SIMULATION AND PIV EXPERIMENT OF THE DUCTED WATER CURRENT TURBINE AND EXTREMELY LOW HEAD HELICAL TURBINE

Sounthisack Phommachanh[1], Obi Shinnosuke[2], Priyono Sutikno[3], and Aryadi Soewono [4]

[1,3,4]Mechanical Engineering, Institute Technology Bandung, Bandung, Indonesia, Tel: 62-87722200553,
e-mail: sounthisack_phommachanh@yahoo.com, sack_naiy@hotmail.com

[2] Department of Mechanical Engineering, Faculty of Science and Technology, Keio University, Tokyo, Japan

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Abstract

This research introduced for the Ducted Water Current Turbine Triple Helix with very low head less than 2m and water current at river or in the ocean, economical ecological use for small hydro power rating between 100 to 1000 kW still represent an unsolved problem. Unlike conventional hydro installation, water current turbine in open flow and generate power from flowing water with almost zero in environmental impact. Developments in water current turbine design are review and some potential advantages of duct or "diffuser augmented" current turbine and extremely low head turbine will be explored. For the output expected from the project is helical turbine with control flow on duct. The turbine design is based on the vertical turbine with helical blades. The basic idea of this research is optimized the helical turbine model, which is usually used in free stream (directly to the river stream line) can be apply with the situation inside the duct. And this research also tries to optimize the duct design. Therefore, get the better efficiency than the free stream flow turbine. The research aims to apply the helical turbine inside the duct to find the parameter of the power coefficient Cp against tip speed ratio λ. Parameters obtained from simulation in Fluent and through the experimental of the flow analysis by using PIV (Particle Image Velocimetry).

Keywords: Duct water turbines, Helical turbine, PIV experiment, Simulation in fluent

Introduction

Nowadays, renewable energy is very important such as bio fuel energy, wind energy, solar energy, geothermal energy, biomass energy, and hydropower energy. Firstly, renewable energy technologies are clean energy that have a much lower environmental impact than conventional energy technologies. Conventional energy technologies rely on fossil fuels which contribute significantly to many of the environmental problems we face today such as air pollution, greenhouse gases, and water and soil contamination, while renewable energy sources contribute very little or not at all. In hydroelectric power plants, the energy of water utilized to drive the turbine, which, in turn, runs the generator produce electricity. Rain falling upon the earth's surface has potential energy relative to oceans towards which it flows. This energy converted to shaft work when water falls through an appreciable vertical distance. However, the growth rate of large hydropower has been decreased over recent years since most major sites are either already being exploited, or unavailable for other reasons such as environmental considerations. In its place, small hydropower systems have been increasingly used as an alternative energy source of hydro power. So a small system is installed in small rivers or streams with little environmental effect. A water head turbine is the most generally used system, and this makes the turbine rotate by converting the potential energy of the water in to kinetic energy. This turbine has the advantage of high efficiency, but the construction cost for a dam or waterway is high and can cause significant environmental problems. In this way such small hydropower systems do not require a dam to be built.

Water stream turbines are rotated by the force of the river or the ocean current. These turbines are essentially like wind turbines underwater, except that the density of water is 800 times greater than the air. Developments in water current turbine design are review and some potential advantages of duct or “diffuser augmented” current turbine and extremely low head turbine will be explored. For the output expected from the project is helical turbine with control flow on duct with very low head condition (less than 2 m). In this paper introduced about ducted water helical turbine, the parameter that effect to the performance of this kind of turbine. Also, the design and the numerical simulation result of flow velocity field compare to experimental result using PIV.

The Ducted Turbines

Ducted Vertical Axis Turbines

Un-ducted turbines extract the flow energy by reducing the flow velocity with little or no pressure reduction as the fluid passes through the turbine rotor. Therefore, the streamlines must expand to maintain continuity as shown in Figure 1. However, they cannot expand indefinitely; hence, there is a theoretical limit to the percentage of kinetic energy that can be extracted from the flow. This limit has been shown by Betz to be 59.3% using single actuator disk theory. Newman [2] showed that the corresponding limit is 64% for a double actuator disk such as a vertical axis turbine.

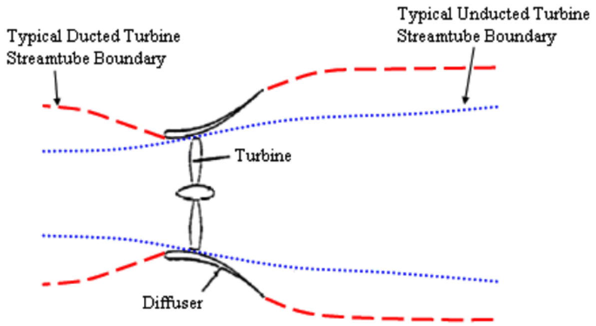


Figure 1. Stream tubes in an un-ducted turbine and a ducted turbine [3]

However, if the turbine is confined in a duct, the flow boundaries are defined and the streamline expansion is limited by the duct geometry. Contrary to un-ducted turbines, the flow energy in ducted turbines is extracted primarily by a pressure drop across the rotor [3]. The pressure drop in a ducted turbine depends on the duct shape and the flow field around it.

The Advantage Associated with Ducting of Vertical Axis Turbine

There are several practical advantages in placing the helical turbine in a duct:

- Higher power can be extracted from a ducted turbine by concentrating the energy of a large area into a smaller area. In this way a smaller, lower cost turbine can be used for a given output power.
- Ducting the turbine decreases the torque fluctuations.
- Low speed sites can be considered for energy conversion, as the flow accelerates in duct.
- Ducts can be used as a float for the structural support of the turbine.
- In areas where there is a danger of divers or floating debris being drawn into the turbine, a grid supported by the ducting could be placed on the upstream opening, thus reducing risk to marine life as well as damage to the turbine from debris.
- Higher velocity in a duct decreases the amount of befouling on the turbine.

Between these extremes, this study proposed placing the helical turbines in ducts to augment the power extracted from a given sized turbine.

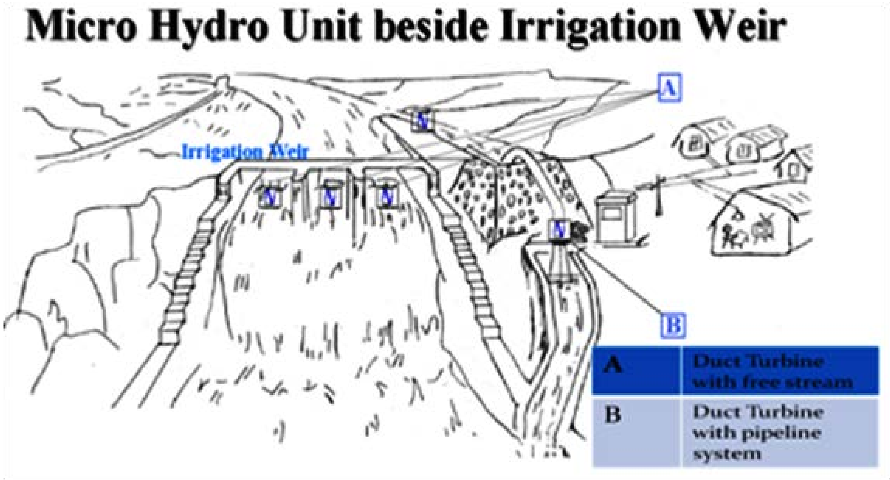


Figure 2. Some application cases for duct water turbine

Helical Blade Vertical Axis Turbines

The Airfoil

An airfoil shaped body moved through a fluid produces a force perpendicular to the motion called lift. Each airfoil is usually the parameter represents by dimension namely C_T, C_N, C_L and C_D. Parameter non-dimension or coefficient resistor airfoil and airfoil lift coefficient of blade related nature of the blade aerodynamics, among other dynamic stall, and boundary layer.

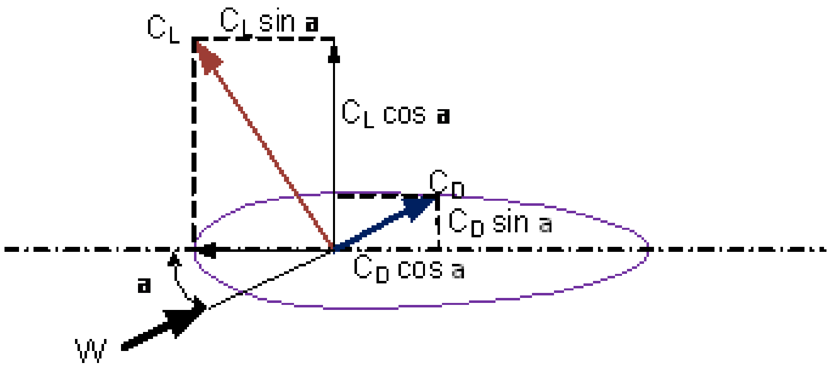


Figure 3. The connection between C_T and C_N through C_L and C_D

Equation of coefficients airfoil is as follows:

$$C_N = C_L \cos\alpha + C_D \sin\alpha \quad (1)$$

$$C_T = C_L \sin\alpha - C_D \cos\alpha \quad (2)$$

The resistor and lift influenced by the speed of the blade is relatively local. The relative speed will give impetus to the blade also the resistor and lift.

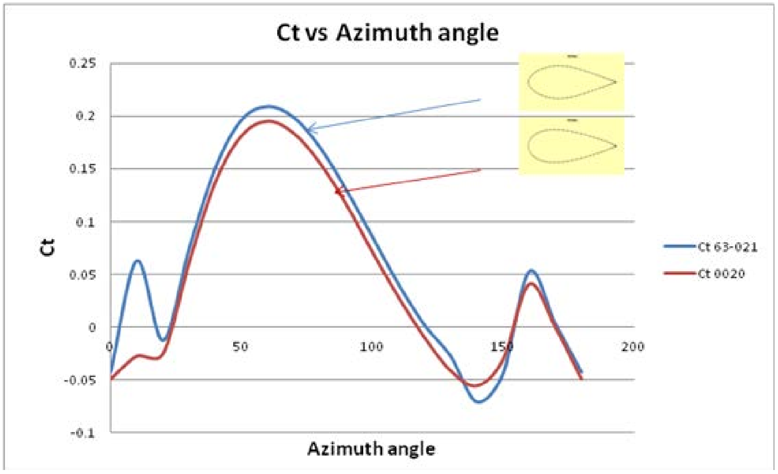


Figure 4. NACA0020 versus NACA63-021 ct and azimuth angle

Naca0020 was originally using by helical Gorlov turbine, from Figure 4 the comparison Ct or tangential coefficient between Naca0020 and Naca63-021 the airfoil of ducted water helical turbine, at Re 14000, tip speed ratio 1.5 shows that Naca63-021 got the better C_T result compare to Naca0020.

The Velocity

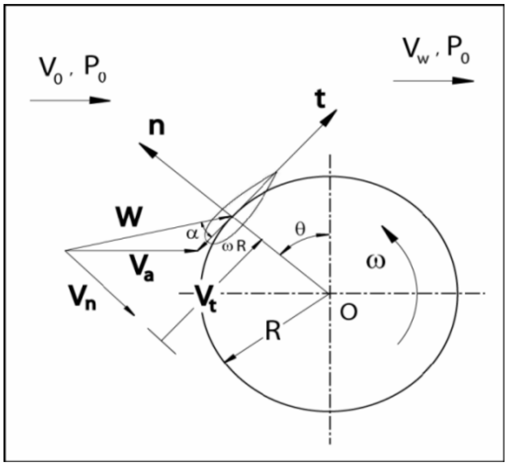


Figure 5. The speed of turbine blade

The connection with the azimuth angle θ and angle of attack α can be found through:

$$W = V_a - \omega R \tag{3}$$

$$V_n = W \times n = V_a \times n \tag{4}$$

So

$$V_t = W \times t = V_a \times n + \omega R \tag{5}$$

Then, it is the result of angle attack α

$$\alpha = \tan^{-1} \frac{-V_n}{V_t} \tag{6}$$

n and t are unit vector to blade chord

$n = \sin \theta$ and $t = \cos \theta$

So the angle attack becomes:

$$\alpha = \tan^{-1} \frac{-V_a \sin \theta}{V_a \cos \theta + \omega R} \tag{7}$$

If the speed ratio $\lambda = \frac{\omega R}{V_a}$. Then the attack angle becomes:

$$\alpha = \tan^{-1}\frac{-\sin\theta}{\cos\theta+\lambda} \qquad (8)$$

Angle α is an angle between relative velocities W with the blade chord. It is the result of the connection between relative velocities W with the azimuth angle by the triangle velocity.

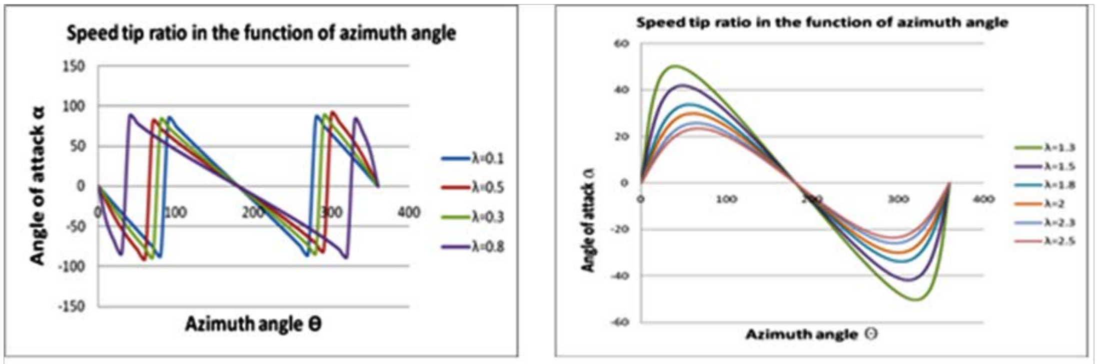
$$W^2 = (V_n)^2 + (V_t)^2 \qquad (9)$$

The relative speed W becomes:

$$W^2 = V_a(\sin^2\theta + \cos^2\theta) + 2V_a\cos\theta \times \omega R + (\omega R)^2 \qquad (10)$$

So that, the relative speed W:

$$W^2 = V_a(1 + 2\lambda\cos\theta + \lambda^2) \qquad (11)$$



α and Θ(λ = 0.1, 0.3, 0.5, 0.8)

α and Θ (λ = 1.3, 1.5, 1.8, 2, 2.3, 2.5)

Figure 6. Angle attack with Azimuth angle

Water Power

Water Power from Kinetic Energy

Water power is come from the kinetic power per second, calculated from the rate of mass flow and speed. The rate of mass flow result from the P_{water} multiply the water volume per second:

$$\frac{dm}{dt} = \rho_{water} \times AV_a \qquad (12)$$

The kinetic power per unit of time:

$$P_{water} = \frac{1}{2}\frac{dm}{dt}V^2 = \frac{1}{2}\rho_{water}AV^3 \text{ .... } (13)$$

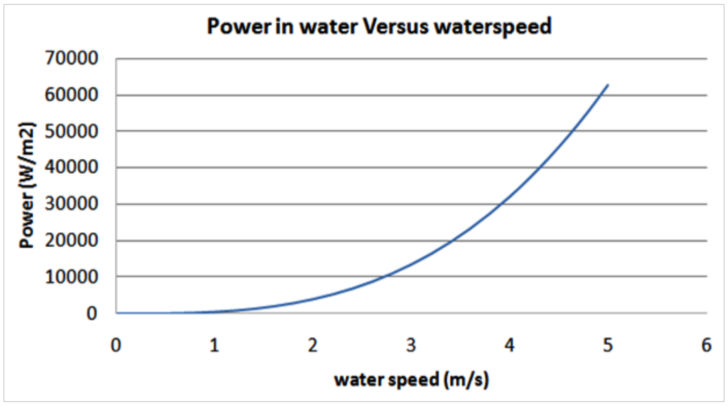


Figure 7. Water Power from Kinetic Energy

Water Power from Potential Energy

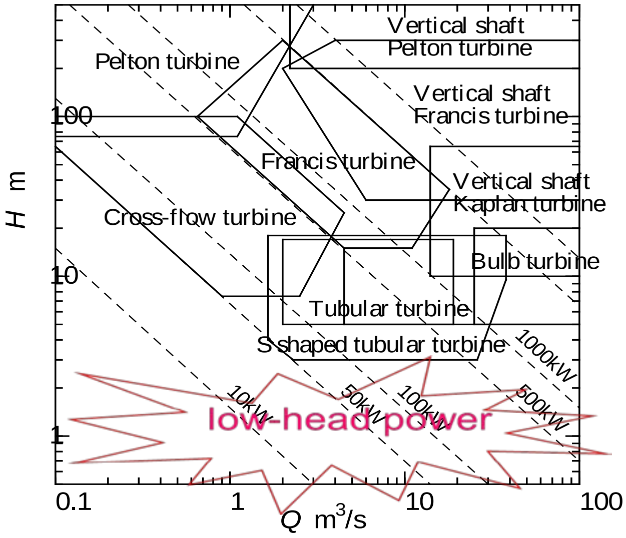


Figure 8. Selection chart of hydro turbine [6]

The low head power is:

$$P_{water} = \rho g Q H \text{ .... } (14)$$

Hydropower generation P_{water} is extracted as an expression of $P_{water} = \rho g Q H$, where, ρ is the water density, g the acceleration of gravity, Q the flow rate and H the head [6]. For developing micro hydropower, in this case the increase of generating power depends on taking lots of flow rate into the turbine. The utilization of further lower head hydropower yields more poor cost effectiveness, exponentially increasing with the decrease of power for commercial based turbine system [9] as shown in Figure 8. Then, another new type of turbine, which has simplified structure and higher performance, is required, different from conventional type. Key factors to develop the micro hydropower are “the cost advantage” and “friendly environment”. To satisfy both factors the turbine system has to be a simple structure with high efficiency, reliable and easy operation, maintenance in ease and long life.

Power of the Turbine

The power produced by the helical turbine is as follows:

$$P_{turbine} = T_{total}\,\omega \qquad (15)$$

The coefficient of the turbine is (C_P).

$$C_P = \frac{P_{turbine}}{P_{water}} \qquad (16)$$

The Turbine and Duct Design

The Turbine Design

For the turbine design the author considered many design concepts to demonstrate the hydro power potential in duct, and the NACA63-021 have been considered to use as and airfoil profile for the blade with the 3 blades turbine. Turbine dimensions are 56mm; Height 65mm; chord length 25mm, 30mm and 35mm (Figure 9). However, in the comparison between simulation and experiment will compare the result of 30mm chord length only, because this case gets the best result in term of rotational speed and efficiency (from simulation) compare to the other cases.

Figure 9. Turbine models for PIV experiment

The Duct Design

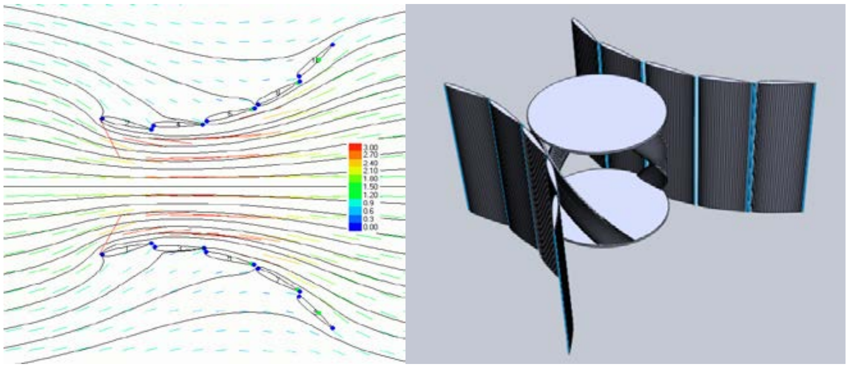


Figure 10. Venturi Duct

The duct design conducted in this research is using the “venturi principle”. In essence, a venturi is constriction or narrowing of flow in channel or pipe this constriction causes a relative velocity increase and pressure drop as flow speeds up through the constriction. The venturi duct dimensions are 0.3x0.135m for the duct inlet; 0.1x0.135m for the throat and 0.3x0.135m for the duct outlet.

Simulation Result

The Duct Water Turbine adopted the helix blade system. In this research, CFD analysis has been carried out to study the performance of the Ducted Water Turbine and the optimal geometries and operating conditions were determined through parametric studies. A three dimensional analysis was acceptable because a helical blade was utilized in the turbine, meant that there was need to consider the span length and the height, the commercial program, FLUENT ANSYS 12.1 was used for the CFD analysis. A moving mesh method was required at the boundary region to simulate the rotor blade rotation. Table (1); (2) lists the parameter of CFD analysis. The fluid property for analysis the model was general data of normal temperature water.

Table 1. Parameter of CFD Analysis

Parameter	**Value**
Analysis type	3D
Scale	mm
Viscous model	Standard Reynolds stress
Azimuth angle	10˚ rotating

Table 2. Geometric Value of the Verification

Parameter	Value
Number of blade	3
Hydrofoil	NACA 63-021
Chord length	25mm,30mm,35mm
Radius of turbine	56mm
Flow speed	From inlet (0.15;0.3m/s)
Speed tip ratio	(Turbulent flow) TRS

At Velocity 0.15m/s

Figure 11 shows the path lines of the simulation at velocity 0.15 m/s, Figure 12 shows the result of the torque at 0rpm and the total moment is always positive, in the other words with the venturi duct, helical turbine can be self-starting at velocity 0.15m/s.

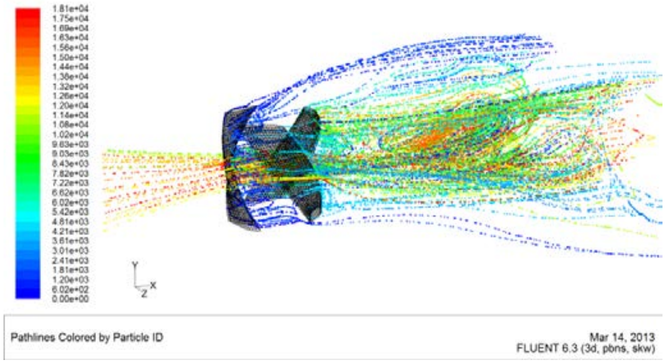


Figure 11. The Simulation path lines V=0.15m/s

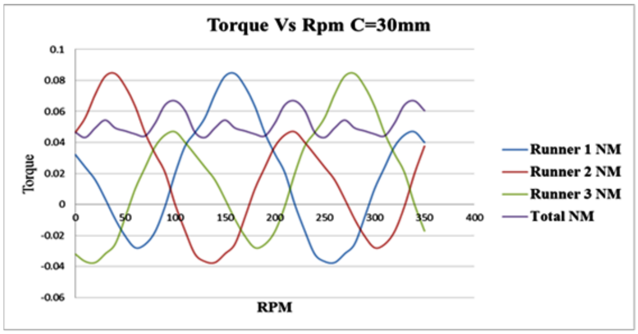


Figure 12. Torque at 0rpm, 30mm chord length

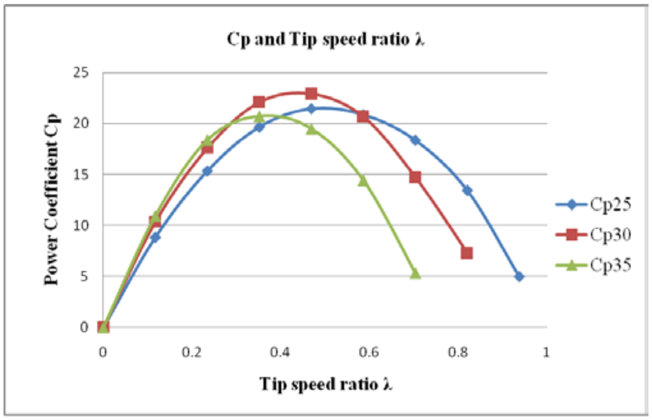


Figure 13. Cp Vs Rpm at Velocity 0.15m/s

Figure 13 shows the data from the simulation by using fluent analysis at V = 0.15 m/s, which show the maximum Cp of the turbine is 23% at 30mm chord length, the maximum tip speed ratio is 0.97 at 25mm chord length and the Cp curve of simulation for all three turbine cases will going down after the optimum point.

At Velocity 0.3m/s

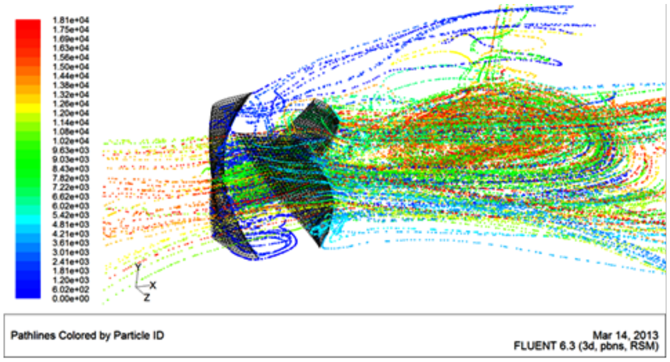


Figure 14. The Simulation path line V=0.3m/s

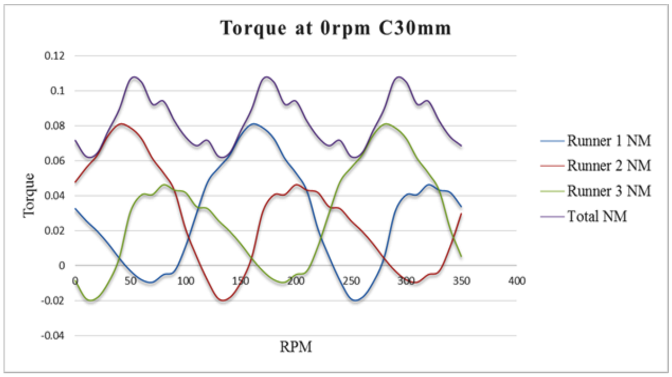


Figure 15. Torque at 0rpm, 30mm chord length

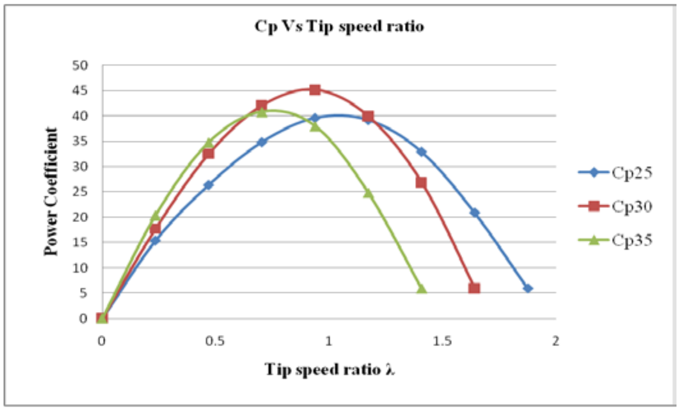


Figure 16. Cp Vs Rpm at Velocity 0.3m/s

Figure 14 shows path lines of the simulation at velocity 0.3 m/s, Figure 15 shows the result of the torque at 0rpm and the total moment is always positive. So, the turbine is self-starting at velocity 0.3m/s.

The Figure 16 shows the data from the simulation by using fluent analysis at V = 0.3m/s, which show that the optimum of Cp is 45% at 30mm chord length, the maximum tip speed ratio is 1.9 at 25mm chord length and the Cp of all three turbine case will going down after the optimum point.

Experimental of Flow Analysis PIV

Particle Image Velocimetry (PIV)

Particle image velocimetry (PIV) is an optical method of flow visualization used to obtain instantaneous velocity measurements and related properties in fluids.

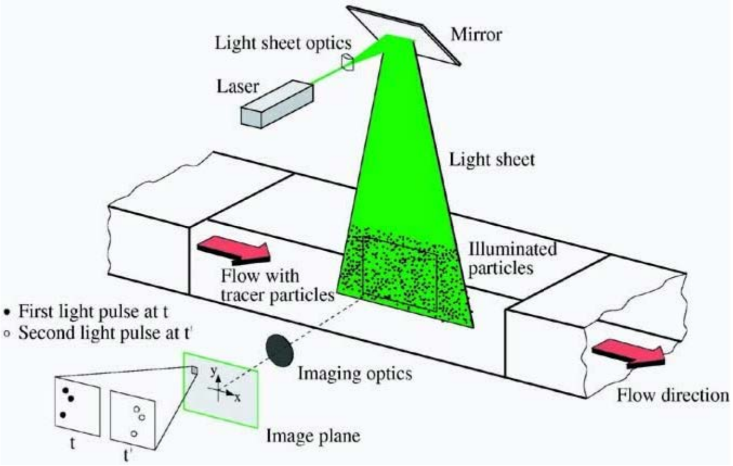


Figure 17. Particle image velocimetry (PIV) [10]

In this research will use the PIV to analyst the velocity field in the upstream and downstream of the duct water turbine.

Experiment

The 2 dimensional of PIV was constructed for the flow analysis of the duct water turbine show in the Figure 18.

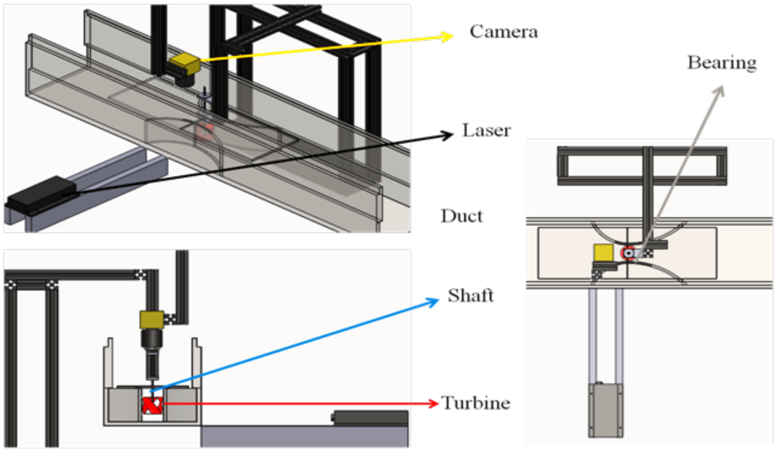


Figure 18. The Experiment set-up for PIV

The sizes of the water tunnel are 0.3x0.135x1.7 m the water tunnel creates the flow velocity at the maximum point is 0.3m/s. The turbine blade profile is NACA63-021, D=56mm, H=65mm, 3 cases of the turbine with difference chord length (c=25, 30, 35 mm). Measure the upstream and downstream of the turbines. In the experiment 5000 images or 2500 pairs have been taken for each case with the time distance between first and second image is 0.0005s (Δt=0.0005s). Therefore, get more accurate result from the statistical analysis.

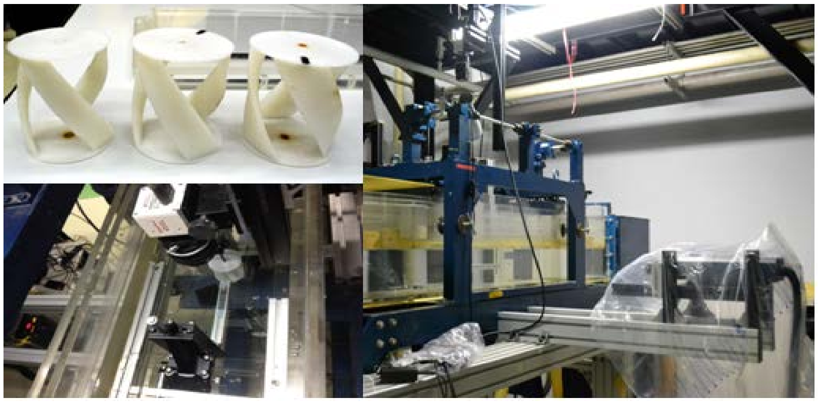


Figure 19. The set-up for experiment in Keio University

The Flow Velocity Field Comparison of the Simulation and Experiment

In the comparison the turbine side 56mm diameter, 65mm high and 30mm chord length, velocity inlet at 0.3m/s and 450rpm turbine rotational speed, have been chosen as the comparison case of the contour and vector image between simulation with the PIV experiment.

The velocity field image from PIV experimental result and simulation result shows some similarities between them in term of velocity field also the direction of the flow, the flow velocity starts to increase when it arrives to the throat of the duct and highest velocity is in the left side of the turbine (in the experiment). For the downstream the PIV result shows one very high vortex behind the turbine and also high flow velocity on the left and right side, the effect from the blade in front and blade behind created the turbulent flow also vortex behind turbine. For the simulation also get the same effect of the blade in front and blade behind but the contour result is not showed only one vortex but many of the vortexes behind the turbine. However, if ignore small vortexes behind the blade 3 so the result of the experiment for contour of the flow velocity field is similar to the experiment.

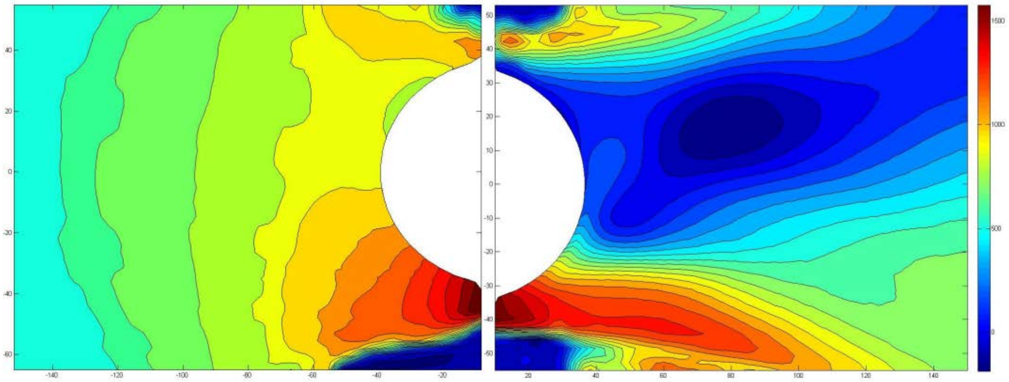


Figure 20. Contour of the velocity from PIV 30mm chord length

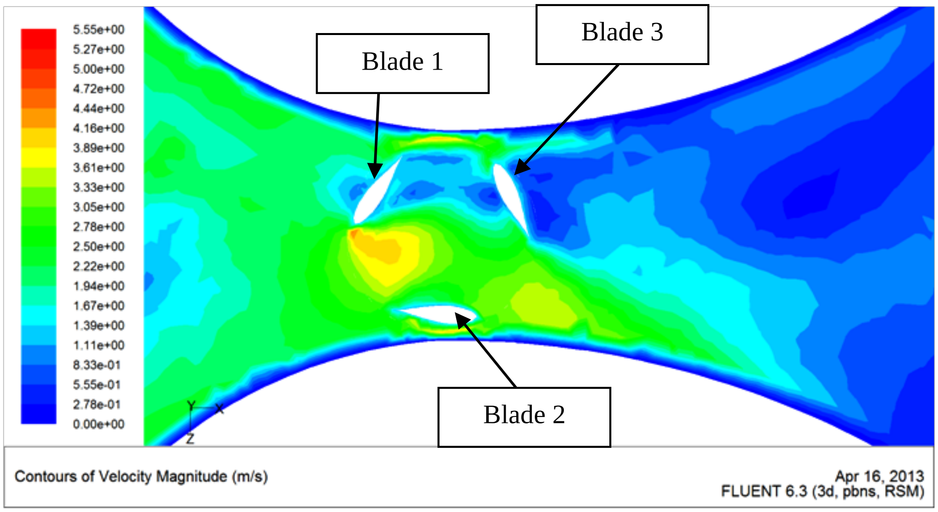


Figure 21. Contour of velocity from the simulation 30mm chord length

The vector comparison shows clearer about the effect of the flow behind turbine, the cause from the effect of blade in front (blade 1) to the blade behind (blade 3); it makes the result of the rotational speed decrease.

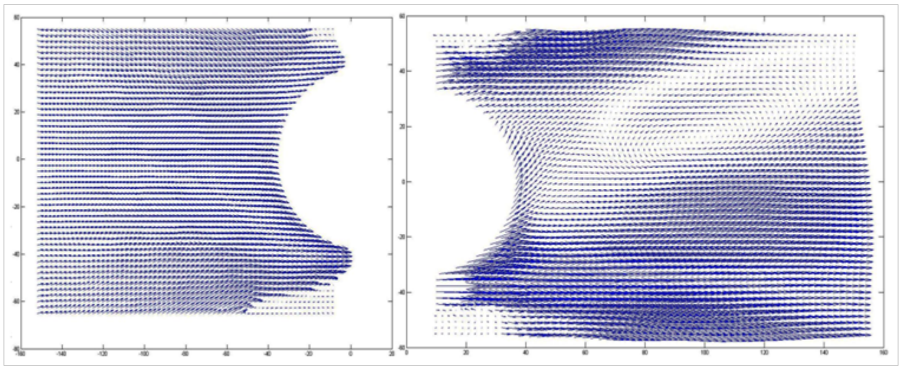


Figure 22. Vector of the velocity from PIV 30mm chord length

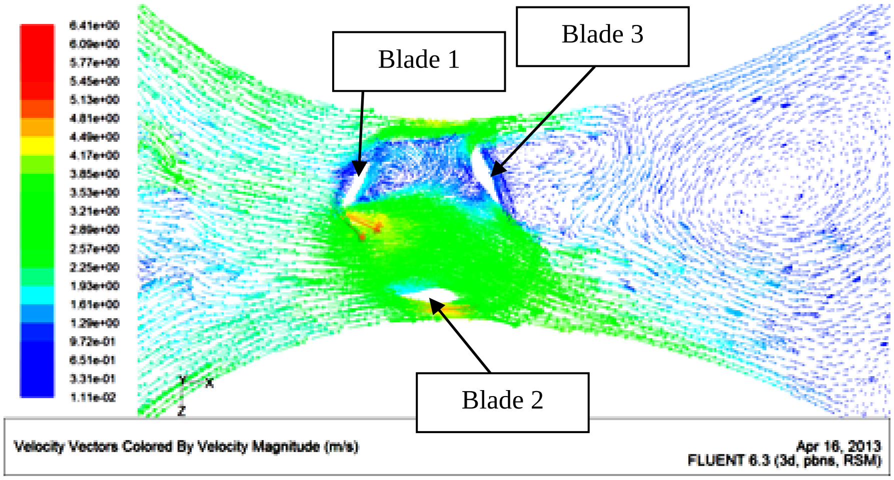


Figure 23. Vector of velocity from the simulation 30mm chord length

Conclusions

In the simulation the efficiency result was 23% at 0.97 tip speed ratio with velocity 0.15 m/s and the highest efficiency is 45% at 1.9 tip speed ratio with velocity 0.3 m/s. At 3 deference types of turbine's chord length, the best result was c=30mm, also with venturi duct design the turbines have a self starting with very low velocity condition 0.15 m/s. The flow velocity comparison between simulation and PIV experiment the result was similar.

According to the result of experiment and simulation, there are three phenomena to get the optimum Cp of the ducted water turbine that become the full attention of the ducted water turbine design, that is the stall phenomenon happened to the angle of attack α which is so high when the turbine rotor rotates slowly. It is also the decreasing the lift forces on the turbine rotor. Because of the helical turbine is one of the turbines uses the lift force principle to get the energy, so of course the Cp got is low. Next, the vortex phenomenon resulted by the turbine rotor blade if the rotor blade rotates very fast and the effect of the blade in front to the blade behind. It will influence the amount of kinetic energy reserved by the turbine rotor, and in the same time it created the vortex that push the turbine blades rotate faster so the Cp got could be increase or decrease depend on the suitable shape between the turbine and duct. And the last phenomena of the ducted turbines the theoretical limit depends on the pressure difference that can be created between duct inlet and outlet, and the volumetric flow through the duct. These factors in turn depend on the shape of the duct and the ratio of duct area to turbine area.

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