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OPTIMIZATION AND DESIGN OF BLADE SHAPES FOR WIND TURBINE ROTORS

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Abstract

This project consists of designing, and testing the performance of a Savonius Vertical Wind Turbine. The project compares the performance of two designs: a classic barrel Savonius design, and the innovative design of Ice wind, an Icelandic startup that makes Vertical Axis Wind Turbines (VAWTs). In order to do so, first a literature review is carried out to understand the theory behind wind turbines and to understand the different types and characteristics of VAWT.
A Computer Aided Design (CAD) tool is then used to make a basic barrel Savonius rotor. Then, the Icewind design is reverse engineered from promotional material available on the company's website. Computer simulations, both 2D and 3D, are run to understand the characteristics of a Savonius rotor, and to obtain its pressure profile when subjected to a wind flow. A physical model of both designs is built to physically test and compare the performance of the two designs under different conditions. Finally, a consumer behavior study is conducted to learn about the design's appeal to the public. From the different steps, we concluded that Icewind does show a better performance on all fronts. Not only is it more efficient –for the same cost-, but it is more accepted by the public.

I. INTRODUCTION

Before we reproduce the Icewind design and run the simulations, we will first explore wind energy technologies and focus more on vertical turbines and more specifically Savonius vertical wind turbines.

METHODOLOGY AND OBJECTIVES

The goal of our project is to investigate whether the design proposed by Icewind is indeed better than the classic Savonius vertical wind turbine, by reverse engineering their design from their promotional material, model it, build it, and test it. Our research first establishes a performance benchmark of a classic Savonius turbine, and then compares the results and draws conclusions accordingly. The project also includes a fabrication step, where the model is going to be built and physically tested to obtain experimental data that describes the rotor's performance.

Our research question is therefore whether the Icewind turbine design performs better than the classic Savonius Turbine Design. We will follow a rigorous scientific method in which claims are confirmed or denied based on results obtained from the analysis we will perform.

This project will make use of the knowledge learned in the different mechanics, design, engineering process, as well computer simulations classes. It will also reinforce knowledge of the scientific research process, and serve as introduction to hands-on engineering and fabrication, a field that our university lacks.

There is nothing worse than developing an inefficient turbine than investing on an efficient turbine that does not sell. Part of the company's claim is that there were aesthetic (and not only functional) considerations to their design. In order to better understand what people think of this design, we will perform a consumer behavior study that will compare the appeal of the Icewind design to that of the barrel design.

BETZ'S LAW

Betz law, named after German physicist Albert Betz, states the maximum theoretical efficiency that any wind turbine can attain. It states that there is a maximum power that can be extracted from a flow of air. Because of conservation of momentum and of mass, energy can never be fully extracted from wind. Betz proved that the maximum kinetic energy that can be extracted from the wind cannot exceed 16/27 (59.3%). Thus according to this law, no turbine can extract all the speed out of the flowing wind, and the wind will always have a flow after passing through the turbine.

Figure 2 is a plot that shows the power coefficient of a turbine Cp (the ratio of the extracted power to the available power) vs. the ratio of the speed of the wind before and after passing through the turbine:

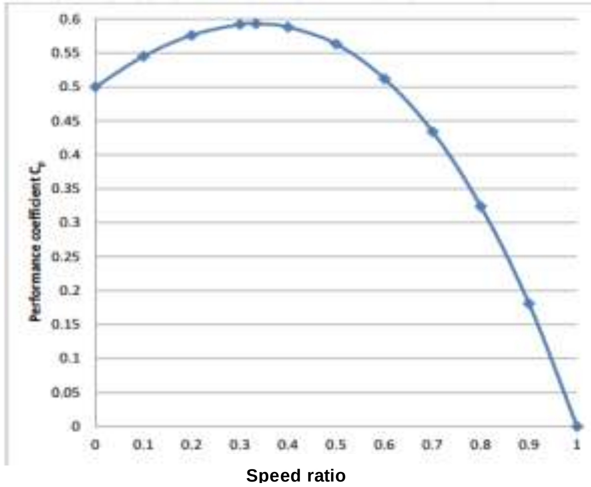


Figure : Power Coefficient plot

The derivation of the Betz limit is based on a horizontal axis wind turbine, and does not apply directly to vertical turbines. The same source argues even that this theoretical limit can be exceeded using an ideal VAWT system. However, it is reported that VAWTs are less efficient than HAWTs, and are less likely -in their current state- to exceed the limit for horizontal axis turbine.

STEEPLE Analysis

This project was not chosen because of its technical characteristics only, but also because it tackles more issues, especially those related to the environment.

Socially, this project aims to provide an alternative small-scale clean energy generation for people with no access and no connection to the grid. These could be people living in remote areas with constant wind strong enough to run a small rotor. The project also aims at increasing awareness of issues of energy and the environment by making the use of renewable sources easy and widespread.

Technologically, the project is centered on designing and building an innovative Vertical Axis Wind Turbine by reverse engineering designs available on the market. The project also involves experimentally testing the performance of Savonius rotors by using both computer simulations and physical tests. By working towards the objectives mentioned before, we are actively taking part in the efforts to develop renewable energy technologies and to solve our energy problems.

Environmentally, the project provides a clean alternative to fossil fuel based generation, which will reduce our environmental footprint. By making use of a renewable and inexhaustible energy source (wind), we will be decreasing the energy related emissions.

Economically, designing and testing an alternative design of wind turbines provides a cheaper way to utilize the energy of the wind as we are building a cheaper vertical rotor. The project also aims at demonstrating the public appeal that a Vertical Axis Wind Turbine design has by performing a consumer behavior study.

Politically, we hope that this project would serve as step towards reducing our country's energy dependence. By proving the usefulness of cheap alternatives, we are helping in pushing political action to promote the use and integration of renewable energies.

Legally, the project aligns with the commitments to the recommendations of the COP

22. Morocco pledged to generate more green energy, and our project represents a step in this direction. The project also allows for small-scale energy generation according the 13.09, and the 58.15 Moroccan laws, that will allow individuals to inject the generated energy into the national grid.

Ethically, this project aims to reduce and undo the vast damage we caused to our environmental systems. By working on renewable energy sources, we take part in the global action to protect the environment. Moreover, the project tests the claims of the Icewind Company in an objective scientific manner to reach well-supported conclusions. Finally, the project provides people with a clean alternative energy source and empowers people with no access to conventional energy sources.

Tip Speed Ratio

The tip speed ratio (lambda λ) is the ratio of the speed of the tip of the blades to the speed of the wind $\lambda = V_{tip} / V_{wind}$

As the tip speed ratio varies, so does the power coefficient and hence the efficiency of the turbine. An optimal value that will result in the maximum Cp is desired. Figure 4 shows the Cp lambda curve for different types of wind turbines as cited in:

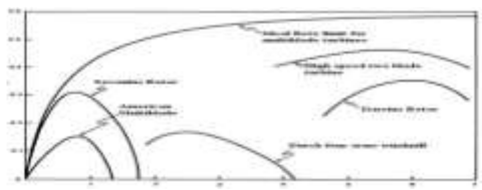


Figure : Power Coefficient curve for different types of turbines

Ratio of Blade Tip Speed to Wind Spee

Low tip speed ratio means not enough energy is extracted from the wind, and consequently a low Cp. A high wind tip ratio can also result in low Cp, as well as high stresses in the blades. Therefore, it is very important to have the optimal tip speed ratio, to maximize the efficiency.

Power Curve

The power curve is a plot that describes the performance of a wind turbine at different wind speeds. It shows the electrical energy power output vs. the wind speed, and gives an idea about the minimum and maximum wind speeds for a wind turbine.

Figure 3 shows a typical power curve as obtained from:

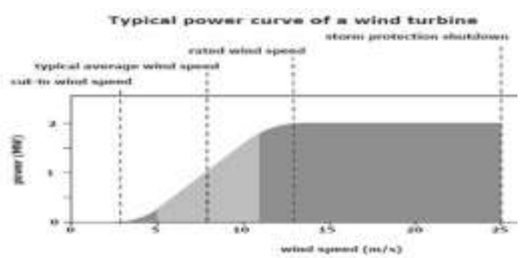


Figure : Power curve

The power generated is of course less than the extracted kinetic energy, as it has to go through a gearbox, and a generator, and both have efficiencies less than 100%.

Every turbine has its own minimum necessary wind speed to run, as shown in the Figure. Turbines are usually shut down at high speeds to prevent mechanical failure that would lead to a catastrophic failure of the turbine system.

Forces Involved

There are two types of forces that cause the wind turbines to rotate. These are drag and lift. Drag force has the same direction as the fluid flow (wind in our case), and lift forces are perpendicular to the direction of the flow. Depending on the type of the blades used, a turbine could be using either lift or drag to cause the rotational motion see in the following sections, utilize the lift force on their blades whereas Savonius turbines make use of the drag force to push the blades.

Turbulence

Turbulence is defined as "instability or disturbance" as well as unpredictability of the weather (wind speeds, direction, duration ...).

Turbulence presents a major challenge for wind turbines as it makes the generation profile inconsistent and decreases the lifetime of turbine blades because of the mechanical stresses. Predicting turbulence is as important as predicting the general weather conditions. The random and sudden changes in wind speed and direction pose many challenges on the turbine components. These components have to be able to accommodate short duration of peak loads at times of high turbulence, and have to be mechanically strong to resist the vibrations generated from the turbulent flow.

There are other concepts and variables that impact the performance and characteristics of turbines, such as twist angle of the blades of HAWTs, pitch angle, friction ..., however as our project deals with Savonius wind turbine we only discuss the concepts that are most pertinent to this specific type of turbines. We will review other factors in details in the section detailing Savonius VAWTs.

II. TYPES OF WIND TURBINES

Horizontal Axis Wind Turbines

As mentioned before horizontal axis wind turbines are the most mature and widely used wind turbines on the planet. In this section, we will briefly look at the principal, advantages, and challenges of this type of turbines. There are multiple factors that determine design of horizontal wind turbine, from material choice for the blades and stress distribution, to turbulence effects and vibrations. As this project deals principally with Savonius vertical wind turbines, we will only give a brief introduction of HAWTs.

Vertical Axis Wind Turbines

The main reason behind developing Vertical Axis Wind turbines is that they work regardless of the wind direction. VAWTs do not require a yaw mechanism and are very fixed in the sense that no change to their direction or that of the blade is made once installed. The lack of a yaw mechanism is one of the reasons VAWTs are not as expensive or complicated to make. This makes them ideal for small-scale applications such as remote areas with very small electric load. Their blades do not require a mechanism to change their angle as they work with any wind direction. VAWTs are considerably less noisy than HAWTs, which makes them more socially accepted. In addition to this, the small size means they can be integrated easily within an urban setting, and present no danger to the wildlife in rural areas.

They still share many components with HAWTs however, such as the shaft, the gearbox, the tower, and the generator unit. The placement of these units is different, since in VAWTs the gearbox and generator are placed at the base of the unit and do not require as much support as HAWTs. This means easier access for maintenance and repairs, which lowers the overall cost of such systems.

As mentioned before, the way the Betz limit is derived uses some assumptions that are not applicable to VAWTs. However, in general VAWTs are far less efficient than HAWTs.

Their small capacity makes them ideal for light load application such as communication systems in remote areas. VAWTs can be used for large capacity installations, but the materials needed and the massive investment make them undesirable. VAWTs are also suitable for either low wind speeds at which HAWTs do not function or high wind speeds at which HAWTs are shut off.

Table 1 below is a summary comparison of the characteristics and performance of VAWTs and HAWTs:

Table 1 Comparison of VAWTs & HAWTs

	VAWTs	**HAWTs**
Tower Sway	Small	Large
Tower Mechanism	No	Yes
Overall Formation	Simple	Complex
General Location	On ground	Not on ground
Height from Ground	Small	Large
Blade's operation space	Small	Large
Noise produced	Low	Relatively high
Wind direction	Independent	Depende
Obstruction for Birds	Low	High

As shown in Figure 5, there exist three types of rotors for the Vertical Axis Wind Turbines: the Darrieus rotor, the H-Darrieus rotor, and the Savonius rotor.

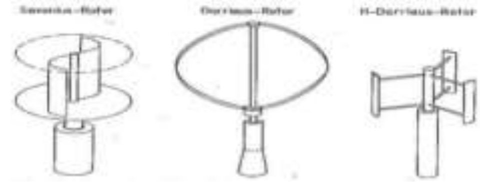


Figure : Types of VAWTs

Darrieus Rotor

Darrieus turbines are vertical turbines whose blades are aerofoils that use lift force to turn the rotor and generate electricity. They were designed and first fabricated by the French aeronautical engineer Georges Jean Marie Darrieus in the 1920s. Their working principle is quite different from that of horizontal axis turbines, even though they both rely on the forces of lift. After the turbine starts rotating, the motion of its blades through the air creates an apparent wind that is relative to the rotating blades. This relative airflow is added to the wind resulting in a force combination. This creates a force that causes a net positive torque in the rotor, making it rotate in the same direction it had originally. If the Darrieus turbine is stationary, most of the time the wind will not cause it to move, as it is the combination of the airflow resulting from the motion of the blades and the wind that sustains the motion, and not just the wind. The Darrieus rotor has to be started by spinning it until it reaches its operation speed, which represents a major disadvantage. Figure 6 illustrates its working principle.

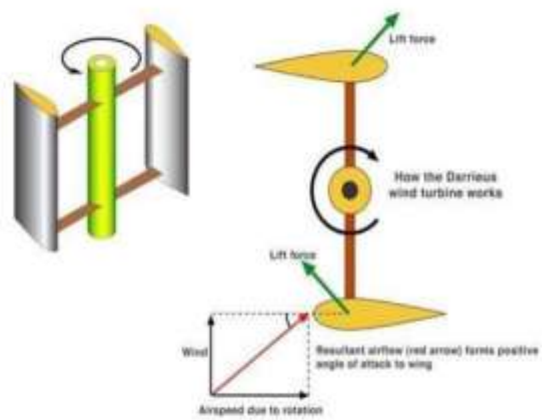


Figure : Working principle of a Darrieus rotor

The Darrieus rotor takes the shape of an eggbeater. This curved shape minimizes the bending moments that result from the centrifugal forces that are exerted on the rotating blade. Figure 7 shows an example of a Darrieus eggbeater turbine:

Figure : Darrieus "eggbeater" turbine

The shape of the blades in these designs is quite difficult and expensive to manufacture (aerofoil, curvature). This led to the development of a second type of Darrieus turbines discussed in the next section.

H-Darrieus Rotor

The H-Darrieus rotor, also known as the Giromill rotor, is a more efficient version of the Darrieus rotor. Its blades are easier to manufacture and offer greater efficiency, making it more attractive both technically and economically. Straight blades replace the curved blades and use the same principal to operate. The two blades version of the Giromill forms the shape of the letter H, and hence the name. Its blades can either be fixed or have a variable pitch depending on the needs, and some of the variable pitch designs are able to self-start.

Figure 8 shows the most common 3 blades H-Darrieus rotor VAWT:

Figure : H-Darrieus rotor

There are other less common experimental variations of the Darrieus rotor, but the ones discussed are the most used and researched. The last type we will discuss is the Savonius Wind Turbine, the focus of this project.

Savonius Vertical Axis Wind Turbines

Savonius wind turbine was invented by the Finnish engineer Sigurd Savonius in 1922. Its most basic design is S-shaped with two blades.

The Savonius turbine uses drag to push the curved blades to generate a torque that will make the rotor turn. Aerodynamically it is the simplest wind turbine to design and build which reduces its cost drastically compared to the aerofoil blade designs of the other VAWTs and HAWTs.

Its working principle is extremely simple. The turbine rotates because of the difference of the drag force acting on the concave and convex parts of its blades. Figure 9 illustrates this principle:

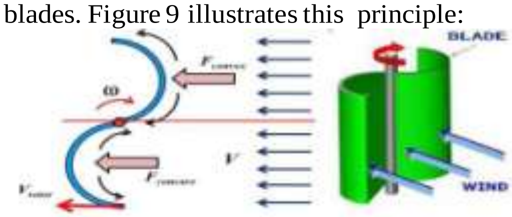


Figure : Working principle of a Savonius rotor

The air is trapped in the concave part and pushes the turbine. The flow that hits the convex part does produce a drag that is lower than the one on the concave part. It is the differential of the drag force that causes this turbine to rotate.

This lowers the efficiency of the turbine as some of the wind's power is used in pushing the convex part and is hence "wasted". More blades can be added to the S shape design, and the same principle causes it to spin as shown in Figure 10:

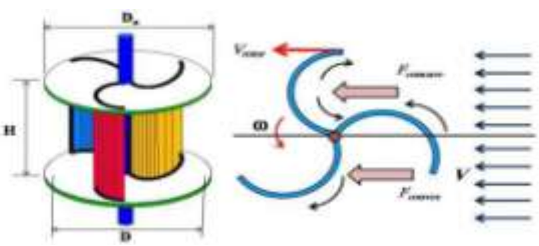


Figure : Three blades Savonius turbine

Savonius rotor requires 30 times more surface for the same power as a conventional rotor blade wind-turbine. Therefore it is only useful and economical for small power requirements. This makes Savonius ideal for small applications with low wind speeds. Savonius are hence desirable for their reliability, as they are able to work at several magnitudes of wind speed.

Characterization of Savonius Wind Turbines

Every Savonius wind turbine is characterized by the swept area $\boldsymbol{A}$. This area influences the energy output of the turbine, and the larger it is, the more energy the turbine collects.

$\boldsymbol{A} = \boldsymbol{H} *$ where H is the height of the turbine and D is its diameter.

The tip speed ratio of the rotor is defined by the equation: is the wind speed, ω is the angular velocity of the turbine, and d is the diameter of the semi-cylindrical blade

The torque coefficient C_t is the ratio between the torque in the rotor and the theoretical ρ is the air density.

The static torque coefficient C_{ts} expresses the turbines ability to self-start. It is the ratio of the maximum static torque in

the turbine and the theoretical wind torque:
The torque in the rotor can be calculated using the following equation: $T = I * \alpha$, where
I is the rotor's moment of inertia and α is the rotor's angular acceleration. Using these factors, we can learn about the turbine's characteristics and analyze its performance.

Two blades Vs. Three Blades

Savonius wind turbines do perform well at low wind speeds (cut in speed at around 2.5 m/s). According to the same study, two blades perform better than three blades as more drag is wasted in the three blades versions. The power coefficient of the two blade design is higher than that of the three blade design.

This result is confirmed that 2 blades do perform better than 3 blades. They also found that 4 blades perform even better than 2 blades at low tip speed ratio (TSR), and that 3 blades perform better at higher TSR.

Wind speed classification

As we keep mentioning high vs. low wind speed, it is important to define what qualifies as high or low speeds.

The IEC 61400 is a comprehensive report that provides detailed comprehensive international standards for wind turbines by the International Electrotechnical Commission. Table 2 shows this classification:

Table 2 Wind speed classification

Wind Turbine Class		**I**	**II**	**III**
Vave (M/S)		10	8.5	7.5
Vref (M/S)		50	42.5	37.5
V50,Gust (M/S)		70	59.5	52.5
Iref	**A**			
	B			
	C			

Where "V_{ave} is the annual mean wind speed at hub height. V_{ref} is the 50-year extreme wind speed over 10 minutes. $V_{50,\ gust}$ is the 50-year extreme gust over 3 seconds. I_{ref} is the mean turbulence intensity at 15 m/s, and A, B and C are the categories of higher, medium and lower turbulence intensity characteristics respectively."

III. EXPERIMENTAL PROCEDURE

SAVONIUS WIND TURBINE: CLASSIC BARREL DESIGN

As the goal is to test the Icewind design (which we will discuss in the coming paragraphs), we will first design a classic barrel Savonius wind turbine, and then later modify it to reach the Icewind design. In the simulation phase, we will first obtain results from the tests on the classic barrel Savonius rotor, and then compare them to the new Icewind design.

The design of a barrel rotor is simple. The basic idea behind the simple two blades Savonius is that the blades are half cylinders (half a barrel, hence the name). These barrels do not often meet at the axis, but are set far apart as shown in Figure 11, to create an overlap:

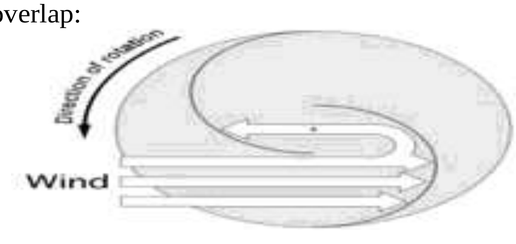


Figure :Overlap of the two blades on a Savonius rotor

As the Icewind design does not have any overlap, we will not have this feature in our barrel Savonius design.

Many variables determine the shape of a Savonius barrel design. The ones we will be using are as follows: **Do**: outer diameter of the base of the rotor; **D** The distance between the two opposite blades; **r** the radius of the blades; and **h** the height of the rotor; we will be using a ratio **D:h** of 1:1. The ratio is the most common design feature of these turbines as they tend to be a square box shape, hence why the 1:1 ratio.

Another ratio we will be using is the **Do:D**, which determines how far the base extends beyond the blade. We will be using a **Do:D** of 1.1:1. The following figures show the design we built using SolidWorks and the measurements used for two, three, and four blades barrel Savonius wind turbine:

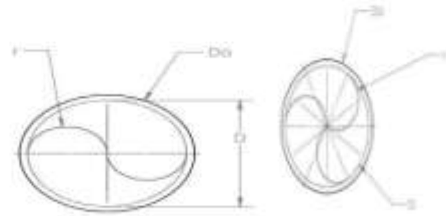


Fig: Two blades Savonius rotor design
Fig: Three blades Savonius rotor design

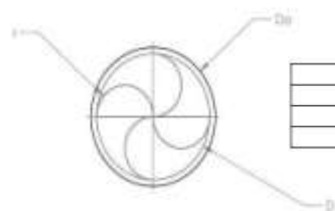


Table 3

Do	0.44
D	0.4
h	0.4
r	0.2

Figure : Four blades Savonius rotor design

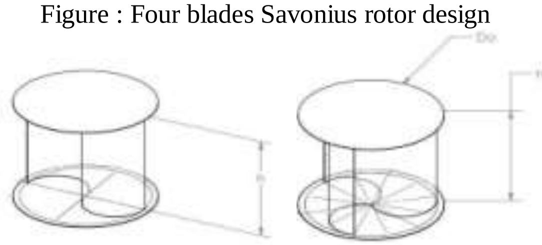


Figure: Two blades Savonius rotor design
Figure : Three blades Savonius rotor design

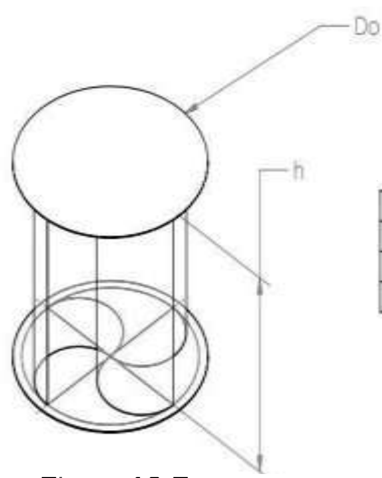


Table 4

Do	0.44
D	0.4
h	0.4
r	0.2

Figure 19 Four

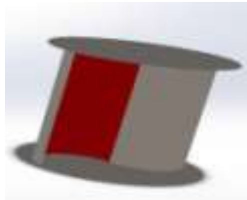
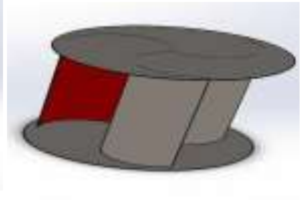



Fig: Two blades Savonius rotor design
Fig: Three blades Savonius rotor design

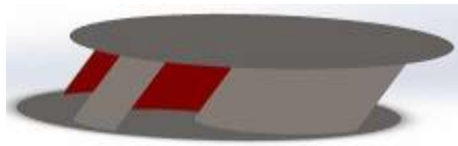


Figure: Four blades Savonius rotor design

The base of the turbine is necessary for structural integrity. It provides support for the blades against the drag force of the wind pushing the blades of the rotor. As we will see in the coming section, the Icewind design does not use a base. In order for our comparison from the simulations to be representative, we will remove the base and connect the blades with a central axis. This will not affect our simulation since we are not performing a stress or a fatigue analysis.

The design is shown in the Figures be

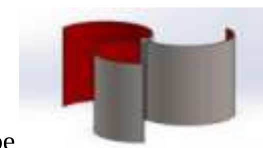
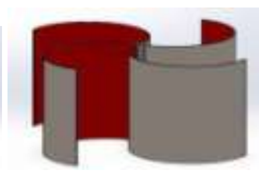



Figure: No base barrel design
Fig: ICEWINDDESIGN

Icewind

Icewind is a startup from Iceland founded in 2012. From their website: “Icewind designs and manufactures small vertical axis wind turbines for telecom towers and residential applications such as homes, cabins and farms”. In the *about* section they say that their work “demonstrates that turbines can be an elegant, quiet, durable, cost effective and nearly maintenance free solution for energy production”. One of their designs offer 1000 W at 10 m/s and smaller one can generate 300 W at10 m/s. they both can produce at speeds ranging from 2 to 60 m/s, without mechanical failure or overheating.

Since they are planning to start selling their products later this year, they are naturally being very secretive about their design. Only a few pictures are available online, in addition to a promotional video we found on YouTube.

From this promotional material, we managed to collect enough pictures to have a clear idea about their design and its characteristics. Using the general features we found, we reverse engineered this design and managed to replicate it.

The following figure shows examples of what we used to understand the features of their design:

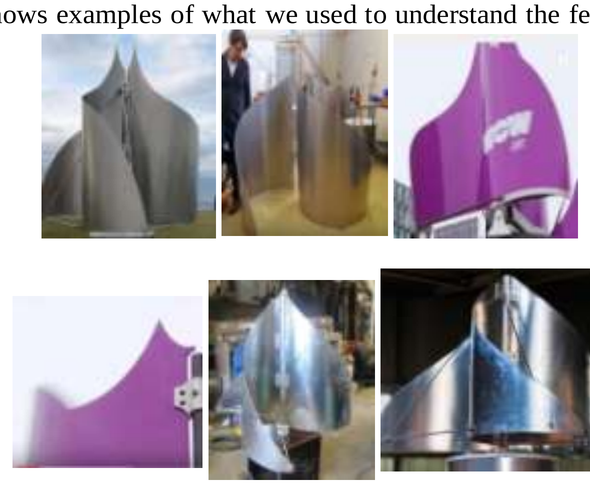


Figure: Images from Icewind's promotional material

IV. DESIGNING THE BLADE

The first thing we noticed is that the blades do not form a half circle at their base, but an incomplete one. This meant that in our design starting from the barrel shape we would cut a rectangular block from the inner side of the blade to make it similar to that of Icewind. The second distinctive feature is that the **D:h** ratio is not 1. We noticed that their blades are quite wide and that the diameter of the complete half circle (D/2) making the blade is the same as the height h (**D:h** close to 2). Once one end of the blade is trimmed to make the shape seen on their designs this ratio appears larger as the rotor blades are slightly less wide than the rotor is high. We achieved this ratio by trimming 1/10 of the blade on the inner end as will be demonstrated.

The outer curves on the blades are cutouts of tangent circles of unknown radius. Using SolisWorks constraint tools we managed to find the radius that will satisfy the position of the tip of the blade (1/5 of the blade's diameter) as well as tangencies to the lower parts of the blades.

This is shown in the following steps:

Step:1 - We start from a normal Savonius blade with 1:1 **D:h** ratio. We add the circles and solve for the mentioned constraints:

Figure: Icewind blade, step.1

Step:2 - We trim the arcs that are needed and define shape of the blade:

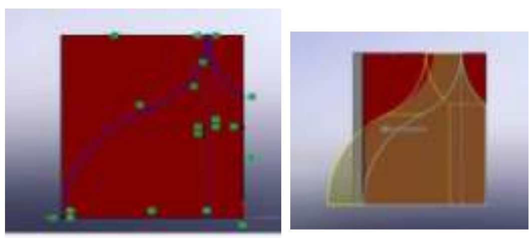


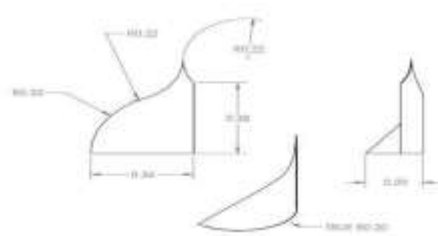
Figure: Icewind blade, step 2

Step:3 - We intersect the created shape with original blade, and keep the intersection only:

Figure: Icewind blade, step 3

Step:4 - We trim 1/10 off the inner end of the blade:

The final blade and its detailed measurements are shown in the Figure below:



Now that we have the blade, designing the 3 and 4 blade rotors involved just attaching the blades to an axis. The designs are shown below:

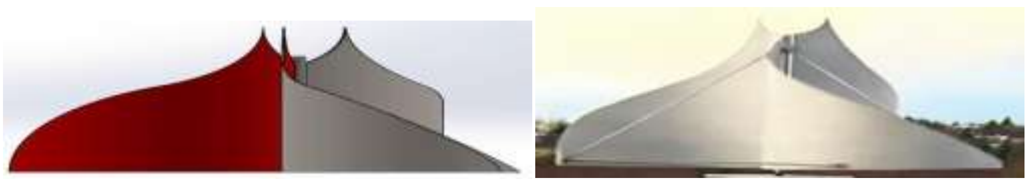


Figure : Three blades Icewind rotor: our design vs. the original

The two designs look somewhat similar. The differences are due to the fact that every picture of the Icewind design we found online had its own characteristics. Consequently, we tried to match the most general and common features between all the different versions we found.In order for our comparison to be accurate, we have to control for some variables (otherwise, the results of the analysis cannot be compared). Although we started from the barrel Savonius and modified it to make the Icewind design, the initial (barrel) and final design (Icewind) have no common ratios. To solve this problem we fixed the height of the two rotors, and modified the Icewind to have the same surface area as the barrel design. As the diameter of the Icewind design is double that of the barrel design, removing half of the blade compensated for the increase in diameter and kept the surface area constant at 0.12 m^2. By modifying, the area cut off the tip of the blade we increased the similarity in surface area to 99.86%, at a surface area of: 0.12441 m^2 for the barrel design, and 0.12459 m^2 for the Icewind design.

We tested the two models we built and measured their rotation speed under different wind conditions. In order to do so, we used a normal house fan and a make shift wind tunnel to minimize turbulence.

Figure: Turbine Test

We marked the exact position of the fan as well as the rotor's base in order to minimize any errors in the experiment.

Using an anemometer that we purchased (Testo 410, Helical anemometer, range: 0.4 to 20 m/s, purchased from A2B-Lab Casablanca), we measured the average wind speed generated by the fan, and using an overhead camera, we recorded the rotation of the rotor.

We used yellow tape to mark one corner of the rotor, and used a black marker to make a permanent mark on the floor. These two marks helped us to compute the time it takes the rotor to complete one full turn and hence compute its angular velocity.

Figure: Anemometer used for measuring wind speed

We used the three speeds that the fan can generate and measured the resulting air speed. We noticed that when we measured the air speed while the rotor was behind the anemometer, we got very inaccurate readings because of the rotor creating air currents that interfered with the reading. We removed the structure, measured the speed resulting for the three settings multiple times and took the average.

To measure angular acceleration, and angular velocity, we used Tracker. It is an open source free physics video processing software. We shot all the videos at 50 fps, and using this software determined the number of frames it takes for the rotor to complete one turn. We processed this data, generated angular acceleration, and angular velocity measurements.

V. COMPUTATIONAL FLUID DYNAMICS SIMULATIONS

The goal of this project is to compare the performance of the Icewind design to that of a classic barrel design. Icewind proposes two designs: a 3-blade design (300 W at 10/m/s) and 4-blade design that promises a higher power generation (1000W at 10 m/s). Classic barrel Savonius turbines come most commonly at two, three, and four blades.

In order to understand the reasons – if any – that Icewind performs better than a classic barrel, we first have to understand the performance of a barrel design. As mentioned in the previous sections, there are multiple factors to account for in a barrel Savonius rotor. We detailed earlier the design considerations that went into making the 3D models. We tried to fix different variables between the Icewind and the barrel (overlap, surface area …), in order to have an accurate comparison. One of these variables is the number of blades. Therefore, it is crucial to understand the effect that the number of blades has on the performance of a Savonius VAWT.

In the next section, we will look at the 2D simulations performed in order to understand the effect of the number of blades.

2D SIMULATIONS: EFFECT OF THE NUMBER OF BLADES

The reason we are using 2D simulations is that on a 2D level, a barrel Savonius is essentially similar to an Icewind design. As they are both close to a semi-circle. By determining the effect on a 2D level, we can safely apply the conclusions to both barrel and Savonius.

We will first be basing our 2D study on the study "An Experimental Study on the Performance of Savonius Wind Turbines Related With the Number Of Blades" by Wenehenubun. In this paper, they perform 2D simulations to determine the pressure differential on the blades of a barrel (as a means of judging the performance).

The first step was to try to replicate the work presented by their study consisted of computer simulations as well as a physical setup. The 2D simulations' output was the pressure profile on a 2D model, and their results showed that four blades generate a higher pressure-difference, followed by two blades, and then three blades.

The simulations were performed at one attack angle (that is actually different from one design to the other), as Figure 32 shows:

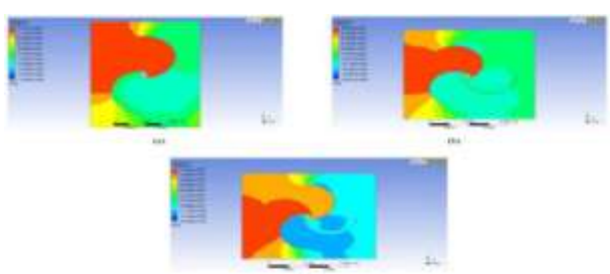


Figure: Pressure difference

The reason why they chose this specific orientation is not mentioned. We initially thought that they choosing the orientation where the blades are most open to the wind. However, this does not apply to the 4 blades as they are not oriented in the direction were the angle formed by two blades is perfectly open to the wind. It is worth stating that no general conclusion can be drawn from such comparison. We cannot compare different angles and judge the performance of the whole rotor just from these results.

Another issue we found with this paper (and similar studies involving computer simulations) is that they do not provide enough information to accurately replicate their work. As we will see later, performing a simulation on ANSYS (the computer tool chosen) involves quite a lot of variables and options. From the viscosity model, the meshing settings, to the tunnel model treatment. These variables and many other have a significant effect on the results. Whether you consider that the rotor will be rotating in a viscous fluid or not will surely affect the results. If the decision not to ignore the viscosity is taken, we still have to determine what kind of viscous model we are using etc. Once all these decisions are made, we need to choose the solver, the size of the tunnel in which the rotor will be tested, the constraints, etc.

Wenehenubun and his co-authors fail to mention any of these important variables, and just show the final results. Therefore, it is practically impossible to accurately replicate their process (and consequently impossible to replicate their results).

In the following paragraphs, we will mention in detail the steps followed as well as the reasoning (based on our limited understanding of these highly complex software tools and mathematical models).

SETUP

To perform these simulations we will be using ANSYS: Fluent. It "contains the broad physical modeling capabilities needed to model flow, turbulence, heat transfer, and reactions for industrial applications […] Fluent covers a broad reach, including special models with capabilities to model in-cylinder combustion, aero-acoustics, turbomachinery and multiphase systems". As shown in Figure 33, a fluent project involves different steps:

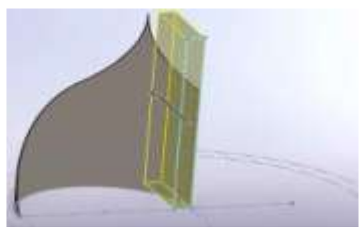


Figure: ANSYS Fluent project

In order to run a simulation we first have to either import the geometry from a CAD software (such as SolidWorks), or use ANSYS Design Modeler (DM) to model the geometry, which is then meshed.

The way computational fluid dynamics (CFD) software works is by solving fluid dynamics equations around the geometry following the constraints we specified. In order to determine the points at which these equations will be solved a mesh is generated. The mesh discretize the physical space into a finite number of points. The higher the number of points (i.e. the mesh size) the more accurate the solution and the more time and power it will take to solve. An example of a mesh will be shown later.

Once the mesh is generated, we specify the setup for Fluent. This part involves the most details, as it requires many variables (models, solver, initial values, number of steps, boundary conditions …). Once the solver setup is done, the solution is found and is visualized in the results tab.

The first part of the simulation is defining the geometry to be simulated. For the 3D simulations, we import the model that we built on SolidWorks; and for the 2D simulations, we rebuild a 2D transverse section of the rotor following the dimensions we presented in the previous sections.

Bilow fig. shows the geometry as built on ANSYS DM. It shows the 2-blade rotor enclosed in a larger rectangle that will serve as the wind tunnel. The wind tunnel is large enough to allow the flow to become uniform after it had passed around the rotor.

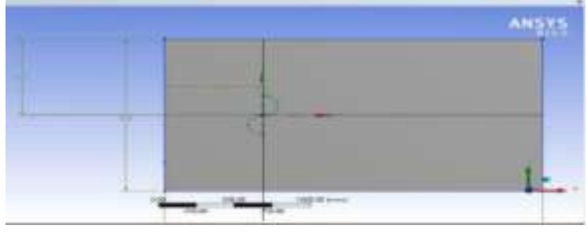


Figure : 2D model of a 2-blade rotor

The next phase is to mesh this geometry. For the most part, we rely on the default settings, but we do specify the number or points around the blades and on the different walls of the tunnel. We define the inlet (the left side, perpendicular to the x-axis), the outlet (the right side, perpendicular to the x-axis), the tunnel walls (the upper and lower sides), as well as the walls of the rotor's blades. Since the point is to understand the effect of wind -coming from the inlet- on the blades, we give the blades a higher number of points (i.e. a higher resolution) than the inlet, outlet, and walls. We use 40 per side for the blades, 20 for the inlet and the walls, and 10 for the outlet. These values are very common on CFD forums as well as published tutorials. For this 2D simulation, we based ourselves on [23], and double-checked the step on online CFD sources. Figure 35 shows the mesh generated by ANSYS:

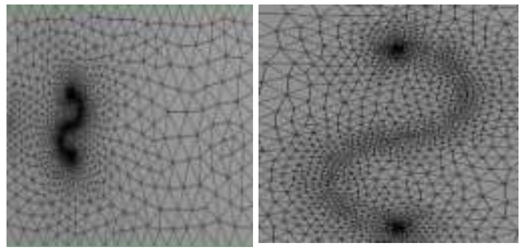


Figure : 2D 2-blade rotor and tunnel mesh

After generating the mesh, we move to the solver where we will specify the methods used, the boundary conditions, the turbulence model, as well as the number of iterations and the convergence condition.

The solver type we will be using is Pressure Based in Steady Time (as opposed to Transient Time). Choosing Pressure Based vs. Density Based will not make a difference in the output for our case, as we are working in relatively low speed. It is recommended to use pressure based approach for low speeds and density based approach for extremely high speeds. From the tutorials on which this work was based, it was recommended to use Steady Time as it converges faster.

The air viscosity model we are using is the "realizable k-epsilon turbulence model with enhanced wall functions". According to this model provides accurate solutions compared to the other k-epsilon models. ANSYS Fluent user's manual specifies that the k-epsilon model "has been implemented in most general purpose CFD codes and is considered the industry standard model. It has proven to be stable and numerically robust".

Next, we specify the boundary conditions. We already created named selections, and marked the inlet, rotor, outlet, and tunnel wall. We will specify that the inlet is of type "velocity inlet", and enter the wind speed and direction. We specify that the tunnel wall is of type "wall", the rotor of type "interior", and the outlet of type "pressure outlet". Specify that the boundary condition for the outlet is a gauge pressure of zero. This means that the pressure at the outlet (relatively far from the rotor) should be the same as that of inlet.

We do not need to specify any reference values as the will not be asking the solver to compute any ratios or coefficients. We specify that we use the SIMPLE scheme for the pressure velocity coupling. As SIMPLE is especially useful for less complicated problems such as the one we are dealing with. We then input the convergence criteria. In our case, the criterion was that the residuals (i.e. the differences between successive iterations) from the solution computation should be less than 1e-06. Figure 36 show the variation of the residuals as the solution is computed:

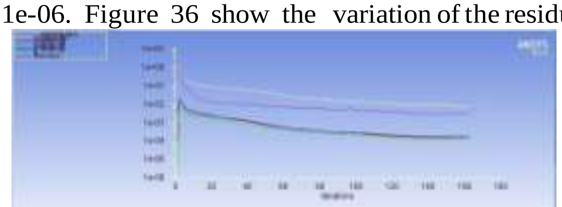


Figure : Residuals plot

Before running the solution, we initialize it with the initial values of the velocity (on the x, y, and z-axis), and the gauge pressure (the difference between the absolute pressure and the atmospheric pressure, initialized at a value of zero).

We set the number of iterations at 1000 (the solver will compute the solution for 1000 times or until the solution converges given the user defined condition), and we run the solution.

Now that we have established that -- judging by the generated pressure difference - a three blades rotor does perform better than two blades and four blades versions of barrel Savonius turbines, we can focus on comparing the performance of the Icewind design to that of the barrel design. It is important to note that the 2D profile of an Icewind rotor is very similar to that of a barrel design (the cuts that make Icewind special happen on the surface of the blade not on the semicircle, and the trimming of the semi-circle is too small to be considered). Therefore, it is reasonable to infer that any conclusions made regarding the effect of the number of blades on barrel Savonius can be extended to the Icewind design as well.

The main problem with performing 3D simulations is that they are much larger in terms of nodes in the mesh and hence require a longer time to solve. Because of the limitations of both computational power and time, we will not simulate the two designs (Icewind and barrel) on all orientations. We will choose the best and worst orientation as found from the 2D simulations and run the 3D simulation on both designs at these orientations at 5 m/s. This will allow us to compare the performance of the two designs at two opposite performance points.

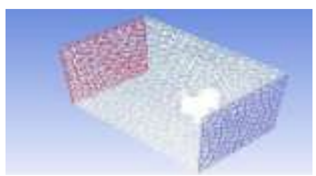
The optimal angle for a 3-barrel design is 30° as it guarantees that the blades are as open as they can to receive the wind, as opposed to a 90° orientation where the blade is blocking the wind. The figure below shows the two orientations:

Figure: 30° vs. 90° orientation

SETUP

Similar to the 2D simulations, we will follow the steps shown in Figure 33. We import the geometry from SolidWorks and enclose it in a rectangular box that will serve as our wind tunnel. We respect the same ratios for the enclosure for both Icewind and barrel design and orient both of them in the same way.

We then, in the same way as the 2D simulation, mesh the two designs while creating named selections so we can identify the inlet, outlet, and other elements, and specify the boundary conditions.
The figures below show the created meshes:



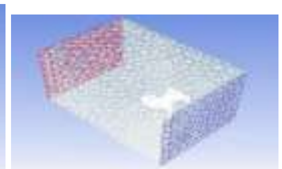


Figure: Barrel design mesh Figure: Icewind design mesh

The area highlighted in blue is the inlet of the tunnel, and in red is the outlet. The box surrounding Icewind is wider as the Icewind design has a larger diameter than the barrel design.

The figure below shows a zoomed in section of the mesh. Same as for the 2D simulation, we chose a higher resolution for the surface of the rotor than the inlet/outlet:

Figure : Barrel Mesh - Close up

We will use the same solver and settings as the 2D simulation. We run the solver for 1000 iterations or until the solution converges. Because of the very high number of nodes in a 3D mesh (around 180 000 nodes), it takes up to 8 hours on 100% computing power to run one of these simulations.

VI. RESULT AND DISCUSSION

The first goal of the 2D simulations is to replicate (or check) the results presented by Wenehenubun. As we mentioned before, it is difficult to replicate their work, as they do not provide enough details. However, for the results needed, we believe that details such as the type of solver, pressure velocity coupling, etc. will not cause much difference as stated by the different tutorials we followed, as well as ANSYS SLUENT user's manual.

We used the same orientation as proposed in for the two, three, and four blade models. We then run the simulation for 1, 5, and 10 m/s on the positive x-axis (from left to right).

We generated nine pressure profiles for the nine cases (3 rotors, 3 speeds), and computed the difference between the front and the back of the blades of the rotor (numerical results are shown in Appendix A). The Figures below shows the results for 5 m/s for the three rotors in their respective orientation:

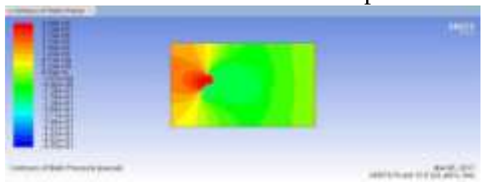


Figure : Two blades rotor at 5 m/s

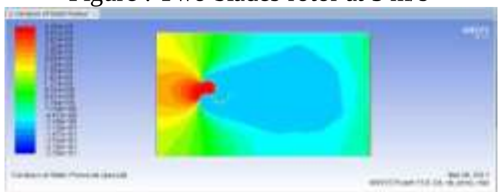


Figure :Three blades rotor at 5 m/s

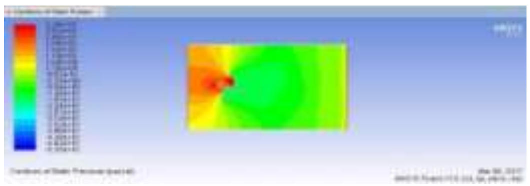


Figure : Four blades rotor at 5 m/s

As we can see in the figures, the prssure is high on the concave side of the rotor blade (the receiving open cup) as that is where the wind will hit the most and will not escape as fast as on the convex side. Negative pressure (vacuum gauge pressure – relative to the atmospheric pressure) is generated on the backside of the rotor, which makes sense as this a static case where the rotor is fixed in this specific orientation. This pressure differential causes a net force on the blades and hence causes rotation.The table below shows the pressure difference on the concave blade of the three rotors at the three wind velocities:

Table : Pressure difference in Pa

	2 blades	**3 blades**	**4 blades**
1 m/s	1.53	1.75	1.39
5 m/s	36.9	43.5	23.4
10 m/s	147	174	133

For this specific orientation, it seems that three blades rotors generate the higher- pressure difference.

It is crucial to note that 1- this is not to be generalized (we cannot say that 3 blades rotors are "better"), and that 2- the orientation is not fixed across rotors (they do not face the wind in the same way). There might be an orientation where two blades would generate a higher-pressure difference and another where it could be the worst. This is a fundamental flaw in the method followed by Wenehenubun.

Even with following their orientation, our results are not consistent with their findings. For one their pressure values are very high, this might be due to the fact they might be because our pressure profiles are generated for static pressure. Static pressure is the pressure that can be measured with a barometer and is generally known as pressure. Dynamic pressure (which usually has a higher value) is a value that has the dimensions of pressure (Pa) but is a measure of the kinetic energy of the fluid at point (derived from the velocity of the fluid). However, choosing static, dynamic or total (the sum of the previous two), should not affect the order of the pressure differences (i.e. we should be able to get the same conclusions in terms of which rotor generated more pressure difference). Find that two blades has high-pressure difference, followed by four blades, followed by three blades.

In order to reach a valid conclusion on the relationship between the number of blades and the pressure difference we will run the same simulation for different orientations of the rotor, for the three different speeds.We will be measuring the orientation of the rotors with respect to the vertical axis (perpendicular to the wind speed) as shown in Figure 40:

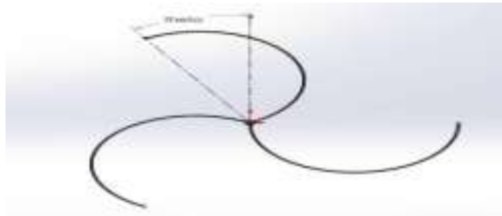


Figure : Rotor orientation

The 2-blade rotor has a 180° symmetry, 120° for the 3-blade rotor, and 90° for the 4- blade rotor. We will be rotating the model with increments of 20° for the three rotors, until we reach the initial orientation again.

This means that we will have nine orientations for the 2-balde rotor, six for the 3-blade rotor, and five for the 4-blade rotor. With three speeds for each orientation (1 m /s, 5 m /s, and 10 m /s), we run **60 different simulations**, and get the pressure results (numerical results are shown in Appendix A). We organize the data with Excel, and generate the following graphs:**2 blades:**

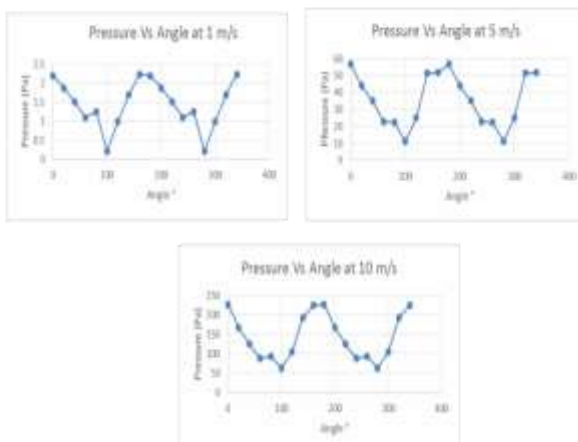


Figure : Pressure difference for two blades rotor

- **3 blades:**

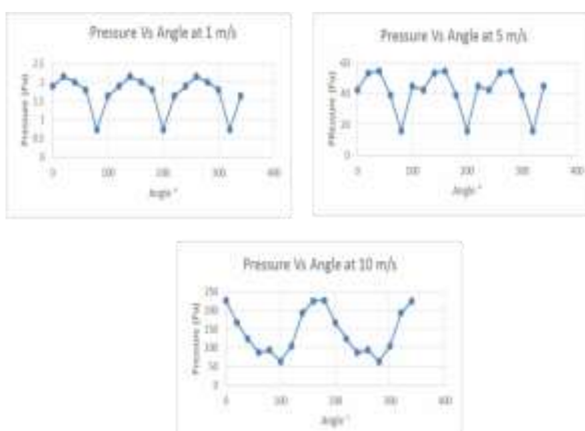


Figure : Pressure difference for three blades rotor

4 blades:

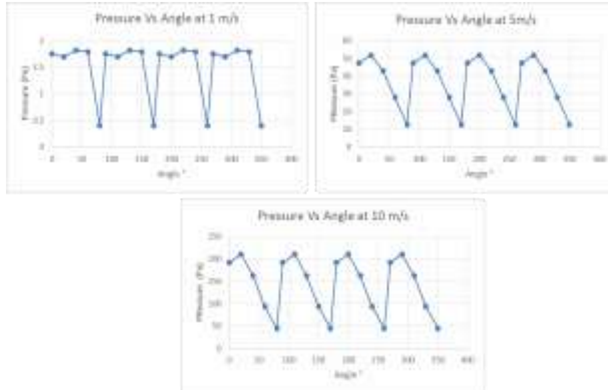


Figure : Pressure difference for four blades rotor

From these graphs, we conclude that the approach is definitely invalid as the performance of the rotor varies depending on its orientation. As the rotor turns, its blades will have an optimal angle that will maximize the exposure to the wind. This angle would be the one at which the rotor is open towards the direction from which the wind is coming. The optimal angle for two blades is hence at 0°, for three blades at 30°, and for four blades at 45°. Similarly we can deduce that the worst angle is when the exposure to the wind is minimized which happens at 90° for 2 blades as well as 3 blades, and at 80° for 4 blades.

The following graph shows a comparison of the pressure difference for every orientation for the three rotors, at a speed of 5 m/s. We find that the same trend is present at 1m/s and at 10 m/s.

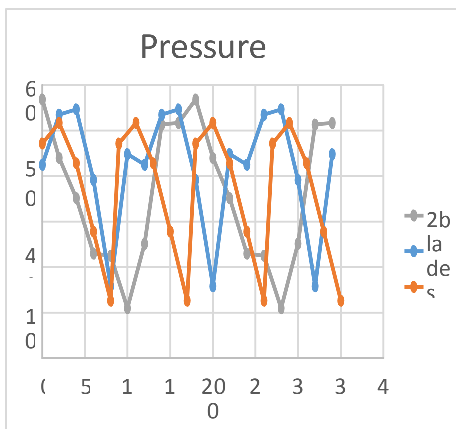


Figure : Pressure values at 5m/s

A more convenient way to look at this data is to average the pressure values. We find:

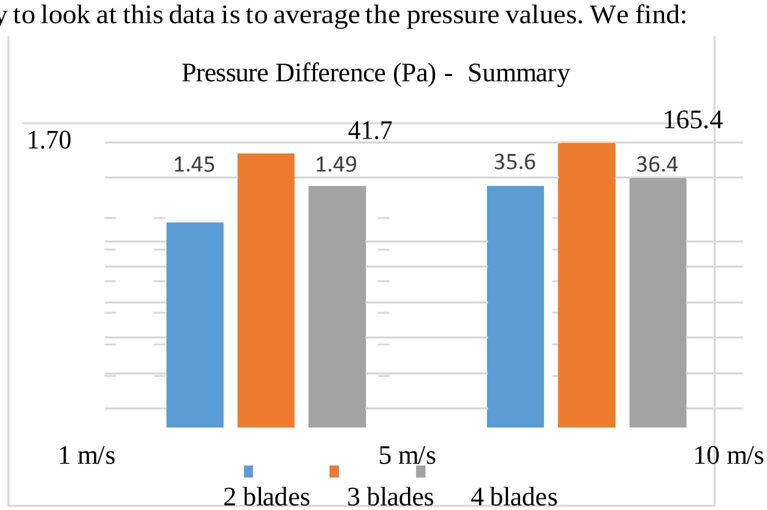


Figure 6.9 Pressure difference summary

We conclude that on average, a 3-blades rotor generates a higher-pressure difference than a 2-blades rotor and a 4-blades rotor.

VII. CONCLUSION AND FUTURE WORK

The principal goal of this project was to test the performance of an innovative design of a Savonius Vertical Axis Wind Turbine proposed by an Iceland based startup. In order to do so, we first modeled the rotors on SolidWorks and then ran simulation on these designs. The simulations we ran were done in the ANSYS workbench using Fluent.

From running 2D simulations, we concluded that three blades is the optimal design as it experienced the highest pressure difference on its wind-receiving blade. We then ran 3D simulations using the same software tool on the Icewind design and the classic Barrel design. Results showed that Icewind experienced a higher torque (twice as much) compared to the barrel design. Through these simulations, we understood some of the design considerations of Icewind. It generated high pressure farther from the axis compared to the barrel design, and hence generated a higher torque.

In order to further test these designs, we built simplified models using readily available materials. Using a makeshift wind tunnel, and commercial fans, we tested the two designs under three different wind speeds. Through angular velocity, acceleration measurements, and numerically calculated moment of inertia, we determined the torque generated by the different designs and calculated their power coefficient. From these tests, we concluded that the Icewind design is 28% more efficient than the barrel design, which confirms the results of the simulation.

Part of the Icewind design is not meant for efficiency or better mechanical properties, but for aesthetics and marketing. What is worse than an inefficient turbine is an efficient turbine that does not sell. Icewind combines both functionality and aesthetics in their product. This is confirmed by the consumer behavior study we conducted -- 57% of the participants stated that the Icewind design looked more aesthetically pleasing, and 63% of the participants stated that they found it more aerodynamic than the barrel design.

To sum up, it does seem that Icewind is winning on all fronts. We can surely say that Icewind have valid and solid claims, and that their design is indeed better than the classic barrel design. We hope that their product will be successful once they begin large-scale production, scheduled for later this year.

Future work would consist of building an actual Icewind turbine that can be used to generate electricity. The field of small-scale wind energy is very promising and largely untapped. This means that there are many questions about Savonius and other types of VAWTs that are worth researching. Variables such as overlap, curvature of the blades, orientation, etc. need to be investigated in order to better understand these designs.

In the end, we would like to mention that this was an amazing learning journey. We hope that this will serve as the first step towards establishing a hands-on and fabrication tradition in the School of Science and Engineering.

Throughout the different phases, we faced and overcame many challenges. It is thanks to the contributions of many people that this project came to be, and the few acknowledgments at the beginning of this report do not do justice to their efforts.

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