Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 118 (2017) 238–242

Energy Procedia

www.elsevier.com/locate/procedia

2nd International Conference on Advances on Clean Energy Research, ICACER 2017,
7-9 April 2017 Berlin, Germany

Analytical Prediction Models for Evaluating Pumps-As-Turbines (PaTs) Performance

Mosè Rossi[a*], Massimiliano Renzi[a]

[a]*Libera Università di Bolzano, Piazza Università 1, Bolzano – 39100, Italy*

Abstract

The hydropower sector is moving to the small-scale generation due to the exploitation of the majority water reservoirs with the aim of providing electrical energy in rural zones. Pump-as-Turbines (PaTs) is one of the most interesting technology due to their use for recovering energy in different industrial applications. Several studies aimed to study the performance of the tested PaTs and to describe their performance curves. The efficiency of these machines at their Best Efficiency Point (BEP) is comparable as much as the pump mode. In this work, a general analytical method for forecasting PaTs performance in turbine mode was investigated.

Peer-review under responsibility of the scientific committee of the 2nd International Conference on Advances on Clean Energy Research.

Keywords: Pump-as-Turbine; Analytical method; Best Efficiency Point; Efficiency; Performance curves

---

1. Introduction

The need to produce energy is one of the most important issues for human life. Through the years, the development of the new energy systems through the exploitation of different available natural sources has been carried on. The energy production technologies based on both carbon and oil overtook the natural sources becoming the primary energy sources worldwide; however, this phenomenon brought to an increase of harmful pollutants in the atmosphere [1] and to a steep increase of the carbon dioxide concentration. For this reason, renewable sources started to be investigated with particular regards to water resources. The use of water was one of the first methods for energy production, moving from the large-scale plants [2] to the small-scale ones due to the exploitation of all

---

* Corresponding author.
E-mail address: Mose.Rossi@natec.unibz.it

1876-6102 © 2017 The Authors. Published by Elsevier Ltd.
Peer-review under responsibility of the scientific committee of the 2nd International Conference on Advances on Clean Energy Research.
10.1016/j.egypro.2017.07.011

the available geodetic altitudes and the maturity of the technology. One of the most used technology in the small-scale hydropower sector, that is taking the field in these last years due to its versatility for being used for both energy production/recovery, its cost and availability, is the Pump-as-Turbine (PaT) technology. In order to take advantage of its pros, many improvements were performed: Zhu et al. [3] carried out a complete study for optimizing a medium-high head PaT taking into account the interaction between the blades, the water and the channel shape. Rezghi et al. [4] studied the effects of the transient flow inside the PaTs that occur in waterways due to the pressure fluctuations. In parallel with these studies, several researches were performed to forecast their performances in turbine mode. Theoretical formulas were provided by Williams [5], Stepanoff [6], Krivchenko [7], Sharma [8] and McClaskey [9] based on experimental data and assuming that the efficiency achieved by a PaT in turbine mode at the Best Efficiency Point (BEP) is the same as that achieved in pump mode operating at the same running conditions. These formulas allow to evaluate the flow rate and the head exploited by the PaTs running at their BEP in turbine mode. The following step is to define a trend line for evaluating their performance in turbine mode: Singh et al. [10], using data obtained by three tested pumps having different specific angular speeds and other data collected by Derakshan et al. [11], developed an optimization routine for forecasting the performance of the centrifugal pumps running in turbine mode. Yang et al. [12] described an analytical method and performed both CFD simulations and laboratory tests of a single stage centrifugal pump running in turbine mode in order to validate the analytical results previously obtained. Furthermore, Yang et al. [13] studied the effect of a PaT impeller trimming through laboratory tests and numerical simulations. Along the same line, Jain et al. [14] performed laboratory tests on a PaT varying its rotating speed and trimming the initial diameter until 80% of its initial size in order to improve its efficiency at part loads. Bozorgi et al. [15] compared the results obtained by CFD simulations, using NUMECA® software, with those obtained in the laboratory tests in order to validate the simulated ones. Tan et al. [16] presented a prediction of PaTs performance running in turbine mode referring to nine previous methods available in literature and taking into account the specific angular speed and the specific diameter as main evaluation parameters. Giosio et al. [17] studied both design and PaT performance suitable for both rural micro-hydro environments and energy recovery installations, although its off-design performance is not so high due to the fixed geometry and the absence of an inlet flow guidance. Finally, Barbarelli et al. [18] performed a one-dimensional numerical code able to predict both design characteristics and performance of a PaT used in a determined application. The aim of this paper is to collect the running data of 32 PaTs that were studied and analysed in the previous works [10-18] in order to define analytical equations for forecasting the main magnitudes involved on the PaTs performance evaluation. Non-dimensional analysis was performed taking into account all the physical data of the PaTs in order to study the behaviour of those machines that operate in fluid dynamic similarity conditions. However, the non-dimensional analysis is not sufficient to generalize the performance prediction of the PaTs because it is not able to distinguish the typology of the analysed machine, so each non-dimensional magnitude of PaTs was divided by the same magnitude achieved by the machine at BEP running in turbine mode. Using this method, an objective analysis that is independent not only of the physical dimensions and of rotating speeds but also of the design typology of the machine is performed in order to forecast the performance of a higher number of PaTs.

2. Research and methods

2.1. Data collecting and data analysis

In this work, data related to laboratory tests performed on 32 PaTs [10-18] were analysed and the main characteristics of the machines were evaluated. The ranges of the different physical magnitudes involved in this study of PaTs are the following: the flow rate ranges from 0.008 m^3/s to 0.222 m^3/s, the head ranges from 1.99 m to 99.52 m, the rotating speed ranges from 750 rpm to 2445 rpm, the impeller diameter ranges from 0.165 m to 0.300 m, the specific speed ranges from 0.17 to 2.39 and, finally, the efficiencies ranges from 0.43 to 0.87.

2.2. Non-dimensional analysis

Characteristic, power, efficiency and flow coefficient vs efficiency curves of the 32 tested PaTs were also developed. These curves were drawn taking into account the rated running conditions in turbine mode. A non-dimensional analysis was performed in order to generalize the results and to compare different typologies of PaTs operating in fluid dynamic similarity. In the non-dimensional analysis, three coefficients are used: flow coefficient (ϕ), head coefficient (ψ) and power coefficient (Λ). These coefficients are evaluated taking into account the flow rate [m^3/s], the head [m], the power output of the PaT [W], the impeller diameter [m] and the rotating speed [rad/s]. This method can be used for prototype testing and, subsequently, the results obtained with a single machine can be extended to other fluid machines that operate in fluid dynamic similarity conditions.

2.3. Normalization of the non-dimensional parameters

The following step of the analysis is to normalize each non-dimensional operating parameter by that achieved at BEP of each single PaT. This methodology allows to better evaluate the variation of both machine performance and characteristics running in off-design conditions.

3. Results and comments

3.1. Main PaTs performance curves

The most important performance curves of PaTs running in turbine mode are depicted. Through these curves, the main characteristic of a PaT can be predicted maintaining an acceptable accordance with the real values. Figure 1 shows the trend of the non-dimensional characteristic curve that was drawn using the data available from 32 PaTs. Both flow and head coefficients are normalized with respect to the corresponding BEP; the obtained R2-value is equal to 0.9171 and the general equation that describes the trend is the following:

$$\psi/\psi_{BEP} = 0.2394\cdot(\varphi/\varphi_{BEP})^2 + 0.769\cdot(\varphi/\varphi_{BEP}) \tag{1}$$

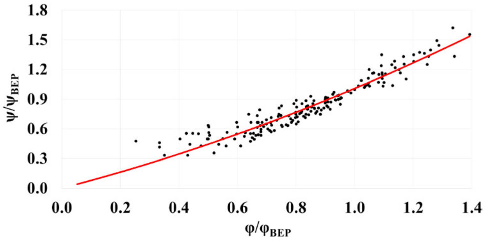

Fig. 1. Trend of the non-dimensional characteristic curve.

As it is shown in Figure 1, the red line describes accurately the trend of a characteristic curve generated by a general hydraulic turbine running in off-design conditions, showing that it is not affected by the different typologies of the tested turbines. Figure 2 shows the trend of the non-dimensional power curve, where both flow and power coefficients are normalized with respect to the BEP of each PaT; the obtained R^2-value is equal to 0.9723 and the general equation that describes the trend line is the following:

$$\Lambda/\Lambda_{BEP} = 1.5831\cdot(\varphi/\varphi_{BEP})^2 - 0.621\cdot(\varphi/\varphi_{BEP}) \tag{2}$$

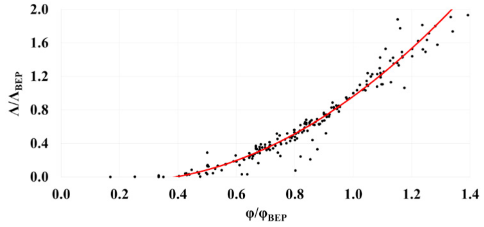

Fig. 2. Trend of the non-dimensional power curve.

The red line in Figure 2 has the same trend recorded in Figure 1 due to the mathematical expression used for evaluating the power produced; it shows a power curve produced by a general hydraulic turbine running in off-design conditions. It is worth to notice that, if the flow rate achieved at BEP is reduced by the 60% of its value, the power produced decreases immediately reaching a value close to zero; this result suggests to not operate in off-design conditions that are too low than those achieved at BEP. Figure 3 shows the trend of the efficiency curve, where both power coefficients and efficiencies are normalized with respect to the BEP of each PaT; the obtained R2-value is equal to 0.946 and the general equation that describes the trend line is the following:

$$\eta/\eta_{BEP} = -0.5602\cdot(\Lambda/\Lambda_{BEP})^6 + 3.7398\cdot(\Lambda/\Lambda_{BEP})^5 - 9.9049\cdot(\Lambda/\Lambda_{BEP})^4 + 13.451\cdot(\Lambda/\Lambda_{BEP})^3 - 10.287\cdot(\Lambda/\Lambda_{BEP})^2 + 4.5495\cdot(\Lambda/\Lambda_{BEP}) \quad (3)$$

In this case and in the following one, 6th order-polynomial expressions are used due to the higher R^2-value obtained. In addition, the trend line fits the points better than a 2nd order-polynomial expression and its shape results to be closer to the realistic one.

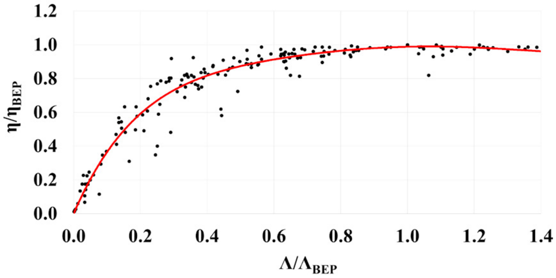

Fig. 3. Trend of the efficiency curve.

Figure 3 pinpoints that, taking into account the Λ/ΛBEP values between 0.6 and 1.4, the efficiency remains more or less the same and close to its maximum value; indeed, the efficiency loss is less than 10% with respect to the maximum one. This result is important because it shows that a PaT can achieve a power output that is -40% or +40% than that achieved at BEP conditions maintaining, anyway, a reasonable efficiency. Figure 4 shows the trend of the flow coefficient vs efficiency curve; the obtained R^2-value is equal to 0.7856 and the general equation that describes the trend line is the following:

$$\eta/\eta_{BEP} = -1.9788\cdot(\varphi/\varphi_{BEP})^6 + 9.0636\cdot(\varphi/\varphi_{BEP})^5 - 13.148\cdot(\varphi/\varphi_{BEP})^4 + 3.8527\cdot(\varphi/\varphi_{BEP})^3 + 4.5614\cdot(\varphi/\varphi_{BEP})^2 - 1.3769\cdot(\varphi/\varphi_{BEP}) \quad (4)$$

The obtained R^2-value is lower than the previous ones due to the presence of different running points located in the middle of Figure 4 that shift the trend line below in spite of being close to the zone where there is a higher concentration of the other running points.

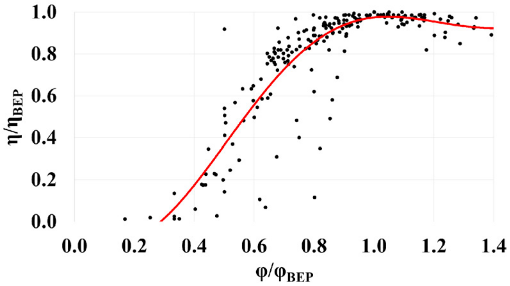

Fig. 4. Trend of the flow coefficient vs efficiency curve.

Figure 4 pinpoints that, taking into account the ϕ/ϕ_{BEP} values between 0.8 and 1.2, the efficiency remains almost the same and close to its maximum value with a loss lower than 10% with respect to the maximum one. This result is important because it shows that a PaT can process a flow rate that is -20% or +20% than that achieved at the BEP conditions without losing too much efficiency. The trend line can be improved considering only the ranges that go from 0.7 to the end scale of each variable involved, losing unfortunately important information provided by the literature that can leads to not reliable results.

4. Conclusions

In this paper, an analysis of the performance of a large number of PaTs was carried out. Studies related to 32 different PaTs available in literature were taken into account and a general trend for depicting the performance of the PaTs was obtained. In order to achieve this goal, a non-dimensional analysis, coupled with the normalization process, was performed. Results show that the R2-values of the performance trend lines are higher than 0.9, except only one that is equal to 0.7856 (ϕ/ϕBEP vs η/ηBEP), meaning that the PaTs behaviour can be foreseen with good accuracy also in presence of machines that present significant geometrical and design differences.

References

[1] World Health Organization (WHO) – WHO releases country estimates on air pollution exposure and health impact.
Available at: http://www.who.int/mediacentre/news/releases/2016/air-pollution-estimates/en/

[2] M.J. Brandt, K.M. Johnson, A.J. Elphinston, D.D. Ratnayaka. Twort's Water Supply (Seventh Edition), Chapter 5 – Dams and Reservoirs, Butterworth Heinemann, Year 2017, Pages 159–204.

[3] B. Zhu, X. Wang, L. Tan, D. Zhou, Y. Zhao, S. Cao. Optimization design of a reversible pump-turbine runner with high efficiency and stability. Renewable Energy, 81, Year 2015, Pages 366–376.

[4] A. Rezghi, A. Riasi. Sensitivity analysis of transient flow of two parallel pump-turbines operating at runaway. Renewable Energy, 86, Year 2016, Pages 611–622.

[5] A. Williams. The Turbine Performance of Centrifugal Pumps: A Comparison of Prediction Methods, Journal of Power and Energy, 208, Year 1994, Pages 59–66.

[6] A. Stepanoff. Centrifugal and Axial Flow Pumps, Design and Applications, John Wiley and Sons, Inc. New York, USA, 1997.

[7] G. Krivchenko, Hydraulic Machines: Turbines and Pumps, Lewis, Boca Raton, Fla., USA, 1994.

[8] K. Sharma, Small Hydroelectric Project-Use of Centrifugal Pumps as Turbines. Technical Report, Kirloskar, Electric Co. Bangalore, India, 1985.

[9] B. McClaskey et al., Can You Justify Hydraulic Turbines?, Hydrocarbon Processing, 1976, vol. 55, p. 163–169.

[10] P. Singh, F. Nestmann. An optimization routine on a prediction and selection model for the turbine operation of centrifugal pumps. Experimental Thermal and Fluid Science, 34, Year 2010, Pages 152–164.

[11] S. Derakhshan, A. Nourbakhsh. Experimental study of characteristic curves of centrifugal pumps working as turbines in different specific speeds. Journal of Experimental Thermal and Fluid Science, 32, Year 2008, Pages 800–807.

[12] S. Yang, S. Derakhshan, F. Kong. Theoretical, numerical and experimental prediction of pump as turbine performance. Renewable Energy, 48, Year 2012, Pages 507–513.

[13] S-S. Yang, F-Y. Kong, W-M. Jiang, X-Y. Qu. Effects of impeller trimming influencing pump as turbine. Computers & Fluids, 67, Year 2012, Pages 72–78.

[14] S. Jain, A. Swarnkar, K. Motwani, R. Patel. Effects of impeller diameter and rotational speed on performance of pump running in turbine mode. Energy Conversion and Management, 89, Year 2015, Pages 808–824.

[15] A. Bozorgi, E. Javidpour, A. Riasi, A. Nourbakhsh. Numerical and experimental study of using axial pump as turbine in Pico hydropower plants. Renewable Energy, 53, Year 2013, Pages 258–264.

[16] X. Tan, A. Engeda. Performance of centrifugal pumps running in reverse as turbine: Part Ⅱ - systematic specific speed and specific diameter based performance prediction. Renewable Energy, 99, Year 2016, Pages 188–197.

[17] D.R. Giosio, A.D. Henderson, J.M. Walker, P.A. Brandner, J.E. Sargison, P. Gautam. Design and performance evaluation of a pump-as-turbine micro-hydro test facility with incorporated inlet flow control. Renewable Energy, 78, Year 2015, Pages 1–6.

[18] S. Barbarelli, M. Amelio, G. Florio. Predictive model estimating the performances of centrifugal pumps used as turbines. Energy, 107, Year 2016, Pages 103–121.