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AERODYNAMIC CHARACTERISTICS OF HORIZONTAL AXIS WIND TURBINE WITH ARCHIMEDES SPIRAL BLADE

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ABSTRACT

To investigate the aerodynamic characteristics of an Archimedes spiral wind turbine for urban-usage, both experimental and numerical studies were carried out. The Archimedes spiral blade was designed to produce wind power using drag and lift forces on the blade together. Instantaneous velocity fields were measured by two-dimensional PIV method in the near field of the blade. Mean velocity profiles were compared to those predicted by the steady state and unsteady state CFD simulation. It was found that the interaction between the wake flow at the rotor downstream and the induced velocity due to the tip vortices were strongly affected by the wind speed and resulting rotational speed of the blade. PIV measurements revealed the presence of dominant vertical structures at downstream the hub and near the blade tip. Unsteady CFD simulation results agreed well with those of PIV experiments than the steady state analysis. The power coefficient (Cp) obtained by CFD simulation demonstrated that the new type of wind turbine produced about 0.25, relatively high value compared to other types of urban-usage wind turbine.

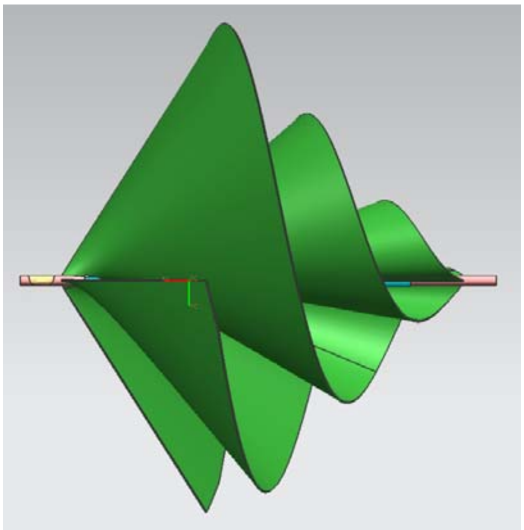
INTRODUCTION

Among all renewable resources, wind energy has been proven to be a relatively matured technology and has tremendous potential in commercialization and mass production. Today the major application of wind power is electricity generation from large grid-connected wind farms. With the expansion of power grid and the reduction of electricity scarce areas, small-scale wind turbine has now been applied in fields such as city road lighting, mobile communication base stations, offshore aquaculture and sea water desalination in several countries [1].

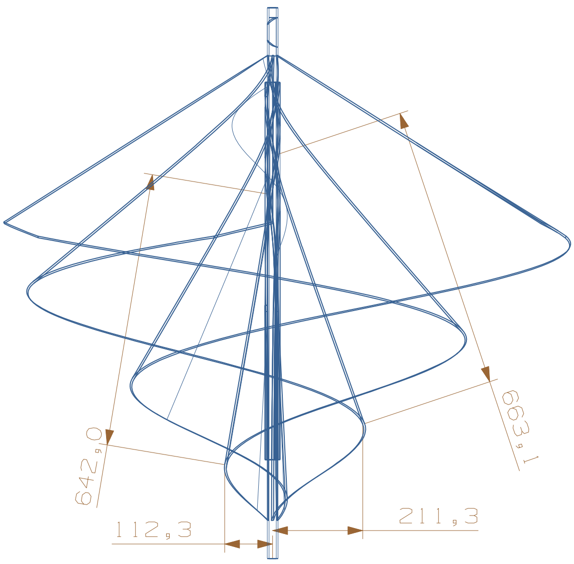
In the small wind turbine field, two types of wind turbine will be classified as HAWT (Horizontal axis wind turbine) and VAWT (Vertical axis wind turbine). Archimedes spiral wind turbine, as new concept structure which using the Archimedes spiral principles [2], is one of the HAWT, but different from traditional HAWT that uses the lift force to take power from wind energy, the Archimedes spiral small wind turbine is mainly depended on the drag force. A schematic diagram of 0.5 kW class Archimedes spiral wind turbine is shown in Fig. 1. The Archimedes spiral wind turbine can be fully stripped of its kinetic energy by reversing the wind. This special structure decides the special aerodynamic characteristics in the small scale wind turbine. Particularly, in the circumstance such as around buildings, the advantage of the Archimedes spiral structure will more obviously according to the facts that there is always wind direction change and wind speeds are low[3].

In the previous researches related on the Archimedes spiral wind turbine, Theoretical and experimental researches have been carried out. Timmer and Toet set one model in the DNW wind tunnel at TU Delft with 0.14m radius and 3mm wall thickness to investigate the aerodynamic characteristics. In their report, the maximum power coefficient was measured at the optimum tip speed ratio. In 2009, the Archimedes spiral wind turbine model was improved by TU Delft. As a result, the highest efficiency measured was 12% [4]. Recently, Lu et al. [5] developed a design method of the Archimedes spiral wind turbine blade and performed a numerical simulation using ANSYS CFX v12.1.

In the present study, an experimental study is conducted to find out the aerodynamic characteristics and evolution of the tip vortex structures in the near wake of the Archimedes wind turbine model installed in an open type wind tunnel. The steady and unsteady CFD simulations on the Archimedes wind turbine are also conducted to test the capability as a design tool for the wind turbine. In addition, aerodynamic characteristics surrounding the wind turbine blade is investigated by using a PIV measurement system. The focus of this research is on quantifying the evolution of the tip vortex properties and velocity distributions, including mean velocities and instantaneous velocities. This research will let us understanding the turbulent wake structures more deeply.



(a) Side-view of Archimedes spiral wind turbine blade



(b) Geometry of 0.5 kW Archimedes wind turbine blade

Fig. 1. Schematic of Archimedes spiral wind turbine blade

NOMENCLATURE

Cp Power coefficient
PIV Particle image velocimetry
X Axial direction
Y Radial direction
λ Tip speed ratio

NUMERICAL AND EXPERIMENTAL METHODS

CFX, one of the analysis programs on fluid mechanics of CFD, which is idealized according to Reynolds Averaged Navier-Stokes Equation and the Finite Volume Method of Governing Equation. The SST (Shear Stress Transport) model has been used in order to predicting the separation of flow accurately [6].

Figure 2 shows that a grid established at preparation phase including flow domain in order to computing the shape of blade on CFX. It separates the grid into the entire domain of using MFR (Multiple Frames of Reference) method, rotating domain of spiral blade and static domain of imaginary wind tunnel simulation. The grid number is about 292,935 on rotating domain, and about 50,106 on static domain, in total it consists of 343,041 grids. In this simulation, we choose three cases to predict the aerodynamic characteristics with inlet wind velocity are 3.5m/s, 4m/s and 4.5m/s; rotating velocity are 300rpm, 400rpm and 500rpm, respectively.

Figure 3 shows the schematic of experimental setup for PIV measurement. The 1/10 down scaled experimental model based on the Archimedes screw was employed to acquire detailed flow information using PIV technique. The PIV system was used to measure the velocity component in 2D plane from horizontal stream-wise (x-y plane). The laser beam illuminated from U wave mini-YAG laser was transformed into a light sheet through cylindrical and spherical lenses. The field of view for velocity field measurement is about 150 mm×120 mm corresponding to the CCD resolution of 1280×1024 pixels. A digital 12bit CCD camera (PCO Sensicam qe camera) was setup vertically under the Archimedes wind turbine to capture particle images in x-y planes. The mean velocity field was obtained by the conventional two frames cross correlation technique with 64 by 64 interrogation window size and 50% overlap. A total of 2000 instantaneous velocity fields were used to provide the ensemble averaged velocity fields and vortical structure.

RESULTS AND DISCUSSIONS

Figure 4 shows the ensemble average velocity fields of the overall flow field on the central of the Archimedes spiral wind turbine at three different wind speeds, through the unsteady numerical simulation study. Remarkably, that is the details of flow behavior that can be obtained at small wind velocities. The highest velocities can be observed at the inner outer most of the rotor in the domain. This nature attributes to the local acceleration around the corner of a blunt shape body.

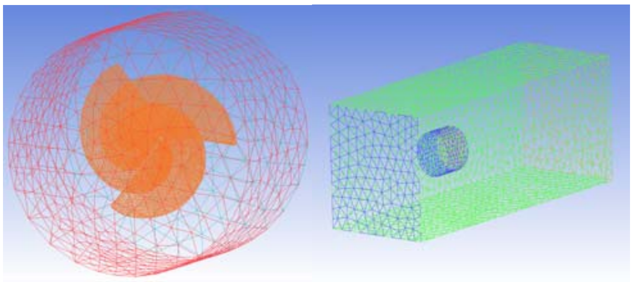


Fig. 2. Meshing of rotating and stationary domain

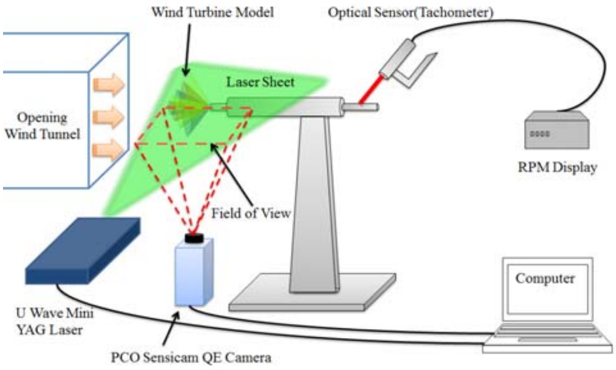
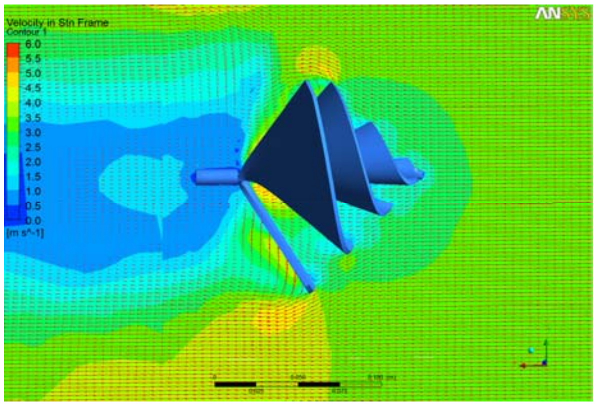


Fig. 3. Experimental setup for PIV measurement

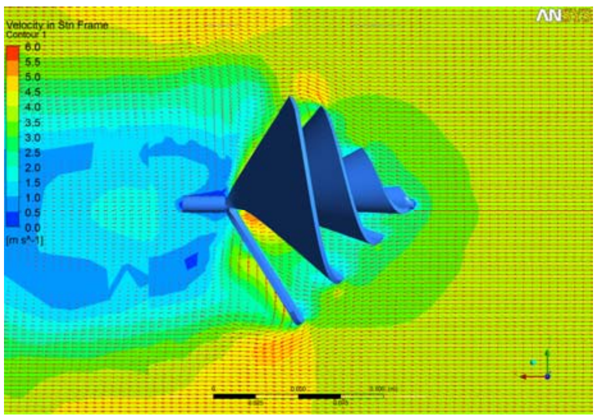
There was a recirculation zone with lower speeds between each blade's spiral sectors. It can also be seen clearly that the incoming airflow was blocked by the hub cone and the rotor. Behind the hub of the rotor, a low-speed region was formed indicating the wake region. As expected, they show geometrically the airfoil with the more twisted angle at the root than the one at the tip. Graphically the longer arrows around the tip on the plots demonstrate that the incoming flow was faster at the tip than at the root. The three plots also suggest that the flow was much slower at the center than the edge. This suggests the stronger flow near the tips of blades would be very beneficial as the flow drives the blade with a longer moment arm.

The ensemble averaged velocity fields near the blade calculated through PIV measurement were illustrated in Fig 5. Here, one can see the incoming air flow can be found to decelerate significantly when it flows across the wind turbine blades. And obviously, it can be seen that the incoming wind speed is much higher than that of local wind speed under blade's rejection. So that, it shows that the position of the kinetic energy of the airflow associated with the velocity deficits has been harvested by the wind turbine. The deformation of flow tube surface is clearly seen due to the tip vortices. It should be noted that there is a large scale vortex structure, which results from a separation behind the blade. The investigation of the time series of instantaneous velocity fields show that there is a fluctuation in the position of the cores of the tip vortices. These fluctuations produce a reduction of vortex intensity when the average values are calculated from the instantaneous fields. The analysis of near rotor wake shows that the blade is a major source of disturbances and unsteady aerodynamic effects. This is due to the spiral shape of the blade. The effects of the rotation speed and wind speed, which means the tip-speed-ratio, of the wind turbine model on the aerodynamic characteristics in the wake were also surveyed. The three PIV experiment results show that they have a similar wake flow mark, and at the same time those contours show that the only differences were just from the comparison of the plots at different tip-speed-ratios. It is obvious that the velocity reductions in the wake region with relatively low tip-speed-ratio are found to be much smaller than that the case with relatively high tip-speed-ratio.

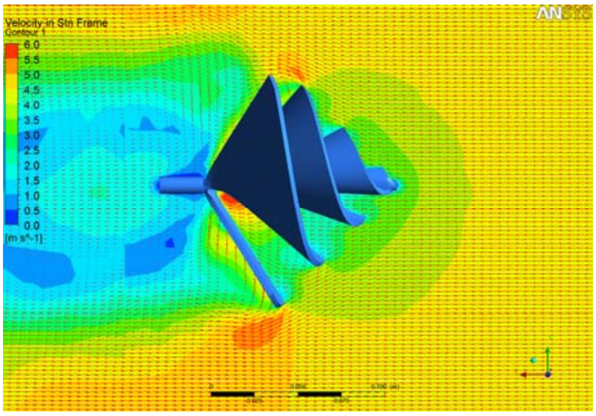
To compare with the results of CFD simulation and PIV experiment for 3.5m/s(300rpm), 4.0m/s(400rpm) and 4.5m/s(500rpm), the line data of ensemble averaged velocity fields have been selected from the blade tip vortex core to the boundary as shown in Fig. 6, respectively.



(a) 3.5m/s and 300rpm

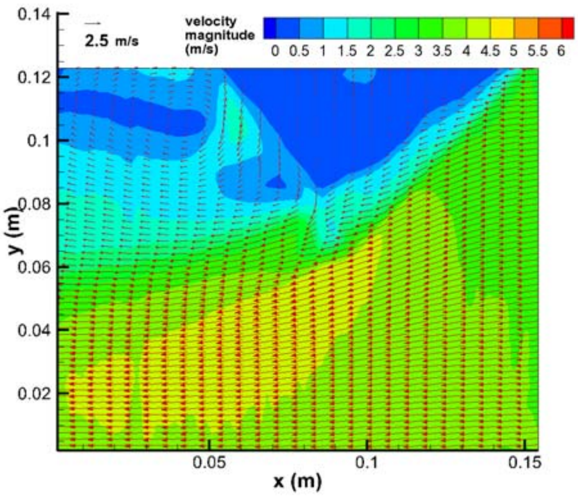


(b) 4m/s and 400rpm

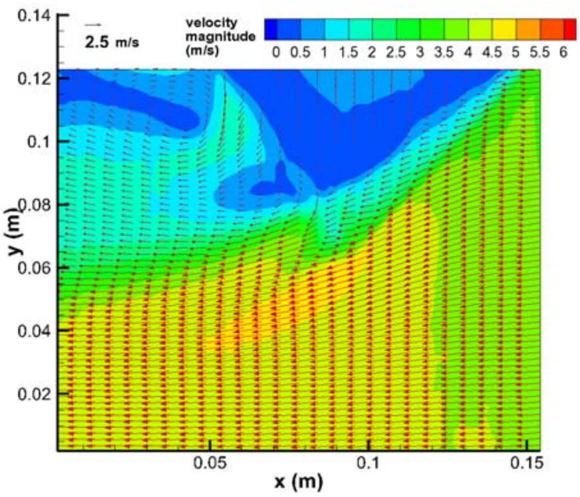


(c) 4.5m/s and 500rpm

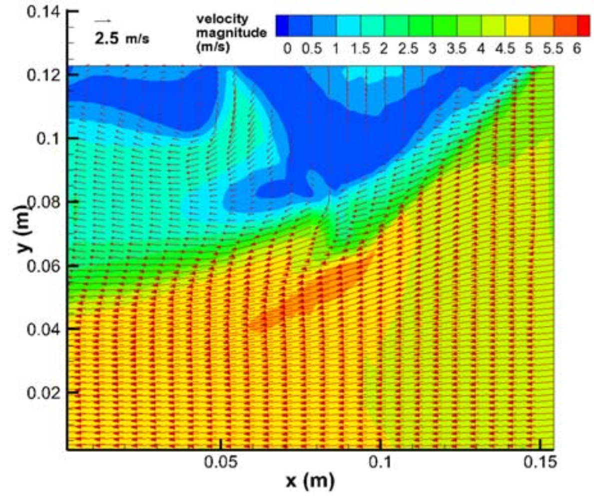
Fig. 4. Ensemble averaged velocity field obtained by unsteady numerical simulation.



(a) 3.5m/s and 300rpm



(b) 4m/s and 400rpm



(c) 4.5m/s and 500rpm

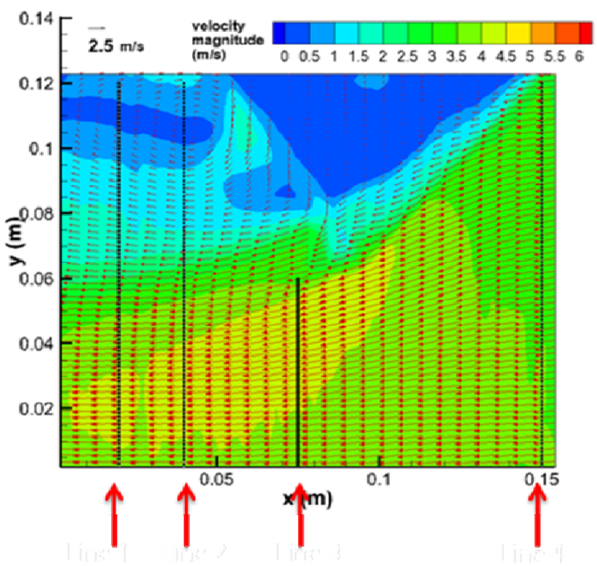
Fig. 5. Ensemble averaged velocity field obtained by PIV measurement.

Figure 7 shows the comparison between CFD and PIV results. It seems that wind velocity of experiment is higher than that in CFD, and at beginning, there is a downward tendency that reflects the situation from upstream to downstream through the core of tip vortex structure. Reading those responses on ensemble averaged velocity field of PIV measurements, it is found that as the relative lower incoming airflow, the tip vortex structures and wake velocity is easier to be influenced because the spiral-shaped blade. And at lower tip-speed-ratio, the influenced region is more widely than higher conditions. From these results, the flow was mainly attached and only separated at the core of tip vortex with similar trend distribution. It means that the downstream mean velocity in the core of tip vortex of PIV is lower than that in the CFX simulation. Around the boundary sections of PIV or unsteady state CFX are similar with each other, especially under 500rpm. In case of the incoming wind velocity is 4.5m/s condition, in this case, the PIV result is in good agreement with unsteady state CFX result. By comparison of the ensemble averaged velocity field and pressure field, because the low pressure area of the suction side gradually moved to the blade tip edge, when the dynamic pressure is less than adverse static pressure, the flow cannot stay at the blade any longer, and the boundary layer would separate, then the separated vortex would form. After that the main separated vortex is further increased and the affected region is even larger. The comparison of the PIV measurement with CFD numerical simulation show that the vector diagram nearly agreed with each other, especially in the shape and the vector trend, as well as the position and size of the tip vortex.

Generally, the flow is explained three governing equation: continuity, momentum, energy. In the case of unsteady state analysis, continuity equation and energy equation are same equations of steady state flow. But unsteady term is consisted of viscous and inertial term. Momentum equation is normalized by characteristic length, characteristic velocity, and characteristic time. In unsteady state, when the air flow passes the blade, the flow has to accelerate to pass the blade surface. As the air continuous passes the wind turbine blade, it will create a low-pressure area on the tip of the blade because the wind across this area will have higher velocity. But the steady state cases have differences from unsteady state that is due to the fact that steady state simulation does not change the relative position between the blade and incoming airflow. And for the region behind blade, due to the fact that Multiple Reference Frames techniques still employs certain steady state assumption to speed up the calculation and thus the initial relative position will still have influence on the following iterations.

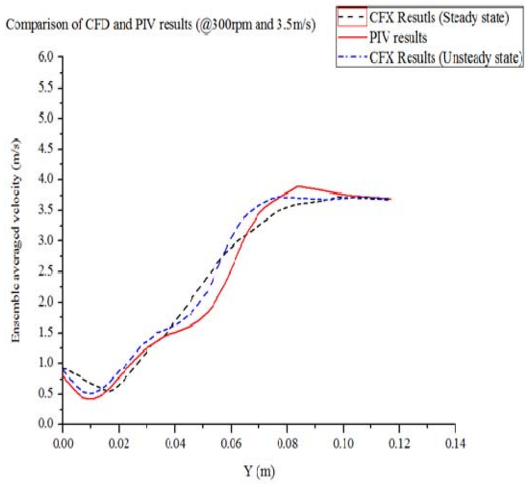
Figure 8 shows Cp versus tip speed ratio curve with regards to the velocity change from 5 m/s to 12 m/s. The maximum power coefficient can be observed near the tip speed ratio is about 2.5 and has approximately 0.25. The power coefficient curves have same tendency regardless of velocities. The modern urban usage 3-blade and Darrieus blade type wind turbines have high rotor efficiency at high tip speed ratio range. It means that high efficiency can be generated in case of high wind speed. Compared to the aerodynamic performance of the other blades in the lower tip speed ratio range, the spiral wind blade with Archimedes shape shows relatively high rotor efficiency.

In addition, the blade had high Cp values in a wider range of the tip speed ratio. Based in the overall aerodynamic characteristics, it can be concluded that the Archimedes spiral blade is suitable axis small scale urban-usage wind turbine.

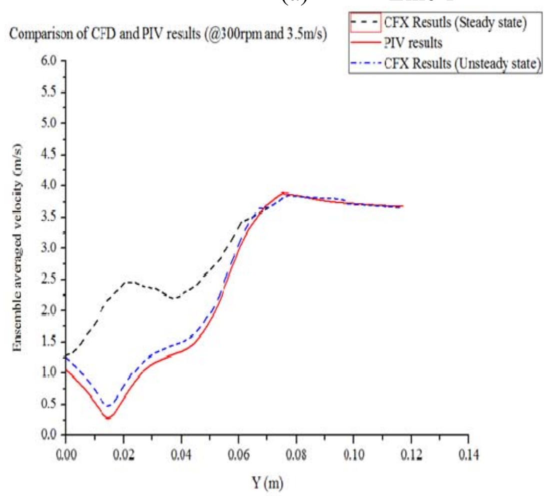


Line 1 Line 2 Line 3 Line 4

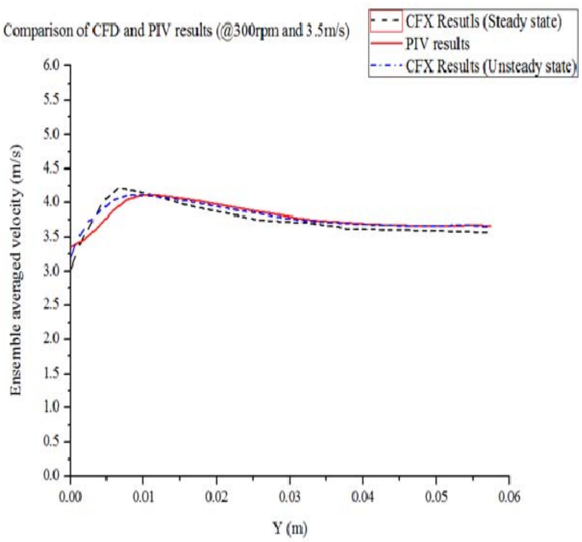
Fig. 6. Data extracted lines for comparison between CFD and PIV results.



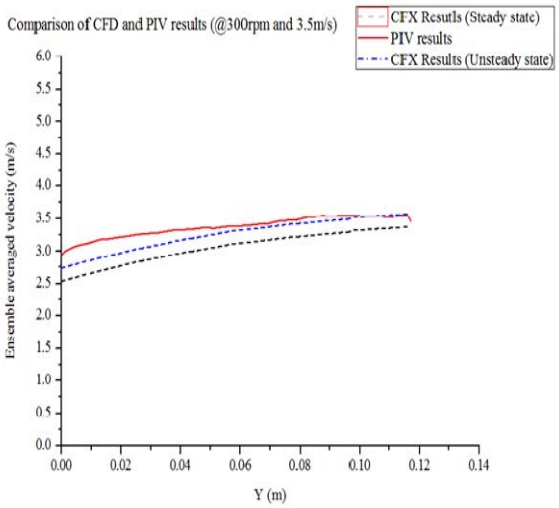
(a) Line 1



(b) Line 2



(c) Line 3



(d) Line 4

Fig. 7. Comparison of experimental and numerical results.

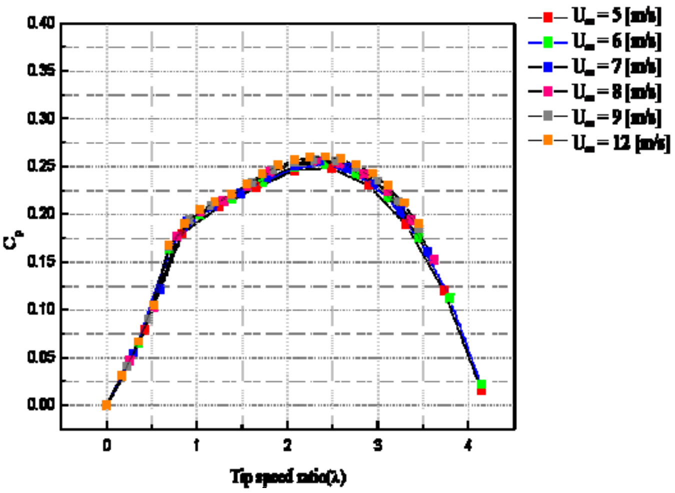


Fig. 8. Cp-Tip speed ratio with respect to the wind velocity.

CONCLUSIONS

In this research, the PIV technique and Numerical study using commercial code is used for velocity investigation in the near wake of the Archimedes spiral wind turbine blade. Through analysis and comparison, the results can be summarized as follows:

1) When there is no drag torque, the pure blade's rotating speed is influenced by inlet velocity, and the predicted blade's rotating speed approach 500rpm while the inlet velocity is 4.5m/s.

2) The inner low speed section rotated the same turning direction of the blade. The relative velocity of the flow is closed zero to the blade.

3) The analysis of the obtained results shows the interaction between the mean flow at the rotor downstream and the induced velocity due to the tip vortices.

4) Measurements revealed the presence of important vortex structures downstream the hub and near the root of the blade. Some instability of the helical tip vortices is also noted. Because of these fluctuations, the instantaneous velocity field is very rich with information.

5) Due to the PIV experiment, the preferable information of the blade flow under different wind velocity of attack is obtained, which would be very helpful to improve the performance and the design method of Archimedes spiral wind turbine.

6) Unsteady CFD simulation results agree well with those of PIV experiments than the steady state simulation.

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REFERENCES

[1] World Wind Energy Association. "*Small Wind World Report Summary 2012*". (2012)

[2] Renewable Energy Policy Network for the 21st Century. "*Renewables 2011 Global Status Report*". (2011)

[3] EDWARD A. ARENS, PHILIP B. WILLIAMS. "The Effect of Wind on Energy Consumption in Buildings". Energy and Buildings 77-84. (1977)

[4] W.A. Timmer and S. Toet. "Verslag van de metingen aan de archimedes in de lage-snelheids windtunnel van dnw". TU Delft. (2009).

[5] Q. Lu, Q. Li, Y.K. Kim and K.C. Kim. "A study on design and aerodynamic characteristics of a spiral-type wind turbine blade". Journal of KSV, Vol. 10, No. 1, pp. 27-33. (2012)

[6] H. Cao. "Aerodynamics Analysis of Small Horizontal Axis Wind Turbine Blades by Using 2D and 3D CFD Modeling". Dissertation of Master degree, University of the Central Lancashire. (2011)