) or a big part of the film is flushed out of the turbine gap. Here, the analytic model fails to predict the bulge.Thus, the analytic model cannot predict film stripping and therefore, it is not suitable for the design of a Tesla turbine with a thin, liquid film at the outlet and high gas velocities. As regards the 15 m s^{-1} simulation, the analytic model overpredicts the film thickness. This leads to a higher calculated condensation rate and thus, the velocity reduction of the gas flow due to condensation is overpredicted. In general, the analytic model needs a refinement e.g. the adaption of boundary conditions to film stripping and the special situation at the outlet of the gap at the disk edge. However, both, simulation and analytic model have shown that a liquid thin film can be maintained in a Tesla turbine gap on the disk surface close to the outlet.

V. Conclusion

Within the presented model, the maintaining of a thin film at the outlet of a Tesla turbine gap is successfully modelled. The obtained film thickness from the analytic model and numeric simulation are compared and it was found thatthe analytic model overpredicts the film thickness and does not considerfilm stripping which occurs in a Tesla turbine gap where a thin liquid film is present. For a first validation, if the film stays on the disk surface at the outlet, the analytic model can be used.For a precise prediction of the film thickness the model should not be used since the influencing factors -film stripping, surface tension and adhesion- are not implemented yet. Thus, the model is only suitable to predict whether a film of a specific length stays on a rotating disk or not. The future work should concentrate on the refinement of the model regarding the prediction of film stripping and film thickness. Therefore, film stripping and the impact of the surface tension and adhesion should be implemented. For the verification of the model, a test rig must be developed to obtain experimental data.

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Authors Bio

Roberto Lisker

Roberto Lisker, born in Herzberg/Elster (GER) on the 19th of December 1982.

Degree:
- 2009 Diploma in mechanical engineering at the Technical University of Applied Sciences Wildau
- 2013 Master of Engineering in Renewable Energies at the Technical University of Applied Sciences Wildau
- Currently enrolled in a PhD program at the University of Rome Tor Vergata.

Professional Career

After finishing his diploma, Mr. Lisker became a full-time researcher at the Technical University of Applied Sciences Wildau. His interests are the Tesla turbine development, Heat transfer and the integration of renewable energy sources into industrial power supplies. Within the years of 2010-2013 he was responsible for the construction of the Biophotonic Combined Energy System, an autonomous and closed cycle system to produce power and valuable materials based on Microalgae. After his Master studies Mr. Lisker designed a 2.2 kW micro Tesla turbine which was investigated and became the basis for further research. Since 2014 he examines the use of a Tesla turbine as a heat exchanger and follows the idea of a condensation turbine.

