ME219 COURSE PROJECT - FLUID MECHANICS

AIM:
Comparative analysis of efficiency enhancement in 2 blade, Tulip-shaped and conventional 3-blade wind turbines and exploring so-called “tulips” as a possible solution to energy eyesores.

BACKGROUND:
As a clean and renewable energy source, wind energy is seen by many as a way to partially solve our nation’s energy crisis. Wind energy has grown by leaps and bounds in recent years.Fluid mechanics can help us analyze the mechanisms of wind flow occurring in nature and understand various factors it is dependent upon. We can use this study of fluid mechanics for various applications ,one being energy generation. Thus, we are researching various pros and cons of tulip shaped turbines and what role fluid mechanics play in.

How Wind Energy Works
Wind is a form of solar energy. Winds are caused by the uneven heating of the atmosphere by the sun, the irregularities of the earth's surface, and rotation of the earth. Wind flow patterns are modified by the earth's terrain, bodies of water, and vegetation. The terms wind energy, or wind power, describe the process by which the wind is used to generate mechanical power or electricity. Wind turbines convert the kinetic energy in the wind into mechanical power. This mechanical power can be used for specific tasks (such as grinding grain or pumping water) or a generator can convert this mechanical power into electricity. So how do wind turbines make electricity? Simply stated, a wind turbine works the opposite of a fan. Instead of using electricity to make wind, like a fan, wind turbines use wind to make electricity. The wind turns the blades, which spin a shaft, which connects to a generator and makes electricity.

Types of Wind Turbines
Modern wind turbines fall into two basic groups: the horizontal-axis variety, and the vertical-axis design, like the eggbeater-style Darrieus model, named after its French inventor. Horizontal-axis wind turbines typically either have two or three blades. These three-bladed wind turbines are operated "upwind," with the blades facing into the wind.

Horizontal-axis turbines are similar to propeller airplane engines

Horizontal-axis turbines have blades like airplane propellers, and they commonly have three blades. The largest horizontal-axis turbines are as tall as 20-story buildings and have blades more than 100 feet long. Taller turbines with longer blades generate more electricity. Nearly all of the wind turbines currently in use are horizontal-axis turbines.

Vertical-axis turbines look like egg beaters

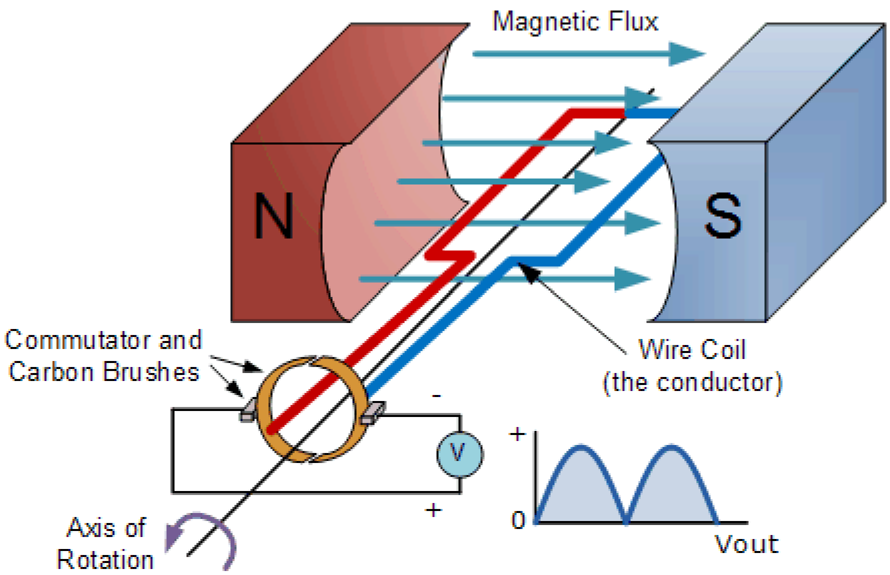
Vertical-axis turbines have blades that are attached to the top and the bottom of a vertical rotor. The most common type of vertical-axis turbine—the Darrieus wind turbine, named after the French engineer Georges Darrieus who patented the design in 1931—looks like a giant, two-bladed egg beater. Some versions of the vertical-axis turbine are 100 feet tall and 50 feet wide. Very few vertical-axis wind turbines are in use today because they do not perform as well as horizontal-axis turbines.

Electrical Circuitry:

Components used:

1. Single stranded wires
2. Dynamo dc motor
3. Arduino uno r3
4. 3.3v LED

Concept involved:



We all know that a dc motor is a electronic device that rotates when applied with voltage across its terminals but Faraday"s law of electromagnetic induction makes the vice versa possible

This law states that when a conductor moves in a magnetic field it cuts magnetic lines of force, which induces an electromagnetic force (EMF) in the conductor.

The magnitude of this induced EMF depends upon the rate of change of flux (magnetic line force) linkage with the conductor. This EMF will cause a current to flow if the conductor circuit is closed.

So we can use the rotation of shaft to generate voltage across the LED load and display the output V on serial monitor

Circuit explained:

Circuit Basically consists of a dc motor of high rpm rating to be used as a battery connected across an LED load and a intermediate wire to take the voltage feedback

All is left to do is to display that Voltage on serial monitor which can be achieved using GPIO ADC(analog to digital converter) pin of any microcontroller board (in our case arduino)

Code explained:

```
const double vRef = 5.00;

float Vout;//reference voltage to map 10 bit analog input (0-1024) to Voltage

const double resConvert = 1024;

double resADC = vRef/resConvert;

void setup(){

  Serial.begin(9600); //rate at which data is published on serial monitor

}

void loop(){

  // Vout is read 1000 Times for precision

  for(int i = 0; i < 1000; i++) {

  Vout = (Vout + (resADC * analogRead(A1)));

  delay(1);

  }

  // Get Vout in mv

  Vout = Vout /1000;

Serial.print("Vout = ");

Serial.print(Vout,2);

Serial.println(" Volts");

delay(1000); //1sec delay given

}
```

Hardware Structure

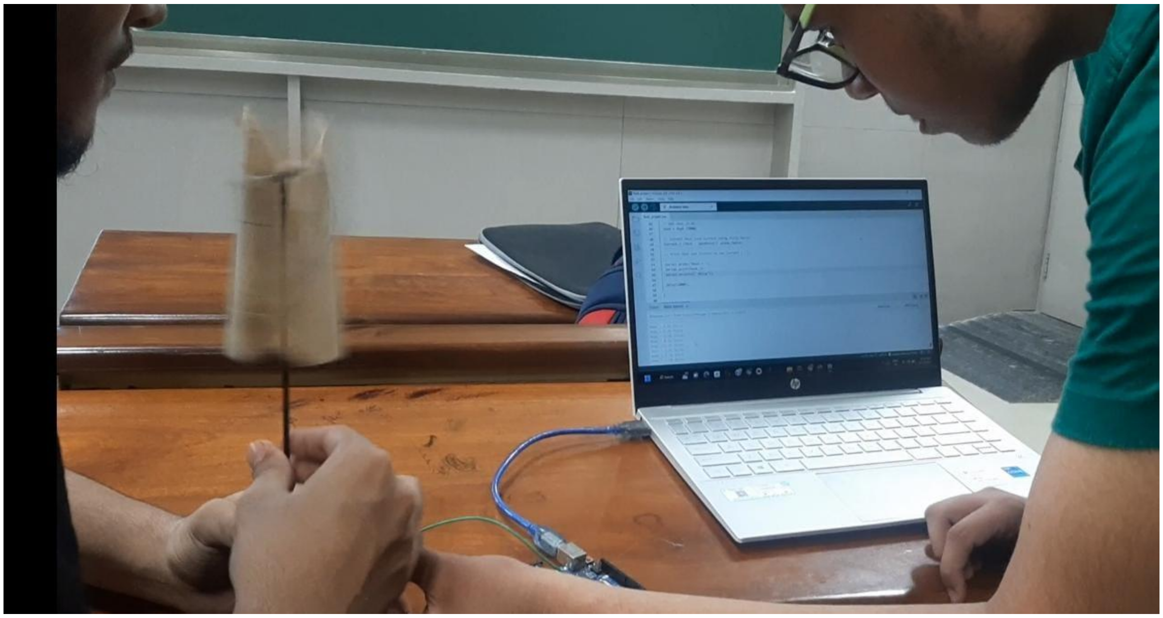
We tried to replicate the tulip shaped turbine to get hands-on experience on the project .

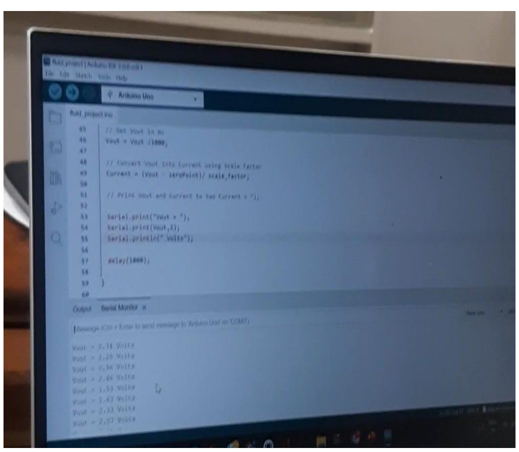
Materials used with reasoning :-

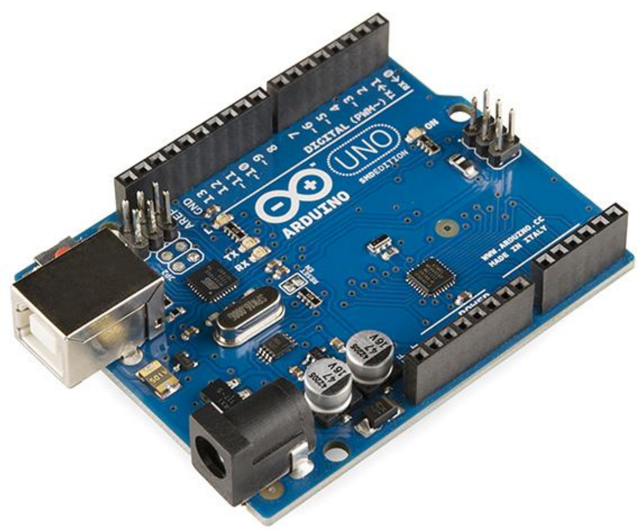
Balsa wood - One of the most lightweight wood ,which can be easily bent without breaking with the help of aqueous ammonia.

Carbon fiber rod- Carbon fiber is lightweight ,stiff and has high tensile strength ,which is suitable to hold the tulip, bear the forces while operating and provide mechanical stability to the structure.

We used a Bondtite and Hot glue gun to assemble the structure as a way to provide strength to the structure without adding much weight.







Serial monitor displays Output Voltage

Arduino

FACTORS OF ENERGY PRODUCTION

Performance and efficiency

Two-blade wind turbines are slightly less efficient than three-blade wind turbines and must rotate faster for maximum efficiency .Two blades will produce more electricity than three blades, but have their own problems. Two-blade turbines are sensitive to gyroscopic precision, which results in wobbling leading to stability problems for the entire turbine. This puts pressure on the turbine's components, reducing its efficiency and lifetime. According to the latest research, a two-blade design for a wind turbine is 3% less efficient than a three-blade counterpart of the same diameter. Additional power can be obtained from the longer wind turbine blades, with the advantage of lower construction, material and maintenance costs . Tulip shaped turbines have higher efficiency compared to the turbines of similar class which allows them to produce electricity at lower wind speeds and their clustering effect allows more turbines in lesser space for better performance.

Balance

A rotor with an even number of blades can cause stability problems in a rigid frame machine. The reason is that the moment from the upper blade is reflected back, and it achieves its maximum wind power and the lower blade passes through the wind shade in front of the tower. Wind turbine's three-blade rotor has more consistent performance than two blades. The tulip shaped turbine doesn't have any balance issues as it is a vertical axis turbine.

Cost

The economic benefit of two-blade wind turbines is associated with lower manufacturing and transportation costs. Research from a previous feasibility study reported that two-blade turbines cost 10−12% less than three-bladed units for offshore wind farms under certain operating conditions.The problem has mainly to do with the cost/performance of nearly all vertical axis designs. The “Tulip” is especially inefficient from an economic standpoint due to the large amount of material required to produce the very large vanes, which must maintain their rigidity and their curved shape when moving through the backwind high-drag phase of the rotating cycle. In order to operate on *economic parity* with more aerodynamically efficient designs (such as Horizontal Axis turbines), a vertical axis turbine must have a much lower cost per unit of swept area.

Weight

Two blade wind turbine designs have reduced cost and weight as compared to a three-blade rotor .Two-blade wind turbines are 30% lighter than three-blade wind turbines. Lower weight is a particular advantage for offshore application, as are ease of handling, transportation and assembly. The tulip generally has low weight since it has been made such that it rotates at lower wind speeds.

Rotor Vibration

Two-blade wind turbines withstand an unbalanced twisting force acting on the hub (and pole) at twice the speed of the blade. This unwanted deflection can return to the blade, causing them to vibrate. A three-blade turbine on the other hand, has very little vibration. The reason for this is that when one blade is horizontal, its two resistances are balanced by the other two blades. So, a three-blade turbine is the best combination of high rotational speed and minimum stress. The hub mechanism and/or post itself may need to be made stronger or more rigid to resist these unwanted torsion forces. In addition, it is expected that load reduction techniques to reduce the effect of load imbalance on the two-blade rotor, such as teetered hub, reduce the high natural vibration of the two-blade rotor by reducing the energy performance of the asymmetric configuration will make it better.

Noise

This category is where tulip shaped turbines have an edge as 2 and 3 blade turbines produce a lot of noise. Due to smaller size and low wind speeds, they cause lesser disturbance and noise. Two blade wind turbines must rotate faster for maximum efficiency. This is a disadvantage for onshore wind turbines, because the noise increases due the increase in tip speed whereas increases in the number of blades lowers blade speed, which reduces the sound of wind turbines.

Wake effect

The turbulent intensity, however, indicates a high variability for the two-blade rotors. The intensity of the turbulence is particularly high in the tip area, due to the strong vortices generated. This higher level of turbulence in the wake supports higher wake recovery rates in two-blade rotors than three bladed rotors, especially behind the turbine.

Aesthetics

Generating energy doesn't have to be ugly. These types of turbines look artistic and can be used in a small space as trees. Another factor influencing the number of blades is aesthetics. It is generally accepted that a three-blade turbine is more satisfying to the eye than one- or two blade-turbines . Although, it is worth noting that five-blade wind turbines are more visually appealing than three-blade turbines. Tulip has good aesthetic,can be used near residential areas and are less harmful to birds too.

PROS AND CONS OF TULIPS

Traditional wind turbines are highly efficient but they cause a lot of noise and visual pollution , not to mention take up a lot of land and are hazardous to birds. In that case , vertical axis turbines which can harness clean energy from smallest amount of wind and can integrate into environment more easily seems to be most viable option , here are some key advantages of so called “tulips” =

1. Omnidirectional Natural of the Rotor

Vertical axis wind turbines are equipped with rotor blades that can pick up wind coming from any direction. Unlike so, horizontal axis wind turbines need to face the direction of the wind to operate. They rely on the yaw system to orientate the rotor in order to capture wind.Due to this difference in operation mechanism, vertical axis wind turbines can be used to generate power even in unstable weather conditions such as turbulent, gusty wind.

2. Closer Spacing

Compared to horizontal axis wind turbines, vertical axis wind turbines can be grouped closer together in a wind power plant. This is because vertical axis wind turbines function well in turbulent wind. Closer spacing would allow a wind power plant to capture more energy per square meter of land. Generally speaking, a single vertical axis wind turbine is not as energy-efficient as an individual horizontal axis wind turbine. However, research suggested that a group of closely-spaced vertical axis wind turbines have the potential to generate as much as 10 times more power per unit of land compared to a group of widely-spaced horizontal axis wind turbines.

3. Lower Starting Wind Speed

Vertical axis wind turbines have a lower starting wind speed compared to the horizontal axis models. The necessary starting wind speed for a typical vertical axis wind turbine is 2 to 3 m/s. This allows vertical axis wind turbines to generate electricity even when incoming wind is relatively weaker.

4. Lower Environmental Harm

Generally smaller, the size of vertical axis wind turbines brings along a few advantages, one of which being the low environmental harm. Because they are built closely around the shaft, the rotor blades of vertical axis wind turbines do not create huge, extend drop shadows. The blades are also easier to spot for birds and other flying animals, decreasing the chance of animal casualty.Furthermore, vertical axis wind turbines operate with quieter noise emission, so they do not disturb people in residential neighborhoods.

Despite these striking advantages , tulip shaped turbines are far from meeting all our renewable energy requirements and are not quite yet to replace all those massive wind farms because of following reasons

1. Less Rotation Efficiency

Vertical axis wind turbines often have less rotation efficiency. Due to the rotor design, not all the blades on the vertical axis rotor receive incoming wind at the same time. In fact, only the wind-facing blades are driven by the wind to turn while the others are simply following along. During rotation, vertical axis rotors are also faced with more drag— or aerodynamic resistance— on the blades.

2. Lower Available Wind Speed

Since vertical axis wind turbines are typically installed on ground level, they do not harness higher wind speeds often found at higher levels. Consequently, less wind energy is available for ground-level vertical axis wind turbines. A common solution to this is to install the turbine on the rooftop of a building.

3.Less Efficiency

Vertical axis wind turbines are known to have less efficiency compared to horizontal axis wind turbines. This is mainly due to the nature of their design and operational characteristics.

Efficiency of a horizontal axis wind turbine lays between 40 to 50 %, meaning the turbine is able to convert 40% to 50 % of the kinetic energy it receives into actual electrical power. On the other hand, a vertical axis wind turbine has an average efficiency of 10 to 17 %

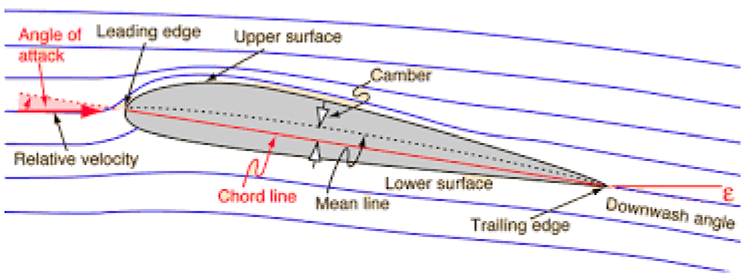
4. Component Wear-down

Often placed on ground level and populated environments, vertical axis wind turbines face more turbulence and issues of vibrations. When in operation, not only do the blades need to withstand more force, the bearing between the rotor and the mast also needs to endure higher pressure. In earlier models, it was more likely for the blades to bend or crack. For others, this can result in more maintenance and therefore more cost.

Fluid Dynamics and calculations behind a turbine

Energy of flowing wind gets transferred to the turbine according to Bernoulli's principle. As the fluid flows over the blade of the turbine, the blades have such design that the velocity of fluid flowing above and below the turbine blades are different and hence creating a pressure difference between above and below the blade and so exerting a net force and giving a rotation to the shaft of the turbine.

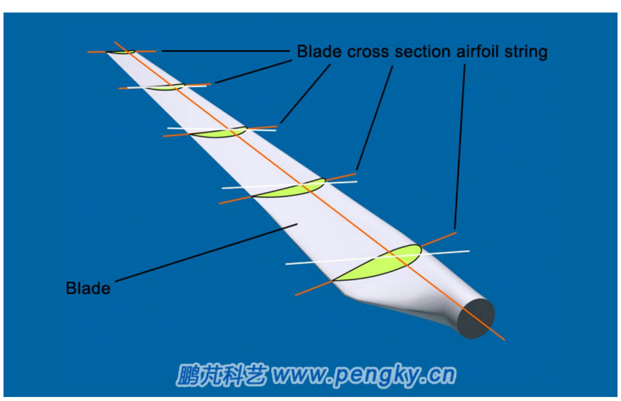
Lift from a Wing and Force on a Turbine Blade(Airfoil)



An upward force is created by the difference in pressure.

The shape of the wing works by splitting the air into two sections, above and below the wing. The top of the wing is curved, which means that the air that flows over the top of the wing must flow faster than the air flowing beneath the wing to allow it to reach the same position in the end. As a result of Bernoulli's equation, when the kinetic energy of the fluid changes, either the pressure or gravitational potential energy must change to ensure energy conservation. The speed of the air above the wing increases, the pressure of the air must decrease.The increasing velocity of the air flowing over the wing decreases the pressure to conserve energy. Since pressure above the wing has decreased, the pressure underneath the wing is now greater than the pressure on top of the wing. This disparity in pressure creates an force that basically helps the turbine blades to capture wind and convert its kinetic energy into electricity

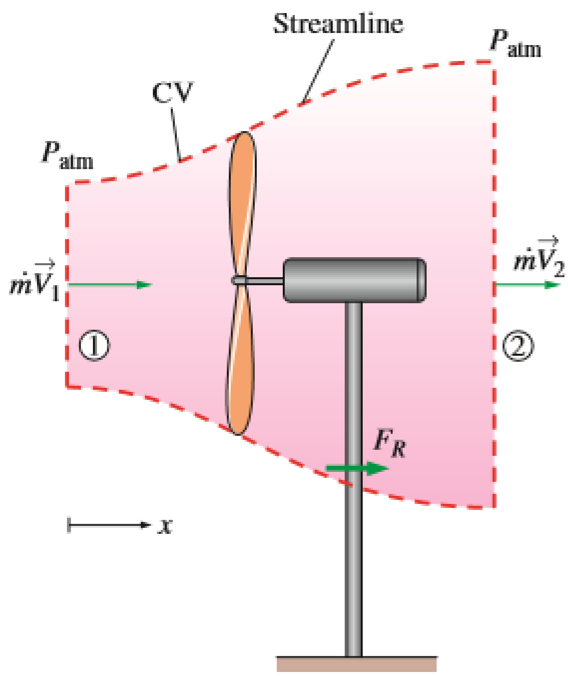
Wind turbine blades design



As shown in the figure cross section of each blade is an airfoil shaped which tends to diverge streamline as explained above

As a result Kinetic energy of incoming air flow is much more than kinetic energy of outflow and this decreases in K.E gets converted into electricity depending on efficiency of turbine-generator

Calculations



ASSUMPTIONS

1 The wind flow is steady, inviscid and incompressible.

2. The frictional effects are negligible, and thus none of the incoming kinetic energy is converted to thermal energy.

3. The wind flow is uniform and thus the momentum-flux correction factor is b = 1.

4. Gage pressure is 0 at both inlet and outlet of shown Control volume

$e_{mech,in} = P_1/p + V_1^2/2 + z_1$

Where P1 Is gage pressure at inlet , V1 is velocity of incoming air, p is density of air and z1 is height from reference

$e_{mech,out} = P_2/p + V_2^2/2 + z_2$

Where P_2 Is gage pressure at outlet , V_2 is velocity of incoming air, p is density of air and z_2 is height from reference

$n_{(turbine)}$ = Mechanical Power output / mech energy decrease of fluid

$n_{(generator)}$ = Electrical Power output / Mechanical Power input

$n_{(turbine\ -\ generator)} = n_{(turbine)} * n_{(generator)}$

= Electrical Power output /m' * ($e_{mech,in} - e_{mech,out}$)

where m' is mass flow

Using $z_1 = z_2$ and $P_1 = P_2 = 0$

=> n = electrical power generated/ (m' * ($V_1^2/2 - V_2^2/2$))

=> electrical power generated = n * m' * ($V_1^2/2 - V_2^2/2$)

Prove that maximum efficiency of a wind turbine system with given assumptions is *0.593*

The upper and lower streamlines can be considered to form an “imaginary duct” for the flow of air through the turbine. Sections 1 and 2 are sufficiently far from the turbine so that P1 = P2 = Patm.

Consider a smaller control volume that encloses the turbine, such that
Section 3 = just before turbine
Section 4 = just after turbine

=> A3 = A4 = A and V3 = V4 since it is so slim.

The turbine is a device that causes a pressure change, and thus the pressures P3 and P4 are different. The momentum equation applied to the smaller control volume gives

FR = (P4 - P3)A

$e_{mech,in} = P_1/p + V_1^2/2 + z_1$

Where P_1 Is gage pressure at inlet , V_1 is velocity of incoming air, p is density of air and z_1 is height from reference

$e_{mech,out} = P_2/p + V_2^2/2 + z_2$

Where P_2 Is gage pressure at outlet , V_2 is velocity of incoming air, p is density of air and z_2 is height from reference

$n_{(turbine)}$ = Mechanical Power output / mech energy decrease of fluid
$n_{(generator)}$ = Electrical Power output / Mechanical Power input

$n_{(turbine-generator)} = n_{(turbine)} * n_{(generator)}$

= Electrical Power output /m' * ($e_{mech,in} - e_{mech,out}$)
where m' is mass flow

Using $z_1 = z_2$ and $P_1 = P_2 = 0$

=> n = electrical power generated/ (m' * ($V_1^2/2 - V_2^2/2$))

=> electrical power generated = n * m' * ($V_1^2/2 - V_2^2/2$)

The Bernoulli equation is not applicable between sections 1 and 2 since the path crosses a turbine, but it is applicable separately between sections 1 and 3 and sections 4 and 2:

$P_1/pg + V_1^2/2g + z_1 \; = \; P_3/pg + V_3^2/2g + z_3$

$P_2/pg + V_2^2/2g + z_2 \; = \; P_4/pg + V_4^2/2g + z_4$

Adding these two equations and noting that $z_1 = z_2 = z_3 = z_4$,

$V_3 = V_4$,

$P_1 = P_2 = P_{atm}$ gives

$(V_2^2 \; - V_1^2)/2 \; = \; (P_{4\,-}\,P_3)/p$

$(P_4\text{-}P_3)*A = F_r$

By momentum conservation (Reynolds transport theoram)

$F_r = m'^{*} (V_2\text{-}V_1)$

Substituting $m' = pAV_3$ and combining above equations gives

$V_3 = (V_1 + V_2)/2$

Thus we conclude that the average velocity of a fluid through a turbine is the arithmetic average of the upstream and downstream velocities.

The velocity through the turbine can be expressed as $V_3 = V_1(1 \text{ -a})$, where a <1 since $V_3 < V_1$.

Combining this expression with expression for v3 gives $V_2 = V_1(1 - 2a)$. Also, the mass flow rate through the turbine become $m' = pAV_1(1\text{-a})$

When the frictional effects and losses are neglected, the power generated by a wind turbine is simply the difference between the incoming and the outgoing kinetic energies:

$W' \; = \; m' \; * (ke_1 \; - ke_2)$

$= m^{'*} (V_2^2 - V_1^2)/2$

$= \{pAV_1(1 - a)[V_1^2 - V_1^2(1-2a)^2]\}/2$

$= 2pAV_1^3a(1-a)^2$

Dividing this by the available power of the wind gives the efficiency of the wind turbine in terms of a,

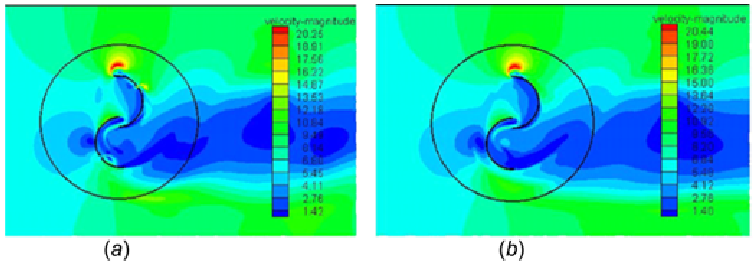
$=> n$ = ($2pAV1^3a(1 - a)^2$) / ($pAV1(V1^2)$ / 2)

The value of a that maximizes the efficiency is determined by setting the derivative of n(wind-turbine) with respect to a = zero and solving for a.

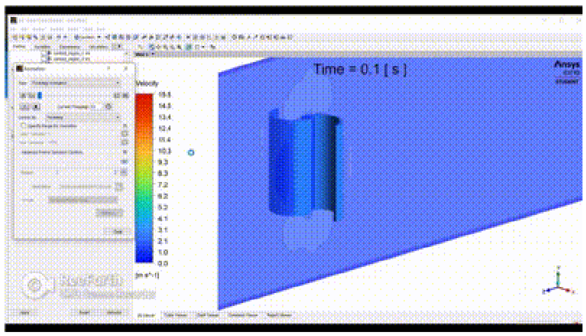
It gives a = 1/3.

Substituting this value into the efficiency relation just presented gives n(wind-turbine) = 16/27 = **0.593.**

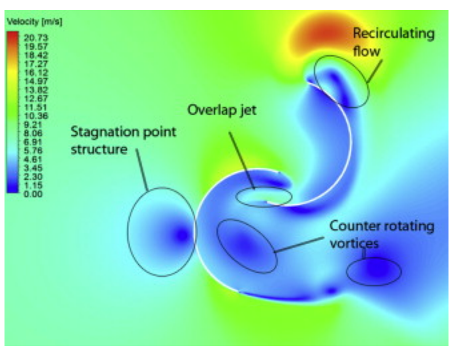
Interpretation of flow generated from Ansys:



Courtesy: From the review paper mentioned below



Made with the help of below mentioned tutorials and help from seinors namely Bishop, Lakshya, Atharva (4th year dual degree mechanical)



Courtesy: from the research paper below

We notice the recirculation zone geometries created on the convex side of the advancing blade.

Another phenomenon we notice overlap jet formed on the concave side of the advancing blade and which affects the second blade. The negetive contribution of the returning blade torque reduces the overall torque.

Also some counter rotating vortices are visible whcih are induced by overlap jets and evolve into bigger structures downstream of the rotor.

The recirculation occuring at the tips also reduces the velocity in those regions thus forming darker shades of blue representing slowed velocity

Conclusion

So called tulips though economically inefficient can harness energy from least amount of wind and can be much closely spaced optimizing available resources but despite these striking advantages , they are far from meeting all our renewable energy requirements and are not quite yet to replace those massive wind farms Nonetheless , possibilities are endless and with further research in subject promising results might be expected after all

“ Generating clean energy doesn’t have to be Ugly “

Acknowledgement

1.Inspiration for exploring tulip shaped turbine

Are ‘tulip turbines’ the answer to energy eyesores?

2. Comparative analysis
(https://iopscience.iop.org/article/10.1088/1755-1315/801/1/012020/pdf)

3.Qualitative analysis of tulips on various factors
https://www.luvside.de/en/vawt

4. Theory and Calculations
   a. Chapter 6 of ‘fluid mechanics fundamentals and applications” by Yunus A. *Çengel*
   b. Review Article-
      Four Decades of Research Into the Augmentation Techniques of Savonius Wind Turbine Rotor | J. Energy Resour. Technol. | ASME Digital Collection

5. Software materials:
Tutorials from the following sites-
Fluenn the performance of Savonius wind turbines - ScienceDirect
Numerical investigation of conventional and modified Savonius wind turbines - ScienceDirect
K-epsilon model of turbulence modeling for CFD-
[CFD] The k - epsilon Turbulence Model - YouTube
K-epsilon turbulence model - Wikipediat Setup - YouTube
Vertical Axis Wind Turbine — Part 1 - ANSYS Innovation Courses
Vertical Axis Wind Turbine — Part 2 - ANSYS Innovation Courses
Flow pattern analysis papers -
A review o

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