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The effect of inlet curvature and flange on wind turbine diffuser performance

Muhammad Nasir[1,*], *Ignasius* Bayu Dwianditya [1], *Kutut* Suryopratomo[1], and *Sihana*[1]

[1] Nuclear Engineering and Engineering Physics Department Universitas Gadjah Mada, Yogyakarta, Indonesia

Abstract. The modification is required to the conventional wind turbine in order to increase the power produced by the wind turbine located in the low wind velocity area. Attaching a diffuser to the conventional wind turbine is one of the ways to increase the wind velocity of the approaching wind thus increasing the extracted power. This research discussed the influence of geometry variation of diffuser augmented wind turbine equipped with inlet curvature and flanged. The analyzed geometry parameters were the length (L), the expansion angle (θ), the angle of inlet curvature (β), the radius of inlet curvature (R), and the flange height (h). In this study, experimental investigations were carried out to measure wind velocity ratio U/U_∞ (wind velocity on the central axis/free stream wind velocity) of various diffuser geometry designs with an installed rotor/wind turbine in it. The present diffuser augmented wind turbine provided higher wind velocity at the inlet section reaching the maximum velocity ratio U_{max}/U_∞ of 2.01 compared to a bare wind turbine.

1 Introduction

The depletion of fossil fuels and global warming issues have led to a reawakening of the interest in renewable energy development. One of the renewable energy sources as the alternative to substitute the utilization of fossil fuels is the wind energy. Wind energy technologies have been developing rapidly in the recent years. However, despite the fast growth of wind energy technologies, the extraction of the energy from the low wind velocity is still a major problem. Therefore, several research groups have tried to find artificial ways to collect and accelerate the approaching wind effectively.

The study on this topic is mainly encouraged by the physical law, which states that the wind power generated by the wind turbine is proportional to the wind velocity cubed approaching a wind turbine. It means that a slight acceleration of the wind gives a large impact on the higher energy generation [1]. This gives a better approach to resolve the low-wind velocity problem.

Attaching a diffuser to the conventional wind turbine is one of the modifications to increase the wind velocity. The diffuser is able to collect and accelerate the approaching wind thus the obtained power is increasing. The use of the diffuser as the wind power augmentation is also known as Diffuser Augmented Wind Turbine (DAWT). Various types and shapes of diffusers have been studying since 1979 [2-5]. One of the very interesting diffuser shapes is the flanged diffuser developed by Ohya et al. [6]. Despite proposing the similar diffuser-shaped structure like others previously developed, the characteristic distinctions of their diffuser feature were the additional curvature-shaped at the inlet section and a flange encircled at its exit section. Its performance is strongly linked to its geometric parameters. Those geometric parameters are the length (L), the expansion angle (θ), the inlet curvature angle (β), the radius of inlet curvature (R) and the flange height (h) (Fig. 1). When a diffuser's shape has the appropriate dimension, a maximum wind velocity ratio U_{max}/U_∞ (maximum wind velocity on the central axis/free stream wind velocity) of about 1.7 and slightly more could be reached [6].

Previous works have shown that the optimum expansion angle (θ) at which the wind speed increase, reached a maximum, was considered to be around 4^o [6] and 6^o [7] for an empty diffuser. Furthermore, for a larger expansion angle (θ) (10^o or more) applied to DAWT with an installed rotor in it, higher wind turbine performance was obtained [8]. It was also shown that there is an optimal ratio flange height/diffuser inlet section diameter (h/D) of 0.25 for the diffuser without the wind turbine in it and 0.5 for the wind turbine installed in it [6]. Those research had clearly explained the influence of flange at the exit section of the diffuser. However, the influence of the curvature shroud at the inlet had not been discussed. Therefore, this research proposed to study the influence of the inlet curvature and the flange when both are attached at the diffuser. Further research experiments that study the influence of inlet curvature and flange are required since suitable data on this topic are hardly available in the published literature and mainly are derived from numerical simulations.

* Corresponding author: muhammad.nasir1995@mail.ugm.ac.id

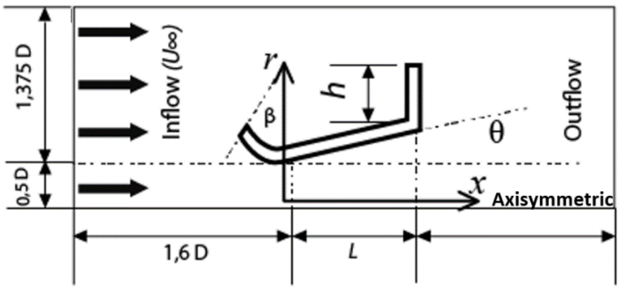


Fig. 1. Geometry condition of Diffuser Augmented Wind Turbine.

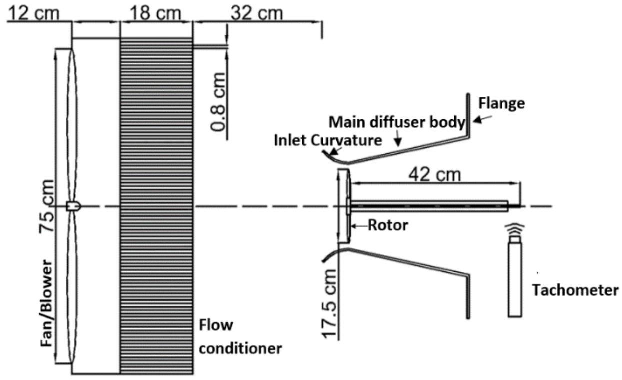
2 Method

Having considered the above background, this research discussed the influence of geometry variation of DAWT equipped with inlet curvature and flange. The analyzed geometry parameters were the length (L), the expansion angle (θ), the angle of inlet curvature (β), the radius of inlet curvature (R), and the flange height (h). In this study, experimental investigations were carried out to measure wind velocity ratio U/U_∞ (wind velocity on the central axis/free stream wind velocity) of various diffuser geometry designs with an installed rotor/wind turbine in it. By processing the obtained data, the influence of geometry variations was analyzed.

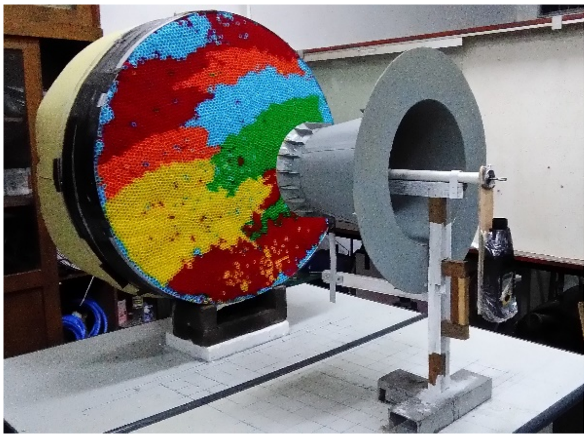
All the experiments were performed at Renewable Energy Laboratory of Nuclear Engineering and Engineering Physics Department, Universitas Gadjah Mada. The source of the wind is generated by a three blades fan with the diameter of 75 cm. The free stream velocities produced by the fan were 1.1 m/s, 1.7 m/s, and 2 m/s. The wind from the fan was turbulent, therefore the flow conditioner is required to minimize the turbulent flow. The diameter of flow conditioner was 80 cm. The flow conditioner was made from the set of straws with the length of 18 cm and the diameter of 0.8 cm for each straw.

In general, the structures of the diffuser are composed of the main body of the diffuser, a curvature-shaped shroud attached at the inlet, and a circular flange section encircled at the rear of the diffuser. The diameter of the diffuser throat was set constant 20 cm. The length of the diffuser (L) was 30 cm and the flange height (h) was 10 cm. The expansion angles (θ) of the diffusers were 4^o, 8^o, and 12^o. While the radius (R) and the angle (β) of the inlet curvature were 5 cm, 8 cm and 40^o, 45^o, and 50^o respectively. The rotor/wind turbine that was installed inside the diffuser has 13 bladed-rotor with the diameter of 17.5 cm and the diameter of the center hub was 4 cm.

The wind velocity on the central axis of the diffuser was measured based on the rotational velocity of the installed rotor inside the diffuser, which was derived by using a tachometer. The rotational velocity was then compared to the velocity measured by an anemometer. The tachometer used in this experiment was a digital tachometer DT-2234C. The resolution of this tachometer was 0.1 RPM (2.5-999.9 RPM) and 1 RPM (>1000 RPM). The accuracy of this tachometer was ± (0.05% + 1 digit) with the sampling time of 0.8 seconds. The Anemometer used in this experiment was a digital anemometer AM 4200 with the measurement range of 0.8 – 30.0 m/s. The resolution of this anemometer was 0.1 m/s and the accuracy was ± (3% + 2 digit).



(a)



(b)

Fig. 2. (a) Detail information of experimental design; (b) The real appearance of the experimental design.

3 Results and Discussion

3.1 The overall behaviour

Six configuration models of the diffuser were tested in this experiment. The experiment was conducted at the same wind velocity conditions. The measurement was obtained from the centerline of the diffuser. By plotting the wind velocity ratio (U/U_∞) derived from experiment against the dimensionless length (X/L), we found that the maximum wind velocity ratio was obtained where the value of dimensionless length (X/L) ranging from 0.03 to 0.10. This range is located in the center line of the diffuser near the inlet. It can be seen from Fig. 3 that the maximum velocity was obtained near the inlet of the diffuser. The maximum wind velocity ratio (U/U_∞) reached values of 2.01 for the diffuser equipped with inlet curvature and flange that having the diameter inlet (D) of 20 cm; L/D ratio of 1.5; expansion angle (θ) of 8^o; inlet curvature angle (β) of 50^o; inlet curvature radius (R) of 8 cm; and h/D ratio of 0.5. This result showed that the wind velocity ratio was greater than the wind velocity ratio provided by the diffuser that only consisted of flange without inlet curvature shroud designed by Ohya et al [6].

In a diffuser, the flow expands along inside wall unless a massive separation occurs in the near wall region, resulting in the increase of static pressure and the decrease of the velocity towards the diffuser exit. This condition suggests that the flow have to accelerate near the inlet in order to cover such a deceleration that happens inside the body of the diffuser toward the exit. This is the reason why the approaching flow accelerates and the maximum velocity was obtained near the inlet.

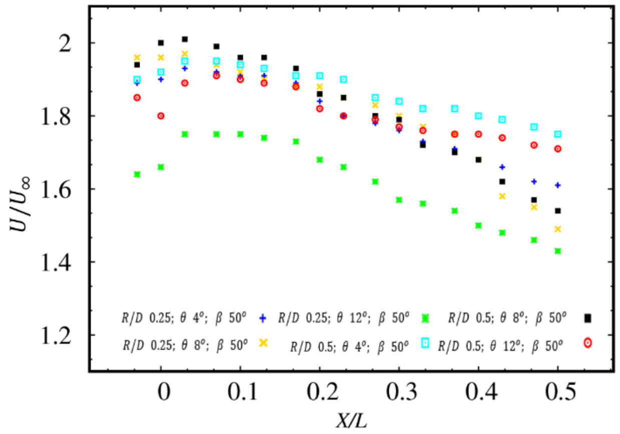


Fig. 3. The wind velocity distribution at the center line of the six diffusion configuration models.

3.2 The effect of inlet curvature and flange

The previous studies showed that as the body of the diffuser becomes longer, the wind velocity obtained will increase [6]. However, in terms of field application, it is not preferable to use a long body diffuser. Therefore, shorter diffuser body that mainly has an L/D of less than 2 is more desirable when it is able to give the similar performance the same as the long diffuser body performance.

In our experiment, we utilized a short diffuser body with the L/D of 1.5. The attachment of a curvature-shaped inlet shroud and the flange were the ideas aiming to improve the performance of the diffuser. During the experiment, we study the performance of the inlet shroud by varying its size which consisted of two variables, the radius (R) and the angle (β) (see Fig. 1). The size of the flange was made the same with the one designed by Ohya et al [6]. It was found by Ohya et al [6] that the h/D ratio of 0.5 provided the maximum wind velocity when the turbine was installed in it.

As a result, when the flange is employed, a higher wind velocity ratio (U/U_∞) was derived compare to the diffuser model only. A greater increased obtained when both curvature-shaped inlet and flange were attached to the diffuser. The derived value noticeably exceeded the case of diffuser model with flange only.

Our work showed that the additional inlet curvature with the specification R/D of 0.25 and β of 50^{o} generated the wind velocity ratio $\pm$7.82 % compared to the diffuser that only has the flange. This result showed that the inlet curvature acted to increase the mass flow through the rotor and, therefore, to increase the wind velocity ratio. The curvature-shaped inlet practically provides a better shape for a smooth flow of the wind to enter the diffuser and well prevents the flow separation to happen near the entrance.

The increase of the wind velocity when a flange attached at the outer periphery exit of a diffuser is mainly due to the emergence of a low-pressure area in the near wake of the diffuser. Therefore, owing to the effect, the vortex is formed at the exit of the diffuser and the flow coming into the diffuser can be effectively concentrated and accelerated.

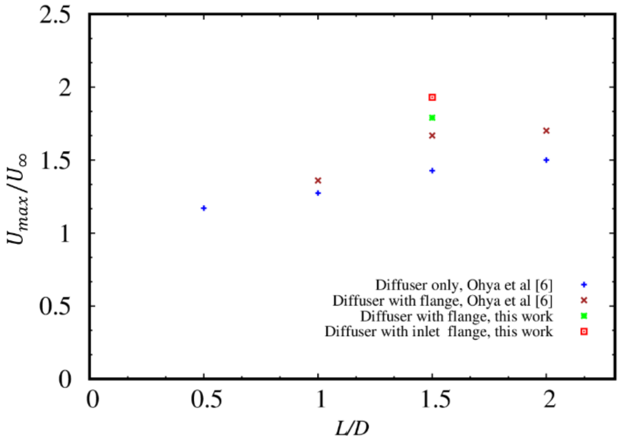


Fig. 4. The increase of the maximum wind velocity due to the diffuser model structure improvement.

3.3 The effect of the expansion angle (θ)

Expansion angle (θ) or also known as the open angle is also a very influential variable to the performance of the diffuser. Therefore, it is very important to understand the effect of the expansion angle (θ) toward the optimization of the diffuser utilization. We found that the wind velocity ratio (U/U_∞) increases with a bigger expansion angle (θ). However, when the expansion angle (θ) bigger than 12^{o}, the wind velocity ratio (U/U_∞) tends to decrease again.

Comparing our result with those Matsushima et al. [7], there is a good synchronization concerning the optimal expansion angle (θ) that was reached in their study which approximately was about 6^{o}. This can be explained by the different method and configuration used in this paper and the work done by Matsushima et al. [7] which was simulated based on 3D thermos hydrodynamic analysis software, I-DEAS, without an installed rotor inside the diffuser and curvature at the inlet section. By doing another comparison with work done by R. Chaker [8], the fairly well relationship is also found. From their simulation and experimental work, it appeared that the maximum expansion angle (θ) is about $\pm$10^{o}. All of these results showed a similarity that optimum wind velocity ratio (U/U_∞) will be derived when the expansion angle (θ) of the diffuser was ranging about 6^{o} - 12^{o}. When the expansion angle (θ) is out of this range, the velocity of the wind tends to decrease. These results suggest that the expansion angle (θ) of the diffuser should not be out of this range.

The remarkable phenomena of the inclination in generating a lower wind velocity ratio (U/U_∞) when the

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expansion angle (θ) bigger than $\pm$ 12^{o} mainly corresponds to the separation of the boundary layer. The detachment of the boundary layer gives a real impact on the aerodynamic performance of the diffuser.

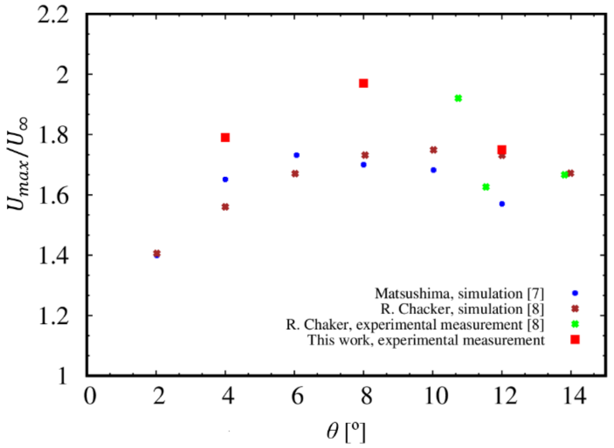

Fig. 5. The relationship between the expansion angle (θ) and maximum velocity ratio.

3.4 Recommended improvement of inlet curvature angle (β) and radius (R)

In order to have a better shape of the inlet shroud, in this experiment, we also tried to improve the inlet curvature radius (R) and the angle (β). As a result of our work, the relationship between the radius of the inlet shroud (R) with the wind velocity ratio (U/U_{∞}) can be studied from Fig. 3. It shows that the increase of inlet shroud radius (R) offers an increase of the wind velocity ratio (U/U_{∞}). However, this phenomenon was partially observed as the radius of the inlet shroud (R) provided in this experiment was limited only to two different values. It will be very crucial to work on another experiment providing more variations of the inlet shroud radius (R) to study the relationship between these two variables.

To study the relationship between the inlet curvature angle (β), three configurations of different inlet curvature angle (β) were tested in this experiment. The condition of these three models was the same. The value of R/D was 0.5; the expansion angle (θ) was 8^{o}; and flange h/D was 0.5. Our result showed that as the angle of the inlet curvature (β) increased, the wind velocity ratio (U/U_{∞}) also increased (see Fig. 6). The inlet curvature angle (β) 50^{o} generated higher wind velocity at the inlet section compared to inlet curvature angle (β) 45^{o} and 40^{o}. This phenomenon occurred due to an increase of the mass flow of the wind as the inlet curvature angle (β) becomes bigger. However, the same as the relationship between the radius (R) of the inlet shroud with the wind velocity ratio (U/U_{∞}), the influence of the inlet curvature angle (β) to the wind velocity ratio (U/U_{∞}) was also partially observed as we have not tested the performances of the diffuser when the inlet curvature angle (β) is bigger than 50^{o}. Therefore, it will be very important to work on another experiment with a bigger inlet curvature angle (β) to enhance the performance of the diffuser.

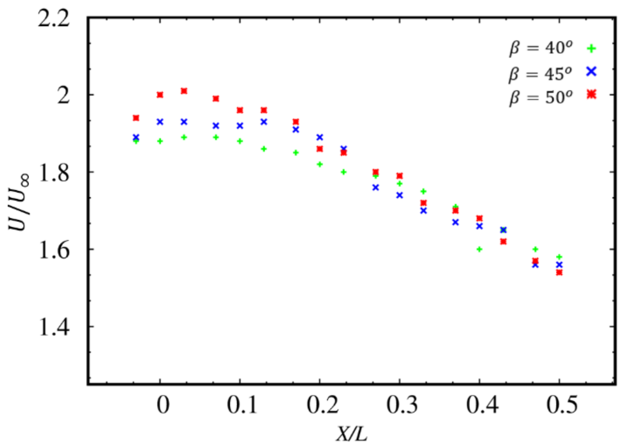

Fig. 6. The effect of the inlet curvature angle (β) to the wind velocity ratio.

3.4 Review of diffusion augmented wind turbine field application

The study of the diffuser augmented wind turbine for the field application had been conducted by several researchers [6,7,9,10]. One of the interesting projects was a project conducted in a desert region of northwest China. This project consisted of six units of 5kW diffuser augmented wind turbines equipped with the flanges that were installed in order to construct an irrigation plant. The greenery inspection on this project had been conducted and it was concluded to be effective. The other three 5kW diffuser augmented wind turbines had also been applied in the seashore Fukuoka city, Japan [10].

A 500 W class prototype of diffuser augmented wind turbine with flange had also been tested in the field. The diameter of the rotor was 0.7 m, while the diameter of the diffuser (D) was 0.72 m. The length and the height of the flange were 1.25D and 0.5D respectively. The field data of 10 min averaged values of the wind speed (m/s) and the power produced by the wind turbine were plotted (see Fig. 7). The result showed that the data derived from the experiment conducted in the field was similar to the data obtained from the wind tunnel experiment where the power curve of C_w = 1.4. The dashed line represented the power produced by the wind turbine that was not augmented with the diffuser. This result also demonstrated that the power generated by the tested diffuser augmented wind turbine with flange was about 4-5 times compared to the conventional wind turbine. During this field experiment, it was also found that the flange was able to rotate the body of the diffuser towards the direction of the approaching wind. Thus, the additional instrument to control the movement of the diffuser towards the wind direction was not required. In addition, the existence of the diffuser was not only generating an increase of the wind velocity ratio (U/U_{∞}) but also played a very important role in order to reduce the noise produced by the wind turbine. Moreover, it also provided an enhancement of the safety in case of the failure of the blades occurred [6].

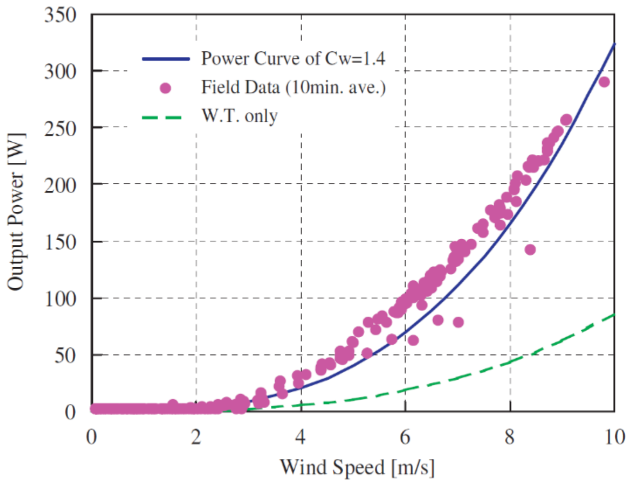

Fig. 7. The output power generated by different wind speed for 500 W class of diffuser augmented wind turbine [6].

4 Conclusion

In order to improve the performance of the diffuser augmented wind turbine, we examined the influence of the additional structure namely a curvature-shaped inlet shroud that was attached at the entrance of the diffuser and a flange that was encircled at the outer periphery of the diffuser. The present study showed that the modified diffuser noticeably provided a higher wind velocity ratio (U/U_{∞}) compare to conventional wind turbine as well as to the wind turbine that only equipped with the flange. The curvature-shaped of the inlet shroud allows a smooth flow of the wind to enter the diffuser. It also plays a role to prevents the flow separation to happen near the entrance. The utilization of the flange creates a low-pressure area that consequently draws and accelerates the wind into the diffuser. Our study also showed that optimum wind velocity ratio (U/U_{∞}) is derived when the expansion angle (θ) of the diffuser was ranging about 6^{o} - 12^{o}**.** The separation of the boundary layer is likely to happen when the value of the expansion angle (θ) is bigger than this range. This separation of the boundary layer causes a decrease of the wind velocity ratio (U/U_{∞}). The study of the relationship between the radius (R) of the inlet shroud with the wind velocity ratio (U/U_{∞}) confirmed that the increase of inlet shroud radius (R) offers an increase of the wind velocity ratio (U/U_{∞}). The phenomenon of an increase of the wind velocity ratio (U/U_{∞}) also observed when the inlet curvature angle (β) increases. However, both of the relations need a further investigation as the work done in this experiment was limited by the variation of the models that were used to observe.

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