American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN: 2320-0936
Volume-12, Issue-8, pp-61-70
www.ajer.org
Research Paper Open Access

Design And Manufacture of Low-Head Propellers Turbine for Pico Hydro

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ABSTRACT :*The propeller turbine was developed with locally sourced materials to extract the water stream in the discharge pipe due to the need to increase the use of efficient and sustainable clean technologies. The design method includes determining the technical specifications of the mains and supporting components. In the manufacture of several tools used such as lathes, milling machines, cutters and saws, rulers, screwdrivers (-) and (+), pliers, sandpaper, laptops, and Solidwork software, while the materials used are steel plates, iron axles ST 40, elbow 60°, pipe iron, angle iron, bolts, nuts, washers, and bearings. The results of the turbine design with four blades to a design power of 0.07 kW at an average specific speed* $n_{QE} = 1.35$, *a head of 3.5m, and an average flow discharge of 0.00244 m*^{3}*/sec. The thickness of the blade is 3 mm with a hub diameter of 3 inches, the turbine blade diameter is 5 inches, the draft tube inlet diameter is 72 mm, the draft tube exit diameter is 144 mm, and the draft tube widening angle is 5 degrees, the draft tube material is ST 37 steel plate, the inlet material elbow is ST 37 steel plate, hub and blade material is copper alloy. The draft tube is 479 mm high and 1.5 mm thick. The test results show that the efficiency increases with increasing water flow rate and angle narrowing. The highest efficiency of 70.67% is obtained at a flow rate of 0.0027 m*^{3}*/s..*

KEYWORDS Design, Manufacture, Propeller turbine, pico-hydro*.*

Date of Submission: 24-07-2023 Date of acceptance: 06-08-2023

I. INTRODUCTION

The increase in energy demand due to population is the biggest challenge now, and in the future, considering that the energy sector is a major need for all other development processes. In the last four decades, globally per capita energy consumption has increased from an average of 1.56 TOE (Tone of Oil Equivalent) per person from 1973 to 1.66 TOE per person in 2000, and 1.92 TOE per person in 2014 [1]. Meanwhile, Indonesia with a population of 261.9 million people [2], is the country with the fifth largest level of primary energy consumption in Asia Pacific after China, India, Japan and South Korea [3]. At the Southeast Asian level, Indonesia is close to 40 percent of total energy use among other ASEAN members. During 2004 to 2014 Indonesia's primary energy consumption level has reached sixty-five percent, and is expected to continue to increase to eighty percent by 2030{4]. The household sector is the largest share in energy consumption, which is thirty-eight percent, while the industrial sector is twenty-nine percent, the transportation sector is twenty-seven percent, non-energy is four percent, while the rest is one percent for other needs [5].

Currently, the production of electrical energy still has dependence on conventional energy sources, but geographically Indonesia has great potential in new renewable energy sources that are very abundant including wind energy of 950 MW, solar energy of 11 GW, biomass energy of 32 MW, bioenergy (biofuel) of 32 MW, marine energy of 60 GW and geothermal estimated at 29 GW. However, the hydropower potential for large scale reaches 75 GW, while the potential on a small scale reaches 769 Megawatt with an installed capacity of 7,059 MW, or 9.4 percent of the total available energy potential [6]. Thus, water energy sources are one of the renewable energy sources that can compete with fossil fuels, gas and biomass because of their low price. According to the calculation of levelized cost of electricity (LCoE) it is known that hydropower plants are the only regenerative energy source in supplying electricity on an industrial scale at competitive prices, when compared to fossil energy plants [7; 8].

The utilization of water energy as a source of electrical energy for Hydroelectric Power Plants (PLTA) works based on the potential energy of water in driving turbines and mechanical energy from turbine rotation is converted into electrical energy by generators[9]. Hydropower can be categorized into several types according to the power produced, one of which is the pico-hydro Power Plant (PLTPH). PLTPH produces power below 5 kW so that it has a simpler construction and installation in operation. The need for lighting for study or research purposes in the field that has not been reached by electricity sources, generally uses generators as one of the alternative options. However, generators are still less efficient in terms of price, weight and require fossil fuels to power them. The purpose of this research is to design and manufacture propeller turbines for pico-hydro power plants that can be applied to sewer pipelines.

II. METHODS

1. Design Concept

The design development stage is the stage to determine the turbine concept, including the form, function, features, and technological solutions needed. The design phase is the stage for producing design plans, constituent subsystems, and process flow diagrams. Then the design stage also consists of determining the technical specifications of the main and supporting components. In designing and manufacturing, several tools and materials are needed as follows; Tools: lathes, Frais machine, cutters and saws, rulers, screwdrivers (-) and (+), pliers, sandpaper, laptops, and Solid work software, which are used as containers for part making, part assembly, and simulation of design results; Material: Steel plate, as Iron ST 40, elbow 60°, pipe iron, elbow iron, Bolts, Nuts, Rings and Bearings. At this stage, the shape of the blade angle problem is obtained. With solution search steps shown in Figure 1.

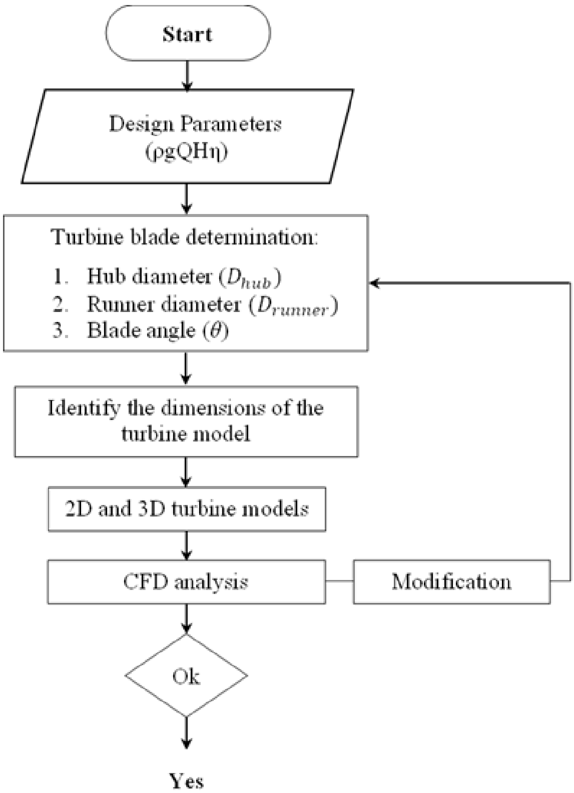

Figure 1. Flow chart for solution search process

2. Calculation Process

According to Frank Kreith 2008, the power of a water turbine is determined by the amount of water discharge and the head as well as the efficiency of the water turbine. When viewed from the capacity and head, the planned turbine power can be determined according to the following equation [10]:

$$P = QH\eta_h \rho g \quad (1)$$

Where Q is the discharge (m^3/sec), H is the effective water fall height (m), η_h is the turbine efficiency (%), ρ is the density (kg/m^3), and g is the acceleration of gravity (9.81 m/s^2).

Water discharge is one of the most decisive things in water turbine planning, because the power produced by the turbine is very dependent on the available water discharge. The flow condition will be steady if the relationship between two velocity prices observed at different points is constant. At the flow rate of fluid through two cross sections A and B of equal magnitude. The flow of water from the intake with a constant head height located higher, which is connected by a pipe to the point where the position is lower is constant. If the cross-sectional area of the pipe is changed in cross-sectional shape, the flow will reach the new equilibrium condition. According to the continuity equation of water discharge flowing in a pressurized pipe can be determined by the following equation 2 [11]:

$$Q = V.A \tag{2}$$

Where $V$and A is the cross-sectional area of the pipe (m^2)

Specific speed is the speed at which the turbine produces one unit of power with one unit of head at maximum efficiency. Different definitions of specific speeds can be found in the technical literature Guide on how to develop small hydroelectric power plants. USBR establishes the correlation between specific speed and net head for propeller turbines in the following equation 3 [10]:

$$n_{QE} = \frac{2{,}716}{H_n^{0,5}} \quad [\text{USBR}] \tag{3}$$

In blade planning, the speed triangle plays an important role in determining turbine performance. This is done to determine the shape of the blade at each point of change. Considering that each point changes its shape according to the speed of the moving water.

On exiting the runner, the flow is seen leaving the runner with no rotating speed, i.e., $C\theta_3 = 0$, and a constant axial velocity. The runner blade will have a fairly high rate of rotation, the magnitude of which depends on the strength of the circulation function *K*, and the magnitude of the axial velocity. Right at the end of the runner, the flow is assumed to be a free vortex and the velocity component is accordingly [12].

$$c_{\theta 2} = \frac{K}{r}, c_x = a\ constant \tag{4}$$

The relationship for the flow angle is,

$$tan\ \beta_2 = \frac{U}{c_x} = \alpha_2 \frac{\Omega r}{c_x} - \frac{K}{(rc_x)}$$

$$tan\ \beta_3 = \frac{U}{c_x} = \frac{\Omega r}{c_x} \tag{5}$$

Where *c* is the absolute speed (m/sec), *U* is the blade velocity (m/sec), *K* is characteristic, *r* is the radius (*m*), *β* is the Betha angle (0), and α is the alpha angle (^{0}).

3. Manufacturing Process

The manufacturing process is a form of activity or production process that changes the form of raw materials into finished materials. In the manufacturing process starts from designing the product, then determining the specifications of the material from which the product will be made. Furthermore, the raw materials are modified and formed into the necessary parts [8]. The manufacturing of the turbine made includes several stages as seen in Figure 2.

Cutting Process

Draft Tube body cutting time(T_{p1})

$$t_p = \frac{L}{v} \tag{6}$$

Where t_p is the cutting time (minutes), *L* is the cutting length (mm/min), *v* is the cutting speed (mm/min).

Drill process

Cutting speed of drill

The circumference velocity of the drill is mathematically written by the following formula:

$$v = \frac{\pi dN}{1000}\left[\frac{mm}{minute}\right] \quad (7)$$

Where *d* is the diameter of the workpiece (*mm*) and *N* is the engine rotation

Drilling delivery

The delivery (*f*) on the stroke is expressed in inches (mm). This conductivity can be converted into linear travel rate, f_r in inch/mm (mm/min) with the formula:

$$f_r = N\, f \text{ atau } f_r = \frac{v.f}{\pi D_o} \quad (8)$$

The machining time, T_m (minutes), required from one end of the cylindrical workpiece to the other end with a cut length *L* (*inch* or *mm*) can be expressed by the equation:

$$T_m = \frac{L}{f_r} \text{ atau } T_m = \frac{L\, \pi D_o}{vf} \quad (9)$$

Material removal rate, MRR (mm^3/min).

$$MRR = vfd \quad (10)$$

The size of the hole being whipped

Generally, a two-strain grind will be drill with a slight excess size. For example, for the diameter of the drill between (3.2 ÷ 25) mm, it can be calculated.

Average oversize = 0.05 + 0.13 *D*
Maximum oversize = 0.13 + 0.13 *D*
Minimum oversize = 0.03 + 0.08 *D*

Where *D* is the nominal diameter of the drill (*mm*)

Lathe Process

Cutting speed

The cutting speed (*Cs*) is generally listed in the text book, but it would be nice to clarify how to set it as follows:

$$Cs = \frac{\pi.d.n}{1000}\ atau\ n = \frac{1000}{\pi}\frac{C_s}{d}[rpm] \quad (11)$$

Where is the average diameter of the workpiece, *n* is $\frac{(d_o+d_m)}{2}$; $mm$the rotation of the main shaft; rev/min $\pi = 3{,}14$, d_o is the starting diameter; *mm*, d_m is the final diameter; *mm*.

Feeding speed

$$v_f = f.n; mm/menit \quad (12)$$

Where *f* is the feeding motion (mm/rev) and *n* is the rotation of the main shaft (rev/min).

Cutting time

$$t_c = \frac{L_c}{v_f}; menit \quad (13)$$

Where t_c is the cutting time (minutes), is the cutting length (mm/min) and $t_c\ vL_c$ is the cutting speed (mm/min).

Welding Process

The balance of power generated in arc welding is defined by the equation:

$$HRw = f_1 f_2 E = Um\ Aw\ v \tag{14}$$

Where, *E* is voltage, *V*, I is current, *HRw* is the rate of heat generation at the weld, *Watt* or *Joule/sec*. or *Btu/sec*. ***Note***: 1 Btu = 1055 J, *Um* is the melting energy for metal. Btu/in ^{3}, is the outer surface of the weld, mm 2 or in $A_W{}^2$, *v* is the welding motion speed *mm/sec*, or *in/min*. Volume rate of metal welded *(MVR*), expressed by the following formula:

$$MVR = \frac{HRw}{Um}, in^3/sec \tag{15}$$

4. Manufacturing *Process Flow*

Turbine manufacture includes several stages and is shown in Figure 1. Broadly speaking, the stages begin with literature study, understanding of working drawings, design, manufacturing, manufacturing process, assembly process, finishing process and testing. The process flow is shown in figure 2.

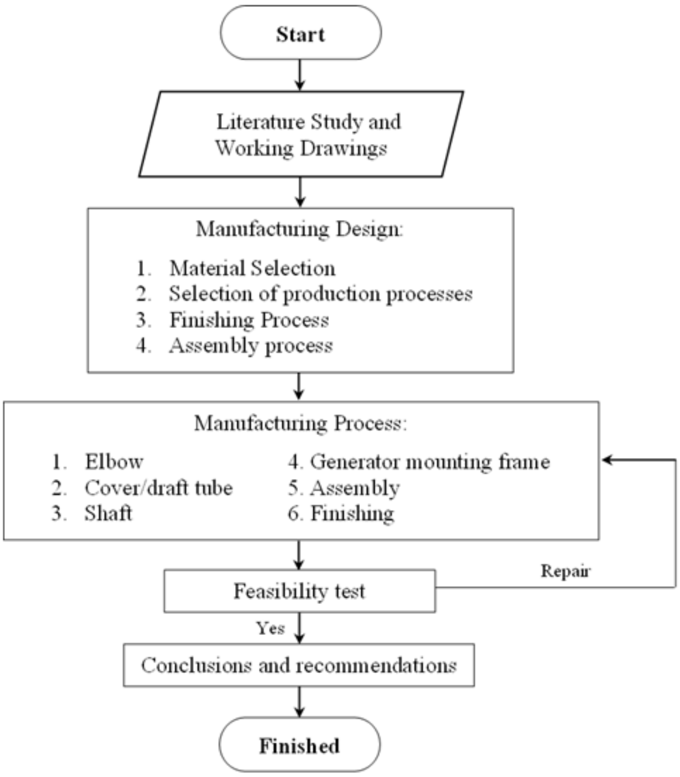

Figure 2. Flow chart of Manufacturing Process

III. RESULT AND DISCUSSION

1. Turbine Design

The turbine manufacturing process includes several stages such as frame turning work, shaft making, reservoir making and cover making. In making a clove grinding machine, there are several things that must be considered, namely preparing materials, providing tools/machines used, preparing working drawings. The design drawings, and manufacturing results are shown in figure 3 a, b and c.

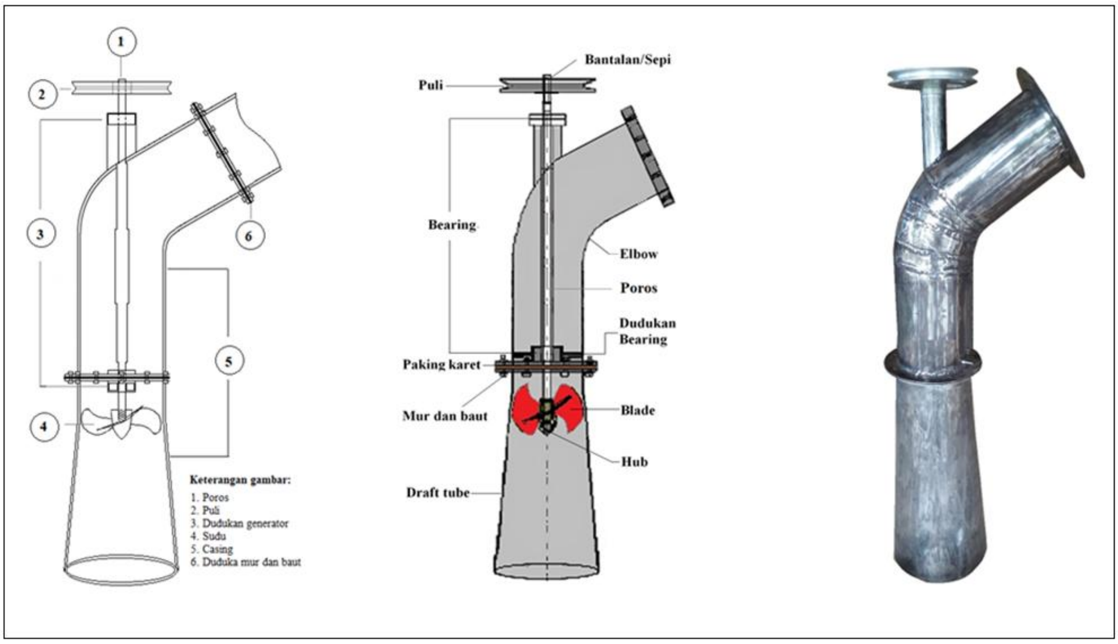

Figure 3. 2D, 3D drawing design and turbine manufacturing

2. Manufacturing *Process*

The manufacturing process of the product (Pico-Propeller turbine) is in accordance with the design previously outlined in the drawing for the process steps as follows:

- Cutting Process

Cutting time of draft tube body

Done to cut steel plates that have a thickness of 1.5 mm with a bottom diameter of 300 mm and a top diameter of 150 mm, and height of 208 *mm* and an inclination angle of 6°.

Circumference of the upper side of the draft tube (s_1) = 144 $s_1 mm$

Circumference of the bottom side of the draft tube (s_2) = 225 $s_2 mm$

Draft tube length (*l*) = 497 mm

To cut the plate it takes time if assuming a cutting speed *(v*) of 30 *mm/min*, then:

$$t_{p1} = \frac{s_1 + s_2 + l}{v}$$

$$t_{p1} = \frac{144\ mm + 225mm + 497\ mm}{30\ mm/minute} = 28{,}86\ minute$$

Inlet cut time

The inlet with blade diameter size 150 mm and channel length (*l*) 128 mm, cutting speed (*v*) 30 *mm/min*.

s_1 (Circumference of the entrance side) = s_2 (Circumference of the exit side) = πD

$$Circumference = \pi \times 150\ mm = 471\ mm$$

$$t_{p\,2} = \frac{s_1 + s_2}{v}$$

$$t_{p\,2} = \frac{471\ mm + 471mm}{30\ mm/minute} = 31{,}4\ minute$$

House bearing cutting time

Cylindrical house bearings measuring 131 mm long, 75 mm in diameter, to cut it takes approximately 15 minutes with a cutting speed (v) of 30 mm/minute.

s_1 (Circumference of the entrance side) = s_2 (Circumference of the exit side) = πD

$$Circumference = \pi \times 70{,}5\ mm = 235{,}5\ mm$$

$$t_{p\ 3} = \frac{s_1 + s_2}{v}$$

$$t_{p\ 3} = \frac{235{,}5\ mm + 235{,}5 mm}{30\ mm/minute} = 15{,}7\ minute$$

The rectangular frame measures 1000 mm x 75 mm x 120 mm with a cutting speed (v) of 30 mm/minute. The rectangular frame measures 1000 mm x 75 mm x 120 mm with a cutting-speeds (v) of 30 mm/min.

Cut length $= \{(2 \times 75\ mm) \times 4\} + \{(2 \times 120) \times 4\} = 1560\ mm$

$$t_{p\ 4} = \frac{s}{v} = \frac{1560\ mm}{30\,\frac{mm}{minute}} = 52\ minute$$

Total cut time

Total cut time$\left(t_{pt}\right) = t_{p1} + t_{p2} + t_{p3} + t_{p4}$

$(t_{pt}) =\ 141{,}8\ minute + 31{,}4\ minute + 15{,}7\ minute + 52\ minute$

$$(t_{pt}) = 240{,}9\ minute$$

- Drill Process

The number of holes needed is 8 holes with a hole diameter of 14 mm. In figure 4 the cutting speed table for holes below 14 mm is close to the rotation of the 747 spandel and the feeding speed of 0.008 in/rev (0.203) (9/16 *inchmm/rev*).

Diameter of drill (in.)	Aluminum	Brass & Bronze	Cast iron	Mild steel 0.2-0.3 carbon (LOW)	Steel 0.4-0.5 carbon (MED)	Tool steel 1.2 carbon and drop forgings	Conn. rod molyb-denum steel	3.5 nickel steel	Stainless steel and monel metal	Malleable iron	Feed per revo-lution (in.)
	MATERIAL AND CUTTING SPEED (FT PER MINUTE)										
	300	200	100	110	80	60	55	60	50	85	
	Revolutions per minute										
1/16	18,336	12,224	6,112	6,724	4,683	3,668	3,404	3,976	3,056	5,192	0.0015
1/8	9,168	6,112	3,056	3,362	2,444	1,834	1,702	1,986	1,528	2,596	0.002-0.003
3/16	6,108	4,072	2,036	2,242	1,630	1,222	1,120	1,324	1,018	1,734	0.004
1/4	4,584	3,056	1,528	1,681	1,222	917	851	994	764	1,298	0.005
5/16	3,666	2,444	1,222	1,344	978	733	672	794	611	1,039	0.005
3/8	3,054	2,036	1,018	1,121	815	611	560	662	509	867	0.006
7/16	2,622	1,746	874	921	699	524	481	568	437	742	0.007
1/2	2,292	1,528	764	840	611	459	420	497	382	649	0.008
9/16	2,037	1,358	679	747	543	407	373	441	340	577	0.008
5/8	1,836	1,224	612	673	489	367	337	398	306	520	0.009

Figure 4. **Table for cutting speed**[13]

The time required for the drill process is:

$$0{,}203\,\frac{mm}{rev} \times 747\,\frac{rev}{minute} = 151{,}7\ \frac{mm}{minute}$$

$$\frac{1}{151{,}7}\,\frac{menit}{mm} \times\ 5\,\frac{mm}{hole} = 0{,}032\ \frac{minute}{hole}$$

$$0{,}032\ \frac{minute}{hole}$$

So, the time needed for 8 holes is:

$$0{,}032\ \frac{minute}{hole} \times 8\frac{hole}{product} = 0{,}26\ \frac{minute}{product}$$

- Formation Process

Plates that have been cut to size in the design are formed by *rolling* using what is done by clamping the plate between two rollers arranged in such a way as to match the desired shape and takes time assuming 100 minutes.

- Welding Process

Welding is carried out with the aim of uniting turbine parts including turbine blades, *elbow* inlets towards the *draft tube*, joining *house bearings* on 60° elbows and generator mounting frames.

- Painting Process

The painting process is the last process of the turbine prototype manufacturing stage. Painting is carried out on all parts with the following steps:

- Sanding the entire surface from all sorts of dirt and rust.
- Cleaning the remnants of sanding.
- Caulking the welded corner parts and uneven surfaces.
- Coat the entire surface with base paint.
- After drying, painting is carried out according to the desired color on all parts until evenly distributed.

3. Comparisonof Design Power Capacity (Pd) and Testing

Power Capacity Design

The amount of water power capacity in a water flow in the exhaust pipe in the PDAM Tirta Meulaboh water treatment plant unit with the following calculation data parameters:

a. Flow discharge 0.00134 m 3/sec up to 0.0047 m^3/sec.
b. The assumed hydraulic efficiency is 0.85%.
c. The height of the water fall (*head*) is 1 m to 8 meters.

So, in theory the power that can be generated based on the potential flow discharge of 0.00134 m^3/second with a height of 1 m, with equation 6 is:

$$P_d = 998 \times 9{,}8 \times 0{,}00134 \times 8 \times 0{,}85$$

$$P_d = 11{,}14\ Watt = 0{,}012\ kW$$

Thus, the average theoretical power of the flow discharge in the exhaust pipe at the PDAM Tirta Meulaboh water treatment plant unit can produce electrical energy as much as:

$$= 9{,}8 \times 0{,}00244 \times 4{,}5 \times 0{,}85 \times 998$$

$$= 91{,}28\ Watt\ = 0{,}0913\ kW$$

4. Testing Power Capacity

Turbine blade testing is carried out by varying the water discharge in the intake line (*inlet*) which is regulated based on the valve opening by passinstalled in the installation for water discharge capacity starting from 0.0013 4 m^3/second at valve opening 1, amounting to 0.0015 m^3/second at valve opening 2, amounting to 0.0017 m^3/ second at valve opening 3, by 0.002 m^3/s at valve opening 4, by 0.0022 m^3/s at opening 5, by 0.0027 m^3/s at valve opening 6, by 0.0033 m^3/s at valve opening 7 and by 0.0047 m^3/s at valve opening 8. Based on the test results, it is known that the power capacity of the turbine is shown in figure 5.

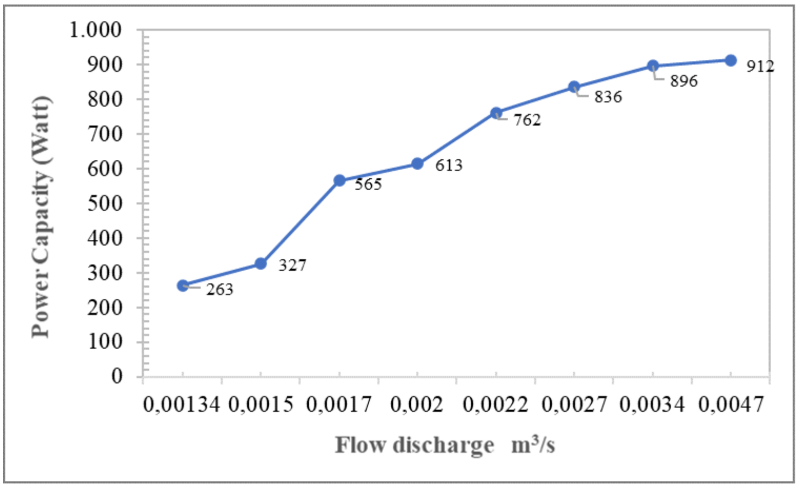

Figure 5. Design and Test Power Comparison Graph

Based on the failures evaluated, the welding process at the joints allows the turbine to schedule repairs in addition to routine turbine maintenance. However, the turbine test results show that the turbine blade rotation increases for a smaller angle, but the rotation begins to decrease with an increase in the maximum flow rate of 0.0047 m^3/s, as shown in Fig. 5.

IV. CONCLUSION

The turbine is designed with four blades to a design power of 0.07 kW at an average specific speed $n_{QE} = 1.35$, a head of 3.5m, and an average flow discharge of 0.00244 m^3/sec. The thickness of the blade is 3 mm with a hub diameter of 3 inches, the turbine blade diameter is 5 inches, the draft tube inlet diameter is 72 mm, the draft tube exit diameter is 144 mm, and the draft tube widening angle is 5 degrees, the draft tube material is ST 37 steel plate, the inlet material elbow is ST 37 steel plate, hub and blade material is copper alloy. The draft tube is 479 mm high and 1.5 mm thick.

The turbinesmanufacture uses local raw materials because they are easy to obtain and cheap. However, this does not reduce the quality of the design. It is proven that the test results show that efficiency increases with increasing water flow rate and narrowing angle. The highest efficiency was obtained at a flow discharge of 0.0027 m^3/s which was 70.67%.

ACKNOWLEDGEMENT

The authors would like to thank everyone who assisted in this study, including the team at the Division of Renewable Energy, Department of mechanical Engineering, Teuku Umar University, who supported the work and helped obtain a high-quality and accurate analysis. Additionally, the authors would like to thank all the friends who gave support and motivation. The first author would also like to thank his family for their spiritual encouragement throughout the process of writing this paper.

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