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An experimental investigation of design parameters for pico-hydro Turgo turbines using a response surface methodology

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ABSTRACT

Millions of off-grid homes in remote areas around the world have access to pico-hydro (5 kW or less) resources that are undeveloped due to prohibitive installed costs ($/kW). The Turgo turbine, a hydroelectric impulse turbine generally suited for medium to high head applications, has gained renewed attention in research due to its potential applicability to such sites. Nevertheless, published literature about the Turgo turbine is limited and indicates that current theory and experimental knowledge do not adequately explain the effects of certain design parameters, such as nozzle diameter, jet inlet angle, number of blades, and blade speed on the turbine's efficiency. In this study, these parameters are used in a three-level (3^4) central composite response surface experiment. A low-cost Turgo turbine is built and tested from readily available materials and a second order regression model is developed to predict its efficiency as a function of each parameter above and their interactions. The effects of blade orientation angle and jet impact location on efficiency are also investigated and experimentally found to be of relatively little significance to the turbine. The purpose of this study is to establish empirical design guidelines that enable small hydroelectric manufacturers and individuals to design low-cost efficient Turgo Turbines that can be optimized to a specific pico-hydro site. The results are also expressed in dimensionless parameters to allow for potential scaling to larger systems and manufacturers.

1. Introduction

The Turgo turbine is a hydroelectric impulse turbine that has gained renewed attention in research because of its potential application to millions of off-grid 5 kW-or-less pico-hydro sites and to energy recovery of discharged water at public water systems [1]. Generally, pico hydro systems are run of the river, which means that impoundment is not necessary. Such a scheme diverts water from the river as needed, feeding it down a steep slope through a penstock, a nozzle and then the turbine, after which the effluent water rejoins the river or is used for irrigation and other community purposes.

In developing countries alone, where 1.6 billion people live without electricity, a recent study showed that there are 4 million potential pico-hydro sites [2]. Furthermore, a World Bank study in 2006 showed that pico-hydropower is the most competitive off-grid power technology on a levelized cost of electricity (LCOE) basis ($/kWh), as shown in Fig. 1 [3,4]. In Rwanda for example, the national utility retail price for electricity in 2009 was $0.24/kWh [5], yet pico-hydro is estimated to cost less than $0.20/kWh. Nevertheless, the installation cost ($/kW) of pico-hydro systems can become cost prohibitive. In 2011, Meier reported a study of 80 Indonesian villages that revealed capital costs per kW exponentially increase with smaller sized systems, potentially surpassing $10,000/kW for low-head systems less than 5 kW [6]. Within the United States it is currently understood that sites with less than 100 kW of electrical potential are “best left undeveloped” because of extremely high installation costs ($59,000/kW on average) [7].

To reduce capital costs, standardized off-the-shelf turbines, as opposed to turbines that are customized to a specific site, are sold commercially by manufacturers worldwide, including the United States, Canada, and China [8–13]. The cost of these pico-hydro turbines can range from $125/kW to over $1200/kW. The

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Nomenclature

α	jet inlet angle
β	relative jet angle with respect to the blade
b	parameter coefficient of linear regression equation
C_p	Mallow's statistic
c_D	discharge coefficient of nozzle
c_v	velocity coefficient of nozzle
δ	angle of blade curvature
D	pitch to center diameter of the turbine (PCD)
d	nozzle diameter
g	acceleration of gravity
H	hydraulic head
k	friction coefficient factor
η	efficiency
$\hat{\eta}$	predicted value from regression equation
N_{sp}	specific speed (units of rev/s or rpm)
Ω_{sp}	specific speed (units of radians)
φ	speed ratio
P	power
p	pressure
Q	flow of water
ρ	density of water
R	relative velocity of jet with respect to blade
R^2_{adj}	adjusted R^2 statistic
s	spacing between blades
τ	torque
θ	angle of the blade's edge: inlet (θ_1) or exit (θ_2).
μ	viscosity of water
u	blade velocity
v	jet velocity
w	width of the blade
ω	turbine angular velocity
X	coded variable, between −1 and 1
Z	number of blades

Acronyms

ANOVA	Analysis of Variance
BEP	best efficiency point
CCD	central composite design
LCOE	levelized cost of energy
MSE	mean square error
MSPR	mean square predicted residual
PCD	Pitch to Center Diameter (D)
PRESS	Predicted Sum of Squares
SAS	statistical analysis software
VIF	Variance Inflation Factor

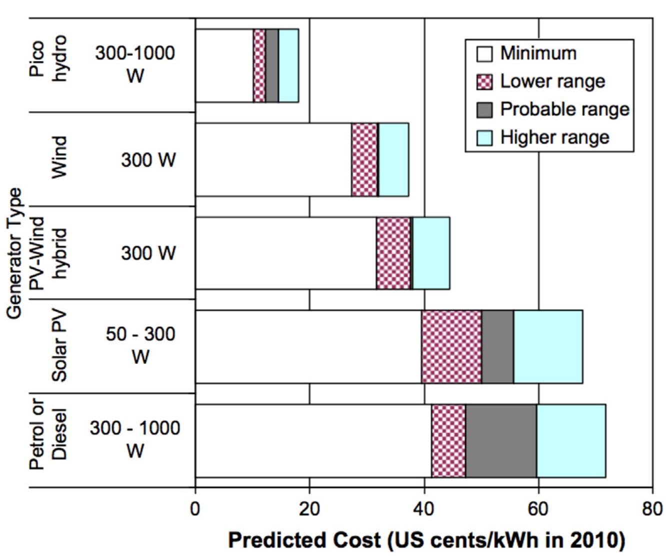

Fig. 1. Cost of pico-hydro systems compared to common alternatives (used with permission from Elsevier) [3].

mechanical efficiency in a laboratory testing environment can be upward of 82%, which is typical of a well-manufactured Turgo machine [14]. However, because standardized turbines are not customized to a specific site, they are prone to be less efficient in the field, some reporting only 40% water-to-wire efficiency [8]. Furthermore, off-the-shelf systems shipped abroad are more difficult and costly to repair and maintain in-country due to the system's proprietary design, the dependency upon imported spare parts with lengthier lead times, which results in longer power outages, and taxes levied by customs, which have been shown to increase equipment costs by 40% on pico-hydro systems [2].

Simpler do-it-yourself turbines reduce installation costs, but these turbines usually suffer from poor efficiencies due to a lack of design guidelines, fabrication facilities, or technical expertise. An example of a simple turbine built in Rwanda is shown in Fig. 2. Meier's assessment of pico-hydropower in Rwanda estimated that simple improvements in turbine design could increase efficiency by 20% with no additional equipment cost [6].

Therefore, this study aims not to build a standardized off-the-shelf turbine, but to develop a set of standardized design equations for optimizing the most important parameters of a Turgo turbine based on a site's available head and flow. This approach can facilitate the custom design and local manufacture of low-cost, yet efficient Turgo turbines. In the present study, a Turgo turbine is built from materials of low cost and a set of empirical design equations is established for optimizing the Turgo turbine's most significant parameters. Specifically, the nozzle diameter, d, jet inlet

Fig. 2. A locally fabricated impulse turbine in Rwanda (Photograph by Kyle Gaiser).