Effect of Rotation and Constant Head Variation on Performance of Three Sizes of Pump-as-Turbine (PAT)

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Abstract- Centrifugal pumps have been tested as an alternative fluid engine to replace water turbines. The challenge that has not been revealed regarding the size variation of the centrifugal pump is how to adjust the PAT size variation with the discharge and head variables to produce maximum PAT performance. Considering this, more open research is needed, namely not only the discharge and head variables that need to be varied but the size of the PAT also needs to be varied. This research is expected to get a more comprehensive conclusion. The test results on the same test installation show that the 1.0-inch PAT performance is better than 1.5-inch PAT and 1.5-inch PAT is better than 2.0-inch PAT. The maximum efficiency of 1.0 inch PAT is 38.10% occurs at 4.20 L/s discharge, 860 rpm rotation, 15.0 m head, and 2.61 N.m torque. This data explains that to produce maximum performance, each PAT requires a different discharge potential and head support. The larger the PAT size, the more it requires the support of a larger discharge and head.

Keywords: Pump, turbine, centrifugal pump, pump-as-turbine, PAT.

I. Introduction

Sustainability and availability of energy are the hope of all countries, both developed and developing countries [1]. The need for energy is getting bigger in accordance with the increase in people's living standards and the increasing world population. Cheap, clean and environmentally friendly energy produced by alternative technologies is expected to meet the needs of the world community [2]. Natural gas, coal and oil as non-renewable energy sources have environmental impacts and limitations. Meanwhile, renewable energy sources have a very important position. Meanwhile, the future of renewable energy is a concern for practitioners and researchers considering that renewable energy has advantages including unlimited potential. and environmentally friendly [3]. The use of renewable energy systems is the best alternative to achieve reduction of the high cost of energy supply and carbon emissions [4]. Many solutions have been tried to solve people's energy needs, but the problem of availability and quality of renewable energy has not been maximized so that it becomes a challenge especially felt by people in villages [5]. Renewable energy innovation and development has increased rapidly in recent years [6]. Innovation of the generator system continues to be carried out by researchers including the generator system built more simple, more compact, not noisy and versatile utilization [7]. The potential of hydro, geothermal and bioenergy energy is quite large, so in 2050 the target of using new and renewable energy can reach around 31% [8]. Water energy is the oldest example of renewable energy, the technology is very developed so it is very promising for the future [9]. Hydropower plants aredivided into three, namely mini-hydro, micro-hydro, and pico-hydro [10]. Small-scale hydroelectric power plants are currently increasingly popular because of their simple construction, easier assembly, easy and inexpensive operation and maintenance, and being environmentally friendly because they do not produce waste and not produce pollution [11-13]. The community development process of micro hydro and pico hydropower plants will be constrained by several challenges, one of which is that the turbine as a prime mover is not sold freely. People have to order turbines in advance which takes a long time [14]. Remote village communities that do not yet have electricity will bear the planning and survey costs [15]. The implementation of maintenance that is disciplined, timely, and appropriate in its utilization has a major impact on service quality and efficiency of generating costs [16].

The topic of micro-hydro and pico-hydropower plants is quite challenging and encourages researchers to design alternative turbines that are different from conventional turbines and are suitable for application in society [17]. Modification of turbine runner geometry is one of the efforts to increase turbine efficiency [18]. Another idea to increase efficiency is to modify the shape and size of the turbine runner [19]. The number of blades on the cross-flow turbine runner affects the performance of the pico-hydropower generation system [20]. The performance of a pico-hydro scale power plant is determined by the speed of the water entering the turbine [21].

The centrifugal pump has been successfully recommended by researchers as an alternative fluid engine to replace conventional water turbines so it is hoped that people will find it easier to get prime movers for micro-hydro and pico-hydropower plants. In the application of the pump as turbine (PAT), the working principle of the pump is reversed, namely water from the forebay flows through the penstock and enters the exhaust side (outlet) of the pump so that the water can drive the pump impeller. This impeller rotation will be forwarded by the transmission system to drive an electric generator [22]. Applications Centrifugal pumps as turbines have several advantages including, a pump as a mass product, the price is relatively cheap, spare parts are easy to obtain, and easy to assemble and install [23]. Pump applications can be connected directly to the generator or use a belt-pulley mechanical transmission if the PAT speed does not match the generator speed [24]. PAT has proven to be an effective alternative for power generation due to its wide use and stable efficiency, especially at large water discharges. PAT performance will decrease if under unstable water flow [25]. Economic analysis shows that, pico-hydropower plants with PAT as the prime mover are more profitable than using conventional turbines when the power generated is lower than planned [26]. The construction of the PAT volute with the Francis turbine volute is relatively the same so that the water discharge when entering the PAT and Francis turbine does not have a different character. Similarly, the triangular analysis of the water velocity at the pump is relatively the same as in the PAT, what distinguishes it is the direction of the water velocity when it goes to and leaves the impeller as shown in Figure 1. This finding strengthens the hypothesis that centrifugal pumps are suitable as alternative water turbines. [27].

Micro-hydro and pico-hydropower plants are suitable for using PAT prime movers, but the challenge is that there is no recommendation on the ideal type of PAT as a water turbine. [28]. The recommended speed of specific for PAT to produce maximum performance is the Ns value between 60 to 150 [29]. PAT is an optimal prime mover alternative for pico-hydro scale power plants because PAT components are easy to obtain. The results of the study concluded that a pico-hydropower plant would be profitable if the amount of electricity generated each month had to be greater than 380 kWh [30]. The test results show that PAT can generate power from the potential utilization of water flowing through distribution channels in urban areas [31]. The best efficiency point (BEP) of PAT can be achieved at specific speeds from 103 to 187 [32]. Reduction of the PAT impeller diameter leads to increased efficiency under normal load operation [33]. PAT efficiency will be reduced if the impeller diameter is reduced [34]. PAT optimization can be carried out at a medium to high heads by considering the interaction between blades, water, and channel shape [35]. PAT performance is influenced by fluid viscosity, the greater the viscosity value, the higher the performance, especially the efficiency [36]. The distance between the tip of the blade and the casing which is called the tip clearance will affect the performance of the centrifugal pump when it functions as a turbine The distance between the tip of the blade and the casing which is called the tip clearance will affect the performance of the centrifugal pump when it functions as a turbine. With the increase in tip clearance, there is a decrease in the potential head and pump efficiency. Tip clearance of 1 mm can reduce PAT performance, namely, the efficiency is reduced by 6.26% and the head is reduced by 10.8% [37]. Centrifugal pumps from the beginning were not designed to be turbines but technically the centrifugal pump construction is not much different from the Francis turbine construction as shown in Figure 1. so centrifugal pumps are suitable as an alternative to water turbines for pico-hydro and micro-hydro scales [38].

Centrifugal pumps as a turbine turned out to be one of the objects of observation that is quite popular among many researchers. Laboratory-scale testing conducted by the researchers aimed to analyze the factors causing the low efficiency of PAT and seek to improve it. Various tests have been carried out, including varying the impeller diameter and pump tip clearance. Another analysis is to predict the PAT characteristic curve to determine the type of PAT that is suitable for a generating system. Another challenge that has not been disclosed is related to the variety of PAT sizes that are widely sold in the market, namely how to adjust the PAT size to the head and discharge variables to produce maximum PAT performance. Taking this into account, further research is needed, namely not only the head and varied discharge variables but the size of the PAT itself needs to be varied so that with this research a more comprehensive and balanced conclusion will be obtained. The output of this study will be to obtain information, how the phenomena of the influence of head, discharge, and rotation variations on the performance of the three tested PAT sizes, namely 1.0-inch PAT, 1.5-inch PAT, and 2.0-inch PAT as shown in Figure 2. This test can identify the optimal head and discharge potential to get maximum PAT efficiency. This study can also explain the comparison between the trend of the PAT efficiency curve with the trend of the conventional turbine efficiency curve and the trend of the efficiency curve of other alternative turbines.

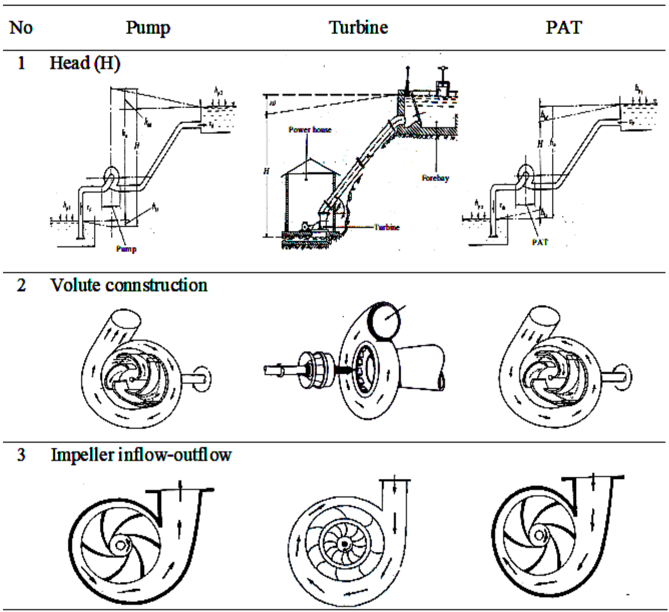

Fig 1. Differences in installation and water flow in pump, Francis turbines, and PAT

Fig. 2. Centrifugal pump sizes 2.0-inch, 1.5-inch and 1.0-inch

2. Research Methodology

This research was completed through several stages, starting with the stage of checking and cleaning the test equipment installation, followed by the stage of obtaining measuring instruments and materials to be used, modifying the pump into a turbine, installing PAT, PAT testing stage, analysis, and reporting. The PAT test takes place in four variations, namely rotation variations, constant head variations, discharge variations, and discharge ratio variations. The variables analyzed in this study are turbine inlet water discharge, PAT rotation, PAT torque, PAT power, potential power, and PAT efficiency. The test will identify the trend of the performance curve that is formed from each of the tested variables. The test will also identify the optimum rotation, constant head, discharge, and discharge ratio that results in maximum efficiency. The PAT that has the highest efficiency will also be identified through this experimental test,

2.1. Material Preparation and Testing Equipment Installation

The test installation used is a standard test installation designed to be used for testing conventional pico-hydro turbines as shown in Figure 3. For the PAT test, it is necessary to make adjustments and slight modifications to the test installation. The installation of the PAT test equipment consists of an electric motor as a prime mover of the pump, valve, spring force gauge, suction pipe and pressure pipe, weirmeter tub to accommodate the water discharge coming out of the turbine, a reservoir for water coming out of the weirmeter as well as a water source for testing. Furthermore, the main materials used are three fluid engine units that will function as water turbines, namely a 1.0-inch centrifugal pump, 1.5-inch centrifugal pump, and 2.0-inch centrifugal pump as described in Figure 2.

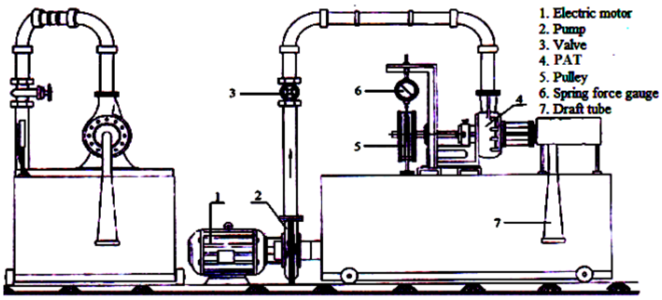

Fig. 3. PAT test installation

2.2. Modify the Pump into a Turbine

Centrifugal pumps cannot directly function as water turbines, but first modifications need to be made involving piping components as shown in Figure 4. The implementation of this modification is not too complicated because the pump is separated from the electric motor as the prime mover. The general modification is to change the function of the pump inlet pipe to an outlet pipe when it becomes a turbine and vice versa change the function of the pump outlet pipe to an inlet pipe when it becomes a turbine. The first modification is to adjust the diameter of the pump outlet pipe to the diameter of the main pipe already installed on the test equipment installation. The diameter of the outlet pipe is smaller than the diameter of the main pipe, so in this modification, it is necessary to involve changing the diameter of the pipe or reducer and elbow. The second modification is to make a draft tube at the end of the pump inlet pipe which involves an elbow, reducer, and additional pipes whose modification results are shown in Figure 5. The next modification is to make a frame for the pump pedestal which will be installed above the weirmeter tub. The size and position of the bolt-nut holes of this frame must be adjusted to the size of the bolt-nut holes that already exist on the pump leg so that the position of the PAT when installed is ensured steady and stable.

Fig. 4. Pump-as-turbine modification process

Fig. 5. 1-inch PAT test installation

2.3. Testing Stage

The testing phase begins with the installation of the PAT on the holder, connecting the main pipe to the PAT inlet pipe, and tightening the pipe connection. Furthermore, the electric motor driving the supply pump is turned on so that water flows from the reservoir to the inlet pipe to the PAT. Water flowing through the main pipe has the potential to be charged and head, the discharge entering the PAT can be seen from the water level in the hook gauge as a component of the weirmeter. Meanwhile, the PAT head is the pressure measured on the pressure gauge. The pressure on the pressure gauge can be converted to units of length referring to the equation that 1 atm is proportional to a water height of 10.0 m [39]. The maximum pressure scale listed on the pressure gauge used is 2.0 atm or equal to a water level of 20.0 m. Tests in this laboratory will identify seven test variables, namely PAT head, PAT inlet water flow, PAT rotation, PAT torque, PAT power, potential power, and PAT efficiency.

Fig 6. PAT is installed near the pressure gauge

Figure 7 shows the process, of testing torque through the braking mechanism. In this testing process, there will be tension on the loose side (F_s) and the tight side of the tape (F_t), the effective force (F_e) is the difference between F_t and F_s. The following equation (1) can be used to determine the PAT torque that occurs [40].

$$T = F_e \times R \tag{1}$$

(1)
Where, R is the pulley radius.

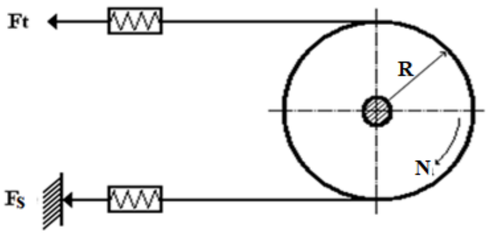

Fig. 7. PAT torque testing process through the braking mechanism

The real power of PAT (P_t) can be known by equation (2) and the potential power (P_p) can be known from equation (3) [41].

$$P_t = 2 \times \pi \times N \times T / 60 \tag{2}$$

$$P_p = \rho \times g \times Q \times H \tag{3}$$

N is PAT rotation, T is PAT torque, is water density (1000 kg/m^3), g is earth gravity (9.8 m/s^2), Q is PAT inlet water flow, and H is PAT head. Furthermore, the following equation (4) can be used to determine the efficiency of PAT [41].

$$\eta = (P_t / P_p) \times 100\% \tag{4}$$

The weirmeter in the test equipment installation serves to measure the flow of water entering the turbine (Q). The weirmeter component consists of a weirmeter tub, a triangular door, and a hook gauge which is installed at the end of the weirmeter tub as shown in Figure 8. The variation of water height on the hook gauge becomes a variable in the measurement of the turbine inlet water discharge. A hook gauge is a box filled with water that is connected to the water in the weirmeter via a small pipe. The hook gauge is installed next to the weirmeter tub near the triangular door. To determine the water flow entering the turbine. The following equation (5) is used to determine the flow of water entering the turbine by entering data on the height of the water in the hook gauge (h_w) and data on the width of the triangular door at the end of the weirmeter [42].

$$Q = c \times h_w^{5/2} \quad (5)$$

c is the discharge coefficient, the following empirical equation (6) can be used to determine the value of c [42].

$$c = 81.2 + (0.24/h_w) + \{(43.08\ (h_w/b \times 0.09)^2\} \quad (6)$$

Fig. 8. The Position of the triangular door and hook gauge

2.4. PAT Performance Curve Analysis

Torque, power, and efficiency curve trends that are formed can be analyzed to determine the performance of PAT. To get a smooth curve, in this test the rotation interval is between 70 rpm to 140 rpm. From the analysis of the trend curve, it will be known the optimum rotation, discharge and constant head that will produce maximum torque, power and efficiency as a measure of the tested PAT performance. The position starting from the PAT rotation at how many rpm the uptrend and downtrend will occur, can be analyzed through the formed curve. The final result of this PAT performance curve analysis is that recommendations can be made, at what rpm and at what discharge L/s the PAT must be operated so that the PAT can produce maximum power and efficiency. Furthermore, from the relationship between PAT size and PAT performance, it can be assessed that the installation of the test equipment used is ideal for which PAT size to use.

3. Results and Discussion

This laboratory test will test three different sizes of PAT using the same test equipment installation. Tests were carried out on five variations of the effective relationship with four constant head variations and ten rotation variations. The next PAT test is the effect of discharge variations and discharge ratios on efficiency and power which is carried out at constant rotation. The following is a recapitulation of data from the analysis of the three PAT sizes for the largest constant head, which is 15.0 m for 1.0-inch PAT, 12.0 m for 1.5-inch PAT, and 10.0 m for 2.0-inch PAT as the results are shown in Table 1-3.

Table 1. Data from the 1.0-inch PAT test at a constant head of 15.0 m

No	Discharge, Q (L/s)	Rotation, N (rpm)	Torque, T (N m)	PAT Power P_t (W)	Potential Power P_p (W)	Efficiency η (%)
1	6.00	0	6.30	0	882.90	0
2	5.70	180	5.79	109.03	838.75	13.00
3	5.40	370	5.05	195.47	794.61	24.60
4	5.10	500	4.39	230.00	750.46	30.50
5	4.60	720	3.27	246.40	676.89	36.40
6	4.20	860	2.61	235.46	618.03	38.10
7	3.60	1060	1.78	197.06	529.74	37.20
8	3.00	1330	0.99	137.73	441.45	31.20
9	2.60	1490	0.59	92.97	382.59	24.30
10	2.40	1610	0.36	61.45	353.16	17.40
11	2.00	1800	0	0	294.30	0

Table 2. Data from the 1.5-inch PAT test at a constant head of 12.0 m

No	Discharge, Q (L/s)	Rotation, N (rpm)	Torque, T (N m)	PAT Power P_t (W)	Potential Power P_p (W)	Efficiency η (%)
1	5.80	0	6.00	0	683.95	0
2	5.50	170	5.46	97.12	647.46	15.00
3	5.50	290	4.78	144.69	618.03	22.80
4	4.80	470	3.76	185.14	563.88	31.80
5	4.40	590	3.11	191.90	517.97	35.10
6	4.10	760	2.20	175.20	482.25	36.30
7	3.40	920	1.56	150.20	400.25	34.00
8	3.20	1010	1.23	130.00	376.70	32.30
9	2.80	1230	0.59	76.25	327.26	23.30
10	2.50	1340	0.33	46.50	294.30	15.80
11	2.00	1480	0	0	235.44	0

Table 3. Data from the 2.0-inch PAT test at a constant head of 10.0 m

No	Discharge, Q (L/s)	Rotation, N (rpm)	Torque, T (N m)	PAT Power P_t (W)	Potential Power P_p (W)	Efficiency η (%)
1	5.70	0	5.40	0	559.17	0
2	5.40	120	5.12	76.03	531.702	14.30
3	5.10	230	4.40	115.00	500.31	23.50
4	4.80	320	4.00	133.95	470.88	27.60
5	4.50	440	3.04	140.26	439.49	32.00
6	3.90	650	1.98	135.05	382.59	35.30
7	3.40	790	1.27	104.95	328.63	33.00
8	3.00	900	0.89	83.87	294.36	28.50
9	2.70	1000	0.59	61.98	264.87	23.40
10	2.40	1100	0.35	40.49	235.44	17.20
11	1.90	1260	0	0	186.39	0

3.1. Trend of Torque Curve due to Rotation Effect

The torsion curve trend formed from the three tested PAT sizes will be analyzed through this test. PAT torque performance testing is carried out due to the effect of constant head variations and rotation variations. The next goal is to analyze the maximum torque that occurs at the optimum PAT rotation at how many rpm. The PAT torque data recapitulation of the test results for each rotation and the constant head is shown in Table 1-3. The PAT rotation and torque data in columns 3 and 4 are then plotted into a curve and the results are shown in Figure 9-11.

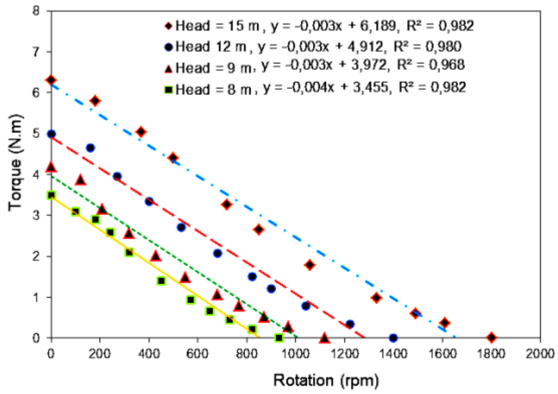

Fig. 9. Trend of 1.0 inch PAT torque rotation effect

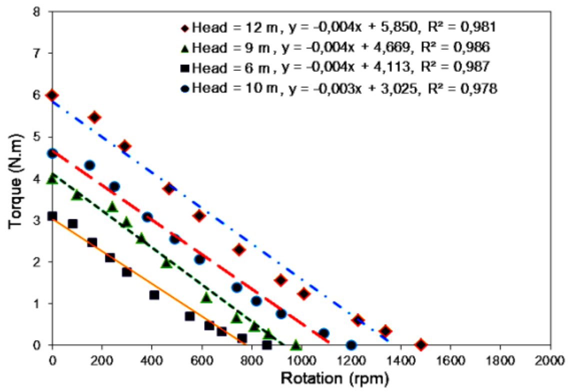

Fig. 10. Trend of 1.5-inch PAT torque rotation effect

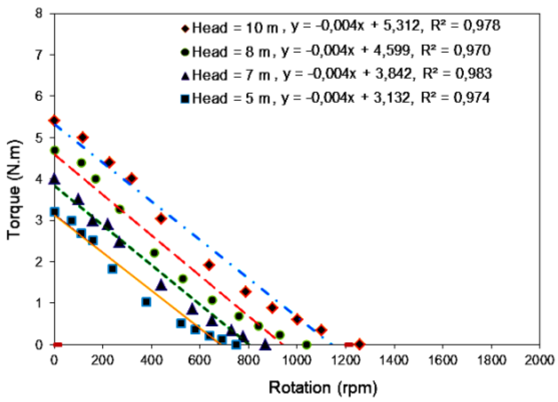

Fig. 11. Trend of 2.0-inch PAT torque rotation effect

The PAT torque curve that is formed produces a decreasing linear line, meaning that there is an inverse relationship between rotation and torque. The greater the PAT rotation, the lower the torque value. The four torsion curves formed from each figure form parallel lines, none of which cross each other. This shows that the three PATs have relatively the same characteristics, even though the head is constant and the rotation changes but the PAT can continue to operate stably. There is an inverse relationship between the size of the PAT with constant head and torque. The larger the PAT size, the smaller the constant head value and torque. The 1.0-inch PAT provides constant head variation and greater torque compared to the 1.5-inch and 2.0-inch PATs. The greatest torque performance of the 1.0 inch PAT, 1.5 inch PAT and 2.0 inch PAT are 6.30 N.m, 6.00 N.m and 5.40 N.m respectively tested at a constant head of 15.0 m, 12.0 m, and 10.0 m. The average maximum torque drop is about 7.30%. Specifically for the 1.0-inch PAT, at a constant head of 15.0 m, 12.0 m, 9.0 m and 8.0 m, it produces a maximum torque of 6.30 N.m, 5.00 N.m, 4.20 N.m, and 3.50 N.m. Furthermore, based on the results of the analysis it can be recommended that, to improve the performance of the PAT, the larger the size of the PAT, the greater the potential for head and discharge. The torque performance of the 1.5-inch PAT and 2.0-inch PAT can be improved by increasing the installation capability of the test equipment especially the discharge and head.

3.2. Trend of Power Curve due to Rotation Effect

This PAT experimental test is to analyze the trend of the power curve due to the effect of constant head variations and rotational variations. Other information that will be disclosed is, how the size of the PAT affects its performance as a turbine. Furthermore, this research will also analyze how many kW the maximum power generated by PAT is, and that occurs at how many rpm the PAT rotation. After the torque data for the ten variations of rotation is known, then through equation (2) the PAT power can be analyzed and the recapitulation results are as shown in column 5 in Table 1-3. Figure 12-14 below explains how the trend of the power curve for the three PATs affects the four constant head variations and the ten rotational variations.

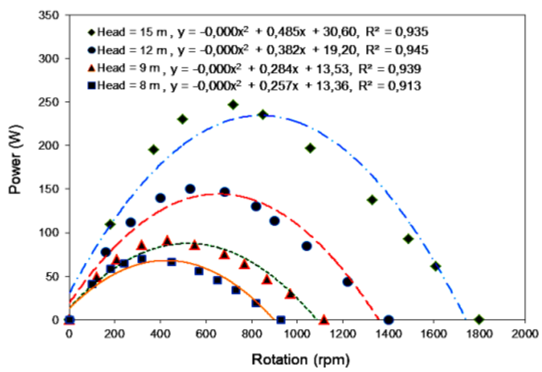

Fig. 12. Trend of 1.0-inch PAT power rotation effect

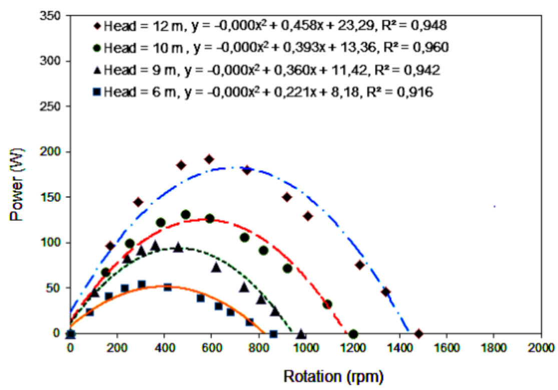

Fig. 13. Trend of 1.5-inch PAT power rotation effect

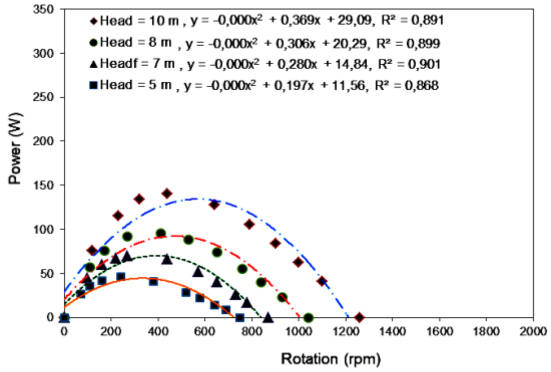

Fig. 14. Trend of 2.0-inch PAT power rotation effect

The power curve that is formed produces a closed parabolic curve with a coefficient of determination (R^2) close to 1.0. The parabolic curve that is formed is quite convincing, approaching the value of 1, meaning that rotational variations and constant head variations have a significant effect on changes in power. The increase in power occurs from the beginning of the rotation to the half-cycle period and then decreases from the half-cycle period to the end of the cycle.

The four curves in each of Figure 12-14 have relatively the same curved pattern, only the size is different. There is a directly proportional relationship between the constant head potential and the power curve that is formed. The greater the potential constant head, the larger the curve size. A curve with a higher constant head covers a curve with a lower constant head, and so on.

From the test results, it is known that the 1.0-inch PAT, 1.5-inch PAT, and 2.0-inch PAT can generate a maximum power of 246.40 W, 191.90 W, and 140.26 W at PAT rotation of 860 rpm, 600 rpm, and 450 rpm. The maximum power drop percentage from 1.0-inch PAT to 2.0-inch PAT is about 43.10%. From this test, it is known that the 1.0-inch PAT has better performance than the larger PAT. These findings indicate that the installation of the test equipment used is more suitable for 1-inch PAT testing. To produce maximum PAT performance, each PAT size requires a different discharge and head. The larger the PAT size will require a larger discharge potential and head, so the performance of the 1.5-inch PAT and 2.0-inch PAT can be improved by increasing the discharge potential and head.

3.3 Trend of Efficiency Curve due to Rotation Effect

This PAT performance test aims to analyze the trend of efficiency curves from 1.0 -inch PAT, 1.5 -inch PAT, and 2.0 -inch PAT due to the influence of four constant head variations and ten rotation variations. Other information that will be disclosed is, how the size of PAT affects its efficiency as a turbine. Furthermore, this study will also analyze how much % of the maximum efficiency is generated by each PAT, and it occurs at how many rpm PAT rotations. After the potential power (P_p) and the PAT real power (P_t) are obtained for ten variations of rotation, then through equation (4) the PAT efficiency value can be analyzed as the results are shown in column 7 of Table 1-3. The following Figure 15-17 shows the efficiency trend of the three PAT measures.

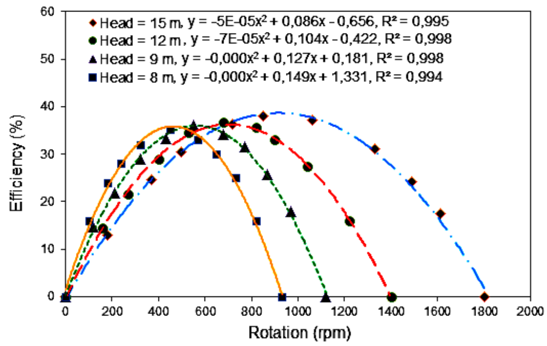

Fig. 15. Trend of 1.0-inch PAT efficiency rotation effect

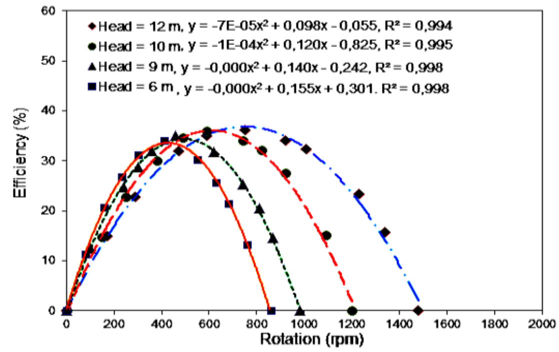

Fig. 16. Trend of 1.5-inch PAT efficiency rotation effect

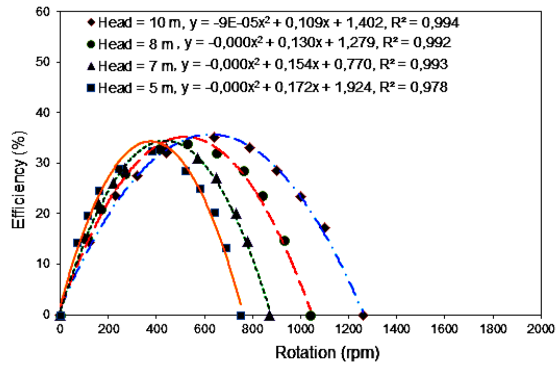

Fig. 17. Trend of 2.0-inch PAT efficiency rotation effect

Figure 15-17 is the trend of the efficiency curve of three PAT measures due to the effect of four constant head variations and ten rotational variations. From the results of the analysis, it is known that the shape of the PAT efficiency curve is a closed parabola with an R^2 value close to 1.0, meaning that the diversity of PAT efficiency data is in accordance with the diversity of rotational data and constant head. From the formed curve, it is known that the constant head has a positive effect on rotation and efficiency, the higher the constant head, the greater the efficiency and rotation interval. As a result, the higher the constant head, the increase and decrease in PAT efficiency occurs gradually as evidenced by the larger curve size and smooth trend. In another test, a low constant head causes the efficiency curve trend to increase drastically initially and then the efficiency curve trend to decrease sharply. This shows that the lower constant head results in the limited effect of rotation on PAT efficiency. Furthermore, the data proves that at a rotational position about half the rotation period will get the highest PAT efficiency, this phenomenon shows that the optimum rotation is not identical to the highest rotation.

From the analysis, it is known that, the maximum efficiency of 1.0-inch PAT, 1.5-inch PAT, and 2.0-inch PAT of 38.10%, 36.30%, and 35.30% occurred at the optimum rotation of 860 rpm, 760 rpm, and 650 rpm and constant head of 15.0 m, 12.0 m and 10.0 m. The average decrease in the maximum efficiency of the three PAT measures is about 7.51%. This finding shows that there is an inverse relationship between PAT size and PAT efficiency. To improve the performance of the PAT, the larger the PAT size must be supported by the potential for a larger discharge and head. To produce maximum PAT performance in the laboratory, each PAT size requires test equipment with optimal head potential and discharge supply and in the field, PAT requires support for river discharge potential and optimal actual head potential as well.

3.4 Trend of Efficiency Curve due to Discharge Effect

This test analyzes the effect of discharge variations on the efficiency trend of the three PAT sizes with four constant head variations. Another objective is to analyze the maximum efficiency and start and optimum discharge of each PAT size. Considering that in this test there are three PAT measures tested, another thing that will be revealed is how the PAT size affects its efficiency performance. Furthermore, the efficiency and discharge data listed in columns 7 and 2 in Table 1-3 are plotted into the curve in Figure 18-20.

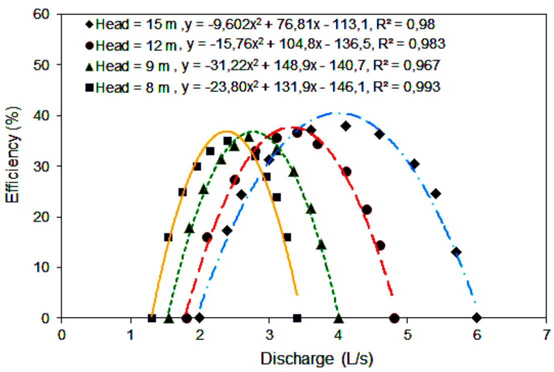

Fig. 18. Trend of 1.0-inch PAT efficiency discharge effect

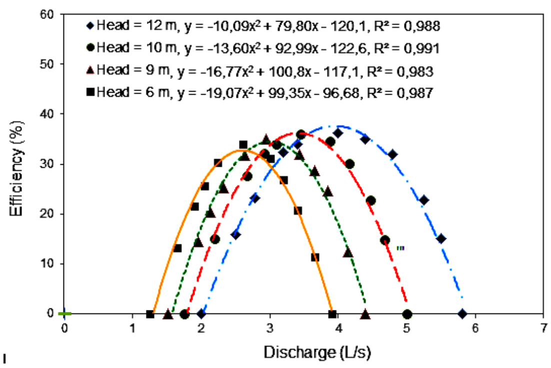

Fig. 19. Trend of 1.5-inch PAT efficiency discharge effect

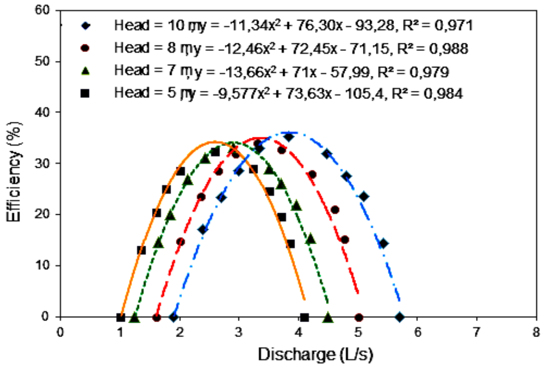

Fig. 20. Trend of 2.0-inch PAT efficiency discharge effect

The curve in Figure 18-20 explains that the efficiency pattern of the four curves from each image has a relatively similar shape, only the size is different. The trend of efficiency at the initial discharge continues to rise steeply and in the next half of the discharge interval, the trend curve decreases steeply until it reaches the lowest efficiency. The trend of the efficiency curve is a closed parabolic curve with a convincing coefficient of determination (R^2) close to 1.0. That is, the diversity of efficiency values is in line with the diversity of the values of the turbine inlet water discharge. There is a PAT measure with efficiency and discharge there is an inverse relationship. The larger the PAT size, the smaller the efficiency performance and the narrower the discharge range. 1.0-inch PAT, 1.5-inch PAT, and 2.0-inch PAT respectively produce maximum efficiency of 38.10 %, 36.30%, and 35.30% at constant heads of 15.0 m, 12.0 m, and 10.0 m with their respective optimum discharges 6.00 L/s, 5.80 L/s, and 5.70 L/s respectively as shown in Figure 21. From the three figures, it can also be commented that each PAT size has a different starting discharge, there is a relationship inversely proportional to the size of the PAT with the discharge starts. 1-inch PAT, 1.5-inch, and 2.0-inch PAT each have a starting discharge of 2.00 L/s, 2.00 L/s, and 1.90 L/s. At a position below the initial discharge, each PAT size has not been able to generate power and efficiency. It can be concluded that the 1.0-inch PAT has better efficiency, discharge, and start discharge performance than other PAT measures. This shows that the test equipment installation used is suitable for 1.0-inch PAT testing and the performance of 1.5-inch PAT and 2.0-inch PAT can be improved by increasing the head and discharge potential of the test equipment installation used.

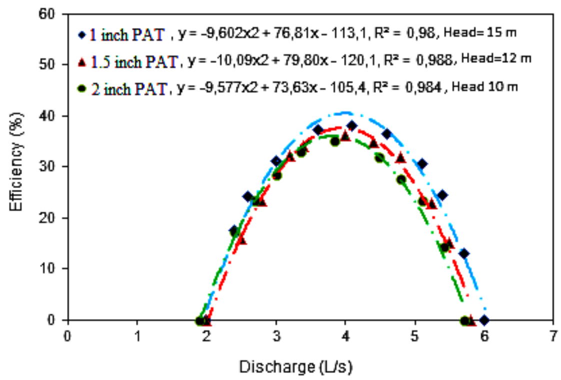

Fig. 21. Maximum efficiency curve

3.5. Effect of Discharge Variation on Power and Efficiency at Constant Rotation 860 rpm

The results of the previous analysis revealed that the 1.0-inch PAT has better performance than the 1.5-inch PAT and 2.0-inch PAT, as evidenced by the higher torque, power, efficiency, head variations, and higher discharge potential. Considering this, the next analysis is focused on the 1-inch PAT. The purpose of this test is to determine the effect of discharge variations on the power and efficiency of PAT with rotation as a constant. Observing the table of the results of the previous 1-inch PAT analysis, it is known that in the four constant head variations, it is known that there is one rotation value that produces the highest efficiency, namely 860 rpm rotation. The data recapitulation of the results of the analysis at 860 rpm is shown in Table 4.

Table 4. Recapitulation of 1.0-inch PAT performance data at 860 rpm.

No	Head, H (m)	Rotation, N (rpm)	Discharge, Q (L/s)	PAT Power, P_t (W)	Discharge Ratio, Q/Q_{max}	Efficiency, η (%)
1	8.0	860	1.44	14.10	0.35	11.56
2	9.0	860	2.06	49.86	0.50	26.78
3	12.0	860	2.98	124.00	0.73	34.69
4	15.0	860	4.20	235.46	1.00	38.10

Furthermore, data on the discharge, power, and efficiency of the 1.0-inch PAT in Table 4 columns 4, 5, and 7 are plotted into a curve so that information on the trend curve of the influence of discharge variations on the power and efficiency of the PAT is obtained as shown in Figure 22.

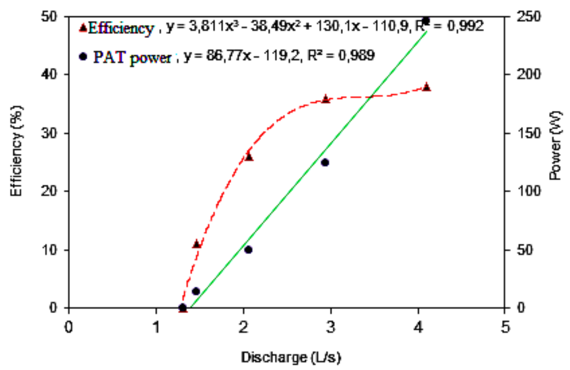

Fig. 22. Effect of discharge variation curve on power and efficiency of 1.0-inch PAT at 860 rpm constant rotation

The curve in Figure 22 explains that the effect of discharge variations on PAT power forms a linear curve, meaning that discharge variations have a more dominant and consistent effect on changes in PAT power. This is in accordance with the turbine power equation, namely $P_t = \rho \times g \times Q \times H \times \eta$, ρ and g are constants while the head (H) and discharge (Q) are the determining variables. From the linear curve, it is known that, at the optimum discharge of 4.20 L/s, rotation of 860 rpm, and head of 15.0 m, it produces a maximum power of 235.46 W and a maximum efficiency of 38.10%. In contrast to the power curve, the trend of the effect of discharge variations on efficiency forms a polynomial line, which means that discharge is not the only variable that affects the efficiency of PAT. There are other variables that have an effect, such as the quality of the PAT, especially the narrow volute construction and the impeller which is quite heavy so it cannot compensate for the increase in discharge and head in accordance with the increase in power demand. In the discharge interval of 1.25 L/s to 2.98 L/s, the trend of PAT efficiency increases dramatically, this shows that at the discharge interval the PAT is very sensitive to changes in discharge. At the discharge position of fewer than 1.25 L/s, the PAT has not been able to generate power so the PAT has no performance. The water discharge of 1.25 L/s is called the start discharge, while the water discharge above 1.25 L/s to 4.10 L/s is called the effective discharge. Starting from the discharge of 1.25 L/s to 2.98 L/s, the efficiency trend increased drastically and after passing the discharge of 2.98 L/s to 4.10 L/s, the trend of efficiency began to increase gradually and tended to be constant. In the discharge interval of 2.98 L/s to 4.10 L/s, the PAT capability begins to saturate or is less sensitive to changes in discharge.

3.6. Effect of Discharge Ratio on 1.0-inch PAT Efficiency at 860 rpm Constant Rotation

Turbine practitioners and turbine researchers use standard curves as a reference to determine the performance of the alternative water turbine tested. The efficiency curve of five conventional turbines with variable discharge ratio is the standard curve for the Francis turbine, Propeller, Pelton, Cross-flow, and Kaplan turbines with the discharge ratio as the independent variable as shown in Figure 23 [43]. In this standard curve, attention focuses on the Francis turbine curve because the Francis turbine construction is relatively the same as the PAT construction as described in Figure 1. The trend of the Francis turbine efficiency curve tends to increase regularly according to the increase in the value of the discharge ratio. In contrast to the Francis turbine, in the Pelton turbine and Cross-flow turbine, the efficiency trend increases dramatically when the discharge ratio is below 0.20 and then the relative efficiency trend remains relatively constant even tends to decrease slightly when the discharge ratio is above 0.2 to 1.0.

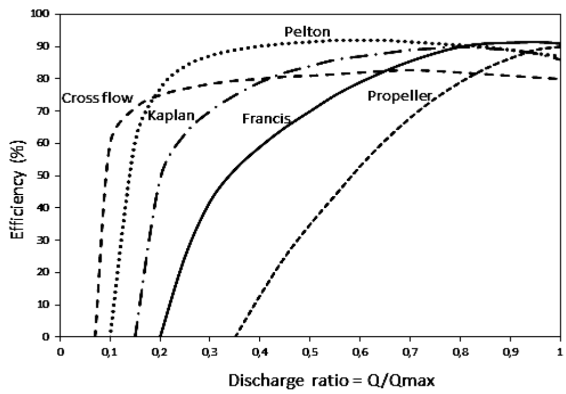

Fig. 23. Conventional turbine efficiency curve

Observing the data in Table 4, the discussion continues to determine the trend of the effect of variations in the discharge ratio on the efficiency of PAT at a constant rotation of 850 rpm. The results of this analysis can be used to determine the trend of PAT efficiency without being limited by the maximum discharge operated by the generating system. In this discussion, we do not analyze the nominal discharge but what is analyzed is the discharge ratio. Furthermore, the discharge ratio as the independent variable and the PAT efficiency as the dependent variable in columns 6 and 7 of Table 4 are plotted into a curve so the results are shown in Figure 24.

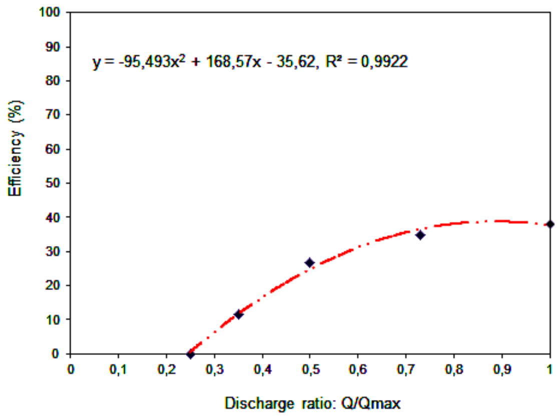

Fig. 24. Effect of discharge ratio curve on 1.0-inch PAT efficiency at 860 rpm constant rotation

Observing the curve of Figure 24, it can be analyzed that the trend of the PAT efficiency curve has a relatively similar pattern to that of the Francis turbine, namely from the beginning it continues to increase gradually, only the starting discharge is different. The starting discharge of the Francis turbine is lower than PAT, this shows that the Francis turbine is more responsive than PAT. At a discharge ratio below or equal to 0.25, the PAT efficiency reaches its lowest point, meaning that although 25% of the maximum water discharge has entered the PAT, the PAT has not been able to generate power. Above the discharge ratio of 0.25, the PAT starts to generate power. At the discharge ratio above 0.25 to 0.85, the trend of PAT efficiency increased significantly quite drastically, this shows that PAT is quite sensitive to the addition of discharge. Furthermore, at intervals of 0.85 to 1.0 discharge ratio, the trend of efficiency tends to decrease. This indicates that PAT becomes less sensitive and saturated to the addition of discharge or changes in the discharge ratio above 0.85. This phenomenon is caused by the increase in water flow which cannot be matched by the construction of the PAT volute housing and impeller which the relatively narrow and heavy. Thus, the discharge ratio of 0.85 is the optimal discharge ratio to obtain the highest efficiency of 38.1% PAT which is a measure of the performance of a 1.0-inch centrifugal pump when used as a water turbine.

3.7. Comparison of PAT Efficiency Curves with Conventional Turbine Efficiency Curves, BAT, W_2KDS, and CAT Curves

The PAT efficiency curve in Figure 24 if plotted in Figure 23 will produce a more complete curve like Figure 25. Observing the curve in Figure 25, it can be analyzed that the PAT efficiency trend is lower than the efficiency trend of five conventional turbines but has a better starting discharge than the turbine. propellers. The trend of the PAT efficiency curve has a relatively similar pattern to that of the Francis turbine, that is, from the start, it continues to increase gradually, only the starting discharge is different. This can happen because the Francis turbine construction is relatively the same as the PAT construction as described in Figure 1. Furthermore, when compared with the blower-as-turbine (BAT) efficiency curve [44], the water wheel knock-down system (W_2KDS) efficiency curve [45], and the compressor-as-turbine (CAT) efficiency curve [46], it is known that the trend of PAT efficiency is lower than BAT, W_2KDS, and CAT. This is very possible because the PAT impeller construction is relatively heavier and the space in the PAT volute is relatively narrower than the BAT and CAT impeller and volute construction. By paying attention to this phenomenon, in the use of PAT in the community, it is necessary to choose PAT with lighter impeller materials such as aluminum and with more open volute holes.

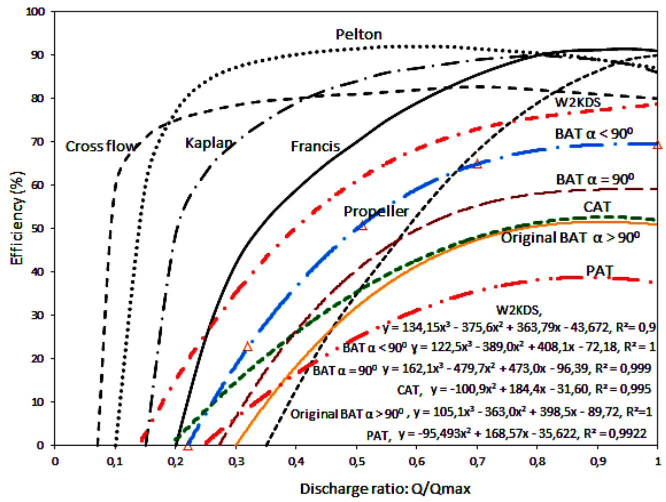

Fig. 25. Comparison of PAT efficiency curves with five conventional turbines, BAT, W_2KDS and CAT

4. Conclusion

Centrifugal pumps are proven to be able to function as water turbines. From the results of the analysis, it is known that the maximum efficiency of 1.0-inch PAT, 1.5-inch PAT, and 2.0-inch PAT of 38.10%, 36.30%, and 35.30% occurred at the optimum rotation of 860 rpm, 760 rpm, and 650 rpm and constant head of 15.0 m, 12.0 m and 10.0 m. This finding shows that is between PAT size and PAT efficiency there an inverse relationship. To improve the performance of the PAT, the larger the PAT size must be supported by the potential for a larger discharge and head. To produce maximum PAT performance in the laboratory, each PAT size requires the installation of test equipment with optimal discharge potential and head, and in the field, PAT requires support for river discharge potential and optimal actual head potential as well. This finding explains that to produce better efficiency, each PAT requires a balanced supply of discharge and head potential. Furthermore, there are many centrifugal pumps sold in the market with various sizes, types, and brands, so that people must be careful in determining the type of centrifugal pump that is most ideal for functioning as a water turbine. Another thing that needs to be recommended to the public is a combination of PAT size with optimal head and discharge potential to produce maximum PAT performance.

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The characteristics and achievements of PAT were successfully revealed through this research, this success is due to the contributions of many parties. The researcher expresses his gratitude to the assistants of the Fluid Dynamics Laboratory, Andalas University who have assisted in the administration stage, procurement of tools and materials, assembly, and testing.

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