ISSN No:-2456-2165

CFD Analysis of Diffuser Augmented Wind Turbine with Various Brim Configurations

Bharath N
B.E in Mechanical Engineering
Analyst, SML Testing Services
Bengaluru, India

Dr. Gautham MG
Assistant Professor, Department of Mechanical Engineering
Siddaganga Institute of Technology
Tumkur, India

Abstract:- Wind energy is one of the most clean and renewable energy sources available in nature. The existing wind energy needs few modifications to meet required energy demand. Diffuser augmented wind turbine can be a potential solution to run a turbine at its rated power. Although research has been lasted for past five decades, still there is a scope to modify the diffuser geometry to maximize the wind velocity at blades with minimum diffuser dimensions. Since larger diffuser dimensions are not practical for efficient use of space. In the current study, four different brim configurations are considered and CFD analysis is done by varying the brim angle for each design and also by keeping all other diffuser geometry unchanged. Brims used are straight, bent, stepped brims and at the last, fins are placed over the brim in order to create the low-pressure region behind it, which in turn increases the wind velocity at the throat section of the diffuser. The results from the analysis have shown the appreciable increase in the wind velocity at different brim angle. Ansys Design modeler is used for 3D modelling of diffuser geometry and 2D meshing is used. CFD analysis is done using Ansys Fluent software.

Keywords:- *DAWT, Brim, CFD, Wind Energy, Ansys Fluent.*

I. INTRODUCTION

The effective use of renewable energy sources such as wind and solar energy is very essential in order to minimize our dependencies on fossil fuels and to prevent the environmental issues mainly air pollution and global warming. The research in the wind energy discipline is an unrivalled opportunity for present and future days, because inconsistent wind and prescribed wind speed at the place of installation is a big challenge for wind turbine. This is when researchers found an appropriate option by enclosing the turbine inside a diffuser which can act as collection-acceleration device. This type of wind turbine is known as diffuser augmented wind turbine (DAWT).

The brim is a vertical barrier which hinders the air flow creating low pressure region behind it. Addition of brim at the end of the diffuser creates a considerable pressure difference with high pressure region at the inlet and low-pressure region at the outlet. This is the principle behind in increasing mass flow rate of the air, with the addition of brim.

The first use of diffuser is by Lilley and Rainbird [1] in 1956. They compared the performance of unshrouded windmills with ducted windmills based on 1D theory. They had estimated 65% increase in maximum power using a duct with a 3.5 area ratio and 15% loss in pressure. However, their analysis was based on rough geometries.

Gilbert and Foreman [2] focused on placing turbine inside a long divergent channel structure and introduced the concept of the shrouded wind turbine around 1970.

The compact brimmed diffuser with the addition of inlet shroud resulting in efficient power output was designed and analyzed by Yuji Ohya and Takashi Karasudani [3]. The analysis was made by varying horizontal length of the diffuser, with a relatively long diffuser (Length = 1.47 times the rotor dia), a remarkable increase in the output power of approximately 4–5-times that of a conventional wind turbine is achieved and also brimmed diffuser was analyzed at different brim heights, which achieved two-three-fold increase in output power as compared to conventional (bare) wind turbines.

The experimental analysis of shrouded micro-wind turbine by comparing between straight diffuser, nozzle-diffuser and diffuser-brim combination was done by Buyung Kosasih and Andrea Tondelli [4]. They have shown the impact of geometrical features on the performance of DAWT, resulting in 60-63% increase in Co-efficient of performance.

Mr.Gade Sagar Tukaram and Dr.Abhang L.B[5] designed variety of diffuser configurations and were analyzed with and without brim. They have designed straight, curved, stepped and bumped diffusers and CFD analysis was made using Ansys fluent. The stepped diffuser with brim had shown the almost 1.93 times increase in velocity, which is maximum among all diffuser designs.

The impact of diffuser angle and brim height was studied by Michał Lipian, and et al.[6], The length of diffuser is equal to inlet diameter D. This Sensitivity study of DAWT was done at different brim height 0.1D, 0.3D and 0.5D by varying the diffuser angle from 0 to 30 degrees with the horizontal. At 0.3D, 0.5D brim height and at 30-degree angle higher turbine power output was observed.

ISSN No:-2456-2165

Mithil M. Darpe and et al.[7] designed a very long diffuser of 1.47 times the inlet diameter D and brim height of 0.1D and 0.5D. 2D analysis was done using Ansys Fluent. The maximum velocity estimate was about 2 to 3 times the free stream velocity. This performance is better among past diffuser geometries.

In the present study, we intensively focused on 4 different brim designs at a brim height of 0.6 times the inlet diameter with minimum length of the diffuser. The angle of brim is varied from 45 to 90 degrees with the horizontal. The CFD analysis is done at every 5-degree change in brim angle.

II. METHODOLOGY

Abbreviations and Acronyms

- DAWT – Diffuser augmented wind turbine
- CFD – computational fluid dynamics
- *k*-ε – turbulent kinetic energy epsilon model
- *k*-ω – turbulent kinetic energy omega model
- D – inlet diameter of diffuser
- L – horizontal length of the diffuser
- h – actual height of the brim
- l – horizontal length of inlet shroud
- t – thickness of the brim
- t_f – thickness of fins that are placed on brim
- θ – angle of brim with horizontal
- Φ – angle of diffuser with horizontal
- β – angle of inlet shroud with horizontal
- U_∞ - free stream velocity
- U_m – maximum velocity at diffuser inlet.
- P – Atmospheric pressure

Units

- Length, m – D, L, h and l are in meters.
- Angle, ^{o} – θ, Φ and β are in degrees.
- Velocity, ms^{-1} –U_∞ and U_m are in meters/second
- Pressure, kPa – P is in kilopascals.

Design of 2D DAWT.

The 2D and 3D design of DAWT is done using Ansys design modeler. The dimensions of DAWT are as shown in Table 1 and both 3D and 2D designs are shown in Fig 1 and Fig 2 respectively.

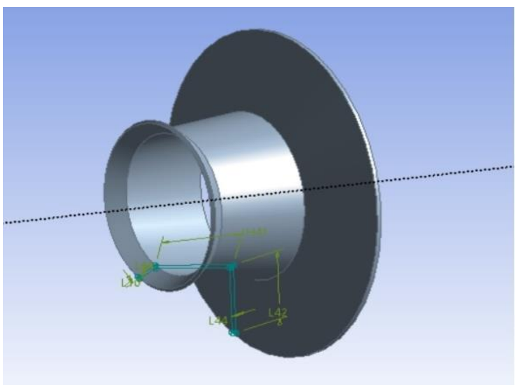

Fig.1-3D view of DAWT with straight brim

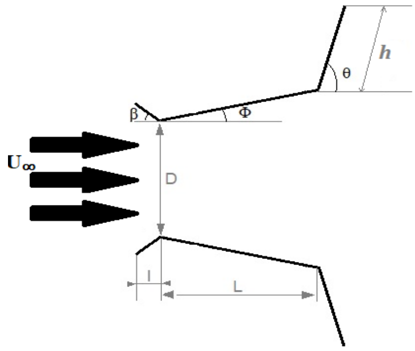

Fig. 2-2D geometry of DAWT with straight brim

Table 1. Dimensions of Diffuser	
D	0.80
L	0.45
h	0.6D
l	0.10
t	0.02
θ	45 ^{o} to 90 ^{o}
Φ	7 ^{o}
β	38.5 ^{o}

Meshing.

The same dimensions in Table 1 are used in meshing and for solving using Ansys Fluent. Meshing is done with an element size of 0.05m. Edge sizing is used with a greater number of divisions at the respective edges. The symmetry boundary condition is applied as the lower geometry is the replica of upper half. Mesh Smoothing is high with the minimum orthogonal quality 0.769704 and maximum aspect ratio 3.59976. The same mesh settings are used in other brim designs with few small changes except in the case of fins, where edge sizing is also applied for the fins that are placed on the brim. The complete mesh is as shown in Fig. 3.

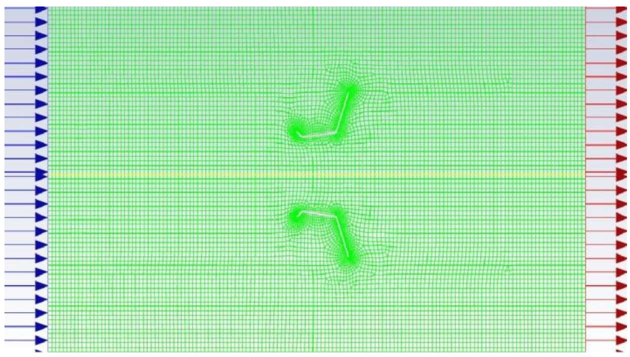

Fig.3-Meshing of 2D DAWT with straight brim

Design of different brim configurations.

Four brim configurations are designed by keeping all other diffuser dimensions unaltered as in table 1. The four designs of DAWT and also cross section of brim in an expanded view is shown in Fig. 4, Fig. 5, Fig. 6, Fig. 7

ISSN No:-2456-2165

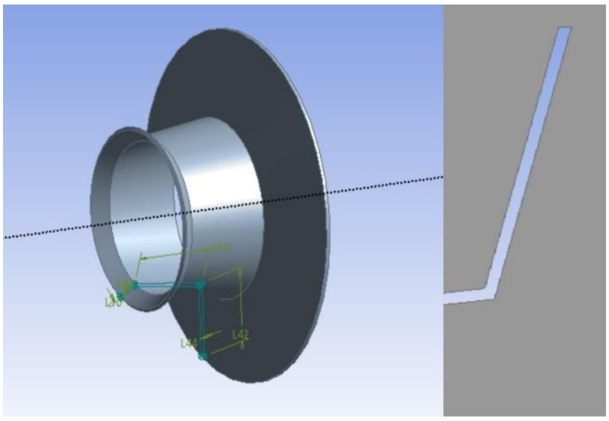

Fig. 4-3D view of DAWT and cross section of straight brim.

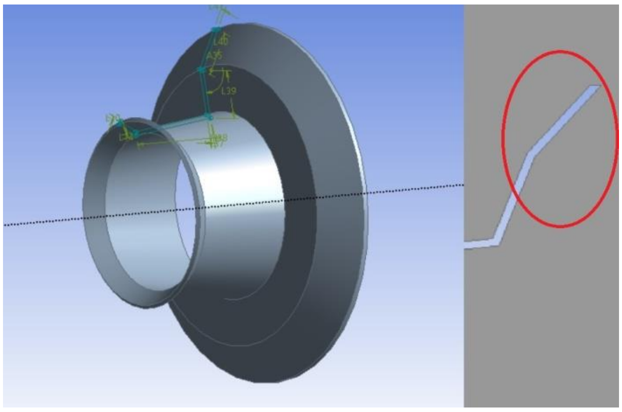

Fig. 5-3D view of DAWT and cross section of bent brim.

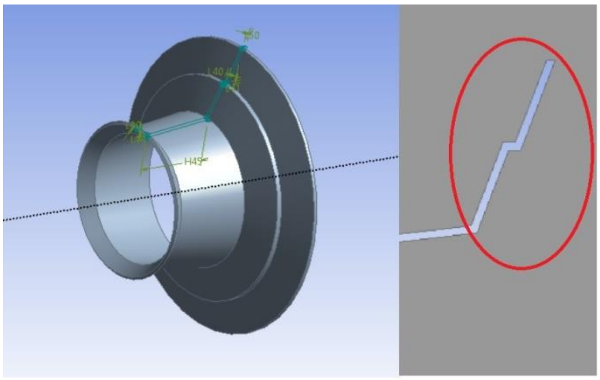

Fig. 6-3D view of DAWT and cross section of stepped brim

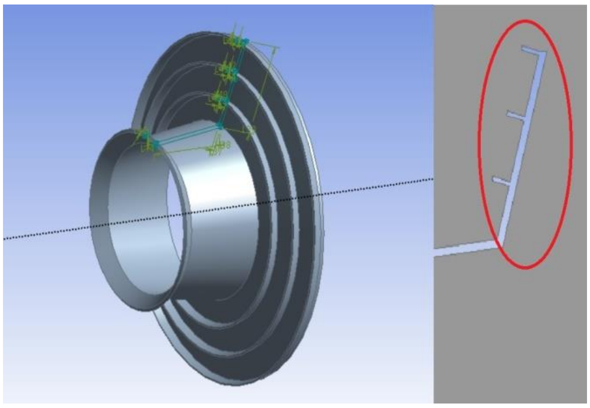

Fig. 7-3D view of DAWT and cross section of brim with fins.

The DAWT with straight brim is well explained in the earlier part while discussing the dimensions used for CFD analysis in the methodology. The other brim designs are also used with same dimensions and expanded view is circled with red mark to ensure the cross section is of same brim design.

The bent brim DAWT shown in Fig. 5 is having brim bent exactly at its middle with straight part height of 0.3D and bent part of 0.3D. Here the angle of brim is b/w the bent part and the horizontal is considered for study of variable angle and the angle b/w lower end of brim and horizontal i.e. θ, shown in Fig. 2 is kept constant at 75 º (The same is a variable factor in other brim designs).

The design of stepped brim is as shown in Fig. 6. Brim is divided into two equal parts of length 0.3D each and is separated by a horizontal distance of 0.03m. This arrangement made the brim stepped. Here the angle θ is same as in straight brim. As in geometry, mesh divisions are also divided into equal divisions by edge sizing tool and a small change is made by applying sizing at horizontal step.

In Fig. 7 three fins of equal cross sections are added on the brim. Each fin is separated by the distance of 0.15m. The sole reason to add fin is to create low pressure area behind the brim. The actual number of fins to be added on the brim was estimated by trial and error method. The optimized results were obtained with 3 fins placed at equal distances. The fins are rectangular in cross section with length of 0.05m and width of 0.01m. In meshing edge sizing is also applied for each fin by giving minimum number of mesh divisions. The fins are placed exactly perpendicular to the brim surface. The angle θ is varied as in straight brim DAWT from 45 º to 90 º.

The all four designs are solved using Ansys fluent, to see whether the change in brim configuration and brim angle θ has any impact on the performance of DAWT. The same settings are used in fluent for all four designs. The setup and solution by fluent are explained in the next step.

III. SOLUTION AND POST-PROCESSING

Before analyzing in fluent, the 2D computational mesh was setup by pressure-based solver and with the absolute velocity formulation. The single solver processor is used.

The turbulent model in CFD prescribed for aerospace and turbo-machinery application is *k*-ω SST, since *k*-ω model is accurate at walls with fine meshing at the wall edges. But we have to observe the impact of brim angle for each configuration at every 5º change from 45 º to 90 º, solution through this model takes a greater number of iterations and time. To overcome this issue, the turbulent *k*-ε model with standard wall functions is applied for the estimation of results with change in brim angle and for the angle at which maximum velocity is attained at the diffuser inlet, *k*-ω SST model is applied and solved only at that particular angle.

The fluid used is air with the density 1.225 kg/m^3 and viscosity 1.7894e-05 kg/ms. Velocity inlet and pressure outlet are specified as boundary conditions with free stream velocity

ISSN No:-2456-2165

as inlet velocity of 1 ms^{-1} and constant operating pressure at 101325 kPa. Symmetry is applied as the lower half of design is the replica of upper half. Solution scheme is set coupled pressure-velocity with pressure, momentum and turbulent kinetic energy at second order. Pseudo Transient is enabled to include unsteady flow factor and to improve the convergence and stability. Solution is initialized with hybrid initialization and calculations are carried out for 100 iterations, but solutions are converged within 35-40 iterations.

The ratios of maximum velocity by free stream velocity at different brim angles are shown in Table 2. All the above analysis was based on the turbulent *k*-ε model and for the optimized design, we have again solved with *k*-ω SST model to analyze pressure and velocity contours at that particular brim angle.

Table 2. Ratio of maximum velocity to free stream velocity (U_m/U_∞)

Brim angle, θ	Straight brim	Bent brim	Stepped brim	Brim with fins
45 °	2.31	2.40	2.26	2.40
50 °	2.47	2.41	2.32	2.45
55 °	2.36	2.43	2.42	**2.50**
60 °	2.47	**2.47**	2.43	2.38
65 °	2.40	2.44	2.42	2.48
70 °	2.33	2.46	**2.53**	2.44
75 °	**2.48**	2.33	2.49	**2.50**
80 °	2.34	2.42	2.34	2.35
85 °	2.43	**2.47**	2.46	2.48
90 °	2.38	2.45	2.40	2.38

The above data shows, the maximum velocity at DAWT inlet is varying with brim angle, the straight brim has attained its maximum velocity at 75 °, bent brim at 60 ° and 85 °, Stepped brim at 70 ° and brim with fins attaining U_m at 55 ° and 75 °.

The graph is plotted for maximum velocity against change in brim angle for each brim design. The Fig. 8, Fig. 9, Fig. 10 and Fig. 11 are the graphs plotted for straight, bent, stepped brims and brim with fins respectively.

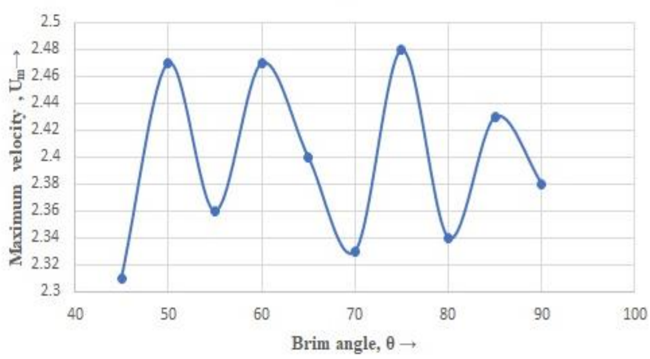

Fig. 8. The graph of U_m and θ for straight brim DAWT

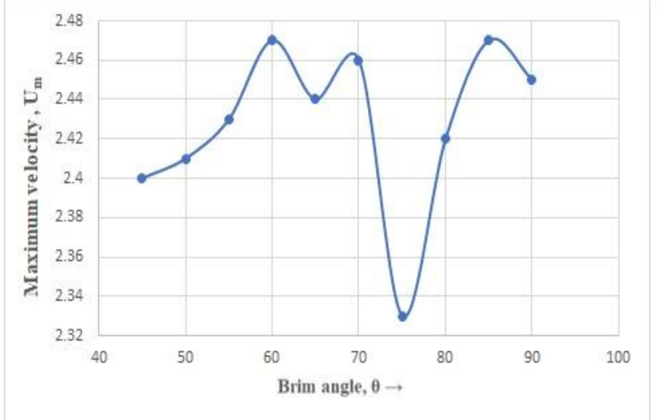

Fig. 9. The graph of U_m and θ for bent brim DAWT

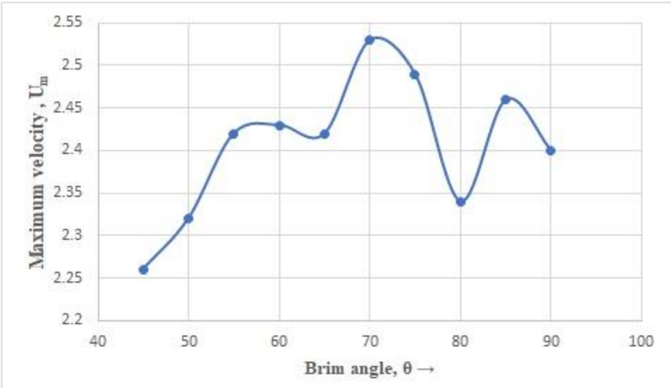

Fig. 10. The graph of U_m and θ for stepped brim DAWT

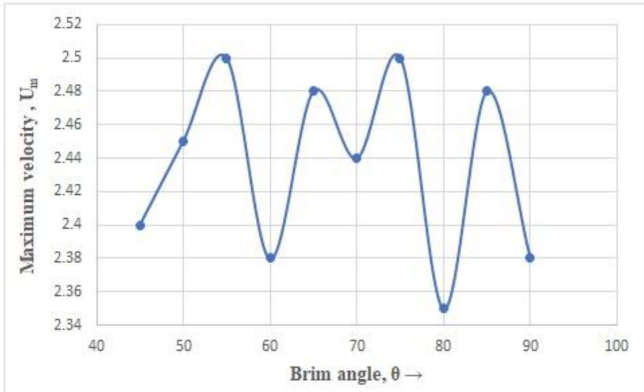

Fig. 11. The graph of U_m and θ for brim with fins DAWT

The configurations at which DAWT has attained maximum velocity are again solved in fluent using *k*-ω SST model. Contours of pressure are shown in Fig. 12, Fig. 13, Fig. 14, Fig. 15 and contours of velocity vector are in Fig. 16, Fig. 17, Fig. 18 and Fig. 19.

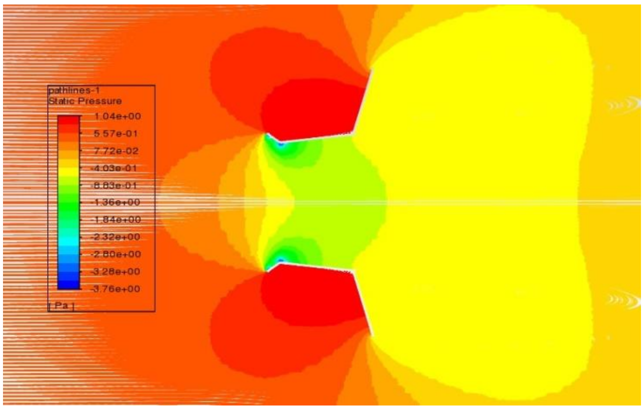

Fig. 11 Pressure contour for straight brim DAWT

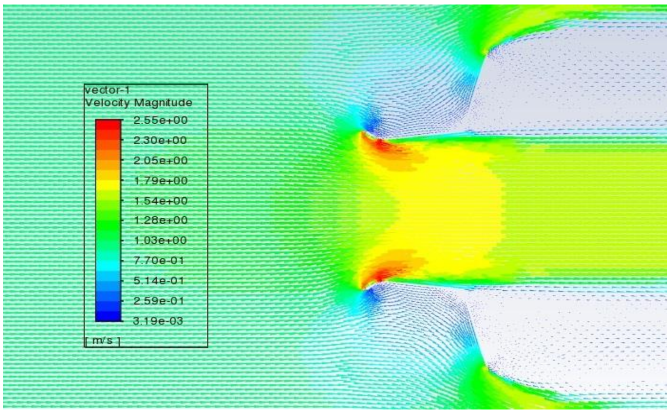

Fig. 11 Contour of velocity vector of straight brim DAWT

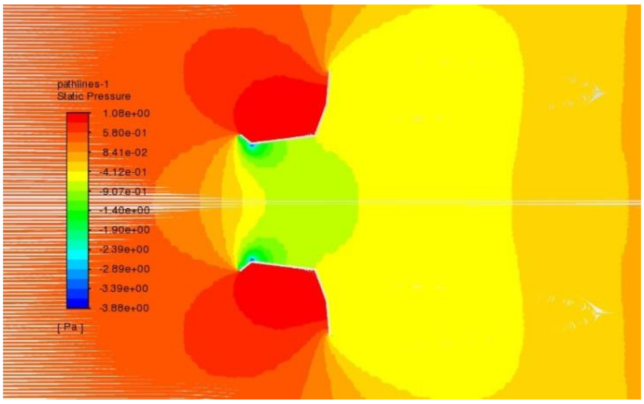

Fig. 12 Pressure contour for bent brim DAWT

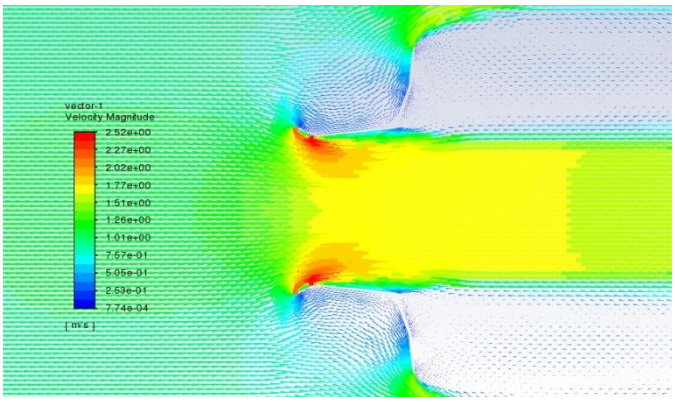

Fig. 12 Contour of velocity vector for bent brim DAWT

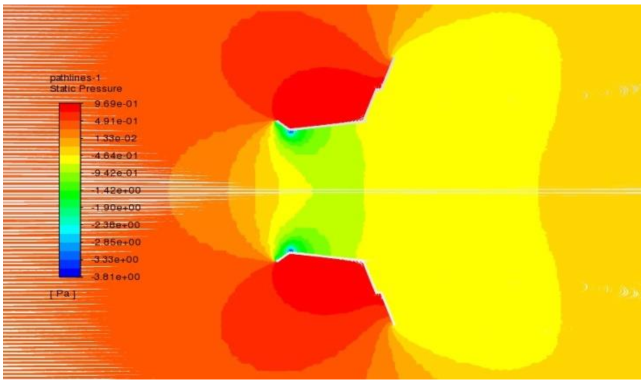

Fig. 13 Pressure contour for stepped brim DAWT

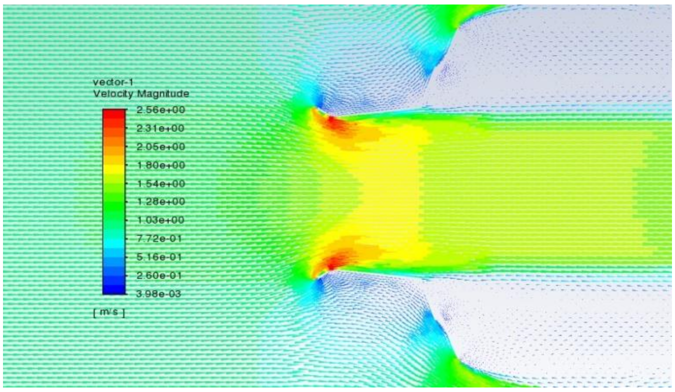

Fig. 13 Contour of velocity vector for stepped brim DAWT

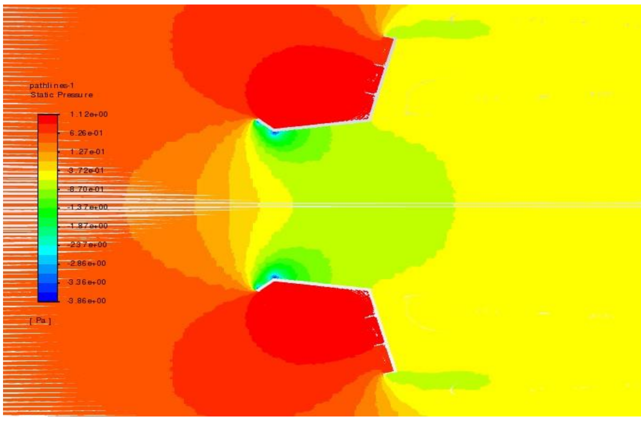

Fig. 14 Pressure contour for brim with fins DAWT

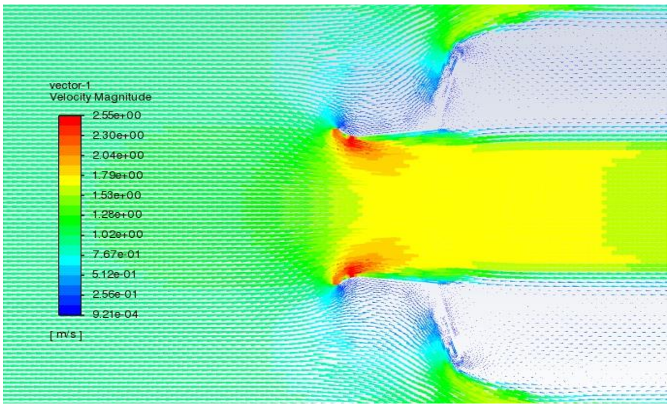

Fig. 14 Contour of velocity vector for brim with fins DAWT

From the above results stepped brim DAWT is more accurate solved with turbulent *k*-ε model, but when solved with *k*-ω SST model, except bent brim DAWT all other configurations are showing best results. The difference b/w the results of both models are shown in table 3. This analysis is only for particular angle at which U_m is maximum.

Table 3. Difference in results b/w two turbulent models.

Brim design	**U_m/U_∞ by *k*-ε model**	**U_m/U_∞ by *k*-ω model**
Straight brim	2.48	2.55
Bent brim	2.47 (at 85° & 60°)	2.52 at 85° & 2.49 at 60°
Stepped brim	2.53	2.56
Brim with fins	2.50 (at 75° & 55°)	2.55 at 75° & 2.54 at 55°

IV. CONCLUSION

The objective of this project is to study the impact of brim design and angle on the performance of DAWT. Each design has shown its own peculiar behavior at different brim angle. The results have demonstrated that the performance of DAWT is affected by its brim angle. Based on the CFD analysis of few journals and the current study, the angle of diffuser and inlet shroud considered to be $\Phi = 7^\circ$ & $\beta = 38.5^\circ$ respectively. Based on the above observations, we have confirmed that the behavior of DAWT has to be studied for every 5° change in brim angle θ. Considerable change in wind velocity was observed when there is a minimum change of angle is 5°.

The minimum average of wind velocity across Bengaluru and nearer places will be around 3.0 ms^{-1} and maximum average around 4.7 ms^{-1}. This data is provided by weatherspark website[11]. This range of wind velocity is enough to run the newly developed hybrid wind turbines. But to run the turbine at its rated power, this velocity should be increased up to 2.5 times the actual wind velocity. In this study we have reached this speed with space constraints. The velocity has increased by 2 to 2.56 times the free stream velocity. Since the power output of wind turbine is directly proportional to the cube of wind velocity, the increase in power will be 16.77 times the usual power output. The optimized design in CFD with the application of both turbulent *k*-ε and *k*-ω model has demonstrated positive results. Among all the designs DAWT with stepped brim has demonstrated the best results with both turbulent *k*-ε and *k*-ω model.

From the experience of present study, we have also analyzed few other factors which are going to improve the performance of DAWT, such as diffuser length(L) and brim height(h). It was found that with the increase of L and h, there will be a distinctive increase in diffuser inlet velocity, which in turn increases the power output of a turbine. Many have used the diffuser length up to 1.5D, but a very long diffuser length and brim height will result in poor structural integrity and design will become more complicated. For this reason diffuser length of 0.45m was used. In the future study, analyzing for more optimum airfoil design and more compact DAWT design is essential for maximum utilization

Acknowledgments

I would like to thank my professor Dr. Gautham MG for his consistent support through out this project. His theoretical guidance about the diffusers and gas dynamics motivated me to study and research in this topic.

REFERENCES

[1]. Lilley, G. M. and W. J. Rainbird (1956). A Preliminary Report On The Design And Performance Of Ducted Windmills, The College Of Aeronautics Cranfield: 1-73.
[2]. Gilbert B.M., Foreman K.L., Experiments with a diffuser augmented model wind turbine, J. Energy Resour. Technol., 1983, 105, 46–53.
[3]. Ohya, Y. and T. Karasudani (2010). "A Shrouded Wind Turbine Generating High Output Power with Wind-lens Technology." Energies 3(4): 634-649.
[4]. Kosasih B., Tondelli A., Experimental study of shrouded micro wind turbine, Procedia Eng., 2012, 49, 92–98.
[5]. Mr.Gade Sagar Tukaram and Dr.Abhang L.B, “Design & Analysis of Diffuser Augmented Wind Turbine” International Engineering Research Journal Page No 226-237.
[6]. Michał Lipian, Maciej Karczewski, and Krzysztof Olasek. “Sensitivity study of diffuser angle and brim height parameters for the design of 3 kW Diffuser Augmented Wind Turbine”. De Gruyter Open, Open Eng. 2015; 5:280–286.
[7]. Mithil M. Darpe, Sharayu K. Bandekar, Prof. S. V. Vanjari. “Design and Optimization of a Diffuser Augmented Wind Turbine (Wind Lens Turbine) using CFD”. International Research Journal of Engineering and Technology (IRJET) Volume: 07 Issue: 04 | Apr 2020.
[8]. Raju Govindharajan, Dr. K. M. Parammasiuam, V. Vivek and R. Vishnu Priya, “Numerical investigation and design optimization of Brimmed Diffuser Wind Lens around a Wind Turbine”, The Eighth Asia-Pacific Conference on Wind Engineering, December 10-14 2013, Chennai, India
[9]. Igra, O. Research and development for shrouded wind turbines. Energ. Conv. Manage. 1981, 21, 13–48.
[10]. Ohya Y., Karasudani T., Matsuura C. T., A highly efficient wind turbine with wind-lens shroud, Proceedings of 13th International Conference on Wind Engineering Amsterdam 2011.
[11]. https://weatherspark.com/y/108998/Average-Weather-in-Bengaluru-India-Year-Round.
[12]. Abe, K., Nishida, M., Sakurai, A., Ohya, Y., Kihara, H., Wada, E., Sato, K., 2005. Experimental and numerical investigations of flow fields behind a small wind turbine with a flanged diffuser. J. Wind Eng. and Ind. Aero., 93:951- 970.