Development of Nomograph for Sizing a Centrifugal Pump as Turbine for Electric Power Generation

Adornado C. Vergara

***Abstract*—Three different sizes and brands of non-self-priming Centrifugal Pump (CP) were used in this study. Sizes of CP were as follows: 75 mm x 75 mm, 100 mm x 100 mm and 125 mm x 125 mm. Each Centrifugal Pump as Turbine (CPAT) was individually coupled to the test rig and subjected to variable heads and flow rates. On-site evaluation of 100 mm x 100 mm CPAT was conducted at an existing Micro Hydro Power (MHP) system.**

Functional relationships presented in the Nomograph were Actual Discharge of CPAT, Rotational Speed and CPAT Brake Power at different heads. To validate the reliability of the developed Nomograph, data in laboratory testing and on-site testing were compared statistically.

During laboratory testing, regression equations developed from 75 mm x 75 mm, 100 mm x 100 mm and 125 mm x 125 mm between net head (H) and actual discharge (Q_a) are $Q_a = 0.0042H^{0.2991}$ with $R^2 = 0.94$, $Q_a = 0.0065 + 0.0006H - 0.0000002H^2$ with $R^2 = 0.98$, and $Q_a = 0.0093H^{0.3581}$ with $R^2 = 1$, respectively. Likewise the regression equations between net head (H) and CPATs shaft speed are $N = 11.608 + 1.5589H - 0.0119H^2$ with $R^2 = 0.98$, $N = 11.08 + 1.5249H - 0.0043H^2$ with R2 = 0.95, and $N = 10.157H^{0.3827}$ and $R^2 = 0.97$, respectively. Similarly, regression equations between net head (H) and CPATs brake power are $BP_{CPAT} = 0.0912H^{1.1392}$ with $R^2 = 0.96$, $BP_{CPAT} = 0.1096H^{1.2624}$ with $R^2 = 0.99$, and $BP_{CPAT} = 0.022H^2 + 0.0248H + 0.4863$ with $R^2 = 0.99$, respectively. The values derived from these equations were used in making the Nomograph.

On the other hand, regression equations developed on-site from a 100 mm x 100 mm CPAT between net head (H) and Qa, net head (H) and N, net head (H) and BP_{CPAT} were statistically comparable during laboratory testing and are as follows: $Q_a = 0.0036H^{0.5662}$ with $R_2 = 0.95$, $N = -0.0022H^2 + 1.335H + 13.044$ with $R^2 = 0.99$, and $BP_{CPAT} = 0.1173H^{1.244}$ with $R^2 = 0.98$. The Nomograph was tested on-site and showed satisfactory performance.

***Index Terms*—Centrifugal pump as turbine, laboratory and on-site testing, micro hydro power.**

I. Introduction

Hydropower is very clean source of energy. It does not consume but only uses energy of flowing water, after which it becomes available for other purposes again. Use of hydropower can make significant savings on exhaustible energy sources [1]. Unlike PV or wind systems, hydro systems generate electricity continuously, as long as water is flowing, and will typically be the most cost-effective renewable energy approach [2].

According to the Department of Energy (DOE) [3] of the Philippines, the country remains to be dependent on imported electro-mechanical equipment for micro-hydro projects. There are several local turbine fabricators in the country who are already trained to manufacture turbine equipment, but significant skills on their part is still required to build this unit. Difficulty would be further highlighted by limited resources.

Generally, micro-hydro manufacturers offer high efficiency turbine performance, however, these turbines are expensive and almost unaffordable particularly for rural communities.

In many developing countries, micro hydropower stations are in demand, especially in remote locations. However, range of micro hydro standard size of turbines are not easily and economically available. So there is a need for a machine like pumps operating in reverse mode since they are available in number of sizes, covering different ranges of head, discharge and capacity. Small centrifugal pumps are suitable for use as hydraulic turbines and have advantage of being mass produced in many countries throughout the world [4]. Centrifugal pump could operate in turbine mode without mechanical problem but give lower BEP running in turbine mode compared to pump mode [5].

Use of CPAT for micro-hydro offers low cost solution as substitute for commercial micro-hydro turbine although efficiency of pump operating in turbine mode was found 8.53% lower than the best efficiency in pump mode [6]. Domestic and industrial end suction centrifugal pumps cover wide range of flow and head. Advantages of CPAT compared to commercial turbines are its simplicity in construction, know-how knowledge is readily available, and low operating and initial costs thus making the technology more affordable [7]. However, data about the performance of the different sizes of CPAT is still limited, pump manufacturers only supply pump mode performance curve and this makes it difficult to predict the turbine mode performance. To attain definite characteristic pump in turbine mode, the pump is required to be tested over range of heads and flows [8], hence this study.

Nomography is graphical representation of mathematical relationships or laws and used extensively for many years to provide engineers with fast graphical calculations of complicated formulas to practical precision [9]. Visualization is an important part of both data analysis and statistical communication. For relating three variables, contour plots will always work, but where they are available, Nomographs might be clearer and simpler to use [10]. Evaluating different sizes of CPAT for MHP is important in making a nomograph

Manuscript received September 2, 2016; revised February 20, 2017. This work was supported in part by the Engineering Research Development for Technology Scholarship Grant of the Department of Science and Technology of the Philippines.

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doi: 10.18178/jocet.2017.5.6.419

for sizing and selecting an appropriate CPAT suited in certain location where value of head and discharge is known. This Nomograph is important in remote areas where power is not available and where computer is not practical to use. Nomograph which is handy and practical to use can give quick and reliable result by simply drawing one or more lines to calculate result. Many nomographs include other useful markings like reference labels and colored regions. All of these provide useful guideposts to users.

Many successful stories are told about micro-hydropower (MHP) in rural electrification. However, true success of electrification program is determined primarily by lives of beneficiaries that have improved, economic activities that emerged and advancement in education and health services in rural areas made possible by availability of electric service. It is therefore, important to pay attention to actions to reduce the whole MHP cost because it is always the main concern of small communities especially in rural areas. Furthermore, the MHP must be reliable, robust, and manageable with minimum technical knowledge by local communities.

II. Objectives

The general objective of the study was to develop a decision tool for sizing locally available CPAT for electric power generation. Specifically, the study aimed to:

1. establish functional relationship between flow rates and heads for different sizes of CPAT;
2. develop a nomograph for determining appropriate CPAT size for a given combination of flow rate and head; and,
3. conduct on-site validation of the nomograph.

III. Methodology

Fig. 1 shows the schematic diagram of the test rig. A feed pump producing greater head and flow was used to supply inverse flow to the CPAT that was studied. In order to attain these conditions, two centrifugal pumps, bigger than or at least equal to size of biggest CPAT studied, were used as feed pumps. The feed pumps were connected in series and were operated at the same speed to prevent cavitation in each pump. The feed pumps put energy simultaneously into the pumping water, so the resultant head are the sum of the individual heads.

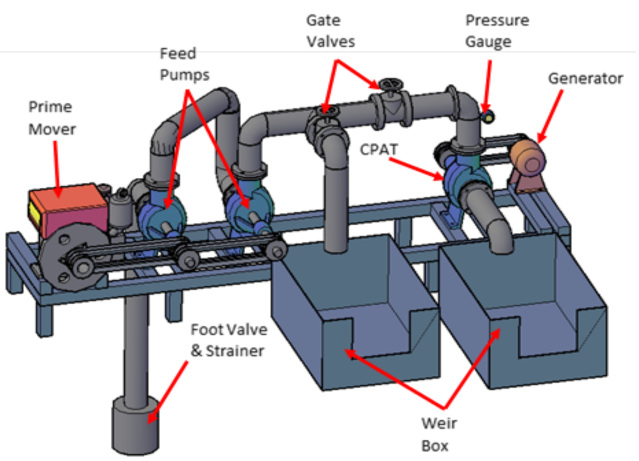

Fig. 1. Schematic diagram of the test rig.

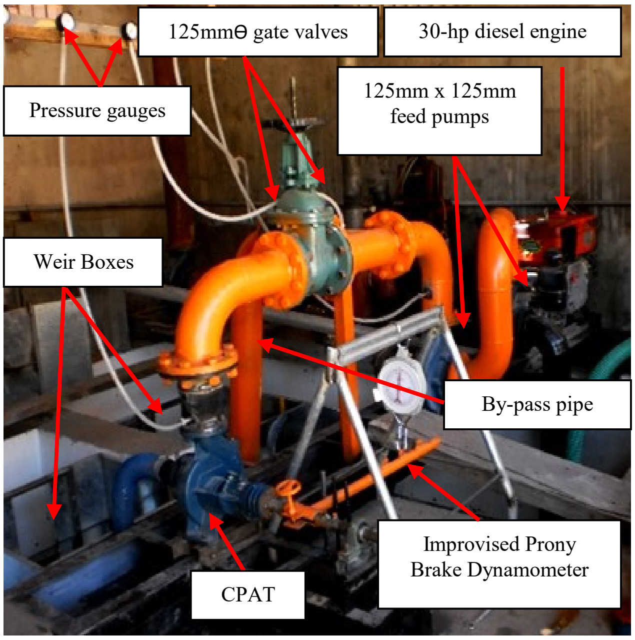

Fig. 2. Actual laboratory layout of the test rig at Central Luzon State University.

Fig. 2 shows the photograph of the actual set-up of the test rig, the feed pumps used were two (2) 125 mm × 125 m centrifugal pumps. Prime mover of the feed pumps is a 30-hp (22.38 kW) diesel engine. The gate valves were located before the CPAT and in the by-pass pipe to control flow rate in the system. It was also provided with pressure gauge to measure the working pressure in pipe lines. Water flow rate in the system was measured by a weir box. A prony brake dynamometer was used to measure torque that is developed in the CPAT shaft. Rotational speed of the CPAT was measured by contact tachometer.

Three different sizes and brands of non-self-priming CP were used in this study. Sizes of CP were as follows: 75 mm × 75 mm, 100 mm × 100 mm, and 125 mm × 125 mm.

The 75 mm × 75 mm CPAT evaluated has the following specifications as pump; Brand: Sakai, Model: SP80, Total Head: 13 m, capacity: 65 m^3/hr, Suction Lift: 6 m.

The 100 mm × 100 mm CPAT evaluated has the following specifications as pump; Brand: Super Yamato, Maximum Capacity: 420 GPM (95 m^3/hr), Total Head: 80 ft (24 m), RPM: 1800- 2400.

The 125 mm × 125 mm CPAT evaluated has the following specifications as pump; Brand: Kuhol, Type: TS-150, Total Head: 8 m, Suction Lift: 4 m, Capacity: 150 m^3/hr.

Each CPAT was individually coupled into the test rig and subjected to variable heads and flow rates. Flow rate and head were controlled into their desired combinations by adjusting throttle of pump prime mover or adjusting gate valves in pipeline or combining the two methods.

Pressure head was directly read from precision pressure gauge in pipe line before the CPAT. A prony brake dynamometer was used to measure torque that is developed in the CPAT shaft. Rotational speed of the CPAT was measured by contact tachometer. The CPAT brake power (BPCPAT) was computed by

$$BP_{CPAT} = (T \times N)/974 \tag{1}$$

where: BP_{CPAT} - CPAT Brake Power, kW
T - shaft torque, kg-m
N - shaft speed, rpm

The pulley combination of the CPAT and the generator was computed by

$$N_1D_1 = N_2D_2 \tag{2}$$

where:

N_1 – RPM of the CPAT
D_1 – Pulley diameter of the CPAT
N_2 = RPM of the generator
D_2 – Pulley diameter of the generator

A 3 kW, 220 V, 13.6 A, 60 Hz, 1,800 RPM, single phase generator head were used as mechanical to electrical converter in this study. Voltage and current were measured using multimeter and clamp meter, respectively.

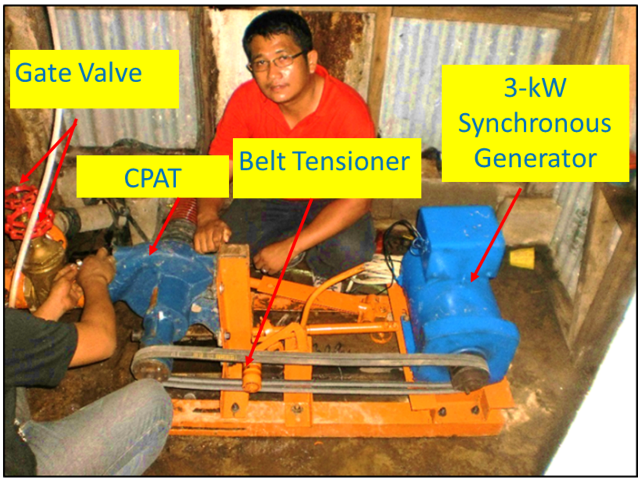

Fig. 3. The new MHP set-up at Dilaktan, Alfonso Castañeda, Philippines.

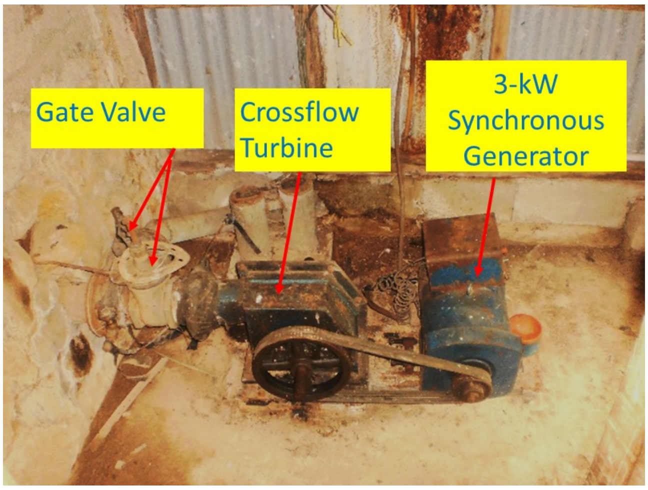

Fig. 4. The old MHP set-up at Dilaktan, Alfonso Castañeda, Philippines.

Functional relationships established were Net Head vs Actual Discharge, Net Head vs Shaft Rotation, and Net Head vs CPAT Brake Power and were presented in a nomograph. The nomograph was drawn using a Computer Aided Design (CAD) software.

On-site testing of the CPAT was done at Dilaktan, Alfonso Castañeda, Nueva Vizcaya, Philippines where there is an existing but unserviceable MHP.

The 100 mm × 100 mm CPAT (Fig. 3) was chosen to replace the 100 mm cross flow turbine (Fig. 4) on-site.

Procedure used in the laboratory were also the same procedure used on-site. Result of evaluation was used to validate the reliability of the developed nomograph. Data in laboratory testing and on-site testing were analyzed using test of hypothesis on correlation coefficient (R).

IV. Results and Discussion

A. Nomograph of the CPATs

In the form of nomograph, functional relationships that are important in selecting and sizing CPATs for MHP such as net head versus the actual discharge, brake power, and shaft speed were plotted as shown in Fig. 5. Each function was represented in different color so that user can easily distinguish one from other. Green color represents function of CPAT brake power. Blue color represents function of actual discharge. Pink color represents function of CPAT shaft rotational speed. Abscissa represents net head in the nomograph. All other functions are represented in ordinates.

Solid portions of different curves are actual values taken during laboratory testing. Test rig can only work at these heads. Dotted portion of curves are just projected values taken from the regression equation developed from data during laboratory testing.

B. Guidelines in Using the Nomograph

To get value of the different functions, draw vertical line from determined value of the net head dissecting curves of different functions, then draw horizontal lines in each intersection on different curves extending to the ordinate representing function.

For instance, 15-m net head of water in 75 mm × 75 mm, 100 mm × 100 mm, and 125 mm × 125 mm CPATs will produce about 2.0 kW, 3.3 kW and 5.8 kW turbine brake power, respectively. A 15-m net head of water in 75 mm × 75 mm, 100 mm × 100 mm and 125 mm × 125 mm has minimum discharge of about 0.0084 m^3/s, 0.152 m^3/s and 0.0245 m^3/s, respectively. Also, from this net head shaft speed of 75 mm × 75 mm, 100 mm × 100 mm, and 125 mm × 125 mm of CPATs are about 1940 RPM, 1980 RPM and 1720 RPM, respectively

The brake power is the basis in sizing the generator used. The discharge is the desired amount of water that passes through the CPAT and it is controlled at the gate valves. The shaft rotational speed is the basis in computing the CPAT and generator pulley combination.

The CPAT as an unconventional type of turbine does not have flow regulating mechanism therefore it can only accommodate certain amount of water at a certain head.

Excess amount goes out in the overflow weir of the forebay, thus excess water supply will not affect the performance of the set-up. On the other hand, if the water supply fluctuated below the minimum discharge, the rotational speed of the CPAT shaft will slow down and can no longer deliver the right amount of rotation to the generator. Low speed in the generator will cause a low frequency in the electrical circuit. Therefore, it will shorten the life span or even destroy the appliance connected in the circuit. In this situation, the remedy is to change the pulley combination of the CPAT and generator in order to meet the correct rotational speed of the generator although it will decrease the amount of power that the generator can deliver.

In many situations, especially with AC systems, it is necessary to adjust transfer ratio so that both turbine and generator run at their optimum (but different) speeds. These types of drive systems can use gears, chains, or belts, each of which introduces additional efficiency losses into the system. Belt systems tend to be more popular because of their lower costs [11].

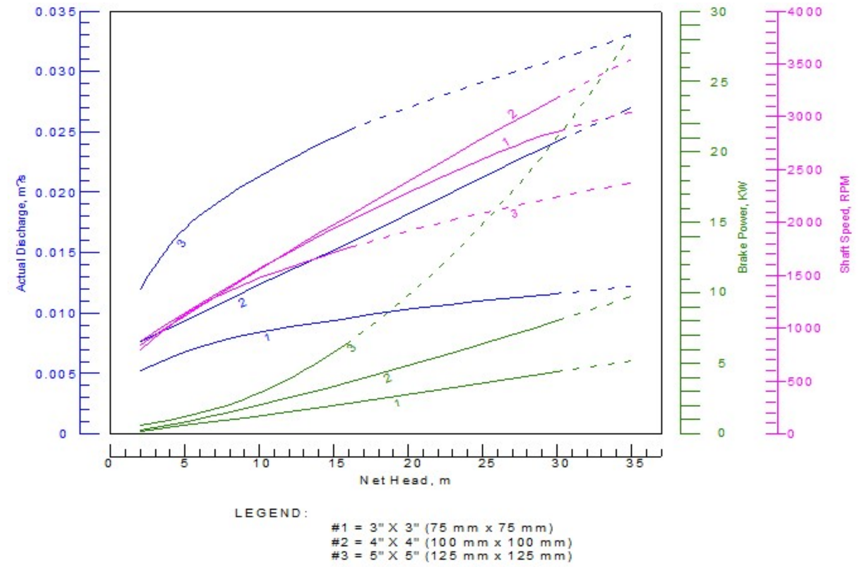

Fig. 5. Nomograph showing the performance of the CPATs

C. Comparison of Performance of 100 mm × 100 mm CPAT in Laboratory and on-site Testing Using Correlation Analysis

1) Discharge

Value of correlation coefficient is 0.99245. Computed value of t (t_c) is 21.40, while tabulated value t (t_{tab}) is 3.50. Since computed value of t is greater than tabulated, then, there is a significant correlation between the discharge of the CPAT on laboratory and on-site testing.

2) Shaft Speed

Value of correlation coefficient is 0.99996. Computed value of t (t_c) is 289.09, while the tabulated value of t (t_{tab}) is 3.50. Since computed value of t is greater than tabulated, then, there is a significant correlation between shaft rotation speed developed by CPAT during laboratory and on-site testing.

3) Brake Power

Value of correlation coefficient is 0.99998. Computed value of t (t_c) is 590.86, while tabulated value of t (t_{tab}) is 3.50. Since computed value of t is greater than tabulated, then, there is a significant correlation between brake power developed by CPAT during laboratory and on-site testing.

D. Performance of the 100 mm × 100 mm CPAT on-site Coupled to 3.0 kW Generator

Using the Nomograph, the setting of the CPAT to run a 3-kW generator was: working net head (H), 13.75 m; shaft speed, 30.98 rev/sec (1860 RPM); and the discharge (Q), 0.0159 m^3/s. The computed pulley diameter combination of the CPAT and generator is 75 mm: 75mm.

Table I is the performance of the 3-kW generator when coupled to the CPAT and upon applying varying load.

In the old set-up (Fig. 4), fifty two (52) households benefited from this project. Each household was allocated 20 watts of power and they use it mainly for lighting during night time and for battery charging during daytime. Summing-up 1,040 watts (1.04 kW) of power was supplied by the MHP to the households. In the new set-up (Fig. 3), it can still supply 20 watt to each household since it can produce 1200 watts at 116 volts (Table I) which is still within the range of voltage needed to light up a LED lamp and to charge batteries.

TABLE I: PERFORMANCE OF THE 3-KW GENERATOR COUPLED TO THE 100 MM × 100 MM CPAT

Accumulated Load, W	Net Head, m	Discharge, m^3/s	Shaft Speed, RPM	Voltage, V	Current, A
0	13.75	0.0159	1815	228	0
300	10.85	0.0159	1635	192	1.2
600	9.3	0.0159	1412	160	2.4
900	8.36	0.0151	1210	134	3.2
1200	7.56	0.0151	1050	116	3.7
1500	6.87	0.0144	942	97	4.3
1800	6.1	0.0144	836	84	4.5
2100	5.7	0.0144	763	78	4.7

The Dilaktan Micro-hydro projects was established in the year 1999 by the Department of Energy (DOE) in the Philippines. During our ocular inspection on April 4, 2015, we found out that the turbine and generator is no longer serviceable. According to the beneficiaries (Fig. 6) of the project, the MHP is no longer functional for almost a year. They also added that, some of them were trained in repairing the MHP system, but they still need the assistance of the DOE to repair the turbine. However, because of communication gap, they do not have immediate access for experts from the DOE. Aside from this, the rural folks cannot afford imported turbines. These are the reasons why micro-hydro projects for rural electrification become unsuccessful most especially in remote areas. With the introduction of locally available CPAT as substitute for imported turbines it would be big help to the rural communities. The technical know-how on the repair of the CPAT is passed on them (Fig. 7) hence, they can now maintain the MHP system without consulting the experts.

Fig. 6. The local people of Dilaktan helping the researcher during the conduct of the study.

Fig. 7. Measuring the available power at the farthest household being supplied by the MHP.

V. Conclusions

Based on results of the study, the following conclusions were drawn:

1. The functional relationships between flow rates and heads for different sizes of CPAT were established during the laboratory test.
2. Nomograph for determining appropriate CPAT size was developed and effectively worked in different combinations of flow rate and head.
3. Nomograph developed from the laboratory testing was successfully validated and efficiently worked on-site.

Acknowledgment

The author would like to express his sincere appreciation and wholehearted gratitude to the following persons who have contributed their efforts towards success of this study. This would not have been made possible without their help in so many ways: the people of Dilaktan, Galintuja, Alfonso Castañeda, Nueva Vizcaya, Philippines for their warm welcome and for their assistance during setting up of the Micro-hydro Power system; Dr. Ireneo C. Agulto, Dr. Victorino T. Taylan, Dr. Armando N. Espino, Jr., Dr. Melissa E. Agulto, and Dr. Teresito G. Aguinaldo professors at the Central Luzon State University (CLSU), Science City Muñoz, Nueva Ecija, Philippines, his Advisory Committee, for their invaluable comments and suggestions from conceptualization of the study until the final editing of the manuscript; Dr. Romeo B. Gavino and Dr. Emmanuel V. Sicat, also professors at CLSU, his Examining Committee, for their constructive criticisms, comments, and suggestions to improve the manuscript.

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