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OPTIMIZED CURVATURE INTERIOR PROFILE FOR DIFFUSER AUGMENTED WIND TURBINE (DAWT) TO INCREASE ITS ENERGY-CONVERSION PERFORMANCE

A. Nasution and D.W. Purwanto
Postgraduate Study Program in Engineering Physics, Dept. of Engineering Physics – Faculty of Industrial Technology
Institut Teknologi Sepuluh Nopember (ITS) Surabaya, Kampus ITS Sukolilo, Surabaya 60111, Indonesia
Email: anasution@ep.its.ac.id

ABSTRACT

Suitable techniques to convert wind availability as a kind of renewable energy source in Indonesia (which are mostly in the low-speed regimes) need to be scrutinized to achieve effective and efficient conversion. The Diffuser-Augmented Wind Turbine (DAWT) concept offers the possibility to cope with such the unfavourable situation. In this paper we describe efforts to step-up potential power- augmentation offered by the DAWT. Modification of internal profile of the diffuser (based on Ohya's configuration without a flange) is done by adding an optimized airfoil-shape as interior profile of the diffuser. Additional velocity augmentation of 65.5% can be achieved in comparison to the one with the original flat-interior.

Keywords: Diffuser-Augmented Wind Turbine, interior profile, optimized airfoil shape

1. INTRODUCTION

Following international agreement in reducing greenhouse gases at Pittsburg's G-20 and COP 15, a National Energy Policy was set, known as Energy Vision 25/25. This policy guides necessary efforts of national energy utilization, which increase the contribution of renewable energy sources to achieve 25% of national energy consumption at the year 2025. Among other renewable energy sources, the wind energy unfortunately gets minor attention in Indonesia due to its low energy density. The wind velocities for most areas of Indonesia are in the low velocity regimes, in average lower than 5 m/s (Suharta, 2007). This condition makes efforts to utilize wind power as an alternative energy source would be inefficient. Then suitable techniques should be scrutinized in order to keep up with this unfavourable situation. The Diffuser-Augmented Wind Turbine (DAWT) concept offers possibility to cope with such low wind-speed regimes. It is actually developed from the horizontal-axis wind turbine, which is equipped with a hollow shroud-ducting. Early efforts to utilize the DAWT concept can be found elsewhere, among others in Ohya et. al. 2008 (Foreman et. al. 1977; Igra, 1981; Phillips, 2003; Ohya et. al. 2008). Ohya et.al. proposed a diffuser-type configuration (i.e. expands the inside cross-section downstream) and equipped with additional flange, which positioned at the trailing edge of the shroud. He demonstrated that the additional flange can increase a power augmentation of 4 to 5 times, for a given turbine diameter and wind speed, in comparison to a standard (bare) wind turbine. Intriguing questions would be then: is it still possible to increase the potential power augmentation offered by the DAWT ? how this potential power augmentation can be realized ? These questions inspire our works to further study on how the additional power augmentation can still being harvested.

Our preliminary approach was accomplished by modifying the internal curvature of the diffuser, based on Ohya's diffuser configuration without a flange, i.e. arbitrary curved interior surface in comparison to the original configuration with a flat surface. This arbitrary surface profile was set such that there is such *a necking* (i.e. smalller cross-sectional areas at certain location from the diffuser's inlet). An experimental work was done to test the hypothesis by measuring the wind velocity distribution inside the diffuser. Using hotwire anemometer, wind velocity for points along the cross-sectional areas downstream over the diffuser was measured. The results were promising, i.e. the curved interior diffuser produced velocity augmentation of 35–40% (at the smallest cross-section) in comparison to the flat one - which yielded only 10% augmentation. Further efforts were devoted to find the optimized curvature's geometrical parameters which will yield the highest possible velocity augmentation inside the diffuser. Adopting the approach offerred by Wauquiez for optimizing the shape of airfoil, and by mapping the values of both coefficient of lift (c_l) and coefficient of drag (c_d) for each range of airfoil's geometrical parameters investigated. The optimized airfoil is determined from the ones that yield maximum value of $c_l \; c_d$. These tasks are implemented by using the program XFOIL 6.9 (Drela and Youngren, 2001), which is controlled under MATLAB. This optimized airfoil's curvature profile is then used as a model for interior surface of the DAWT. The CFD technique was then implemented to simulate the velocity distributions across the diffuser for all investigated profiles. Results show that the optimized curvature can produce velocity augmentation of 65.5 % in comparison to the one with flat interior.

Future works will be devoted to studying possibilities to harvest further power augmentation, through modifications on external diffuser geometry. These proposed modifications will be aimed to create external velocity fields, which will succeedingly produce an augmentation to the wind velocity inside the diffuser. Then the respective experimental measurements will be accomplished to validate experimentally these simulation results. We believe that these efforts to step-up the potential of energy conversion performance in the rotor’s functional block, in addition to other successive functional blocks of a wind energy system: i.e. gear box and generator, which significantly increase the effectiveness and efficiency of wind energy conversion despite the low availability of wind speed in Indonesia. It is finally hoped to be able to change the current minor attention into one of eager options of renewable energy technology, which offers advantages of clean, less maintained, efficient, as well as economical.

Beside contribution to accelerate the realization of Energy Vision 25/25, these efforts will also support national program to achieve 100 % electrification in year 2015, particularly for regions with specific local topographies which make the electrical networking difficult.

2. THEORIES

2.1 Wind Energy Conversion System

Utilization of wind as a source of energy has a long history which begins in ancient time. Recorded documentation on the first use of windmills was notified in Persia (ca. 200 BC) for grinding grains. It was then diverse as primary energy source for transportation and pumping the water. The Europeans brought along the spread of windmills across the world as they colonizing the world (Mathew, 2006; Nelson, 2009). Meanwhile the wind utilization as a source for electricity was established circa the end of 1800. The first modern wind turbine was constructed in Denmark in 1890, and the developments of similar technology have spread to many countries in European as well as in American continent. Related technological development tracks can be found in (Nelson, 2009) and references therein. In principle, the conversion of wind energy into electricity can be depicted as a system with several functional blocks as follow.

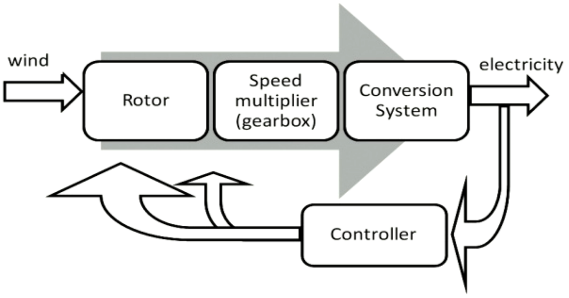

Figure 1 Typical functional blocks of wind energy conversion system

The rotor is the front-end functional block, which converts wind’s energy content into rotational power. Output of rotor will be fed to a multiplier (gearbox), which steps-up the angular velocity by some multiplication factor. Then a generator is utilized to convert this enhanced rotational power into electricity. In principle, efforts to step-up the performance of a wind energy system can be devoted to each of these functional blocks. Wind turbines are grouped (based on the position of its axis-of-rotation relative to the direction of wind stream) into two types: the horizontal-axis (parallel to wind stream) and the vertical-axis (perpendicular to wind stream) wind turbines. Most of the available commercial turbines are in the first type. The power extracted from the wind is proportional to the air density, cross-sectional area of rotor, and to the stream’s velocity (in cubed power). The last plays a significant role in harvesting power from the wind.

2.2 Diffuser-Augmented Wind Turbine (DAWT)

Developmental concept of the Diffuser-Augmented Wind Turbine (DAWT) came up as a modification from the Horizontal-Axis Wind Turbine (HAWT) system. A hollow shroud-ducting is added to cover the rotor blades. The idea behind this modification is to collect and accelerate the approaching wind, as it strikes rotor blades. Such a collection and stream’s acceleration are realized by conditioning the vortices formation behind the shroud. The working principle of DAWT can be visualized in the following figure (Ohya et. al. 2008).

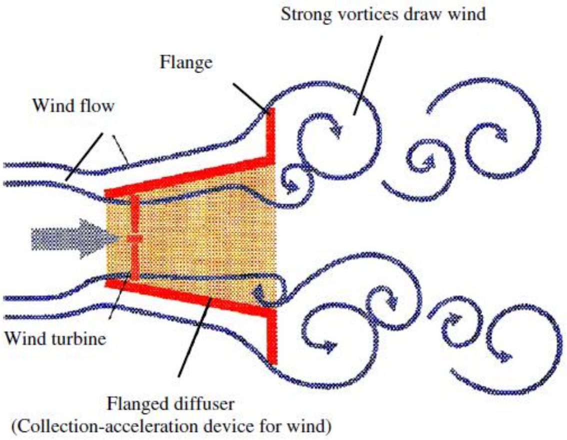

Figure 2 Pictorial concept of flanged DAWT working principle

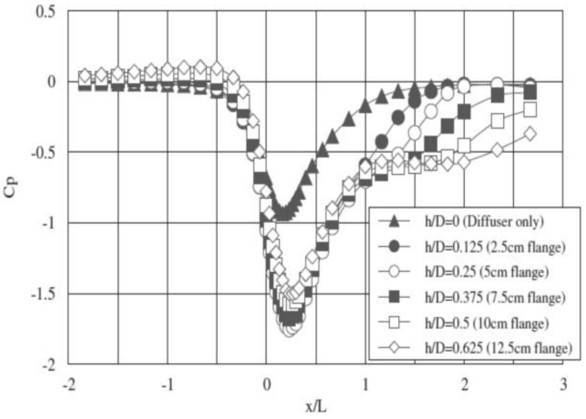

Figure 3 Changes in static pressure distribution (central axis) for different flange size

Additional flange at the exit periphery of diffuser will enhance the formations of vortices at regions behind the shroud. These vortices, having low pressure regions around, will subsequently draw more wind to flow through the diffuser. Experimental results obtained by Ohya are shown in the following figure. Efforts to step-up the power harvesting capability of the DAWT will be accomplished based on the above mentioned working principle.

2.3 Airfoil: Aerodynamics and its Shape Optimization

An airfoil profile is defined as any cut of the wing by the planes perpendicular to y-axis (see Fig. 4a), and the respective nomenclature is given in Fig. 4b (Hansen, 2008). The mean camber line is the locus of points in the halfway between the upper- and lower surfaces. The leading and trailing edges are the most forward and rearward points of the mean camber line, respectively. These two edges are connected by a stright line, called the chord line, which has a chord length c. Meanwhile the distance between the upper and the lower surfaces of airfoil (which measured perpendicular to the chord line) is called the airfoil's thickness, and the maximum distance between the mean camber line and the chord line is known as the camber (also measured perpendicular to the chord line).

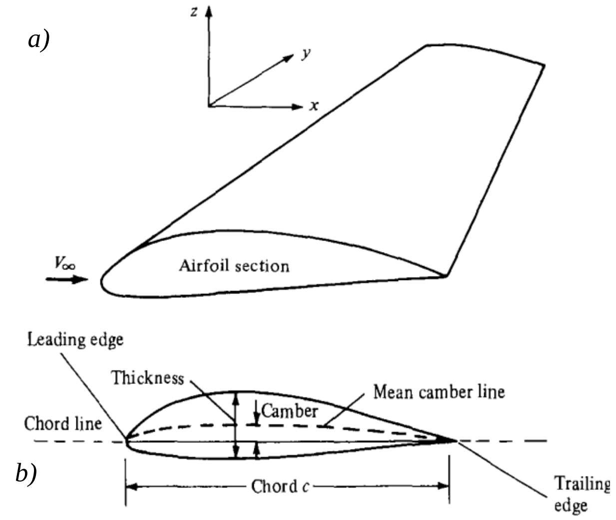

Figure 4 Definition *(a)* and nomenclature *(b)* of an airfoil

Different shapes of airfoils have been classified by the National Advisory Committee for Aeronautics (NACA) using a logical numbering system based on their shape parameters. The earliest numbering system was known as four-digit series, which was developed in 1930s. In this system, an airfoil with specific shape is labelled as for example NACA abcd , where:

- The first digit *a* represents the maximum camber (in hundreths of chord)
- The second digit *b* is the location of maximum camber along the cord from the leading edge (in tenths of chord)
- The last two digits gives the maximum thickness (in hundreths of chord)

So a NACA 2412 airfoil has the maximum camber of $0.02c$, which is located at $0.4c$ from leading edge, and with a maximum thickness of $0.12c$. As the wind flow attacks the airfoil at an angle of α, there will be a reacting force developed, as can be seen in Fig.5.

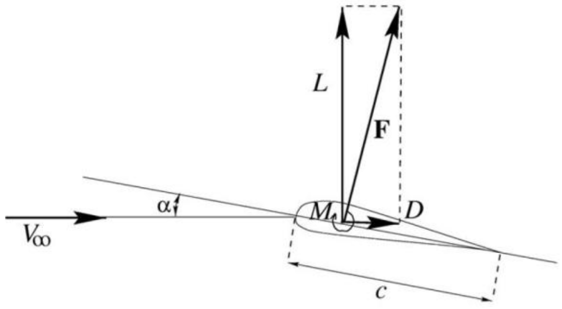

Figure 5 The lift (L) and drag (D) and moment (M) components of the reacting force on the airfoil surface due to attacking flow

The lift , drag, and moment components are defined as:

$$L = C_l \frac{1}{2} \rho V_\infty^2 c \tag{1}$$

$$D = C_d \frac{1}{2} \rho V_\infty^2 c \tag{2}$$

$$M = C_m \frac{1}{2} \rho V_\infty^2 c^2 \tag{3}$$

where ρ, V, C_l and C_d are air stream density, velocity, and coefficients for lift, drag, and moment, respectively. The fluid velocity above an object depends strongly on the geometry of the object. So the highest possible velocity around the object is achieved by optimizing object's geometry. This proposed work aims to increase the fluid velocity inside the diffuser by optimizing the geometry of the airfoil shape, which is proposed to be used as an interior surface of the diffuser. Meanwhile the diffuser's exterior is modelled as straight lines connecting both the leading and trailing edges. In general, steps for optimization includes determination the objective function, determining variables, limits of optimization, and optimal regions (a.k.a. feasible areas). The optimal point is found by solving the objective function with all of its influencing parameters. So optimizing the object's geometry in terms of fluid flow needs to solve both of flows and geometrical functions (Thevenin and Gabor, 2008). The model of flow function used in this work is determined by using the panel method – which combined with the boundary layer method, and implemented under XFOIL 6.9 (Drela and Youngren, 2001). The optimization process is done sequentially, i.e. finding most feasible areas and continued with finding the optimal point. The objective function for optimization is determined based on the highest lift force and lowest drag force, that is simply represented as (Wauquiez 2000):

$$Airfoil_{\mathrm{opt}} = max \ \frac{L}{D} = max \ \frac{C_l}{C_d} \qquad (4)$$

The optimization limits can be determined by assessing how the airfoil's parameters influence the objective function. The influence of airfoil thickness and angle of attack α to C_l can be shown in Fig.6. This figure shows that the maximum values of C_l are achieved as the thickness of airfoils greater than 0.07c (while for the ones lower than 0.07c can never achieve maximum). Up to thickness of 0.20c the values of C_l are around 1.6. So the limit of thickness should be in the range of 0.07c ~ 0.20c. Additionally, these maximum values of C_l are achieved for α under20°.

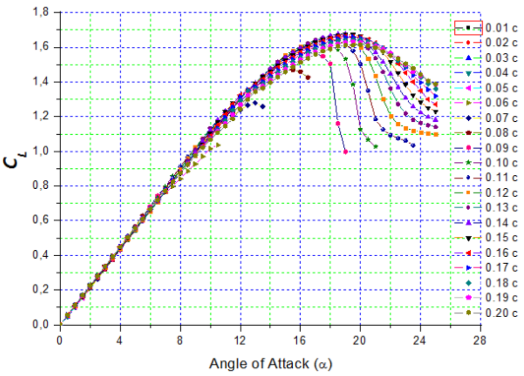

Figure 6 Influence of airfoil's thickness and angle of attack α to the C_l

The variation of maximum camber and the location of maximum camber along the cord to the C_l (represented by color variation) can be described in the following figure.

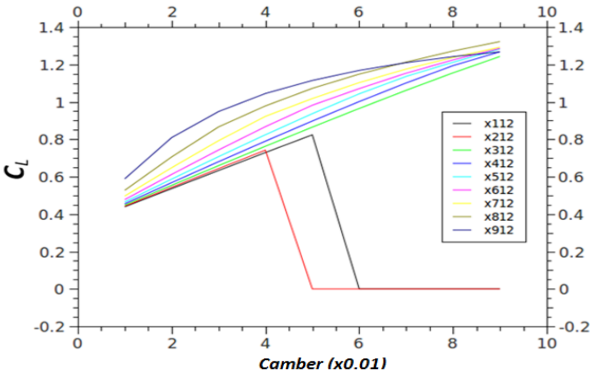

Figure 7 Influence of *camber* to the C_l

The figure shows that the maximum camber gives more pronounced effect to the C_l in comparison to the location of maximum camber. Based on these results, a map of C_l and C_d values will be calculated under parameters limitation as follow:

- maximum camber: 0.01c ~ 0.09c
- location of maximum camber: 0.3c ~ 0.8c
- thickness: 0.07c ~ 0.20c, and
- angle of attack α : 0° ~ 20°

The optimized airfoil geometry is obtained from the ones that yield maximum $C_l \ C_d$.

3. MATERIALS & METHODS

Preliminary experimental work was done to test our hypothesis: that changing the internal curvature of diffuser instead of a plain surface might result an additional velocity augmentation inside the diffuser. Two conical diffuser models were set, i.e. one with a flat surface as used by Ohya without flange (indicated by green line) and another one with an arbitrary curved surface. These diffusers can be shown in the following figure.

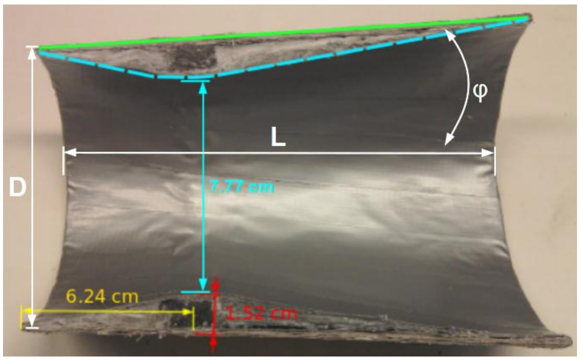

Figure 8 Diffuser geometry used in the preliminary experiment work. L = 20 cm, D = 10 cm, and $\varphi = 3.72°$

The wind velocity inside both of the diffusers were measured at every points in xy plane as indicated in Fig. 9 for any points downstream along the z-axis. Then the obtained velocity profiles are compared using derived turbulence intensity parameter.

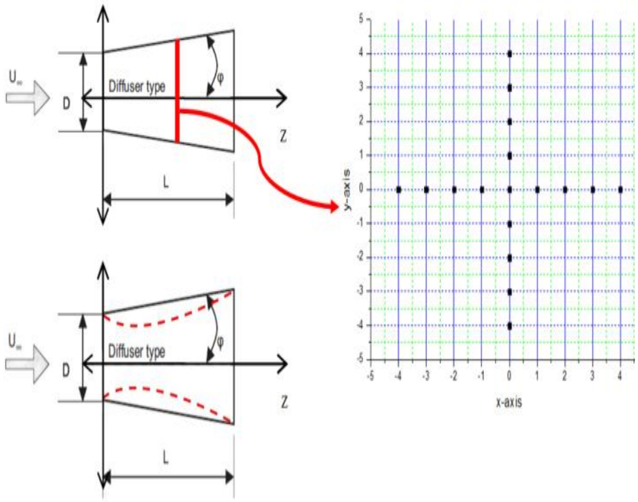

Figure 9 Wind velocity measurement points using hotwire anemometer

Further efforts to obtain the optimized curvature profile as an internal surface of DAWT are accomplished by calculating the values of C_l and C_d for each airfoil profiles used using the above mentioned parameters limitation. Optimized curvature geometry of an airfoil will be obtained from the ones which will yield the maximum$C_l \ C_d$. A CFD simulation is subsequently accomplished to simulate the wind flow behavior inside diffusers with different curvature geometry. This simulation will asses how the wind velocity behaves inside the diffusers with different internal curvature geometries. In this step, we compare the original flat surface, arbitrary-curved surface (which was used in the preliminary experimental work) and the proposed optimized curvature geometry as the internal surface of a DAWT.

4. RESULTS AND DISCUSSIONS

Measurement results on the two diffuser geometries as mentioned in Fig. 8 can be depicted in the Fig. 10.

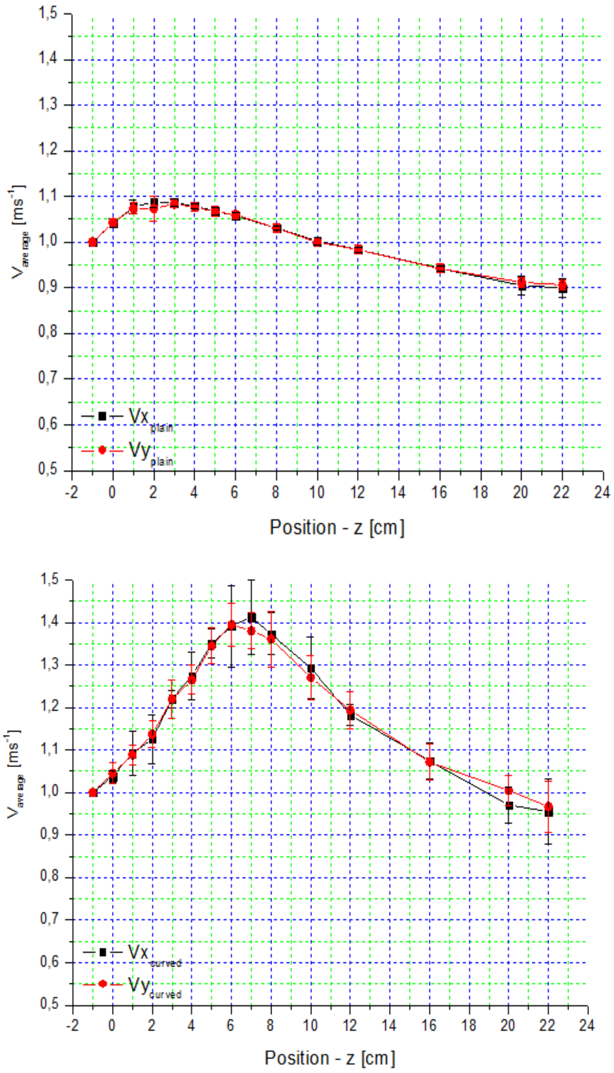

Figure 10 Velocity inside the diffuser for different internal curvature geometries: plain- vs curved surface

In diffuser with a plain surface case, the maximum relatif velocity to the inlet velocity U_∞ may achieve 10% at locations of $1 < z < 4$ cm from the inlet. This result is also confirmed with the one obtained by Ohya. Meanwhile the use of additional arbritrary curve contributes to a maximum relatif velocity up to 35-40% at locations of $5 < z < 8$ cm. It means that an additional arbitrary curved surface yields a local velocity augmentation of 25–30% in comparison to the one with a plain surface. The derived values of turbulence intensity for both geometries can be shown in Fig. 11. The axial turbulence intensity along the diffuser with a plain surface shows that the flow is relatively steady, followed by slowly increments until the oulet of diffuser. The flow near the walls as well as the one behind the diffuser is more fluctuated. Meanwhile in case of diffuser with arbitrary curved surface, the axial flow along the diffuser is more turbulence and shows increasing turbulence up to highest curvature which continued with a slow decrease. Then this flow is followed with steep increase of turbulence towards the outlet diffuser. These turbulences behind the diffuser are guessed as an influencing factor causing the creation of local velocity augmentation inside the diffuser.

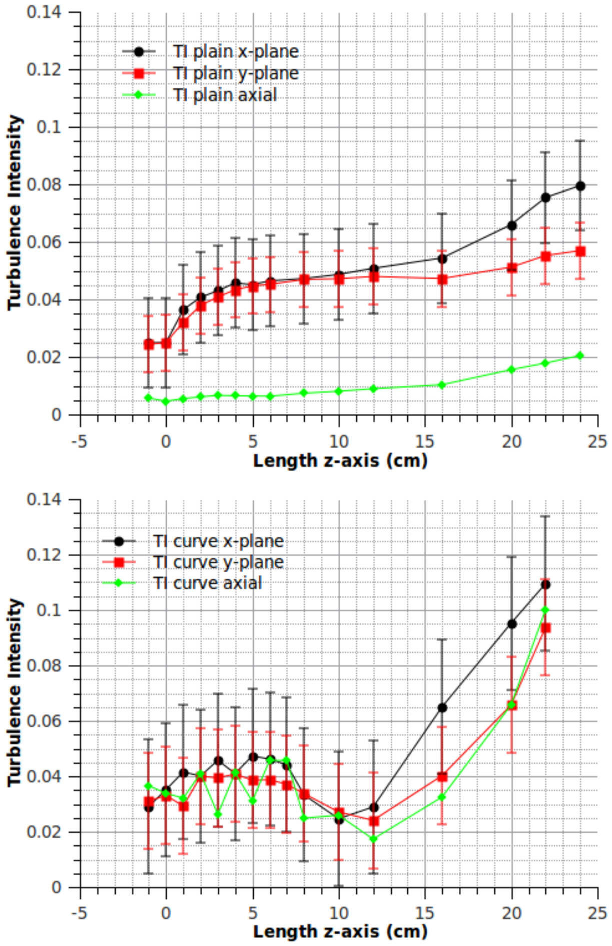

Figure 11 Turbulence Intensity values for different internal curvature geometries: plain- v.s. curved surface

Mapping the values of C_l and C_d for all influencing parameters that maximized the value of $C_l\ C_d$ will result an airfoil with following geometrical parameters, i.e.:

- maximum camber: 0.05c
- Location of maximum chamber (from leading edge) : 0.8c
- Maximum thickness: 0.07c, and

- Angle of attack $\alpha = 6°$

Under these parameters, the respective value of $\frac{L}{D}$ is 15.507. An airfoil with these parameters is similar to the one which classified as NACA 5807. From the results of CFD simulations, the behavior of velocity augmentation for the three investigated diffuser's interior curvature profile can be extracted, which is showed in Fig. 12. The maximum relative axial velocities for diffuser with a plain surface, arbitrary curve, and optimized curve are 1.191, 1.558, and 1.846 respectively, which occurs at positions $x \quad L$ of 0.145, 0.305, and 0.300, respectively.

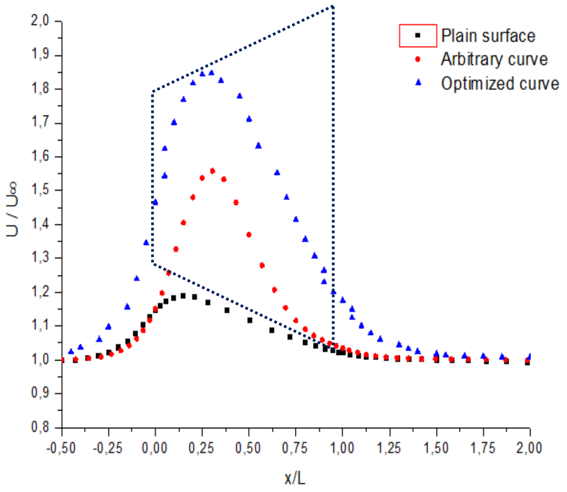

Figure 12 CFD simulation results: axial relative velocity for three different internal curvature geometries: plain, arbitrary curve, and optimized curve

Meanwhile the values of maximum relative velocities obtained from the preliminary measurement were 1.086 and 1.404 for plain- and arbitrary curve surface, respectively. These values show a bit lower (ca. 8-10% lower) in comparison to ones obtained from CFD simulation. This might due to real surface characteristics of material used in the diffuser model, which is different to the assumption of a smooth-surface model that was used in the simulation. The additional velocity augmentation by adding an optimized curve as the interior of a diffuser may achieve 65.5 % in comparison to diffuser with a plain surface. Future efforts will be devoted to validate these simulation results by experimental measurements in the wind tunnel. Modifications on the external geometry of the difuser (such as the inlet and rear flange) are still promising to harvest a more additional velocity augmentation inside the diffuser, which are planned for future research.

5. CONCLUSION

The use of a curvature profile as diffuser's interior may provide local velocity augmentation in the diffuser. This augmentation is contributed from the formation of turbulences behind the diffuser, which are indicated by excessive higher turbulence intensities. The proposed optimized airfoil geometry, which is similar to one classified as NACA 5807 airfoil, provides a local velocity augmentation of 65.5% in comparison to diffuser with a plain surface. This technique makes the harvesting of wind energy potential with a high effectiveness and efficiency feasible, especially for regions with low wind velocity regimes as the case of Indonesia.

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