Technical report

Design and simulation of the Hanna turbine

Théo DELECOUR

October 8, 2017

Introduction

The report summarizes the work I have done on the Hanna turbine during my Master's thesis between April and September 2017. My Master's thesis subject was the numerical study of self-rectifying turbines for air energy recovery in the Channel Tunnel. The thesis was written in French, the only part written in English is the abstract. This abstract is included in the beginning of this report, it answers the general situation in the Channel Tunnel. The next parts of this report give more general elements on the design and behaviour of the Hanna turbine. All the results have been obtained in the context of the study for Eurotunnel, but they can be applied for the Hanna turbine in any context.

The results are generally very promising for the Hanna turbine, they revealed the possibility to design an efficient axial self-rectifying turbine which avoids most defaults seen on other designs (Wells and Impulse turbines).

Contents

1 Abstract of the Master's thesis

The Channel Tunnel has an interesting potential of air energy recovery. Piston relief ducts join the 2 railway tunnels to let the air flow from one tunnel to the other when trains pass. Nearly 200 ducts are drilled, they are 2 meters in diameter and are equipped with throttles creating pressure loss to limit the speed of the airflow. The project initiated by the company Eurotunnel is to replace these throttles with axial turbines to generate electricity from the kinetic energy of the airflow. The turbines must work with bi-directional flows while keeping the same direction of rotation to make the transmission to the alternator easier, which gives them the name of self-rectifying turbines. This represents the main distinctive feature of this project.

This present study focused on the design and simulation of self-rectifying turbines for the situation of the Channel Tunnel. Such systems have been developed as wave energy converters in Oscillating Water Columns. This work has thus evaluated the adaptation of different existing designs with the use of monodimensional aerodynamical calculations and 2D Computational Fluid Dynamics simulations. Optimal designs meeting the aeraulic requirements of the project have been obtained through an optimisation process.

The most popular self-rectifying turbine, the Wells turbine, offers a very simple design but has shown poor adaptation to our case because of blade stalling and transonic flows. Another well-known system is the self-rectifying impulse turbine, which avoids the problems of the Wells turbine but shows poor performance because of fluid separation linked to its symmetrical geometry. The last studied concept, recently patented by its inventor John Hanna in 2013, is promising for our application. This system includes two rotors engaged on a common shaft with freewheeling clutches and central guide vanes between the two. This present work represents the first numerical simulation of this prototype. After several iterations, a working 2D design was obtained. It fulfils the requirements of the project with an interesting efficiency and avoids the problems seen on the other studied turbines. It is planned to continue the project with complex 3D simulations and experimental studies to give more results and reach complete 3D designs.

Keywords: self-rectifying turbines ; Wells turbine ; Hanna turbine ; Impulse turbine ; Computational Fluid Dynamics ; design optimisation ; performance comparison.

2 Description of the functioning of the turbine

This part summarizes the specific points of the functioning of the Hanna turbine. These distinctive features will represent complex design points. The present study focuses only on the reaction effect of the axial flow on the main blades, it doesn't consider the radial flow on the collector vanes. This choice was made to simplify the study, because the effect of the collector vanes is very hard to predict with only numerical tools (it would be best studied with an experimental setup).

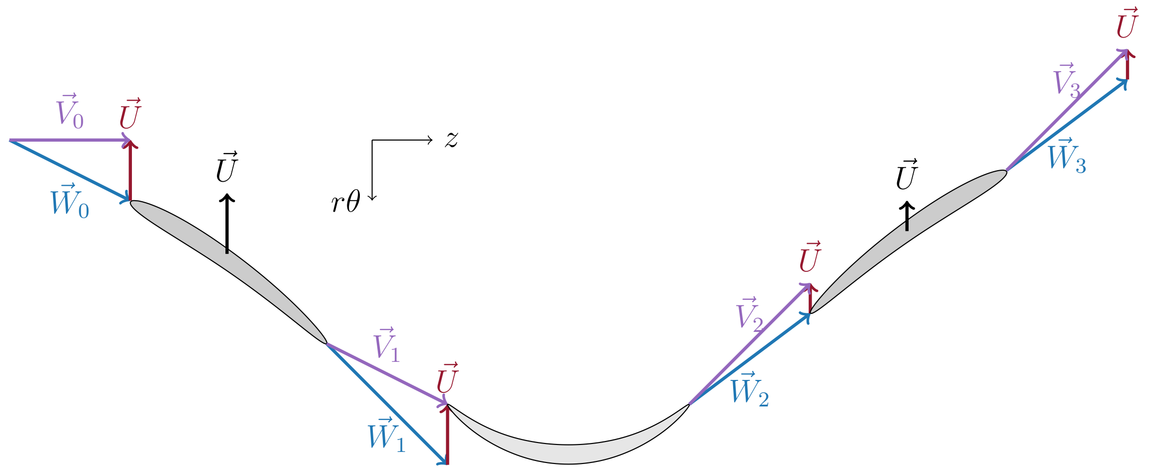

Figure 1: Schematic of the functioning of the Hanna turbine in the blade-to-blade plane

The Figure 1 shows a schematic of the functioning of the Hanna turbine in the blade-to-blade plane. The velocity triangle is drawn between each blade row (the relative length of the vectors are representative of typical functioning values). The velocity vectors represent the following motions:

- $\vec{V}$ is the absolute mean velocity of the flow, it represents the velocity of the fluid as seen from a fixed frame of reference
- $\vec{U}$ is the velocity of the solid blades, it represents their rotating motion, its value equals $U = \Omega r$ with Ω the rotating velocity of the blade row
- $\vec{W}$ is the relative velocity of the flow, it represents the velocity of the fluid as seen by the rotating blades

The following relation is always verified:

$$\vec{V} = \vec{U} + \vec{W} \tag{1}$$

The relative velocity $\vec{W}$ ideally follows the shape of the rotor blades. The entry relative velocity is usually oriented in the direction of the leading edge of the blade. The motion $\vec{U}$ of the blade is then determined as the difference between $\vec{V}$ and $\vec{W}$. For a stator, as its rotating velocity equals zero, the relative velocity is the same as the absolute velocity, so the absolute velocity $\vec{V}$ ideally follows the shape of the stator blades.

The power collected P on the driving rotor of the Hanna turbine (on the left in Figure 1) is the product of its rotating velocity Ω and its torque C, the torque is linked to the camber of the rotor blades. The Euler equation gives the collected energy on the rotor:

$$\Delta h_0 = \Delta(UV_\theta) \tag{2}$$

where ΔV_θ is determined by the camber of the blades. This shows that a rotor needs to spin fast or to have high-cambered blades to collect a large amount of energy. This also shows that for the free-wheeling rotor we have $\Delta V_\theta = 0$: the fluid is not deflected by this rotor (as shown on Figure 1 where the free-wheeling rotor is on the right). The free-wheeling rotor only provokes pressure loss without collecting energy, so its camber must not be too high or it will provoke many losses. Thus, an efficient design of the Hanna turbine has rotors with moderate camber and moderate rotating velocity. The flow coefficient $\phi = V_0/U$ is moderate for the driving rotor: between 1 and 1.5 on the simulated designs (the flow coefficient is higher for the free-wheeling rotor as it spins slower than the driving one).

A particular point in the design of the Hanna turbine is the design of the central guide vanes. In order to make to free-wheeling rotor spin in the correct direction, the central stator must direct the flow with a correct angle. Due to the imposed symmetry of the shape of the blades, the direction of the leading edge is imposed by the direction of its trailing edge. As a consequence, the leading edge of the blade may not be aligned with the flow coming from the driving rotor. The flow impacts the central guide vanes with some incidence. This can be seen on the Figure 1, where the central blade is not aligned with the incoming absolute flow $\vec{V_1}$. This incidence can be the source of important losses if it is too high.

3 Simulation of the original OSU model

Numerical simulations have been conducted on a 2D recreation of the model designed at the Oregon State University. The model used is available in AutoCAD and STEP formats. Revisions of the model may exist, the model used here is probably the original one. The blades were drawn in the blade-to-blade plane with the following definitions:

- Rotor blades are NACA 3509 airfoils, which have a camber of 13° and a maximal thickness of 9 %. The leading edge of the first rotor has a pitch of 39.5° (its trailing edge has a pitch of 52.5°).
- The curved guide vanes are drawn using two arcs, the intrados arc has a total angle of 70° and the extrados arc has a total angle of 139°. This values were computed to recreate the curved guide vanes seen on the model.

The diameters, chords and lengths were adapted to fit the turbine to the Eurotunnel situation. The radius at the tip of the blades is 0.8 m while the radius at the hub is 0.185 m. The rotor chords equal 200 mm and the stator chord equals 125 mm. The number of blades per row were slightly changed so that the turbine presents a repetitive pattern: the rotors have 18 blades (instead of 19 originally) and the stator has 36 blades (instead of 33). The simulated pattern, which represent 1/18th of the turbine in the blade-to-blade plane, is shown in Figure 2. The axial spaces between rows were extended to better simulate the development of turbulent structures.

Computational Fluid Dynamics simulations have been conducted on this 2D model. The simulation is stationary, the methods used are described further in subsection 4.2. The entry velocity is $27\,\mathrm{m\,s^{-1}}$ here, it was chosen for the Eurotunnel situation. The rotating velocity of the first rotor is set so that the incidence of the fluid is nominal on the blade. The rotating velocity of the second rotor is not known as it is free-wheeling, so it is first set to zero and will be adapted so that the resulting effort of the fluid on the blade equals zero (then the rotor will indeed be free-wheeling).

The convergence of the simulation was difficult because of the development of large fluid separations on the central guide vanes. The fluid does not follow the guide vanes well and has a

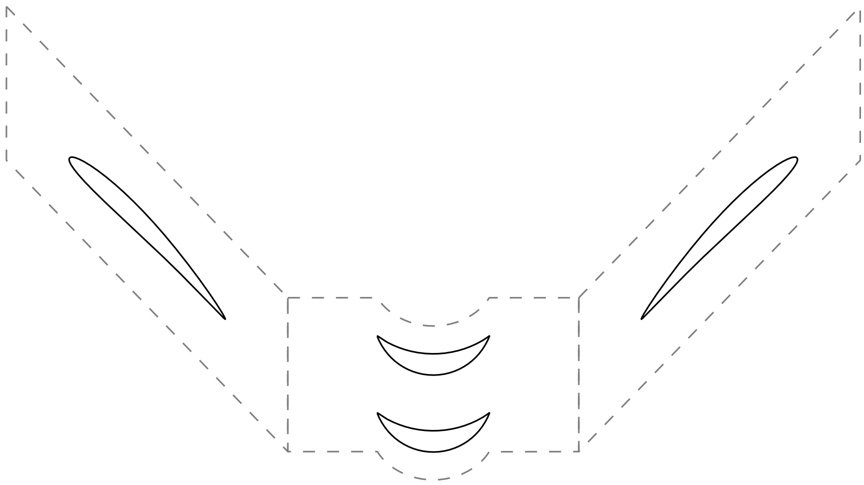

Figure 2: 2D view of the original design of the Hanna turbine (1/18th of the turbine is represented)

tendency to make the second rotor move in the opposite direction of the first one. The resulting effort on the second rotor equals zero when it moves in the opposite direction, at about half the rotating velocity of the first rotor.

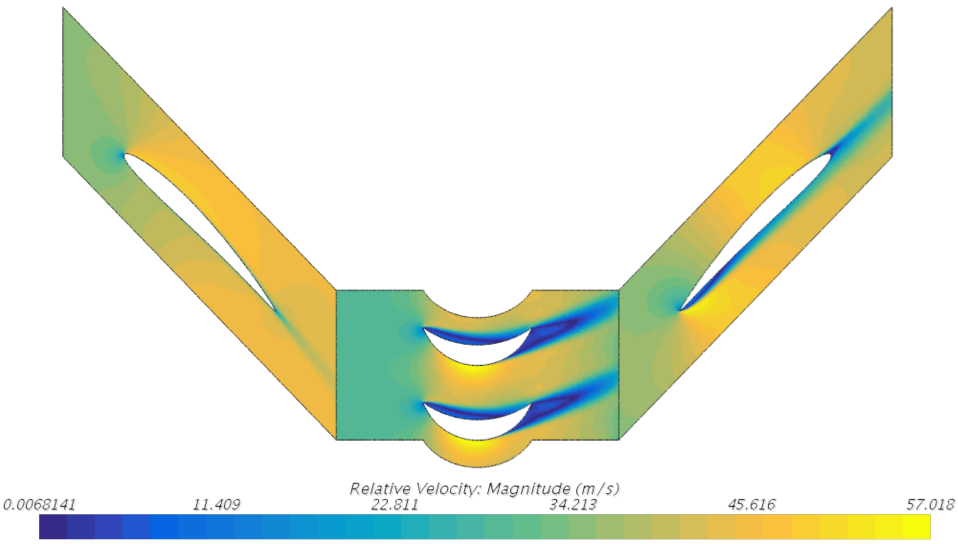

Figure 3: Relative velocity at each row on the original Hanna turbine design, the second rotor on the right moves in the opposite direction of the first rotor

This design does not seem to satisfy the concept of the Hanna turbine, the central guide vanes don't work as expected and provoke high losses. The global efficiency of the concept is 48 % on this simulation. With a proper design of the turbine, the second rotor could spin in the same direction as the first and the global aerodynamic behaviour could be much better. The efficiency of the turbine would then be higher. This is why a monodimensional analysis and optimization of the shape and functioning conditions of the turbine has been developed. It is presented in part 4, and the designs obtained with this process are presented in part 5.

4 Numerical methods for the design of the turbine

This section briefly describes the numerical methods used for the study of the Hanna turbine. The approach is explained with more details in my Master's thesis. The aim of the methods is to find the optimal design parameters to build an efficient and reliable Hanna turbine, and study its behavior.

4.1 Monodimensional analysis

The Hanna turbine is a concept of a system, instead of a precise fixed design. This concept can be adapted to a range of different situations. A process of monodimensional analysis has been developed to test a multitude of different designs and determine the most efficient and adapted ones for a given situation. This process has been applied to the Eurotunnel situation during this work, but it can be applied to other situations as well, even if the optimal designs would probably be similar to the ones seen in this study.

Monodimensional or mean-line analysis is a simplified study of the turbine where the properties of the flow are averaged in the radial and azimuthal directions. The computations are stationary and can give the mean velocities and pressures at the inlet and outlet of each row of the turbine. The blades have no thickness here. The flow is considered incompressible, which is in standard conditions valid if the Mach number is under 0.3 (which is generally verified for the Hanna turbine). Pressure loss is computed with empirical models, mainly the Soderberg model for turbines here.

The development of inverse computations lets us design turbines that validate the required conditions for a given situation (known inlet velocity and wanted pressure drop). By doing an optimization on the several variables given for a computation (such as flow coefficient and hub-to-tip ratio), an optimal design is obtained. A compromise may be done to avoid particular points or problematic cases at the expense of a slightly better efficiency.

The monodimensional analysis of the Hanna turbine showed interesting results and has been able to highlight the specific points in the functioning of the turbine. However, this method showed limits: the performance are often overestimated, and the computations don't predict the fluid deviation (the fact that the fluid does not perfectly follow the blades at the trailing edge) which can require corrections of the camber of the blades later. Nevertheless, it has greatly help the design of an efficient Hanna turbine.

4.2 Numerical simulations

Once an optimal monodimensional design has been determined, it is drawn in 2D in the blade-to-blade plane by giving the blades thickness and setting the axial spaces between the rows. We have a true 2D view of the turbine such as seen in Figure 2. This domain can be simulated using CFD methods. During this study, the commercial CFD code STARCCM+ was used to simulate the behavior of the turbines in 2D.

The simulations done during this work are stationary, they aim to estimate the performance of the turbine without looking at its dynamics (during a flow inversion for example). The fluid is viscous air, the flow is turbulent and incompressible. The turbulence was modelled using the $\kappa - \omega$ SST (Shear Stress Transport) model, which is a RANS (Reynolds-Averaged Navier–Stokes) model. It is known to be precise and efficient for performance estimation in turbomachinery. More complex simulation models that could be used later have been identified, like 3D unsteady simulations and DES or SAS models, they are more detailed in the Master's thesis.

For each simulation, the inlet velocity of the fluid and the velocities of the rotors are set. A mixing plane is placed between each row and periodic conditions are applied to let us simulate only a portion of the turbine.

The meshing of the domain is optimized to give precise results without costing too much resources (a refined mesh generally give precise results but means much longer simulations). The turbines seen in the next part were meshed with around 200 000 cells.

The CFD simulations let us correct or validate designs and estimate their global efficiencies, the aerodynamics are much better analyzed than on monodimensional computations to understand the behavior of the turbine.

5 Design

5.1 Behavior of free-wheeling rotors

This paragraph is a short note on the general behavior of turbine rotor in a free-wheeling motion. We consider that the turbine rotor blade is designed in 3D using the radial equilibrium law. If it is in free motion, then its tip acts like a compressor blade and its foot as a turbine blade, like drawn in Figure 4. Globally it does not exchange energy with the fluid.

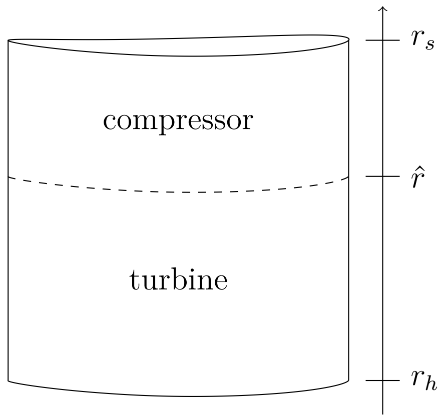

Figure 4: Behavior of a free-wheeling rotor blade

The radius $\hat{r}$ at which the blade locally does not exchange energy with the fluid is:

$$\hat{r} = \sqrt{\frac{r_s^2 + r_h^2}{2}} \tag{3}$$

with r_s the shroud radius and r_h the hub radius. The 2D studies of this work were conducted at $r = \hat{r}$ to simulate the free rotation of the rotor. Once a 2D design at $\hat{r}$ is validated, it can be designed in 3D to simulate the behavior of the entire blade.

5.2 Design of a Hanna turbine

The design of a Hanna turbine started with a monodimensional analysis. The specific points of the functioning of the turbine were imposed: the second rotor is free-wheeling at a slower velocity than the first rotor and in the same direction. The analysis showed that the optimal designs have a second rotor which is not moving, like a stator (its velocity equals zero on optimal designs). This situation has been avoided because the advantage of having the two rotors always moving would be lost, and the second rotor would be in an unstable situation: it could easily start moving in the opposite direction. Thus, a compromise was made to adopt designs with a slightly lower expected efficiency but better operating conditions. The design process is more detailed in my Master's thesis.

A first 2D simulation done on the obtained design is not detailed here, as it showed that the camber of the central guide vanes had been underestimated in the monodimensional analysis (and as a consequence the second rotor was spinning in the opposite direction). A correction led to the final design described here.

The geometry of the 2D design of the turbine is described in Table 1 and drawn in Figure 5. The rotor blades are based on NACA airfoils, the trailing edge is blunt. The stator blades are based on arcs with blunt edges too. The number of blades per row and chords were chosen to give a good aerodynamic behavior, the most notable point is that longer chords and more blades are needed for the central guide vanes as its camber is high. However the chosen values could be optimised for a slightly better efficiency.

Table 1: Final design of the Hanna turbine

Parameter	**Value**
Tip radius	0.8 m
Hub radius	0.32 m
2D study radius	0.61 m
Number of rotor blades	16
Rotor blades chord	300 mm
Rotor blades camber	22°
Rotor blades maximal thickness	8 %
Number of stator blades	48
Stator blades chord	400 mm
Stator blades camber	104°
Stator blades maximal thickness	8 %
Flow coefficient (driving rotor)	1.5
Flow coefficient (free-wheeling rotor)	5

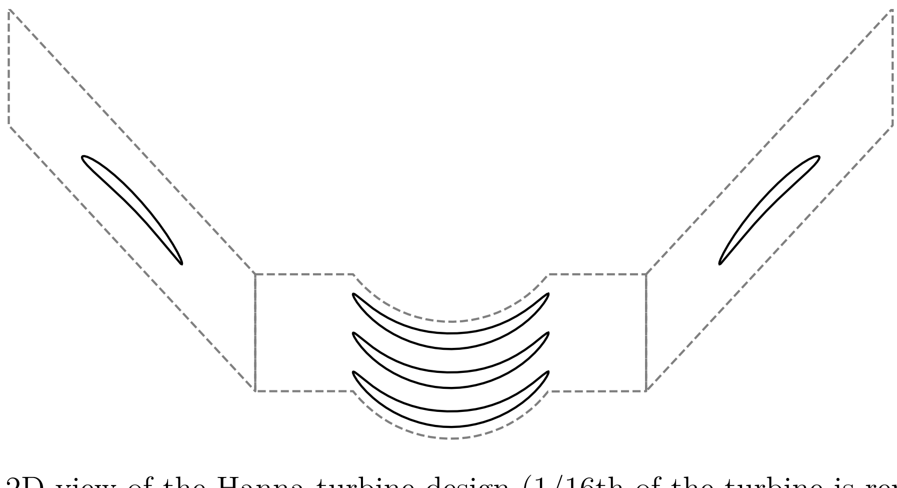

Figure 5: 2D view of the Hanna turbine design (1/16th of the turbine is represented)

The stationary simulation went well, the relative velocity field is shown in Figure 6. The rotating velocity of the free-wheeling rotor was well predicted. The aerodynamic behavior is very satisfying, no major fluid separation is seen (the blunt edges of the blades may help here). The estimated efficiency is 70 %, which is very satisfying compared to the efficiency obtained on other self-rectifying turbines in my Master's thesis.

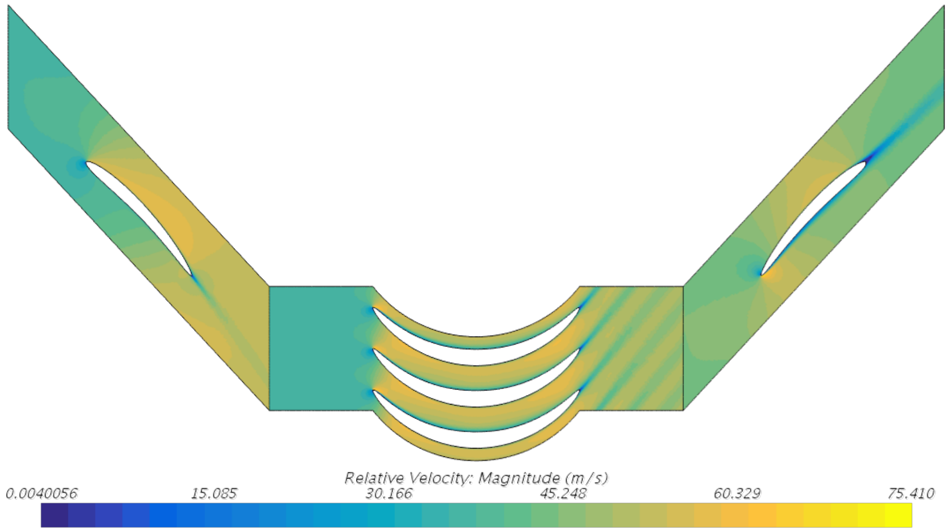

Figure 6: Relative velocity in each row on the Hanna turbine design

5.3 Design with 2 joined rotors

During my Master's thesis has emerged the idea to join the 2 rotors of the Hanna turbine to the common shaft. The rotors could have a higher camber, which could lead to more collected energy, or let the turbine rotate at a slower velocity and avoid potential mechanical problems.

The monodimensional analysis led to a design similar to the previous one, the main differences are the higher camber of the blades and the slower rotating velocity of the rotors. The camber of the rotor blades equals 40° and the camber of the central stator blades equals 112°. The flow coefficient for the rotors equals 3.5, which is much higher than the flow coefficient of the driving rotor on the previous design: the rotors spin twice as slow as the previous driving rotor. The radii, number of blades per row and chords are the same as before.

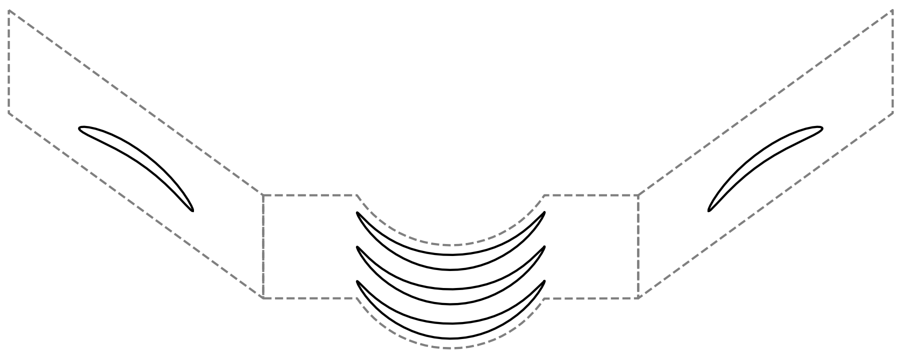

Figure 7: 2D view of the Hanna turbine design with 2 joined rotors (1/16th of the turbine is represented)

The 2D view of the design is drawn in Figure 5. The simulations are done on the mean radius of the turbine, which equals 0.56 m: the second rotor is not free-wheeling, so its behavior does not have to be simulated at a specific radius.

The stationary simulation went well, the relative velocity field is shown in Figure 6. The aerodynamic behavior is globally satisfying. However slight fluid separations can be seen of the stator due to the high incidence of the flow, and the second rotor produces large wakes. As a NACA blade is not designed to work well with inverse flows, the second rotor does not recover much energy.

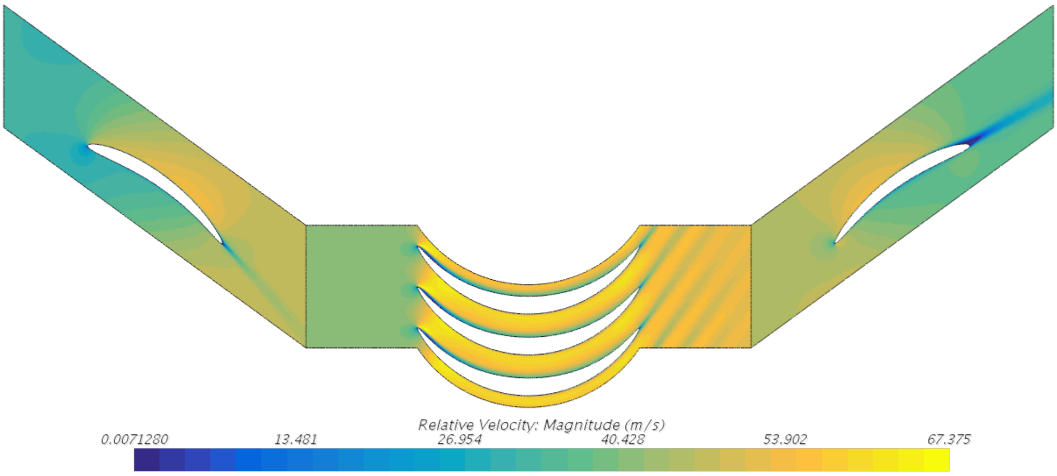

Figure 8: Relative velocity in each row on the Hanna turbine design with 2 joined rotors

Thus, while the global pressure drop is the same as on the previous design, the global efficiency is lower: it is estimated at 57 % on this simulation. The higher camber of the blades actually provokes more pressure loss, specially on the central guide vanes. Designing the Hanna turbine with 2 joined rotors is not more efficient or interesting. However, it was seen that this design is still more efficient than the well-known self-rectifying Impulse design.

Conclusion

The current work proved that the Hanna turbine design is very satisfying and adapted for the Eurotunnel situation. Generally, the idea of its inventor J. Hanna is relevant and promising for all situations involving the design and use of a self-rectifying turbine.

As the present obtained design is only in 2 dimensions, the next step would be to design a full 3D turbine. Simple radial design techniques have been briefly used in this work to obtain the designs at hub and shroud radii. These techniques could help create a 3D design for more complex and complete simulations. Further changes will certainly be done on the design presented here, but it already shows the promising performances of the Hanna turbine, which deserves a future complete experimental study.