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Increase drag coefficient for special design cavity frame vertical axis wind turbine

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ABSTRACT

Wind energy as a power source is attractive as an alternative to fossil fuels, because it is plentiful, renewable, widely distributed, green, and produces no greenhouse-gas emissions. A performance improvement of the scoop-vane vertical axis wind turbine is described. To improve the performance of the power generation system design of special frame of vertical axis wind turbine which consists of three movable vanes, this uses more effectively the wind energy and depends only on the acting area of the movable vanes. The frame of the wind turbine is designed to increase the drag coefficient. The new frame design makes using the kinetic energy of the wind to increase the positive torque of our model and tested it practically in wind tunnel as well as tested by solid works software. This model shows batter performance in terms of high drag coefficient and increase torque per frame in the direction of wind.

Introduction

Horizontal axis wind turbines (HAWT) dominate the wind energy market. However, the turbine can produce a power that is proportional to the turbines swept area. As a result, HAWT designs are continuously getting bigger to produce more power, which means that the blades must be made continuously larger. Increasing blade size adds extra weight to the blades, leading to higher centrifugal and inertial forces that the blade must be able to withstand. In addition, increased blade size leads to large bending moments on the blades at high rotational speeds. For these reasons, it has been suggested that HAWT technology will likely peak in the next few years [1], making way for the vertical axis wind turbine (VAWT) design, which allows for increased sizing without the limitations incurred by the HAWT.

It is accepted that vertical axis wind machines represent a suitable alternative for wind power extraction in many developing countries. The reason is mainly due to advantage over the horizontal axis type such as:

i) Simple construction

ii) Extremely cost effective

iii) Acceptance of wind flow from any direction without orientation.

In spite of these advantages vertical axis turbine is not gaining popularity because of low efficiency of the Savonius type [2] rotor and low starting torque of the Darrieus type [3] wind machines.

It is not known when exactly the first windmills were built but it is most commonly agreed that the origin of windmills is likely to be in the area of Sistan and Khorasan in eastern Iran on the border to Afghanistan, where windmills were recorded already in the 9th century AD. These first windmills had a vertical axis and relied on drag forces in order to function. They can be expected to have been similar in their basic design to the mills which were used in the region of the Sistan Basin and Greater Khorasan well into the 20th century [4].

From the literature, it is observed that scientists largely deal with Savonius or Darrieus individually [5].

The main energy advantage realized through wind turbines is that power is proportional to the wind speed cubed. However, a turbine cannot extract 100% of the winds energy because some of the winds energy is used in pressure changes occurring across the turbine blades. This pressure change causes a decrease in velocity and therefore usable energy. The mechanical power that can be obtained from the wind with an ideal turbine is given as: $Pm = 0.593\ P_w$, where (Pm) is mechanical power and (P_w) is wind power.

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To improve the output power efficiency of the wind turbine, we have designed the frame to be in the shape of scoop shape when the rotating vanes are closed in order to capture the largest amount of wind. This design gives a significant increase in the drag coefficient, which in turn increases the torque abroad, and ultimately increases power output.

The vertical vanes fastened on the vertical bars that located in hinges of the frame. Under action of the wind force the vanes with bars turned until stopper that locates on the neighboring bars. All vanes close the frame's hole. To increase the turbine efficiency, the vanes construction designed with cavities that increase drag force dramatically, under action of the wind force, vanes on left side of the frame are closed and bear the wind force in full scale. The vanes on the right side of frame are turned by the wind force and frame is opened. The wind force is passing through the open frame. This design enables the wind force to close left side vanes and simultaneously opens the right side vanes. [6, 7]

The drag force is a reactive force that tends to slow an object down as it falls through a medium. The drag coefficient is a value for a particular object that describes the ratio of the drag force to the factors that influence the drag force. The drag coefficient depends on the size, shape and weight but it is usually associated to which the object is streamlined. Generally, the larger the drag coefficient, the more a drag force that will produce while falling, and therefore, the slower it will fall.

The drag force (F_D) is related to the density (ρ) of the medium in which the object is located, the planar area (A) perpendicular to the movement, and the velocity (V) of the object relative to the velocity of the medium. If the object were a sphere, the planar area is a circle of the same radius. If the object was a cube, then the planar area is a square. If an object was moving at a velocity of 4 m/s into a wind speed of 6 m/s, then the relative velocity would be 10 m/s. If the wind speed of 6 m/s was in the same direction as the previous velocity, then the relative velocity would be 2 m/s.

Determination of drag factor (C_D) is the most difficult part of this procedure. It is highly variable, and many parameters can affect the final C_D. Shape, altitude, inclination to the wind direction and wind speed, surface roughness, spin, and nose bluntness are just a few that can influence C_D Many researches dedicate to study the drag factor and results of investigations are quite different. The drag factor can vary on C_D = 1.2 to 2.1 for simple 2D flat plate. However, from three methods calculating C_D, (experimental; theoretical–simplified and numerical CFD) the most realistic and straightforward method is using a wind tunnel. This involves solving Eq. (1) for C_D, then placing a model in a wind tunnel (ρ, A, and V already known) [6]. Tested results are used to measure the force acting on the device that holds the model:

$$C_D = \frac{F_D}{0.5\rho A V^2} \tag{1}$$

The main objective is to maximize the coefficient C_D. In general drag factor C_D is a function of the turbine element geometry, Reynolds number (Re) and Froude number.

The Reynolds number is a dimensionless quantity that is important in drag coefficient analyses. It is computed as:

$$\mathrm{Re} = \frac{\rho V D}{\mu} = \frac{\rho D}{\upsilon} \tag{2}$$

Where, μ is the dynamic viscosity; υ is the kinematic viscosity and D is the length parameter such as the diameter of the object [7].

Proposed impeller type turbine works under action of the wind force, which acts on area of vanes closed that at one side of the turbine design. The vanes of another side of turbine are opened and wind passes freely through the frame.

Proposed impeller type wind turbine designed with three vanes of vertical location on bars in frames as shown in fig.1. Under action of the wind force vertical vanes is closing the frame's hole and take the cavity shape. Upper and lower frame's side is covered by boards. Such cavity has closed form to accept wind action and enables to increase the drag force.

The value of the drag coefficient is quite variable and may vary with the relative velocity [4].

On the other side of the frame; opposite to the direction of wind, vanes moving under an action of wind entering the turbine. This movement makes the vane open the frame and be in a position parallel to the air direction, which reduces the blade resistance to the

air because the surface area which hit the air is small. In this way, the negative momentum will be reduced to the minimum and hence increase the power output of the Turbine [7, 10].

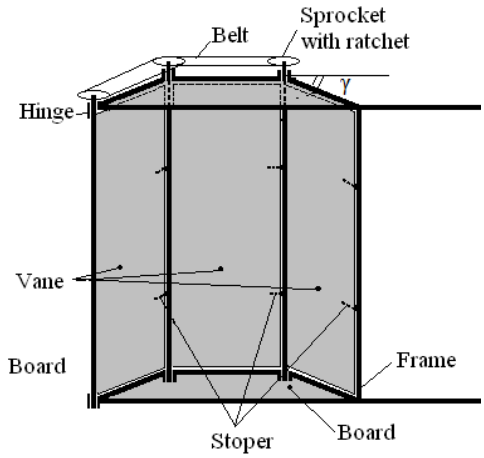


Figure 1. Complete Frame cavity vanes wind turbine

Analytical Approach

To determine the starting torque (*T*) on wind turbine vanes, it is necessary to define the whole vane area, and distance from the centre of the output shaft to the centre of wind pressure, then the formula has the following expression

$$T = (1/2)\, AC_D \rho V^2 R \sin\alpha \quad (3)$$

Where *R* is the distance from the shaft centre line to the centre of pressure of the vane surface, ρ is air density and other parameters are as specified above.

The output power (W) is calculated by the following equation:

$$W = T\,\omega = (1/2)\, \rho\, AC_D V^2 R \sin\alpha\, (V/R)$$

$$= (1/2)\, \rho\, AC_D V^3 \sin\alpha \text{ (Watt)} \quad (4)$$

where ω is the angular velocity of the rotating turbine and R is impeller turbine radius.

The torque created by the frames with group of vanes calculated by the following equations:

$$T = C_D\, p[hc(b + c/2)]\sin\alpha \quad (5)$$

where the drag factor (C_D) of a frame is a function of the rotation angle (α) (Fig. 6), *p* is wind pressure, and all the parameters are specified in Fig. 2.

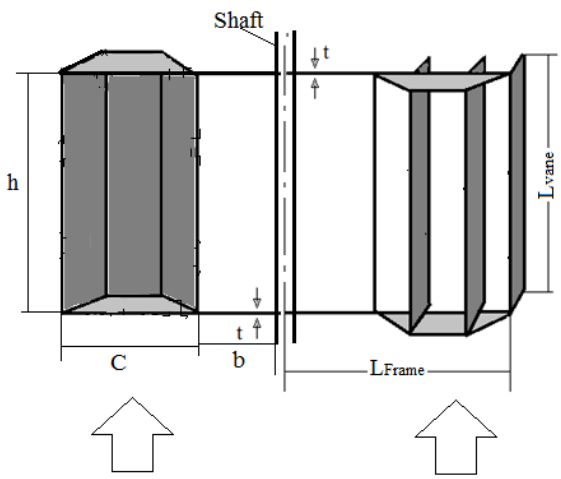


Figure 2. Rotor dimensions open and closed vanes

Practical Test

The object of the wind-turbine test is verifying the ability of performance design, to get real data, compare with theoretical results and analysis efficiency of product testing.

The wind tunnel is installed in University Malaysia Perils, School of Mechatronic, the testing area of the length is the cube with dimensions 300x300x300 mm^3. The model is located in the middle of the wind-tunnel testing area and connected with generator. The range of the wind speed used is between 5 m/s and 17 m/s. The wind speed measure by recorded pressure drop from a pittot tube (Δp) and use Bernoulli equation to get wind velocity.

Bernoulli's Equation,

$$P_1 + \frac{1}{2}\rho V_1^{\ 2} + \rho g h_1 = P_2 + \frac{1}{2}\rho V_2^{\ 2} + \rho g h_2$$

$$V = \sqrt{\frac{2 * \Delta P}{\rho}} \qquad (6)$$

Where P is pressure (N/m^3), ρ is air density (kg/m^3) and V is velocity (m/s).

The tachometer model compact instrument advent tachopole was used to measure the rotation speed of the wind turbine shaft with the piece of white paper attached, which reflects light.

For Wind Tunnel Blockage Corrections, the solid blockage depend on the size of the model in the wind tunnel, Correcting velocity measurements and subsequent data modifications to allow for these changes are shown, summarizing 2D corrections by Eq. (7): (subscript u values are uncorrected) (Pope. 1966)[14]

Velocity correction: $V = V_{Wind}\,(1 + \epsilon t)$ (7)

Pope. (1966) explains that for finding the blockage corrections for some unusual shape that needs to be tested in a tunnel the Eq. (8) is suggested

$$\varepsilon_t = \frac{1}{4}\frac{Model\ \ frontal\ \ area}{Test\ section\ \ area} \qquad (8)$$

Propose vertical axis wind turbine uses the drag force and has a design of the frame depending on calculation the higher values of the drag factor. The blade of wind turbine testing used the three model fabricated by metal with the same dimensions, b= 0.07 m, h = 0.116 m, t=1mm. The analyses considered drag force test, and drag force coefficient various with wind velocity. The typical wind tunnel used stationary turbofan engines that sucked air through a duct equipped with a viewing port and instrumentation where models on the shaft are mounted fig.3. The shaft is connected to a digital scale and used to measure the drag force.

$$C_D = \frac{F_D}{0.5\rho A V^2}$$

$$C_D = \frac{F_D}{A\Delta P} \qquad (9)$$

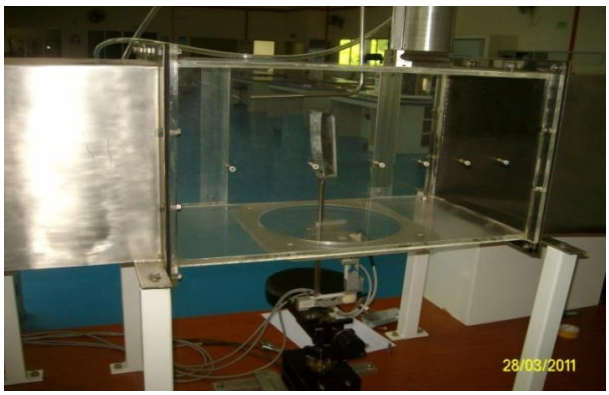


Figure 3. Scoop-vane model in wind tunnel

Results and discussion

Figure 4 shows result of test used the three models, first one vane at the angle (γ = 45°) with an upper and lower board, and the second one vane at 45° without upper and lower board, the last one is flat plate vane.

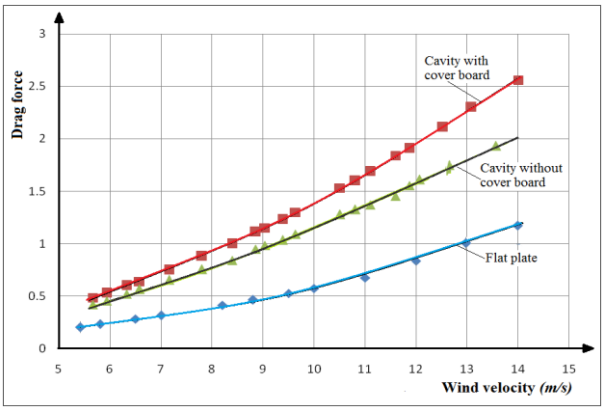


Figure 4. Drag force for different vanes angle in frame versus wind speed

The drag factor is calculated by test each vane separated in a wind tunnel. Figure 5 shows testing of two models, scoop vane with angle45°and the other one scoop vane with 30°. The frame vanes type with scoop-vanes has more high drag factor compares with flat vanes, this is caused wind turbine enables to capture wind energy. And the torque will be high.

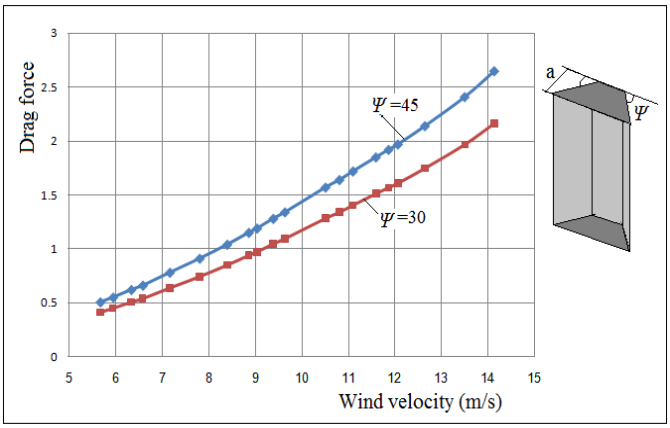


Figure 5. Drag force for cavity vane with different vane angle (Ψ) versus wind speed

Figure 6 shows the result of test scoop vane at 45° with angle from 0 to 180 for multi wind speed. The obtained results have the maximum drag coefficient at low speed.

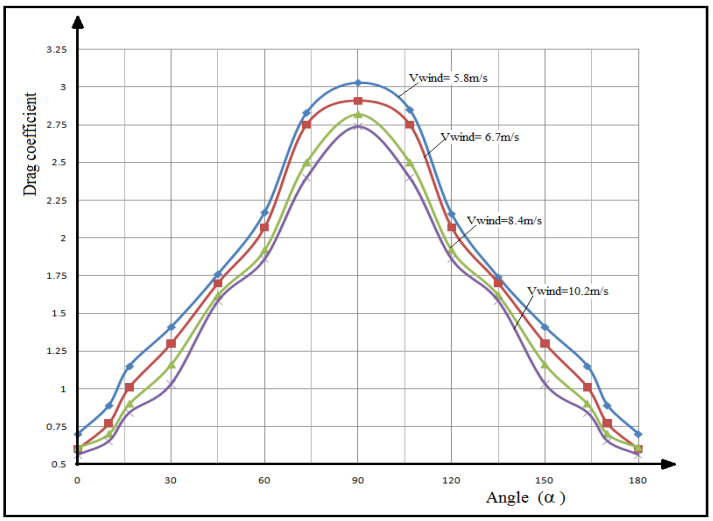


Figure 6. Drag coefficient for vane angle 45 versus turn angle (α) at different wind speed

Results obtain from the test of frame in solid works software is in Fig. 7 is the same as results get it for the test in wind tunnel as shown in Fig. 8. The drag coefficient for frame with vane's angle 45° is about (2.98).

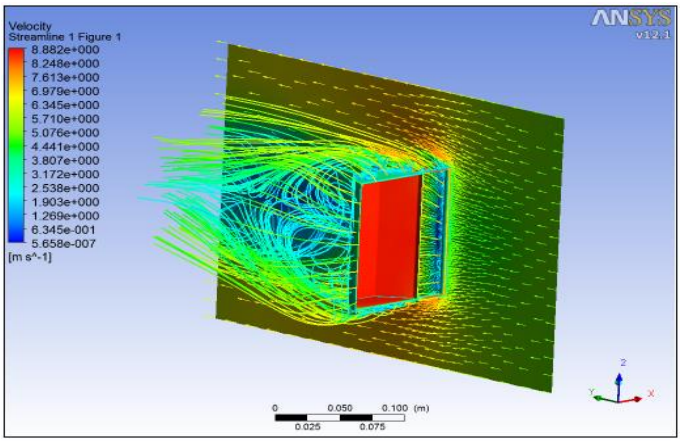


Figure 7. Frame test in solid work software

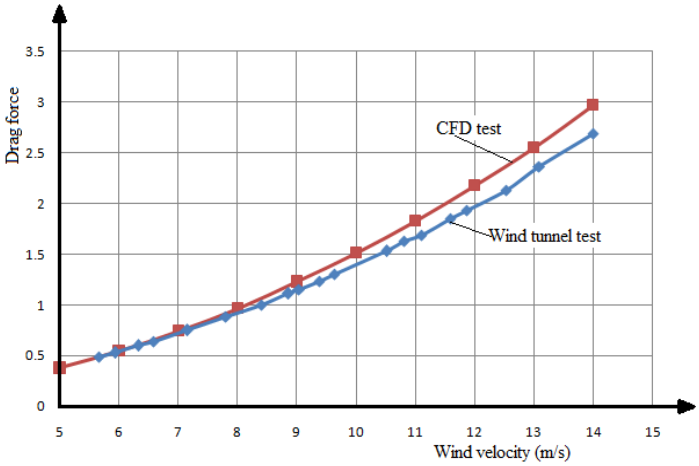


Figure 8. Drag force virus wind velocity for frame test in wind tunnel and compare with CFD test

Fig. 9 shows the test of frame with open vanes wind turbine in the wind tunnel. Fig. 10 shows the results of the drag force varies wind velocity obtained by the tests for blade with open vanes (the drag coefficient is about 0.35).

Figure 9. Test open vanes frame in wind tunnel

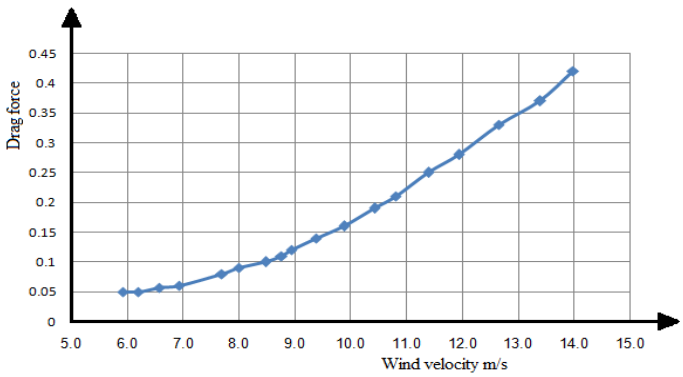
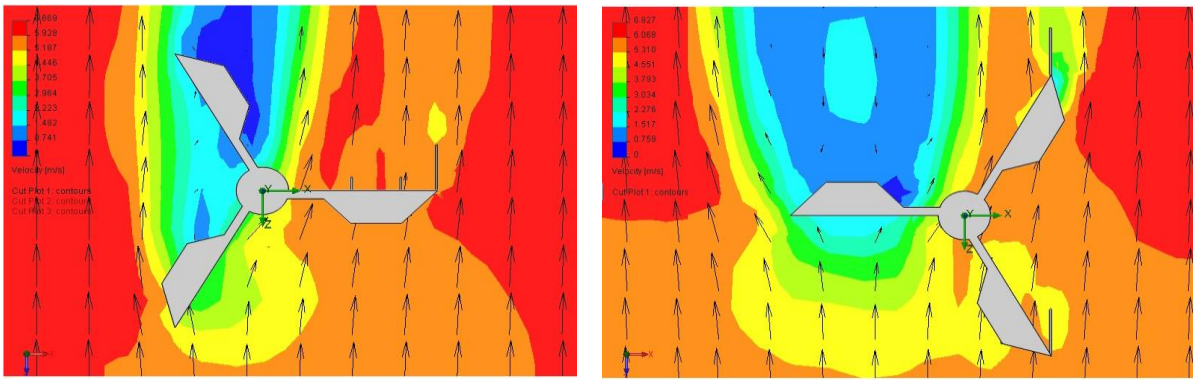


Figure 10. Drag force for open vane frame varies wind velocity in a wind tunnel

Fig. 11.a and b, shows the top view of the velocity distribution. Results obtained by observing the Figure (11.a) shows the frame rotating in the opposite direction of the wind; the velocity have kept their values when the air movement through the frame because the vanes are opened under action of wind and the drag coefficient of the frame is decreased to less and the wind pass without resistance. On the other side, for the frame rotates in the direction of the wind movement, the velocity of the air is a significant drop when the air is passed through the frame because the drag coefficient is high.

Results obtained by observing the Figure (11.b); in the right side that the frame rotating in the opposite direction of the wind, the velocity of the air keep for its value when passing through the frames with open vanes at the angle 330˚, 210˚; and the impact of wind is on the frame at angle 90˚, i.e. when there is a frame rotating in the direction of the wind which the vanes are closed under action of the wind. The velocity of the air was dropped when the air is passing through the frame with closed vanes which rotate in the direction of the wind at angles 90˚, and there is the region of still air consisting behind the frame.

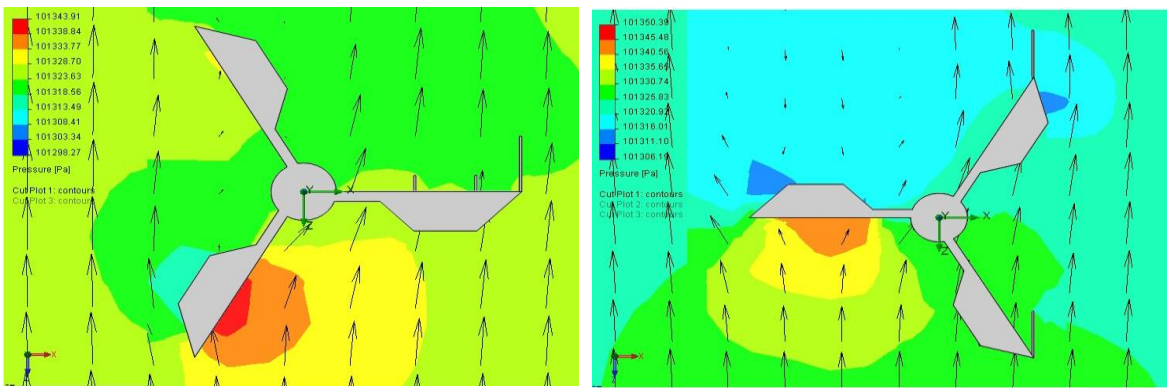


a) α = 30 b) α = 90

Figure 11. Top view Velocity distribution diagram for a rotor at different frame angles

Fig. 12.a and b, shows the top view of the pressure distribution. Results obtained by observing the Figure (12.a) shows the frame rotating in the opposite direction of the wind; the pressure have kept their values when the air movement through the frame because the vanes are opened under action of wind and the drag coefficient of the frame is decreased to less and the wind pass without resistance. On the other side, for the frame rotates in the direction of the wind movement, the pressure of the air is increase when the air is passed through the frame because the drag coefficient is high.

Results obtained by observing the Figure (12.b); in the right side that the frame rotating in the opposite direction of the wind, the pressure of the air keep for its value when passing through the frames with open vanes at the angle 330˚, 210˚; and the impact of wind is on the frame at angle 90˚, i.e. when there is a frame rotating in the direction of the wind which the vanes are closed under action of the wind. The pressure of the air was raising when the air is passing through the frame with closed vanes which rotate in the direction of the wind at angles 90˚, and there is the region of still air consisting behind the frame and there are some air movement counters the wind stream after the frame.



a) α = 30 b) α = 90

Figure 12. Top view Pressure distribution diagram for a rotor at at different frame angles

Figure 11 and 12 display the speed and pressure have kept their values when air movement through the frame. Therefore, the negative torque value is very little.

Conclusion

It has concluded that the frame type scoop-vanes with an upper and lower board has a higher drag factor compares with another frame types. This is caused the wind turbine enables to capture more wind energy. And the torque will be high. Results obtain in Fig. 5 show vanes diagonal with 45° and give a high drag factor than 30°. Increase drag coefficient in the frame rotates in the direction of wind will increase the torque and finally increase the power. On the other side, the frame rotating in the obesity direction of wind, the drag coefficient decrease to less and the wind pass through without resistance, as a show in solid works diagrams, that decreases the negative torque and increases the power.

Test model in solid work software shows good results for design. This type wind turbine has good technical properties and can be used for generating a power more efficiently for the low speed of the wind. Moving vanes and open the frame work in the opposite direction of wind that gives a low drag coefficient, small project area, and decreased negative torque.

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