Applied Energy 231 (2018) 343–354

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Development of a physics-based model to predict the performance of pumps as turbines

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HIGHLIGHTS

- Set-up of a physics-based model to predict the performance curves of pumps as turbines.
- The model is calibrated on experimental data from four centrifugal pumps taken from literature.
- The predicted performance curves are physically consistent over the entire range of operation.
- Model prediction error is acceptable, compared to other methods available in literature.
- The physics-based model is powerful and reliable to estimate PAT complete performance curves.

ARTICLE INFO

Keywords:
Pump as turbine
Pump
Performance curve
Simulation model
Hydraulic energy
Optimization

ABSTRACT

This paper presents the development of a physics-based simulation model, aimed at predicting the performance curves of pumps as turbines (PATs) based on the performance curves of the respective pump. The simulation model implements the equations to be used for the estimation of head, power and efficiency for both direct and reverse operation. Model tuning on a given machine is performed by using loss coefficients and specific parameters identified by means of an optimization procedure, which is first applied to the considered pumps and subsequently to the same machine running in PAT mode.

The simulation model is calibrated on data taken from literature, reporting both pump and PAT performance curves for head, power and efficiency over the entire range of operation. The performance data were acquired experimentally from four different centrifugal pumps, running in both pump and PAT mode and characterized by specific speed values in the range of 1.53–5.82. The accuracy of the predictions of the physics-based simulation model is quantitatively assessed against both pump and PAT experimental performance curves. Prediction consistency from a physical point of view is also evaluated.

The results presented in this paper highlight that all the performance curves predicted by the simulation model are physically consistent over the entire range of operation. In general, the prediction error on the head of PATs is acceptable, while the accuracy of the prediction of PAT power, and thus of PAT efficiency, is more case-sensitive and usually higher. The relative deviation of model prediction with respect to the field data regarding head and power at the PAT best efficiency point always seems acceptable compared to the uncertainty of the original experimental data and to typical deviations of other methods available in literature.

As a conclusion, the physics-based simulation model developed in this paper represents a powerful and reliable tool for estimating PAT performance curves over the entire range of operation based on pump characteristics.

1. Introduction

Today, hydropower accounts for more than 16% of the world's net electricity production, according to a recent study carried out by Balkhair and Rahman [1].

Small hydro power plants are one of the most important renewable energy generation sources for developing countries. In fact, they represent a cost-effective technology that is being used for rural electrification in developing countries, such as India [2,3]. Small-scale hydropower systems are also becoming increasingly successful options for hydropower generation in small localities and remote areas, as demonstrated in [1] for a case study in Pakistan. Another example is

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https://doi.org/10.1016/j.apenergy.2018.09.054
Received 8 December 2017; Received in revised form 27 June 2018; Accepted 5 September 2018

Nomenclature

a	interpolation curve coefficient
b	width
BEP	best efficiency point
c	absolute velocity
d	diameter
D	pump nominal diameter
g	gravitational acceleration
H	head
k	index of pump/PAT (k = 1, 2, 3, 4)
n	rotational speed
N	number
OF	objective function
P	power
PAT	pump as turbine
Q	volume flow rate
RMSE	root mean square relative error
s	casing clearance
u	circumferential velocity
x	parameter for pump/PAT model tuning
y	model parameter
Y	nondimensional performance parameter (π, η, ψ)
Z	hydraulic loss
α	angle between direction of circumferential and absolute velocity
β	angle between relative velocity vector and negative direction of circumferential velocity
ε	wrap angle
ζ	loss coefficient
η	efficiency
λ	angle between vanes and side disks
π	nondimensional power defined as $P/(\rho n^3 D^5)$
ρ	density
ϕ	nondimensional volume flow rate defined as $Q/(nD^3)$
ψ	nondimensional head defined as $gH/(n^2D^2)$
ω	angular velocity
Ω	specific speed defined as $\omega \cdot Q^{0.5}/(gH)^{0.75}$

Subscripts and superscripts

A	outlet casing
ax	axial
B	blade
BEP	best efficiency point
e	experimental
E	inlet casing
er	friction created by the components of axial thrust balance devices
h	hydraulic, hydrostatic bearing
int	calculated by means of interpolation curves
k	index of pump/PAT (k = 1, 2, 3, 4)
La	impeller
Le	diffuser
m	mechanical, meridional component
P	pump
Rec	recirculation
RR	disk friction
s	simulated
s3	throttling
sp	volute
st	stage
T	PAT
th	theoretical
u	useful
V	volumetric
Y	nondimensional parameter
η	efficiency
π	nondimensional power
ψ	nondimensional head

provided by a small-scale hydro/PV/wind-based hybrid electric supply system located in Ethiopia and analyzed by Bekele and Tadesse in [4].

Micro-hydropower also presents new opportunities for generating electricity from the existing water infrastructure in OECD countries. One of the first examples of such an opportunity was presented by Bakos in [5] within the framework of a hybrid wind/hydropower system aimed at producing low-cost electricity in Greece and in [6] by Zakkour et al., where the recoverable power in the UK water industry was estimated in the order of 17 MW. More recently, Carravetta et al. [7] estimated the theoretical convertible power in the European Union area to be equal to 28.5 MW.

Several papers have investigated the possibility of converting waste hydraulic energy in the water supply and distribution networks into useful electric energy. Giugni et al. analyzed different approaches suitable for locating and setting turbines in order to maximize their effectiveness and minimize water losses [8]. Puleo et al. developed a hydraulic model to evaluate the potential energy recovery from the use of centrifugal pumps as turbines (PATs) in a water distribution network characterized by the presence of private tanks [9]. Carravetta et al. investigated the benefit of a combination of a PAT, two regulating valves and two pressure meters in urban pipe networks [10]. Sitzenfrei et al. exploited water surplus in water distribution systems in order to maximize profits over one decade of operation [11]. Rossi et al. performed some laboratory tests to investigate pump performance in turbine mode in the case of an aqueduct installation [12]. Capelo et al. studied the application and optimization of a PAT in water systems when the type of recovery solution is off-grid [13]. Meirelles Lima et al. proposed a method for identifying the best network location for installing PATs [14]. Kramer et al. [15] presented the results of two research projects undertaken in collaboration with local drinking water supply companies. An extensive review of suitable hydraulic machinery, an evaluation of the energy recovery potential within the South German drinking water supply system and several field studies (including investment costs) were presented and discussed.

A structured four-step methodology for assessing potential energy recovery sites in water and wastewater infrastructures in regions of the UK and Ireland was presented by Gallagher et al. in [16]. The same authors also analyzed the potential for eco-design measures to improve the environmental and resource balance of five small-scale hydropower case studies [17] and also quantified the environmental impacts of electricity generation from three micro-hydropower case studies, using a life cycle assessment approach [18]. Su and Karney evaluated the economic feasibility of energy recovery turbines in municipal water systems, by means of a micro hydroelectric plant located in Vancouver (Canada) [19]. The feasibility of recovering waste energy from typical bio-gas upgrading facilities by means of a centrifugal pump operating in reverse flow in a specific test rig was analyzed by Bansal and Marshall in [20].

In 2018, two studies investigated the use of PATs for irrigation networks. Perez-Sanchez et al. [21] proposed a new maximization methodology for recovering energy by also considering the feasibility of the installation, while Morillo et al. [22] quantified the potential of hydropower energy recovery in a pressurized irrigation network, assessing both its technical and economic feasibility.

As highlighted by Sammartano et al. in [23] and by Carravetta et al. in [24], PATs are suitable for low and variable power, since they combine low installation costs with acceptable energy production.