Design, Fabrication and Testing of Hydraulic Turbine Runner for a Double Suction Centrifugal Pump in Turbine Mode

Mark D. Villanueva and Joffrey E. Hapitan

***Abstract*—A double suction centrifugal type of pump was converted into a hydraulic turbine (PAT-Pump Acting as Turbine). The casing was maintained and the pump impeller was replaced by a hydraulic runner. It was made of stainless steel with a diameter of 0.662 meter. It had 12 blades as compared to the 5 blades of the original pump impeller. It was assembled inside the original pump casing and was installed along the existing 0.9 m diameter water pipeline of the Rio Verde Water Consortium Inc. Water Treatment Plant has an elevation of around 100 meters above sea level. A bypass line was connected along the existing pipeline to accommodate the installation of the PAT. A portion of the water flowing along the main line was diverted to the bypass line to drive the PAT then flow back to the main line. This gave variation of water flow rates through the PAT by controlling the opening and closing of the valves without altering the total flow rate along the main line. The PAT was commissioned and its operation was observed and tested as to its performance for more than one month. The lowest recorded PAT efficiency was 29% generating electrical power of 5.5 KW, effective head of 7 m. and flow rate of 1311 cu.m. per hr. The electric generator used was an electric motor running in reverse with an efficiency of around 85%. The highest recorded PAT efficiency was 69% generating electrical power of 16 KW, effective head of 7m. and flow rate of 1439 cu.m. per hr.**

***Index Terms*—PAT-pump acting as turbine, hydraulic runner, solidworks.**

I. Introduction

The demand for energy keeps on increasing. It is set to grow by 37% in 2040 [1]. Energy is supplied by sources such as oil, gas, coal, and low carbon sources. The first three aside from its limited sources are the major contributors of carbon dioxide emissions.

Carbon emission is a global concern as it will result to climate change and a continuous increase in global temperature. The long-term global temperature increase due to carbon emission is set at 3.6°C. Intergovernmental agencies met to slowdown this increasing global temperature. Their goal is to reduce the increase to avert the most sever and widespread implications of climate change due to increasing global temperature. Nuclear energy is a low carbon emission source of energy. The generation of electricity through nuclear energy means reduced amount of energy generated from fossil fuels (coal, gas and oil). Less use of fossil fuels means lowering greenhouse gas emissions (CO_2 and others) and lesser climate change effects. However, it has disadvantages and the major one is the management of its nuclear waste. It will take a very long time to eliminate its radioactivity and risks. Renewable energy on the other hand is a clean non-carbon dioxide emitting energy source. Its supply is unlimited; however, it is site specific which means it is feasible to be generated in some areas only. With the alarming effect of climate change, the global trend is towards a clean energy future. In response to this, the government of the Philippines passed Republic Act No. 9513 known as Renewable Energy Act of 2008 which emphasizes on the exploration, development and utilization of renewable energy sources such as biomass, solar, wind, hydro, geothermal and ocean energy sources, including hybrid systems. The strategic building blocks that will propel our country towards the achievement of the goals set forth in RA 9513 is outlined in the National Renewable Energy Program [2]. The NREP sets out targets for the delivery of renewable energy within the time frame of 2011 to 2030. The massive targets up to 2020 will be very challenging as they involve capability building, detailed planning, financing, and construction of renewable energy infrastructures within a time frame at a scale never done before.

The target renewable energy capacities as presented in the NREP Roadmap (2010-2030) is shown in Table I [3].

TABLE I: NREP Roadmap

Year	Renewable Energy Source	Capacity
2022	Wind	2,345 MW
2023	Hydro	5,398 MW
2025	Ocean	75 MW
2030	Solar	350 MW

Hydro power has the largest potential capabilities as shown in the above table. Hydropower plants are classified based on their capacities as: (1) pico-hydro – 1KW to 5 KW, (2) micro-hydro – 5 KW to 100 KW, (3) mini-hydro – 100 KW to 1 MW, (4) small – 1 MW to 10 MW, (5) medium – 10 MW to 100 MW, (4) large hydro – more than 100 MW. Large hydroelectric projects are not given the top priority because of the following reasons:

Very expensive to build (High Capital Cost). This means a long return of investment period (ROI).

Creation of water reservoir dams resulting to flooding of

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large areas of land. This is the most difficult to deal with as it will destroy the natural terrain of the environment, damage the natural habitat of flora and fauna, and may displace the people living in the area to be flooded. It will cause a lot of water access problems which means those living downstream may no longer have control of water flow for their utilization.

There are few sites ideal for the building of a large hydro-electric projects.

Aside from the above reasons, much attention is given to small scale hydroelectric power generators because most potential hydro power sources in the country are suited for pico, mini, and micro hydro sized projects. There are many potential sites for small scale hydro projects and they are evenly distributed in all the regions of the country.

There are many types of hydraulic turbines that can be used for small scale hydro installation. Selection depends on factors such as head of water, volume of flow, ease of installation, availability of local maintenance, efficiency in converting the potential power to useful power, and that it can be designed, manufactured and assembled locally at lower cost. One of the types of hydraulic turbines that can be used in harnessing these small-scale hydro potential resources is the pump as turbine (PAT) type [4].

Pumps are generally classified as Centrifugal Pumps (or Roto-dynamic pumps) and Positive Displacement Pumps. Centrifugal Pumps are classified as end suction pumps, in-line pumps, double-suction pumps, vertical multistage pumps, etc. while positive displacement pumps are the piston, plunger, and diaphragm types, and the rotary types, gear, lobe, screw, vane, etc. Among them only centrifugal types are considered to be feasible to operate as a turbine.

Centrifugal pumps of different capacities are commonly used in small and large industrial and power plants. The demand for centrifugal pumps is very much higher than hydraulic turbine resulting to mass production and many competing manufacturers. This results to lower cost of installing PAT as compared to a typical hydraulic turbine for the same capacity.

A centrifugal pump is physically and hydraulically similar to a Francis turbine operating without flow control device. It converts the mechanical energy of the impeller into pressure energy and kinetic energy of water while Francis turbine converts pressure energy and kinetic energy of water into mechanical energy of the runner. Therefore if a centrifugal pump is operated in reverse mode, i.e., the pump inlet and discharge sides become the discharge and inlet respectively then it can function as a Francis turbine.

The performance of a pump when operating as a turbine will have different best efficiency point flow parameters. This is because the energy losses due to friction etc. must be derived from the flowing fluid in a turbine whereas in a pump, the energy losses are included in the mechanical energy supplied to the pump drive shaft and are not transmitted to the fluid. Therefore, for a unit operating at a particular speed, the flow and head will be less when in pump mode than in turbine mode.

The efficiency of a PAT if operated without any modification is relatively low. There is a need to research and study the modifications that can be done to increase its efficiency with minor effects on its feasibility as compared with the conventional hydraulic turbine. One way is by retaining the configurations of the casing, and then modify only the pump runner to be suited to operate as a turbine. The modification will be done by first doing computer simulation of the performance of the PAT with different configurations. The configuration with the best performance will be considered in the fabrication of the runner. The runner will be installed in the original pump casing and tested for its performance as a turbine.

II. Theory

A hydraulic turbine is a device which converts the energy of flowing water from an elevated source into mechanical energy. The generated mechanical energy can be directly used or be converted into an electrical energy by an electric generator coupled to the rotating shaft of the turbine. The theoretical power (available hydraulic power) from the flowing water can be calculated using the equation below.

$$P_h = \rho g Q H = \gamma Q H \quad (1)$$

where: $\rho =$ density of water, kg/m^3
$g =$ gravitational constant, m/sec^2
$Q =$ volume flow rate of water, m^3/sec
$H =$ net head available, m
$\gamma =$ specific weight of water, N/m^3
The shaft power at the turbine shaft, *Ps* is,

$$Ps = \gamma Q H \eta_t \quad (2)$$

If the efficiency of the electric generator is η_g , then the electrical power, *Pe* is,

$$Pe = \gamma Q H \eta_t \eta_g \quad (3)$$

PAT concept which is radial type turbine was designed based on a Francis type hydraulic turbine. The volute casing of the PAT will act as the spiral casing of a Francis turbine. The flow of water as it enters and leaves in a PAT is similar to the Francis turbine, i.e., flowing water enters to the spiral/volute casing radially and leaves axially at the center of the spiral/volute casing excluding stay and guide vanes as difference. Fig. 1 shows the typical Francis type of hydraulic turbine where the arrows indicate the direction of flow of the water. A double suction centrifugal pump converted as turbine will have the same pattern of flow except that there are two axial exits, i.e., both sides of the volute casing.

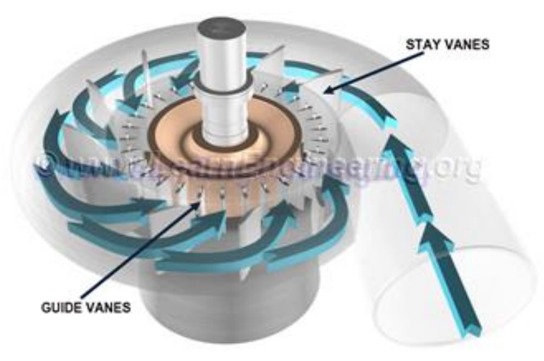

Fig. 1. Francis turbine [6].

Velocity triangle was based on a Francis turbine as shown in Fig. 2 [5].

In this study, the velocity triangle was the basis to create a 3D model that will be used in flow simulation based on Navier-Stokes equations that govern the motion of fluids and can be seen as Newton's second law of motion for fluids. They are composed of different terms corresponding to the inertial forces, pressure forces, viscous forces and the external forces applied to the fluid. These equations are always solved together with the continuity equation. The Navier-Stokes equations represent the conservation of momentum, while the continuity equation represents the conservation of mass. Their solutions are very useful in many practical applications. However, theoretical understanding of the solutions to these equations is incomplete.

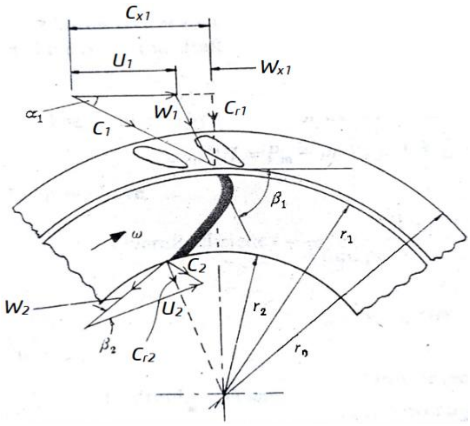

Fig. 2. Velocity triangles for a Francis turbine.

Flow Simulation numerically solves the Navier-Stokes equations, which are formulations of mass, momentum and energy conservation laws for fluid flows [7]. The equations are supplemented by fluid state equations defining the nature of the fluid, and by empirical dependencies of fluid density, viscosity and thermal conductivity on temperature. Inelastic non-Newtonian fluids are considered by introducing a dependency of their dynamic viscosity on flow shear rate and temperature, and compressible liquids are considered by introducing a dependency of their density on pressure. A particular problem is finally specified by the definition of its geometry, boundary and initial conditions. But just like in any numerical calculation the existence of the solution to a particular problem will only be verified once the iterative process converges.

III. Methodology

The study involved actual installation of a large PAT along an existing pipeline supplying one thousand seven hundred cubic meters per hour of processed water to Cagayan de Oro City. The installation of the PAT along the pipeline must entail a relatively low amount of money and that the flow of water through it does not alter the volume of water to be supplied to the City. Shown in Fig. 3 is the Process flow diagram.

A 900mm bypassed pipeline was installed for the purpose of accommodating the PAT assembly without hampering the flow of the processed water to the city. It allowed varying flow rate of water to the PAT depending on the pressure and water flowrate demand in the city. Fig. 4.1 shows the schematic diagram of the bypassed pipeline.

Measurement of the volumetric flow was done at the pump house located around 3.5 kilometers downhill from the PAT set up towards the city. The pump house measurement is part of the operating procedures of Rio Verde Water Consortium Incorporated. The measured volume is the total of the bypassed and inlet volumes in the PAT set up. In the computation of the power available the volume to be considered is the volume passing through the inlet valve. The inlet valve volume is determined by considering the inlet valve area opening percentage as compared to the total opening of the inlet valve and the bypassed valve. The percentage multiplied to the measured total volume is considered the volume of water passing through the PAT. The valves used for the intake and the bypass are of the butterfly valve type. They are similar and of the same size having a diameter of 0.6 meter (0.3meter radius).

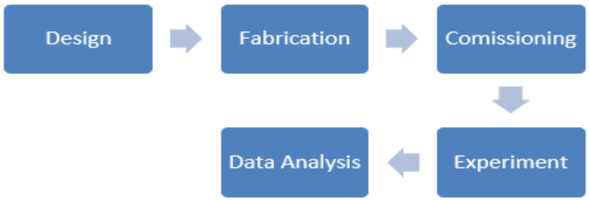

Fig. 3. Process flow diagram.

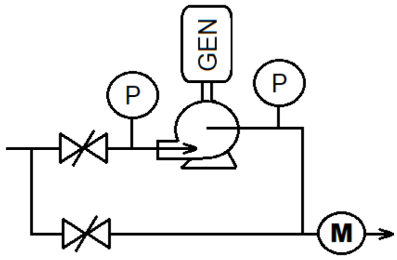

Fig. 4.1. Schematic diagram of the bypass pipeline.

The area of opening is calculated using the following equation:

$$A = \pi R^2(1 - cos\theta) \qquad (4)$$

where: R = Radius of the butterfly valve, 0.300 meter, θ = angle of rotation in radians

The angle θ is computed as

$$\theta = \frac{\frac{\pi}{2}}{N_f} N \qquad (5)$$

where N_f = number of turns from fully closed to fully opened, 48 turns, N = number of turns.

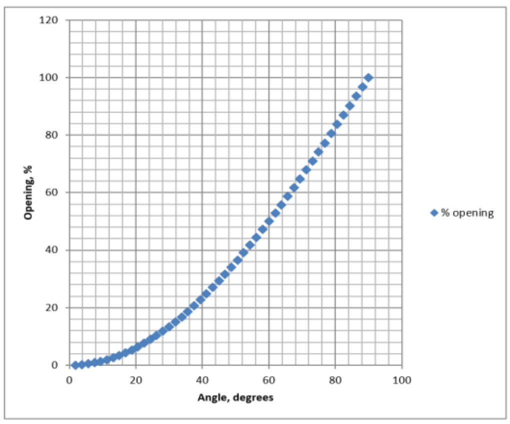

Fig. 4.2. Percentage opening angle of turn of butterfly valve.

In this study the butterfly valves for the inlet and bypass are similar with the following having values shown below.

N_f =48, turns from fully closed to fully opened, R= 0.300 meter, the radius of the butterfly valve that turns from zero to ninety degrees as it fully closes or fully opens the valve respectively. Shown in Fig. 4.2 is the relationship between percentage opening and angle of turn.

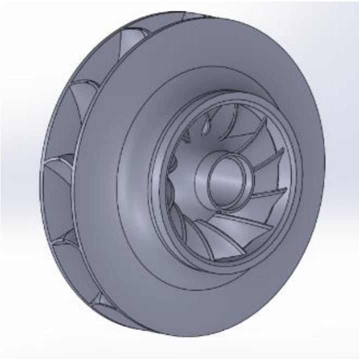

Fig. 5.1. The 662mm turbine runner model.

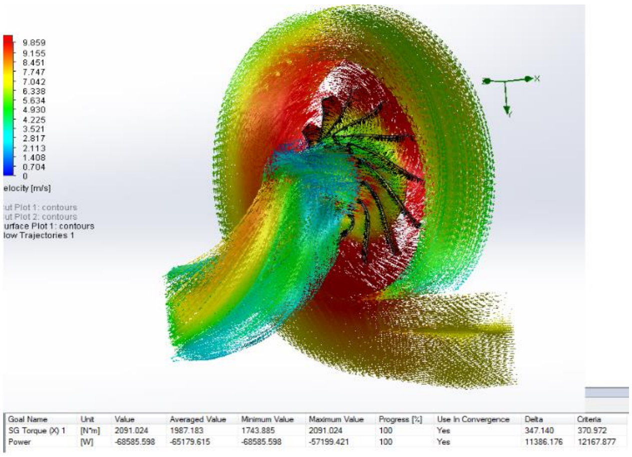

Fig. 5.2. Velocity profile and flow trajectories of the PAT using solid works flow simulation.

The runner for the double suction centrifugal pump acting as a turbine was designed using a Solid Works software based on Euler turbine equation to attain the inlet and outlet two dimensional angles with a diameter equal to the original impeller which is 662mm. The design process started by having a model of the PAT to be simulated. Only half of the double suction centrifugal pump acting as a turbine was analyzed and simulated since the other half is just the mirror image. Several configurations, i.e., angle of twist and number of blades, were considered. Flow rates and pressure heads were varied. Among the many simulations conducted, the configurations shown in Fig. 5.1 and Fig. 5.2 was considered the best model, a 12-blade runner.

Fig. 6. Three-dimensional printed blade model.

The manufacture of the runner started by making a pattern. The model for the blade was 3-D printed. Fig. 6 shows the 3-D printed blade. The pattern for the mold making of the turbine is shown in Fig. 7.

Fig. 7. Pattern for the inner part of the runner.

The runner was then casted and machined by First Asian Metals Corporation in Cagayan de Oro City. The material used for the runner was stainless steel. The main reason for using stainless steel was to avoid contamination due to corrosion of the water that would propel the turbine. The water is the product of the water treatment plant of the Rio Verde Water Consortium Incorporated and is distributed for consumption to the people living in the city. The casted product is shown in Fig. 8.1 and Fig. 8.2.

Fig. 8.1. Side view of the casted runner.

Fig. 8.2. The runner after machining.

Fig. 9. Comparison between original impeller and the turbine runner.

Fig. 9 shows the original impeller placed side by side with the turbine runner. The differences of the two can be obviously observed, mainly the number of blades which are five for the pump impeller and twelve for the turbine runner and the curvature directions of the blades. The pump impeller blades are curved counter clockwise while clockwise for the turbine runner.

Manufactured PAT Turbine runner and other parts needed for the PAT assembly such as the shafting, bearings, valves, seals, pressure gauges, power meter and mountings for the PAT and generator were prepared and machined. The installed generator was a recycled electric motor operated in reverse. Although its efficiency in converting shaft power to electrical power was lower than a commercially available generator, the consideration that it was not already used, readily available and would entail no additional cost was given favorable attention. Shown in Fig. 10 is the actual PAT assembly.

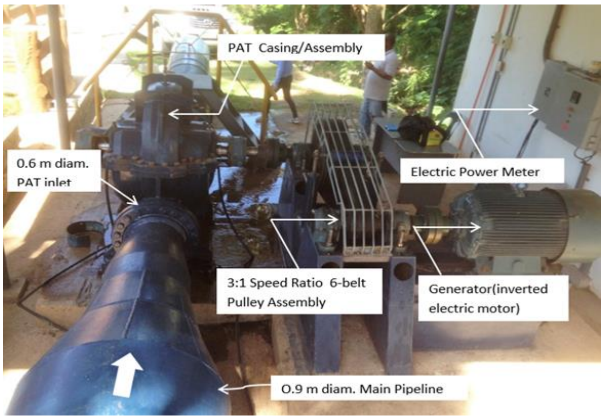

Fig. 10. Actual PAT assembly.

TABLE II: 15 HOUR DATA

Q_{PAT}	H	P_a	P_g	% η_g	% η_T
1169.98	7.025	23.396	5.50	25	29
1311.02	7.025	25.096	6.10	24	29
1416.38	7.025	27.112	6.10	24	31
1441.87	7.025	27.60	15.70	57	67
1443.57	7.025	27.63	15.40	56	66
1430.82	7.025	27.39	15.10	55	65
1440.17	7.025	27.57	15.10	54	64
1479.25	7.025	27.649	15.4	56	63
1444.42	7.025	27.308	15.4	56	66
1432.52	7.025	27.503	15.7	57	66
1426.58	7.025	27.584	15.70	57	66
1436.77	7.025	27.503	15.7	57	67
1441.02	7.025	27.584	15.70	57	67
1438.47	7.025	27.535	16.20	59	69
1472.46	7.025	28.19	16.40	58	68

There is a diameter reduction from 0.9 meter to 0.6 meter at the connection of the pipeline and the inlet of the PAT. The pipe and the PAT inlet were connected by bolted flange connection. It must be noted that the inlet of the PAT was the outlet of the then double suction centrifugal pump and is smaller than the exit side. At normal operation the turbine shaft rotates at 600 RPM. With a 3:1 speed converter, the generator rotates at 1800 RPM, the recommended operating RPM. The generator is an inverted electric motor. The electric power meter shown in the figure displays digitally the instantaneous power generated. The set up was subjected to hydro test and was allowed to run for several hours during the commissioning process. Observations for leaks, vibrations, unusual noise due to metal to metal contact, alignment of the turbine and generator shafts, switching connections to the electrical power lines were conducted. After doing these, final adjustments and retightening of the bolted connections and others were done in preparation for the actual test run and operation.

IV. Results and Analysis

Shown in Table II and Fig. 11 is the relationship between available power and power generated by PAT with a motor efficiency including speed conversion factors equivalent to 85%. Maximum turbine efficiency attained was 69% with the following parameters equal to (H = 7m and Q = 1439 cum/h) Flowrate range was only limited to 1010 to 1585 due to present plant operation requirement.

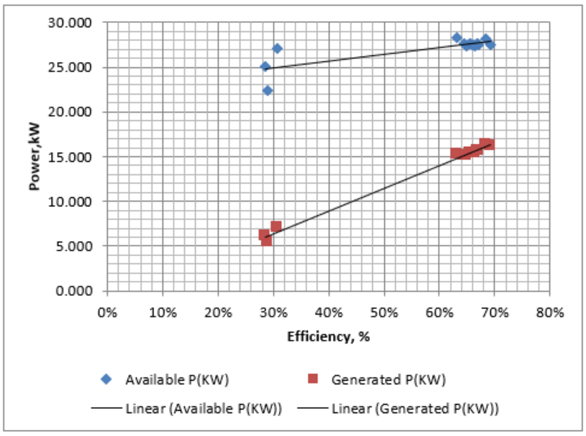

Fig. 11. Relationship between available and generated power by PAT.

V. Conclusion

It can be then concluded that a reliable and efficient PAT can be designed, and fabricated locally using the available Solid Works software and that installation of PAT along an existing water pipeline with ample potential head can be installed without hampering its normal operation.

The following are the reasons for the improvement of the efficiency:

1. Increased number of blades
2. Correct angle of entry and exit
3. Correct angular speed

VI. Recommendation

Continues data collection of the installed PAT. The data can be used to analyze and maybe derived correlations or empirical equations relating the performance of the PAT of this type (double suction centrifugal pump) to parameters like head, inlet and outlet pressure gauge readings, openings of the main and bypass valves, and flow rates.

Design, fabricate and test another runner that is more similar to the Francis turbine in terms of its crown diameter.

Acknowledgment

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