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Optimization of Output Parameters of The Horizontal Tidal Turbine by Modifying Its Meridional Section

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Abstract*—The velocity of tidal current at the location of Haya Strait shows that the velocity of ocean currents could reach 2.54 m/s with the available power density of P_d = (0 - 3670) x10-3 kW/m². To utilise the available energy, then a prototype of bulb propeller tidal turbine in the form of Venturi canal was designed and tested using a raft platform. The dimensions of the turbine; inlet diameter D_0 = 4 meter and impeller diameter D_1 = 1.5 meter and outlet diameter = 2.60 meter. At the speed stated above, hydraulic force obtained reached 324 kW. Optimization of turbine output parameters is carried out through structural modification and cross-view geometrical modification. Turbine meridian cross view section is modified to be streamlined. In this case, cross view modification by adapting ducted-turbine that is carried out without changing the inlet dimension. Flow velocity was measured at three turbine sections, namely at the inlet section, the impeller housing section and the outlet section. Rate of meridian flow is measured at three meridian positions, which are V_0 at the inlet, V_1 at the impeller and V_2 at the outlet. Output parameters are calculated based on the water velocity and the data measured at the three corresponding sections. The maximum power coefficient was found to be 0.593 that occurs at the induction factor value of a = 0.346 and the maximum thrust coefficient of C_T = 1 was found at the induction factor value of a = 1. The hydraulic power is changed from 0.00 ÷ 226 kW to 0 ÷ 324 kW, or an increase of 43%. The turbine brake power is changed within the range of 0.00 ÷ 194 kW to 0 ÷ 221 kW that is equivalent to 14% of power increase.

***Keywords*—Sea current velocity, bulb turbine, turbine geometry modification, power and thrust coefficients, power output characteristic**

I. Introduction

The use of Renewable Energy as an energy source is the focus of providing energy on the economic, ecological and social development of the community as well as an effort to support Renewable Energy Based on Industrial Development (RE-BID) program.

The physical properties of tidal currents in several Indonesian archipelago areas provide an opportunity to be converted into electrical power. Ocean current power is generated from the kinetic energy of ocean currents has the high load capacity resulting from the high density of fluid. [1,2] The tidal currents velocity in the straits between small islands in Maluku regions may reach of V_0 = 0 ÷ 2.54 m/s, which is a potential source of energy that can be developed [3] through the use of tidal turbines.

Research results show that the more popular available turbines model is the horizontal axial tidal turbine [4], [5] which uses a shrouded or unshrouded free stream [6]. Studies of the characteristics of shrouded turbines have been carried out by Much [7] who examined the design and assessed ducted turbine performance, which describes the the relationship of energy parameters as a function of current velocity. A similar study was done by Belloni [8] who examined the hydrodynamics of ducted and open-center tidal turbine and described the relationship between power coefficient and thrust coefficient as a function of dimensionless parameters 'a'. Both of these studies were carried out using numerical methods based on CFD.

A study for optimization of the power output has been carried out by C.J. Lawn [9] by modifying the meridional section geometry of the ducted turbine. The analysis was done by using the one-dimensional theory.

The research team of the Faculty of Engineering of Pattimura University in 2015 designed and tested the performance of the prototype of the horizontal Venturi bulb propeller tidal turbine with an impeller diameter of D_1 = 1.5 m (Fig.1).

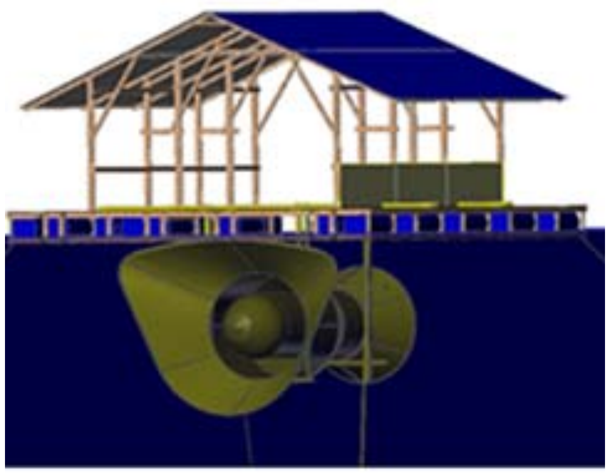

Fig 1. Scheme of tested turbine under a raft

Similar to the studies above, in this study, the Venturi bulb turbine geometry [8] was modified by adopting the ducted turbine model [7,8] to optimize turbine output parameters.

The performance of the turbine was determined by using one-dimensional flow analysis through a turbine section. The turbine characteristics are the relationship between power coefficient C_P and thrust coefficient C_T as a function of the induction factor value a [9, 10] and thrust (kN) and power (kW) parameters as a function of current velocity that is measured by the turbine testing.

II. RESEARCH METHODS

A. Determination of the power availability

The daily current velocity vector in Haya Strait showed that the free velocity of ocean currents at the turbine inlet reaches 2.4 m/s, with its direction parallel to the turbine axis. The flow entered the turbine through the inlet section. The mass rate of flow entering the turbine wass very dependent on the shape and geometry of the meridional cross-section of the turbine. This dependence was described by discharge coefficient value C_Q. By using the principle of mass conservation, and take to the account the value of C_Q, the flow rate entering the turbine was calculated as

$$Q = C_Q \cdot Q_0 \tag{1}$$

The peak power of the turbine is explained by the momentum theory [4] or the Fraenkel equation [5,11]:

$$P = \frac{1}{2}\rho A_{ref} C_p U_{ref}^3 \tag{2}$$

Where, C_P is turbine power coefficient, one of dimensionless numbers characterizing the tidal turbine [4], ρ is sea water density = 1025 kg/m^3 and A_{ref} and V_{ref} are the cross-sectional area and velocity references, respectively.

B. Turbine Design

Turbine design was carried out by using continuous flow equation in the Venturi and ducted turbine. The impeller diameter was calculated based on the meridional velocity V_m and discharge Q. The inlet cross-sectional area was calculated to guarantee the merional velocity and the amount of discharge that must enter the impeller area.

According to the construction and strength of the shaft calculations, which took into account impeller diameter D_1 and hub to tip ratio $\bar{d}_{bs}=d_b/D_1$, the meridional velocity was

$$V_m = \frac{4Q}{\pi D_1^2\left(1-\bar{d}_{bs}^{\,2}\right)} \tag{3}$$

According to the power design, the turbine construction parameters were determined as follows: the diameter of the turbine prototype impeller was D_{1V} = 1.5 m (case 1), with the number of blades z = 4 pieces, the angle of attack α_1 = 75^o, the angles of the blade slope β_1 = 35^o and β_2 = 33^o.

In this study, the shape of the meridian cross section was modified from Venturi type by adapting ducted turbines. Modifications were made for $\bar{d}$bs size and outlet diameter with D_{1d} = 1,84 meters (case 2). Schematically the cross-section of the turbine meridian is shown in Fig. 2. The other geometry parameters of the turbine parts was calculated based on D_1 size.

C. Calcutation of turbine characteristics

Modified cross-section geometry of the ducted turbine in study optimization power output from aducted turbines [9] showed that changes in turbine parameters was a function of the resistance coefficient K, which depends on the value of flow velocity V_1 in the impeller area. Defenition of resistance coefficient K is

$$K = 2\left(\frac{U_0}{U_1} - \frac{U_2}{U_1}\right) \tag{4}$$

Theoretically, the power coefficient of Cp was calculated as a function of the resistance coefficient K.

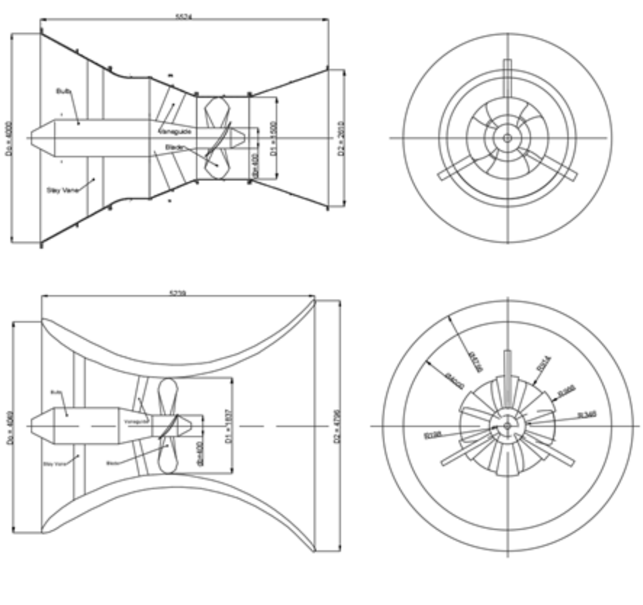

Fig 2. Both cases meridional sections

Two important parameters characterizing the tidal turbine aee the power coefficient Cp and the thrust coefficient C_T. Definition of the power coefficient is (6) [7, 8,12]:

$$C_p = \frac{P}{0.5\rho A_{ref} A_0^3} = 4a\left((1-a)^2\right) \tag{5}$$

For the ducted turbine, the value of power coefficient is reached to C_P =0.593 [3]. The thrust coefficient C_T is defined in equation (7) [7, 8] :

$$C_T = \frac{P}{0.5\rho A_{ref} A_0^2} = 4a\left((1-a)\right) \tag{6}$$

Where, induction factor a = $(V_0\text{-}V_t)/V_0$, P is turbine power, V_0 is tidal current velocity, V_t – water velocity at impeller area.

The specific energy was determined by pressure change and velocity at the inlet and outlet cross-section of the turbine. A solution for Bernoulli equation for two poits in one flow line on upstream and downstream of impeller was obtained as [13]:

$$\frac{gH_T}{\omega} = (rV_u)_1 - (rV_u)_2 \tag{7}$$

The rotational moment was calculated from different of local water velocity before and after impeller at meridional-section of impeller area which was equal to the thrust T multiplied by the impeller's radius R_1. The rotational moment was defining by equation (9)

$$M_x = 0.5 A_1 V_1 \left(V_0^2 - V_1^2\right) \cdot R_1 = T \cdot R_1 \tag{8}$$

According to equation (9), the power generated in the impeller was calculated by equation (10)

$$P_t = M_x \cdot \omega \tag{9}$$

Turbine characteristics were described as the relationship between the output power of the turbine P as a function of the free flow velocity V_0.

Water velocity in each cross section was measured using current meters, which were installed in each section (Fig. 3).

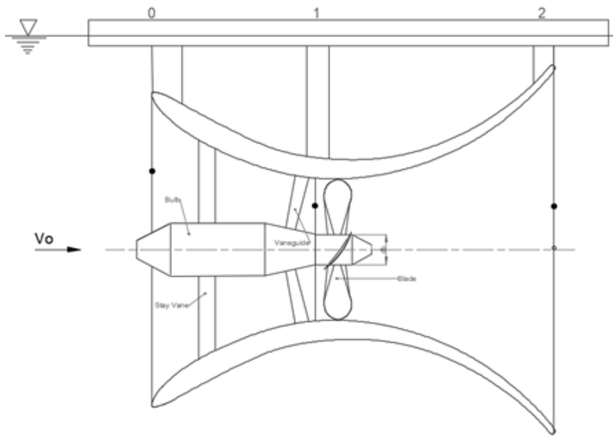

Fig. 3.Testing model of the turbine

The velocity measurement data was used to calculate the energy parameters that characterized the turbine performance in testing the turbine prototype at the location.

III. Results and Discussion

A. Power density

The daily current velocity data was used to calculate the local power density of Haya Strait. Fig. 4 shows the power density (kW/m^2) as a function of changing of the free stream velocity of V_0 (m/s).

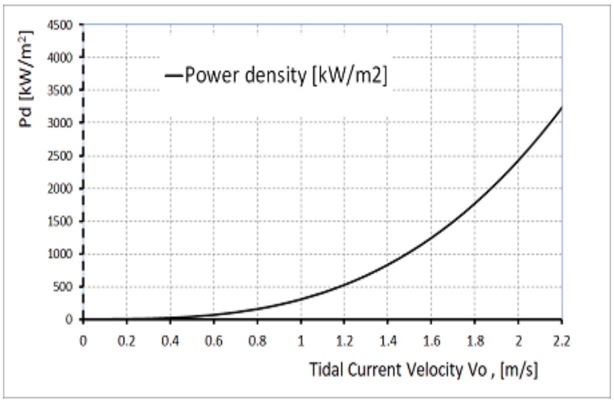

Fig. 4. Local power density of Haya Strait.

Fig. 7 shows that at sea current velocity V_0 = 0.2÷2.4 m / s, the power density value ranged between P_d = (0.3 ÷ 3670) x10^{-3} kW/m^2.

B. Experimental data

Flow measurement results at three cross sections of turbine showed that for each sea current velocity V_0, the velocity value at Venturi cross-section 1-1 (case 1) ranged from V_{1V} = 0.0 ÷ 5.42 m/s, and at the cros-section 2-2 velocity values ranged from V_{2V} = 0.0 ÷ 2.38 m/s.

After modifying the impeller diameter D_1, outlet diameter D_2 and the meridional cross-section (case 2), the average velocity at cross-section 1-1 ranged from V_{1D} = 0.0÷7.51 m/s, and at cross-section 2-2 ranged from V_{2D} = 0.0÷1.05 m/s.

Changes in the flow velocity value at the measuring point in the cross-sections 1-1 and 2-2 as a function of the free stream velocity V_0 in the turbine before and after the modification are shown in Fig. 5.

Based on the flow velocity value in the turbine, the discharge coefficient values for both cases were equal C_{QV} = 0.45 and C_{QD} = 0.593. This shows that the flow rate passing through the modified turbine (case 2) with the cross section A_{1D} was higher than the flow rate through the turbine with cross-section A_{1V} (case 1), whereas in case 1 the discharge ranged from Q_V = 0 ÷ 12.71 m^3/s, while the discharge through cross section in case 2 ranged from Q_D= 0 ÷ 18,965 m^3/s.

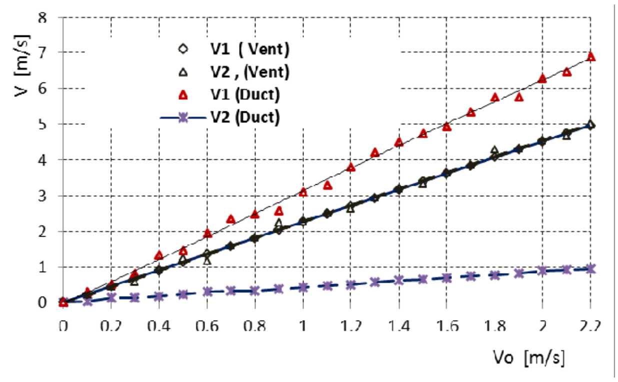

Fig. 5.Distributions of flow velocity in the turbine.

C. Turbine Performance

Theoretically, the relationship between the value of power coefficient and variation of the value of the resistance coefficient K shows that the value of the power coefficient reaches the maximum number of C_{Pmax} = 0.593 at the value K = 2 for the two types of turbine cross section, as shown by C.J. Lawn [9]. The Cp/ηt parameter value as a function of the varied K value is shown in Figure 6.

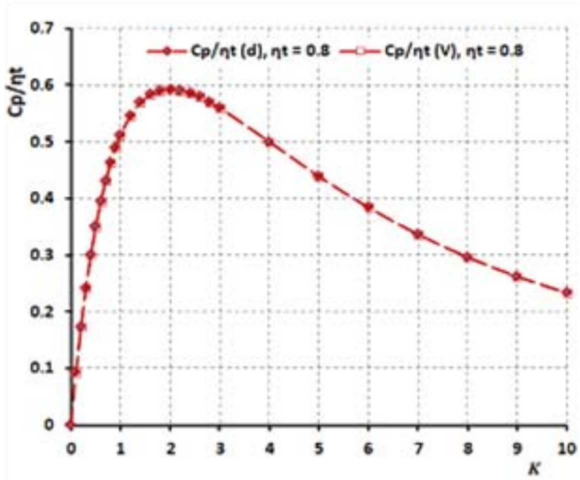

Fig. 6. Theoretical Power Coefficient.

In the case of modification with the selected sectional flow, based on equation 4, for case 1, the value of Cp_{max} = 0.591 at a value of K_V = 0.785, while for case 2 the value of Cp_{max} = 0.593 at a value of K_D= 0.375. This proves that at this value, the Venturi effect accelerates the flow rate or enlarges the flow entering the turbine.

The calculation results of the power coefficient and thrust coefficient were as a function of the reduction factor a in the turbine according to equation (5) and (6). This result (Fig. 7) shows that the power coefficient C_P and thrust coefficients C_P in both cases had values close to the values obtained by modeling the CFD, as investigated by Belloni [8] and the results of C.J Lawn experiment [9], where the C_{Pmax} power coefficient = 0.593 occured at the factor induction value of a = 0.324 or the value of V_0 = 1.0 m/s. In the other side, the value of C_{Tmax}= 1 occured at a factor induction value of a = 1 or the free stream velocity of V_0 = 1.5 m/s.

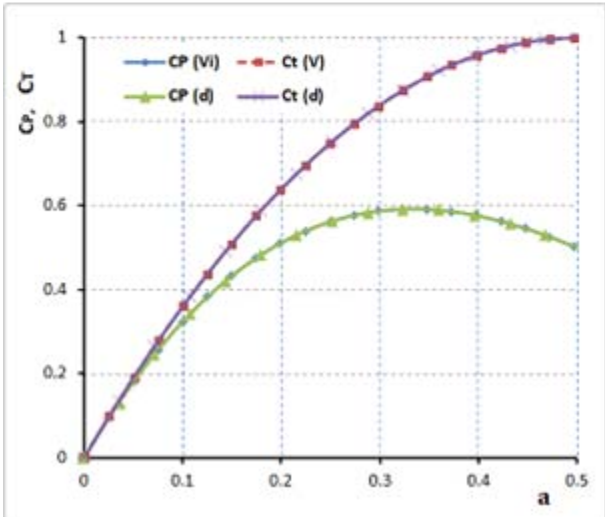

Fig. 7. Relation of CP and CT to induction factor a

Hydraulic power P_W and the turbine shaft power P_T were calculated by using equations (1), (9) and (10). Figure 8 shows the result of the calculation of hydraulic power and the power of the turbine shaft as a function of the values of V_0 in both cross-section types.

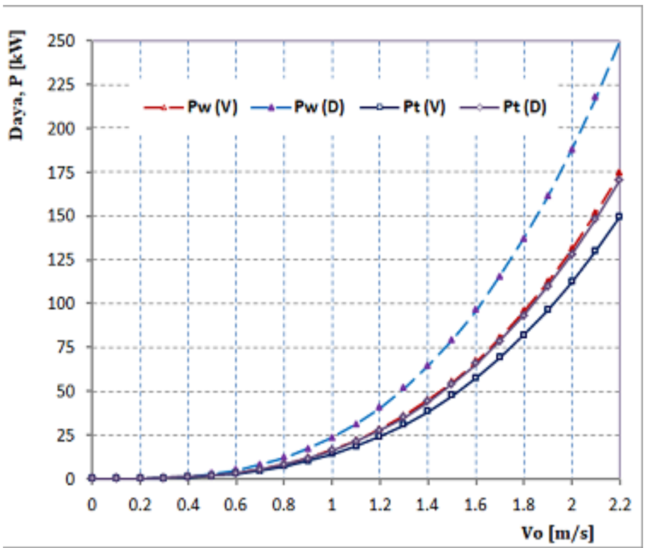

Fig. 8. Relational power as a function of the tidal currents

Fig. 8 shows that changes in the size and shape of the turbine meridian section by increasing the impeller diameter from D_{1V} = 1.5 m to D_{1D} = 1.84 m and changes in outlet diameter from D_{2V} = 2.60 to D_{2D} = 4.8 m, and changes in shroud lines from the inlet to the outlet, resulted in a more stable flow from the inlet to the outlet. This phenomenon was actualized by the increase of output power significantly, due to an increase in the amount of flow rate through the turbine. An increase in flow rate occured as a result of the increase in discharge, power, and thrust coefficients. The speed ratio determined the last three parameters for each turbine section.

Hydraulic power (2) of the turbine in case 1 ranged from P_{WV} = 0.00 to 226 kW, with turbine power (1) ranging from P_{TV} = 0.00 to 194 kW. For the tidal turbine in case 2, the hydraulic power ranged from P_{WD} = 0 to 324 kW, with turbine power ranging from P_{TD} = 0 to 221 kW. Thus, by the modification of the shape and the geometry of the existing turbine meridional section, the hydraulic power of P_W (case 1) increased by 43%, whereas the turbine power of P_T (case 2) increased by 14%.

With this increases in turbine output parameters, the turbine in case 2 could be proposed to be applied to ocean current power plants.

IV. SUMMARY AND CONCLUSION

The turbine output parameters of two cases were analyzed by using one-dimensional theory of flow from the inlet to the outlet, based on the results of speed measurements on three cross sections, namely inlet (section 0-0) with a diameter D_0 = 1,9 = constant, the impeller cross-section (section 2-2) with diameters D_{1V} = 1,5 m and D_{1D} = 1,84 m, outlet cross-section (section 2-2) with diameters D_2 = 2,6 m and D_{2D} =4,8 m. From study, several results can be concluded as follows:

1. By increasing the impeller and outlet diameters and making the shroud line stream-lined, then the discharge coefficient value will be higher.
2. The values of the power and thrust coefficients of both cases show to be close to the values in results of the CFD modeling conducted by Belloni [8].
3. Due to the increased sizes of the impeller and outlet diameters, the speed ratio of inlet and outlet to impeller areas decreased. Consequently, the rotational speed decreased, and the thrust and the rotational moment values increased.
4. The ratio of hydraulic and turbine powers for both cases show the increase of the power significantly. The increase in hydraulic power reached 43%, whereas the increase in turbine power reached 14%, so that the turbine with modification in case 2 could be proposed to be applied to ocean current power plants.

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