Design and Analysis of Diffuser Augmented Wind Turbine using CFD

D.Lokesharun[1], S.Rameshkumar[2], B.S.Navaneeth[3], R.Kirubakaran[4]

[1] Assistant Professor, [2] Project Student, [3] Assistant Professor, [4] M.E Graduate

[1234]PARK College of Engineering and Technology, Coimbatore, India - 641659

Abstract: In recent years, the need for renewable energies keeps on increasing. Thus there is a need to improve the methods for harnessing the renewable energy such as wind. One such improvement is Diffuser Augmented Wind Turbine (DAWT). Our main objective of this research paper is to optimize the Diffuser design of DAWT and to determine the maximum velocity obtained inside the diffuser for placing the blades to achieve more power output. Diffuser designs are simulated using Computational Fluid Dynamic (CFD) software ANSYS Fluent with wind inlet velocity of 5m/s and the values are compared to get a optimized model to achieve good power output. From the results, that Diffuser with flanges gives higher performance with blade located at 0.13m from the entry of diffuser which is of 1m in length. A significant increase in power is obtained which is higher than the conventional wind turbine.

Keywords: Renewable Energy, Diffuser Augmented Wind Turbine, Computational Fluid Dynamics, Performance.

I. INTRODUCTION

The development and application of renewable, clean energy have become an important issue in recent years due to the serious effects of global warming and rapid depletion of fossil fuels. In order to address the current energy crisis various means of alternative energy are being evaluated [1]. Wind energy technologies have become one of the fastest growing energy sources in the world and it symbolizes a feasible alternative, as it is a virtually endless resource. However, in comparison with the overall demand for energy, the scale of wind power usage is still very meager. As for the reasons various causes are possible including cost [2].Therefore, the introduction of a new wind power system that can produce higher power output even in areas where lower wind speeds are expected would be cost effective. Alison in conventional wind turbine the air flow is slowed down and widened. This effect causes a loss in the efficiency of the turbine. By creating a field of low pressure behind the turbine, that effect reduced and the corresponding loss in efficiency can be avoided [3].One of the most promising concepts in the wind energy field is the development of wind power augmentation systems. By the use of diffuser in the wind turbine, wind power augmentation system is called Diffuser Augmented Wind Turbine (DAWT).

1.1 DIFFUSER AUGMENTED WIND TURBINE

A Diffuser Augmented Wind Turbine (DAWT) is one in which the Wind Turbine Rotor Blades are mounted within the Diffuser. This arrangement helps in increasing the efficiency of converting wind power to electrical power. This increase in efficiency is due to the increased wind speeds that the diffuser provides. DAWT is limited by Betz's law, which states that for a bare turbine in open wind, no more than 16/27 of the total wind kinetic energy can be converted to electrical energy.59% is not the most efficient rate, so several designs have been made in order to get around this limitation.

Fig 1: Diffuser Augmented Wind Turbine

A DAWT would have a duct surrounding the wind turbine blades that increase in cross sectional area in the stream wise direction. The pressure behind the turbine will drop due to the wind turbine being enclosed by the diffuser, thus the wind velocity approaching the wind turbines will be increased. The Vortex 7 was the first full scale DAWT constructed. The aerodynamics of a diffuser are such that more air flows through the blade plane, and more power can be generated compared to a conventional 'bare turbine' of the same rotor blade diameter [4].

A smaller blade diameter in DAWT produces the same power output as of a conventional bare wind turbine due to the concentration of the wind energy density. It can work on a lower cut in wind velocity as well. It was noticed that DAWTs can reduce the sensitivity of the yaw (the misalignment between wind and turbine pointing direction) and can significantly reduce noise. DAWTs should capture more energy than normal conventional wind turbine when the winds are fluctuating and it can align itself with the flow [5]. With these benefits, a diffuser augmented wind turbine can lower the cost to produce energy.
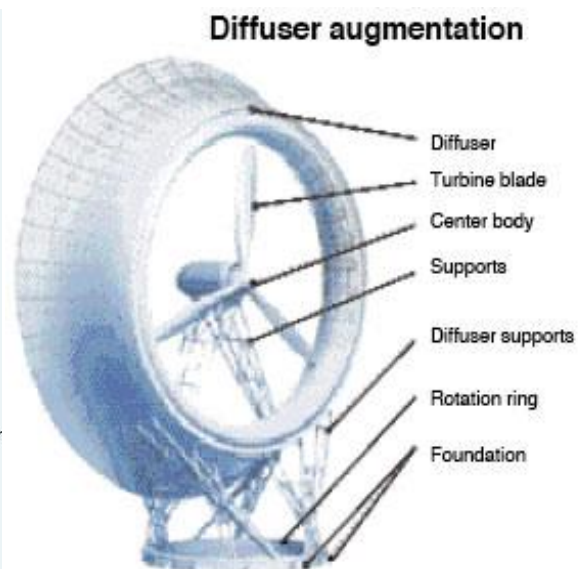

Fig 2: DWAT comparision

Fig 3: DAWT Parts

Advantages of DAWTs are as follows:

- Smaller rotor diameters to produce the same amount of power as conventional horizontal axis wind turbines.

- Lower cut-in wind speeds than conventional wind turbines

- Lower rotor axial loads

- Lower turbulence levels at the rotor plane due to the contraction of the flow

- Increase rotor RPM resulting in a reduction of gearbox ratios

- Reduced noise levels

- Reduction in tip losses of the rotor

- Reduction in yaw sensitivity

All of these benefits come at a price. The construction of the duct increases the material, fabrication, transportation and installation costs. DAWTs are also more susceptible to environmental effects such as the aggregation of ice, snow, temperature fluctuations and windborne particulates. The diffusers also could have some aero elastic instabilities caused by flow separation. The flow separation would also lead to fluctuating power output.

DAWTs also suffer from increased tower structure from the weight of the whole system as well as increase tower top loads due to the drag of the duct. The visual impact of the DAWT system could potentially limit the number of available installation sites. All of these drawbacks may cause the only potential commercially viable large-scale DAWT sites to be off shore. However, small scale DAWTs could be commercially viable in urban environments, depending on the sitting of the wind turbine.

1.2 PRINCIPLE OF DIFFUSER AUGMENTATION

The concept of diffuser is to increase the power output of a wind turbine by accelerating the wind velocity that approaches the wind turbine. To increase the wind velocity, a lower pressure would appear at the back of the wind turbine to act as a vacuum to suck the wind and accelerate it towards the blades. The region of areas surround or near the vortex would have typically lower pressure where the suction force will be formed by the vortex. Therefore, it will act as an accelerator to accelerate the wind velocity approaching the wind turbine .It was stated that vortex core will collapse the pressure field flow reversal and therefore no augmentation occurs [11]. This statement showed the alternative approach, where the vortex is used to generate a low pressure region in the wake of the turbine. "Vortex should appear at the wake of the diffuser but as little as possible inside the diffuser "
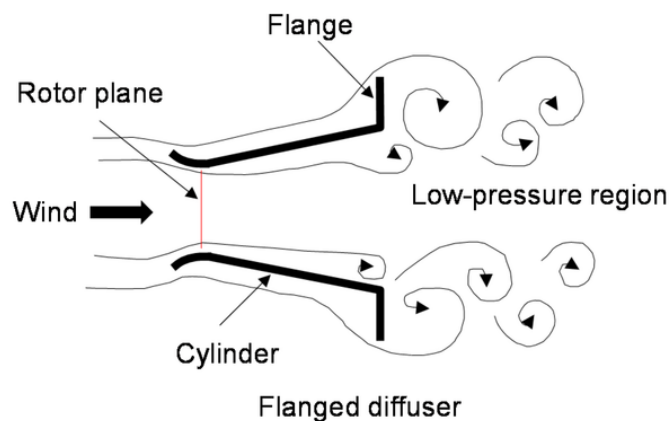

Fig 4: Principle of DAWT

If the vortices formed inside the diffuser, the pressure inside the diffuser might be lower than the pressure at the back of the wind turbine. In this circumstance, the wind speed exiting the diffuser augmented wind turbine will be decelerated and this only provides very low power coefficients. To get optimum increased acceleration on the wind speed, the pressure inside the wind turbine should not be lower than the pressure at the wake of the diffuser. This can be achieved by reducing or avoiding separation of fluid flow on the inner diffuser wall and cause vortices while creating as much vortices as possible at the back.

Wind power generation in wind turbine is directly proportional to the wind speed served. Therefore, a large increase in output is brought about if it is possible to create even a slight increase in the velocity of the impending wind to a wind turbine. If we can increase the wind speed by exploiting the fluid dynamic nature around a structure or topography, the power output of a wind turbine can be increased substantially. In conventional wind turbine the wind speed served from the location is directly used to generate power. But in DAWT, the available wind speed is increased by the diffuser to

generate high power output. Also the smaller diameter blade in DAWT produces the same power output as of a conventional 'bare wind turbine' due to the concentration of the wind energy density [5]. Currently very few studies have been reported the effect of diffuser shape in wind speed using computational simulations.

2. ACTUATOR DISC MODEL AND BETZ LIMIT

The simplest one-dimensional wind turbine model is so-called as actuator disc model where the turbine is replaced by a circular disc through which the flow streamlines passes with a velocity, U_{∞}. The following equations presented in this section were based from Wilson &Lissaman(1974), Jonkman (2003), Manwell et al. (2002), Kulunk (2011). The analysis assumes a control volume and are need to consider some assumptions:

- Wind is steady, homogeneous and have a fixed direction; air is incompressible, in viscid ; an infinite number of blades need to be considered; a non rotating wake is considered; uniform thrust over the rotor needs to be assumed and the static pressure far upstream and far downstream of the rotor is equal to the undisturbed ambient.

In order to study this control volume, four regions (Figure 7) need to be considered as: 1: free-stream region; 2: before rotor; 3: after rotor and 4: far wake region. In free-stream region is assumed that $U_{\infty} = U_1$

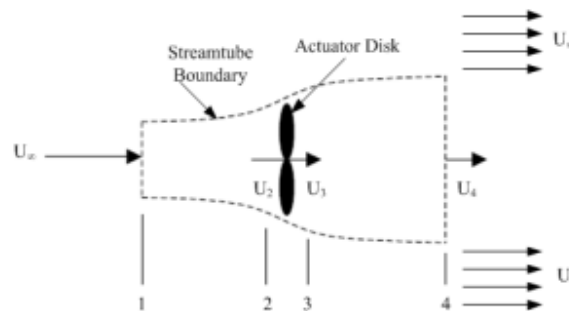A simple schematic of this control volume is shown in Figure

Fig 5: Actuator Disc Model of A Wind Turbine

Applying the conservation of linear momentum to the control volume, and considering a steady-state flow, the thrust is equal to:

$$T = \dot{m}(U_1 - U_4) \qquad (2.1)$$

where, $\dot{m}$ is the mass flow rate, and is equal to $\dot{m} = (rAU)_1 = (rAU)_4$, representing, r, air density, A the cross sectional area and, U, the air velocity.

The thrust is positive so the velocity behind the rotor, U_4, is lower than the U_1. Since the flow is frictionless and there is no work or energy transfer is done, Bernoulli equation can be applied on both sides of the rotor.

$$p_1 + \frac{1}{2}\rho U_1^2 = p_2 + \frac{1}{2}\rho U_2^2 \qquad (2.2)$$

$$p_3 + \frac{1}{2}\rho U_3^2 = p_4 + \frac{1}{2}\rho U_4^2 \qquad (2.3)$$

where it's assumed that the far upstream and far downstream static pressures are equal($p_1 = p_4$) and the velocity across the rotor stays equal ($U_2 = U_3$).

The thrust on the rotor disk, T , is also the differential pressure between stations 2 and 3 multiplied by the disc area:

$$T = A_2(p_2 - p_3) \qquad (2.4)$$

Using Equations 2.2 and 2.3 and substitutes that into Equation 2.4 is obtained:

$$T = \frac{1}{2}\rho A_2(U_1^2 - U_4^2) \qquad (2.5)$$

Recognizing now that $\dot{m} = A_2 U_2$ and equating the thrust Equations 2.1 and 2.5, are obtained:

$$U_2 = \frac{U_1 + U_4}{2} \tag{2.6}$$

Thus, the wind velocity at rotor plane, is the average of the upstream and downstream wind speeds.

An axial induction (or interference) factor, a, measures the influence of the wind beings lowed down as result of power extraction by the rotor. It's defined as the fractional decrease in wind velocity between the free stream and the rotor plane:

$$a = \frac{U_1 - U_2}{U_1} \tag{2.7}$$

$$U_2 = U_1(1 - a) \tag{2.8}$$

$$U_4 = U_1(1 - 2a) \tag{2.9}$$

The power extracted from the wind by the rotor, P, is the product of the thrust, T, and the wind velocity at the rotor plane, U_2.

$$P = TU_2 \tag{2.10}$$

$$P = \frac{1}{2}\rho A_2(U_1^2 - U_4^2)U_2 = \frac{1}{2}\rho A_2 U_2(U_1 + U_4)(U_1 - U_4) \tag{2.11}$$

Substituting for U_2 and U_4 from Equations 2.8 and 2.9 gives:

$$P = \frac{1}{2}\rho A U^3 4a(1 - a)^2 \tag{2.12}$$

where the control volume, A_2, is replaced with A, the rotor area, and the free stream velocity U_1 is replaced by U.

Wind turbine rotor performance is usually characterized by it's power coefficient, C_P, '2representing the fraction of available power in wind that is extracted by the turbine, is defined as:

$$C_P = \frac{P}{\frac{1}{2}\rho A U^3} \tag{2.13}$$

Substituting the extracted power form Equation 2.12 into Equation 2.13:

$$C_P = 4a(1 - a)^2 \tag{2.14}$$

The theoretical maximum power coefficient from an idealized rotor, $C_{P\,max}$, known as Betz limit, can be found by setting the following derivative with respect to a equal to zero ,and solving for a:

$$\frac{\partial C_P}{\partial a} = 4(1 - 3a^2) = 0 \rightleftarrows a = \frac{1}{3} \tag{2.15}$$

Substituting into Equation 2.14, yielding:

$$C_{Pmax} = \frac{16}{27} \approx 0.59259 \tag{2.16}$$

For an idealized wind turbine, the maximum efficiency is equal to 59.3 %. In practice, some considerations can be listed for real wind turbines do not present this efficiency: Rotation of the wake caused by the rotor; finite numbers of blades; viscid flow causes nonzero aerodynamics drag.

3. DAWT POWER EQUATION

The following data shows the meaning of variables used in this model:

E = Kinetic Energy in J	ρ = Density in kg/m^3	m = Mass in kg
A = Swept Area m^2	v = Wind Speed in m/s	C_p= Power Coefficient
P = Power in W	r = Radius in m	dm/dt = Mass flow rate in kg/s
x = distance in m	dE/dt = Energy Flow Rate in J/s	t = time in s

At constant acceleration, the kinetic energy of an object having velocity (v) and mass (m) is equal to the work done (W).

E =W = Force × Displacement= F×s

According to Newton's Law, we have:

F = m × a

Hence,

E = m × a × s … ……………. (1)

From the third equation of motion:

$v^2 = u^2 + 2as$

We get:

$a = (v^2-u^2)/2as$

Since the initial speed of the object is zero, i.e. u = 0,we get:

$a = \frac{v2}{2s}$

Substituting value of 'a' in equation (1), we get the kinetic energy

$E = \frac{1}{2}mv^2$…………………….. (2)

The power in the wind is equal to the rate of change of energy:

$P = \frac{dE}{dt} = \frac{v2dm}{2dt}$ ………………. (3)

As mass flow rate is given by:

$$\frac{dm}{dt} = A\frac{dx}{dt}$$

and the velocity is given by:

$V = \frac{dx}{dt}$

We get:

$$\frac{dm}{dt} = \rho.A.v$$

Hence, from equation (3), the power can be defined as:

$$P = \frac{1}{2}\rho Av^3$$

A German physicist Albert Betz concluded that any wind turbine cannot convert more than 59.3% of the kinetic energy of the wind into rotary mechanical energy. Nowadays, this is known as the Betz Limit or Betz's Law. The maximum theoretical efficiency of any wind turbine is 0.59. This is called as the power coefficient and is defined as:

$$C_p\,max = 0.59$$

Also, at this higher limit wind turbines cannot operate. The Cp value is same to each turbine type and it is a function of wind velocity that the turbine is operating in. Once we deals with various engineering requirements of a wind turbine – durability and strength in particular – the real world limit is below the Betz Limit with values of 0.35-0.45. By taking all other parts into account in a whole wind turbine system - e.g. the generator, gearbox, bearings etc., only 10-30% of the power of the wind converted into usable electricity. The available power from the wind is given by:

$$P_{Available} = \frac{1}{2}\rho A V^3 C_p$$

The turbine swept area is given by:

$$A = \pi r^2$$

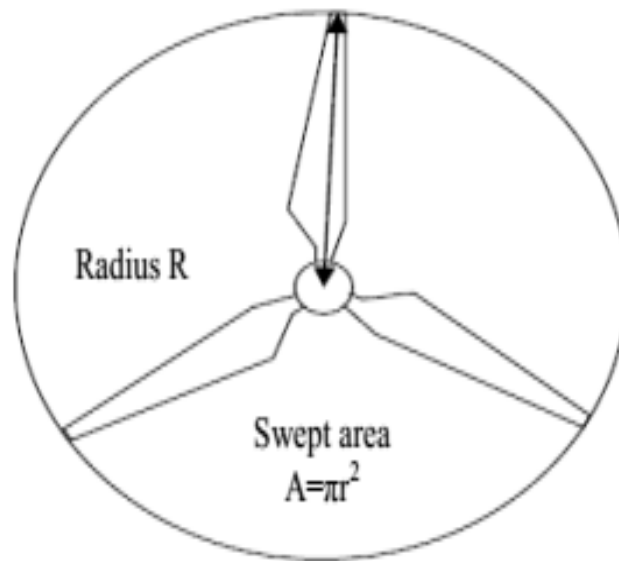where the radius is acts as the blade length as shown by figure below

Fig 6: Swept area of blade

4. DESIGN CONCEPTS

Matsushima et al. [10] studied the effect of diffuser's shape on wind speed. Results showed that the wind speed in diffuser was greatly influenced by the length and expansion angle of the diffuser, and maximum wind speed increases 1.7 times with appropriate diffuser shape. As per the study, the wind speed in the diffuser was simulated by varying the external dimensions of the diffuser. Solid works simulation software is used for modelling [11]. Wind speed in the diffuser is simulated for varying dimensions of the diffuser. The diffuser was set in the 20 m × 10 m analysis apace and after the uniform amount of wind was sent from the inflow inlet toward the outlet. The following diffuser parameters were taken for simulating the wind speed: The diffuser's main body length (L), entrance diameter (D), its expansion or diffuser open angle (α) flange length (h) and splitter open angle (α_1). Simulations were conducted on the diffuser without a wind turbine in it.

Concept 1 The dimension of the diffuser L, D, h will be fixed as 1 m, 0.4 m and 0.2 m respectively. The diffuser is provided with flanges
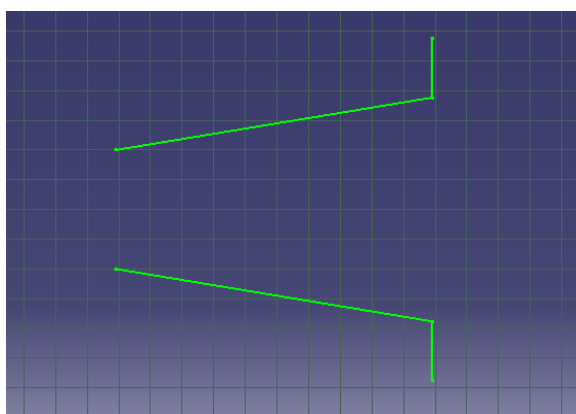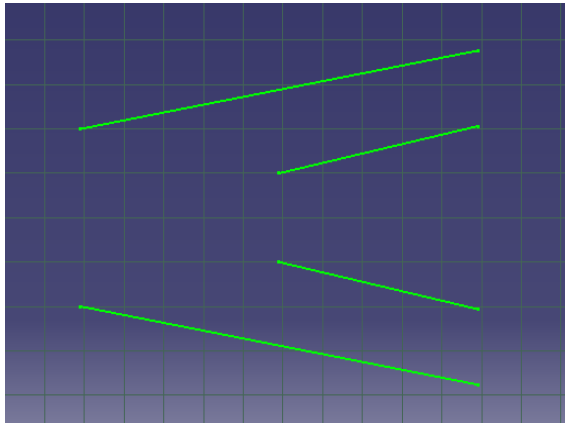

DIFFUSER WITH FLANGE

L = 1 m

D = 0.4 m

H = 0.2 m

Fig 7: Diffuser with flange

Concept 2 is shown in Fig. 9. The splitter is a smaller diffuser within the main diffuser. In this concept, the vortex would collapse the pressure field. Therefore, another smaller diffuser is placed inside with splitter angle α_1 and splitter length $L_l$of 0.5 m and splitter diameter $D_l$of 0.2 m with in main diffuser to direct and avoid separation and cause vortex inside the diffuser wall.
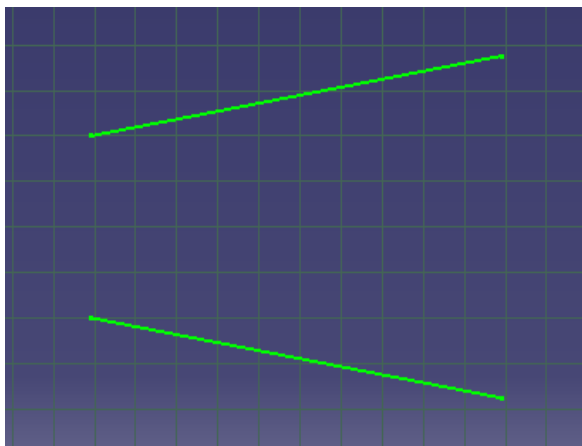
DIFFUSER WITH SPLITTER

L = 1m

D = 0.4m

l =0.5m

Fig 8: Diffuser with splitter

Concept 3 is shown in Fig. 10. The separator or splitter is not provided. The dimensions *L* and *D* are fixed as 1 m, and 0.4 m respectively. The flanges are also not included in this design to compare the characteristics of those structures.

DIFFUSER WITHOUT FLANGES
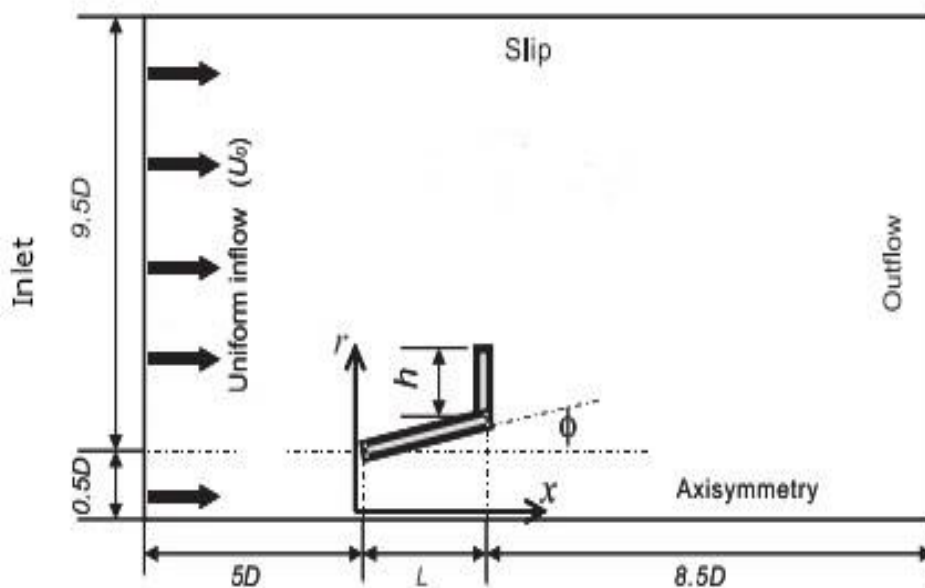
L = 1 m

D = 0.4 m

Fig 9: Diffuser without flanges

Fig 10: Boundary Conditions Used In Gambit

5. ANALYSIS

5.1 DIFFUSER WITH FLANGES

- Wind Velocity = 5 m/s

- Vmax = 7.62 m/s obtained
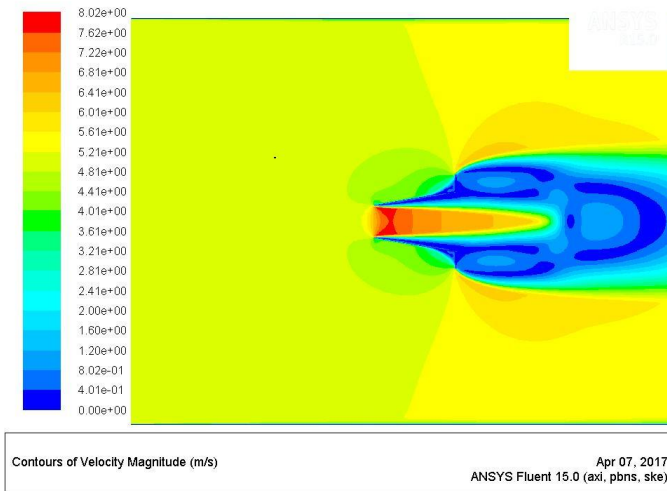
Fig 11: VELOCITY CONTOUR OF CONCEPT 1

5.2 DIFFUSER WITH SPLITTER

- Wind velocity = 5m/s

- V_{max} = 6.69m/s obtained
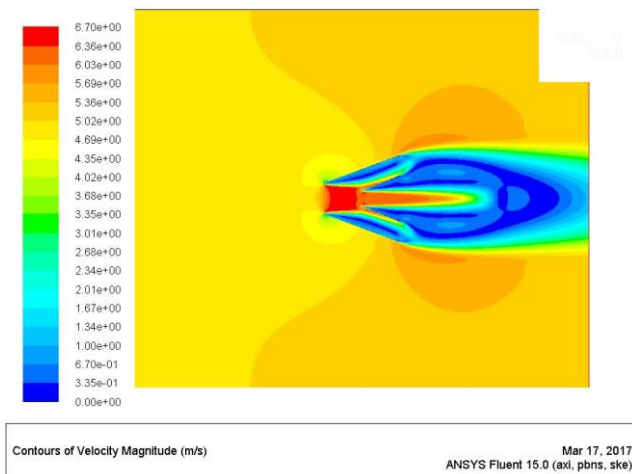
Fig 12: VELOCITY CONTOUR OF CONCEPT 2

5.3 DIFFUSER WITHOUT SPLITTER AND FLANGES

- Wind velocity = 5m/s

- V_{max} = 7.27m/s obtained
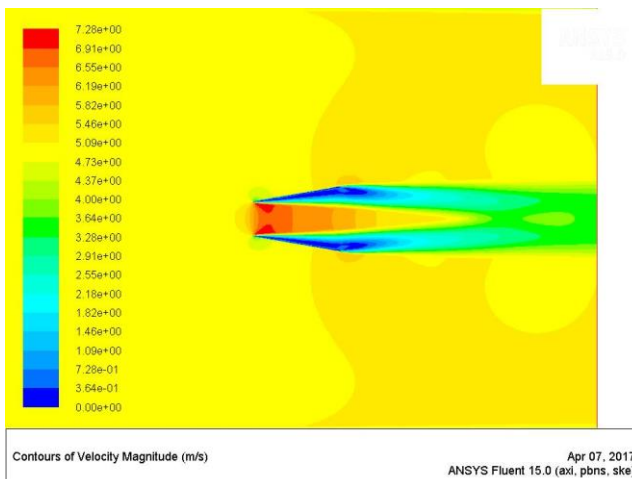
Fig 13: VELOCITY CONTOUR OF CONCEPT 3

Table 1: Analysis Results of the specified concepts

Concepts	Inlet Velocity simulated(m/s)	Maximum velocity obtained(m/s)	Percent increase in velocity	Increment in Power
Diffuser with Flanges	5	7.62	52.4	3.53 times
Diffuser with splitter	5	6.69	33.8	2.39 times
Diffuser without splitter and flanges	5	7.27	45.4	3.07 times

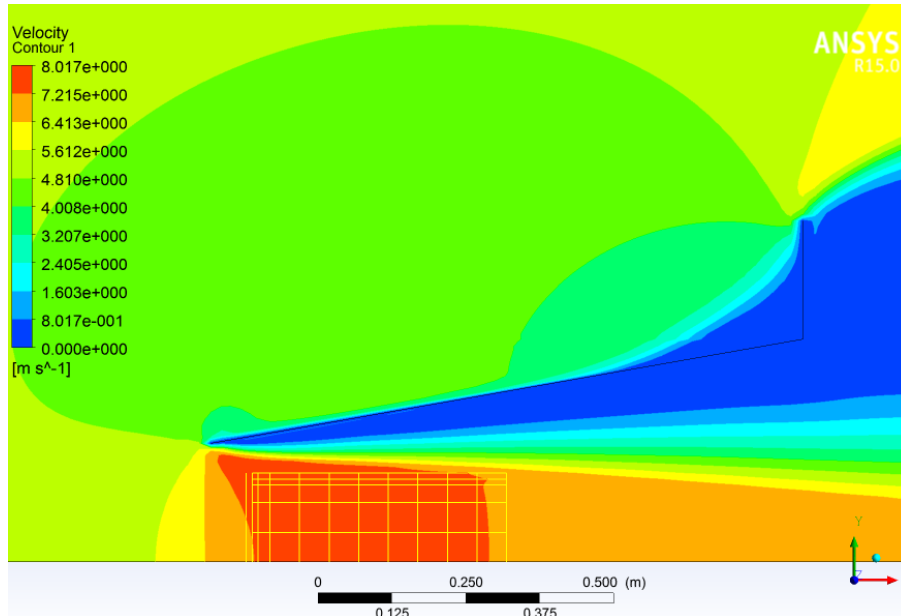## 6. POST PROCESSING RESULTS& DISCUSSION

6.1 WITH FLANGES

Fig 14: Method for Finding Linear Velocity Region in Concept 1
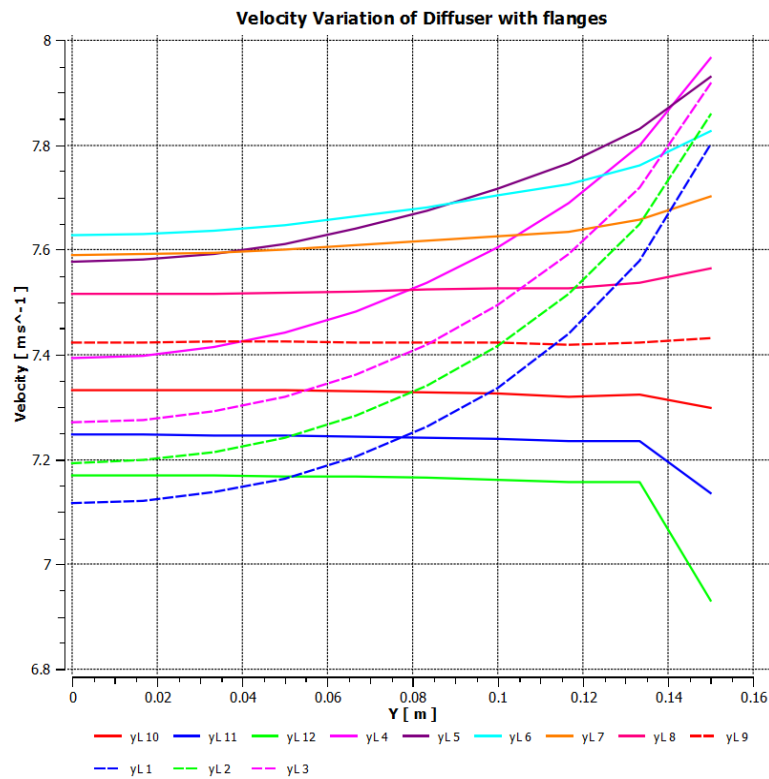

Fig 15: Velocity Variation of Concept 1 along Y Axis
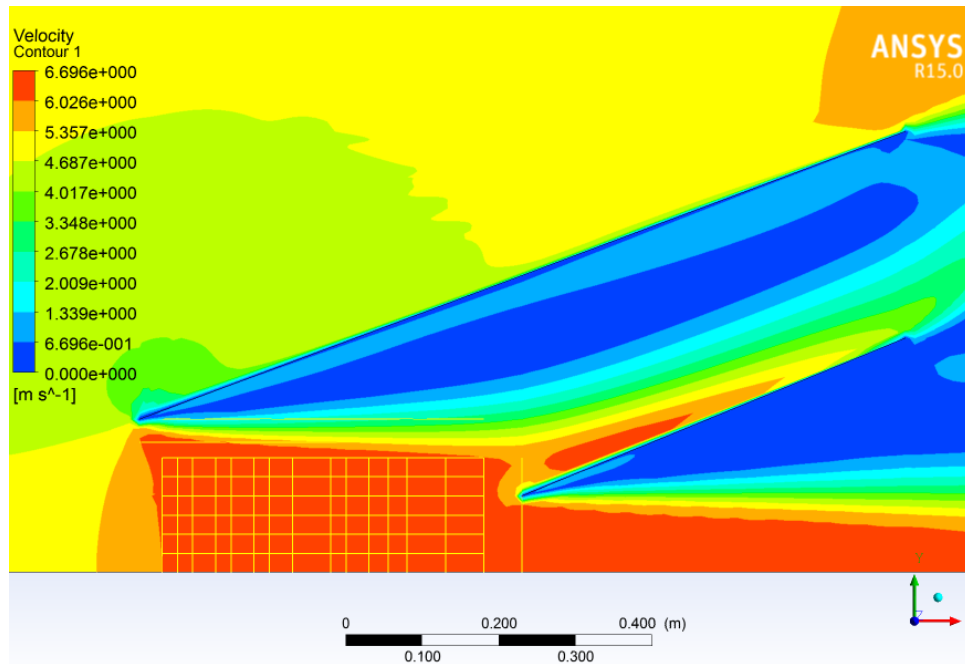
6.2 WITH SPLITTER

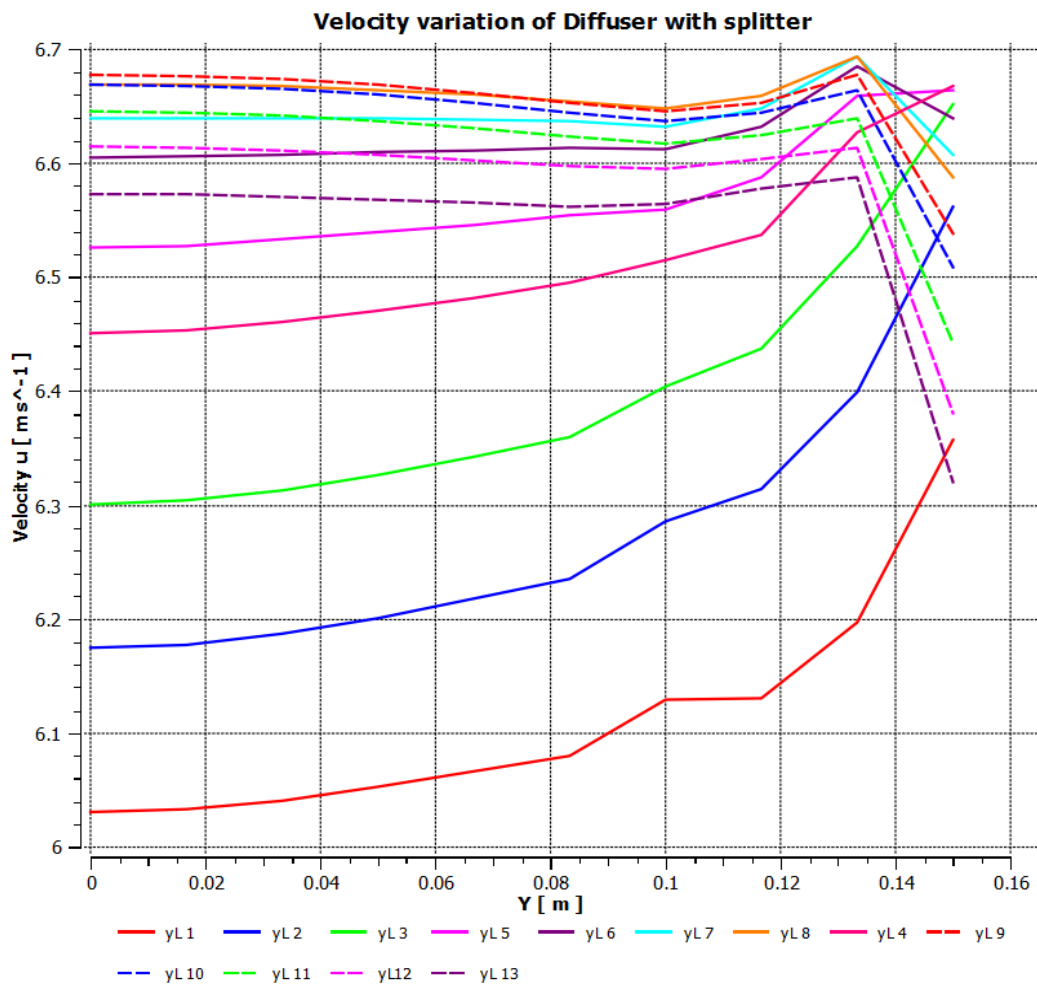**Fig 16: Method for Finding Linear Velocity Region in Concept 2**

Fig 17: Velocity Variation of Concept 2 along Y Axis
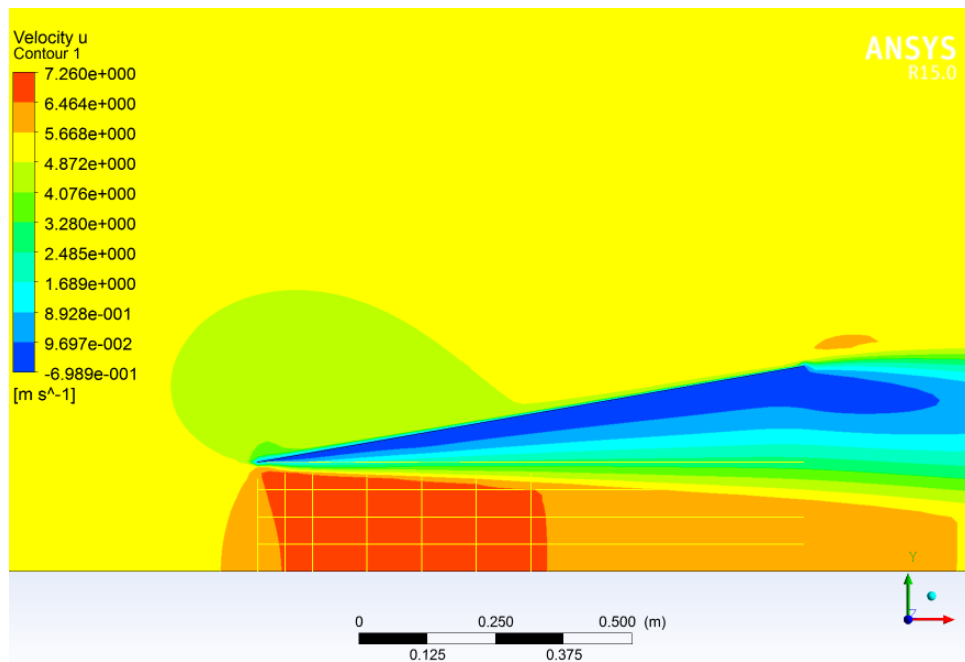
6.3 WITHOUT SPLITTER & FLANGES

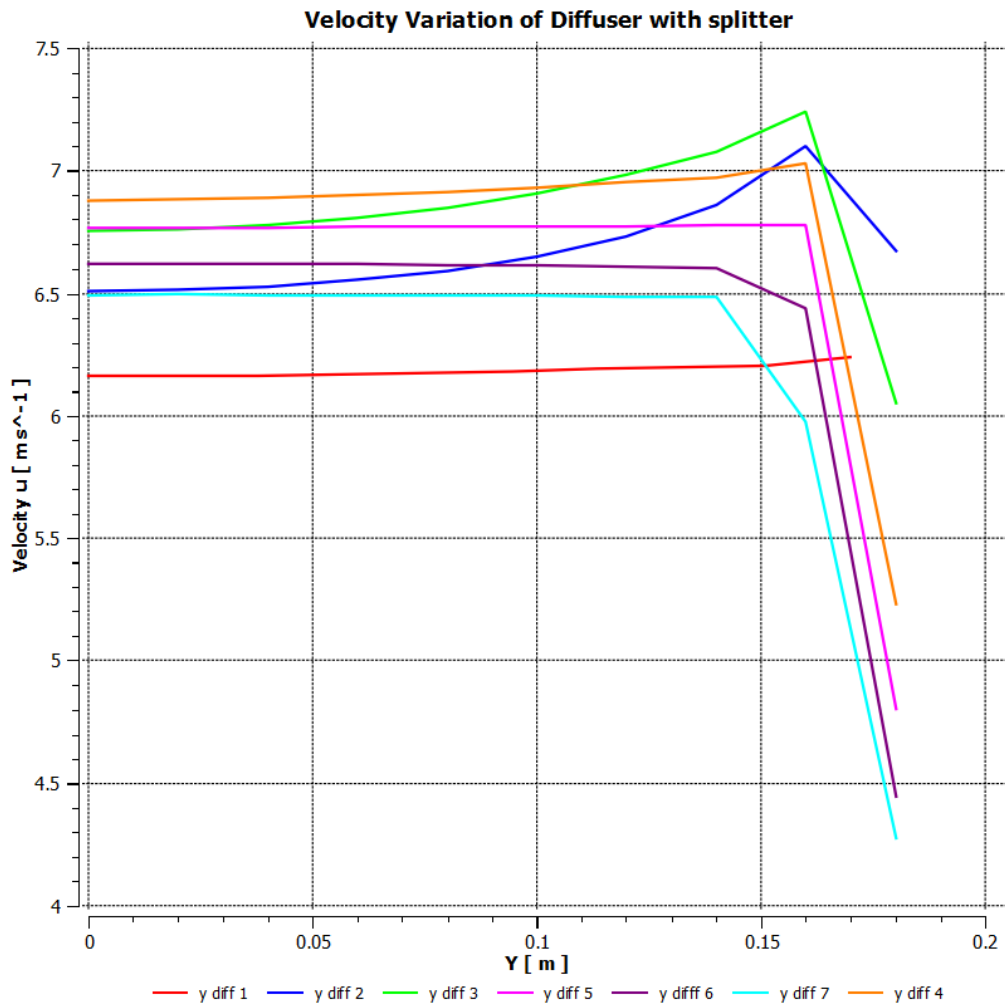**Fig 18: Method for Finding Linear Velocity Region in Concept 3**

Fig 19: Velocity Variation of Concept 3 along Y Axis

7. CONCLUSION

- From the above figures and graphs, we can come to an understanding that CONCEPT 1 encounters a higher velocity of 7.62 m/s .

- CONCEPT 1 only has a linear velocity region with a value of 7.62m/s[Table 1]

- CONCEPT 2 does not have a linear velocity region & CONCEPT 3 does not have a higher velocity than CONCEPT 1.

- Thus the CONCEPT 1 will serve as a good choice for DAWT and the Blade of 0.15 m radius at a distance of 0.13 m from the entry of Diffuser.

- Therefore increase in power of 3.53 times can be obtained.

REFERENCES

[1] Ackermann, T.; and Soder, L. (2002) 'An overview of wind energy-status', Renewable and Sustainable Energy Reviews, 6(1-2), 67–127

[2] Frankovoc, B.; and Vrsalovic, I. (2001) 'New high profitable wind turbines', Renewable Energy, 24(3-4), 491-499

[3] Ueno, H.; and Serada, T. (2002) 'Wind turbine generation system &photovoltaic power generation system'. NTT Power Build Facil J, 39(231), 42-45.

[4] Van Bussel, G.J.W. (2007). 'The Science of making more torque from wind: diffuser experiments and theory revisited'. Journal of Physics: Conference Series,75,1-12

[5] Lewis, R.I.; Williams, J.E.; Abdelghaffar, M.A. 'A theory and experimental investigation of ducted wind turbines'. Wind Eng. 1977, 1, 104–125

[6] Abe, K.-I.; and Ohya, Y. (2004) 'An investigation of flow fields around flanged diffusers using CFD'. Journal of Wind Engineering and Industrial Aerodynamics, 92(3-4), 315-330.

[7] Chen, T.Y.; Liao, Y.T.; and Cheng, C.C. (2012) 'Development of small wind turbines for moving vehicles: Effects of flanged diffusers on rotor performance'. Experimental Thermal and Fluid Science, 42, 136-142.

[8] Abe, K.; Nishida, M.; Sakurai, A.; Ohya, Y.; Kihara, H.; Wada, E.; and Sato, K. (2005) 'Experimental and numerical investigations of flow fields behind a small wind turbine with a flanged diffuser'. Journal of Wind Engineering and Industrial Aerodynamics, 93(12), 951–970.

[9] Ohya, Y.; Karasudani, T.; Sakurai, A.; Abe, K.-I.; and Inoue, M. (2008).'Development of a shrouded wind turbine with a flanged diffuser. Journal of Wind Engineering and Industrial Aerodynamics', 96(5), 524-539

[10] Matsushima, T.; Takagi, S.; and Muroyama, S. (2006). 'Characteristics of a highly efficient propeller type small wind turbine with a diffuser'. Renewable Energy, 31(9), 1343–1354