Paper-308-21

19th International Conference on Renewable Energies and Power Quality (ICREPQ'21)
Almeria (Spain), 28th to 30th July 2021
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.19, September 2021

Application of a central composite face-centered design in the optimization of an Archimedean hydrokinetic turbine

J. Betancour[1], L. Velásquez[1], L.Y. Jaramillo[2], E. Chica[1], A. Rubio-Clemente[1,2]
[1]Facultad de Ingeniería, Tecnológico de Antioquia–Institución Universitaria TdeA, Calle 78b, No. 72A-220, Medellín, Colombia
Phone/Fax number: +57 2198553, e-mail: ainhoarubioclem@gmail.com
[2]Grupo de Investigación Energía Alternativa, Facultad de Ingeniería, Universidad de Antioquia UdeA, Calle 70, No. 52-21, Medellín, Colombia

Research problem

Currently, in the literature, there are no general guidelines for the optimal hydraulic design of Archimedean screw turbines (AST) used in hydrokinetic applications. Therefore, this study is aiming at selecting the most significant geometric factors, such as the diameter ratio between the inner (D_i) and the outer (D_o) diameters (i.e.,D_i/D_o), the axle length (L) and the blade stride (p), influencing the AST performance by using a central composite face-centered (CCF) experimental design combined with the response surface methodology (RSM). The statistical analysis of variance (ANOVA) identified with a significance level of 0.05 that the most significant variables on the performance of the turbine were p and D_i/D_o. The AST efficiency was evaluated by means of the power coefficient (C_P), which was calculated using computational fluid dynamics (CFD) methods coupled to the 6-degrees of freedom (6-DoF) approach. The second-order polynomial model was used to predict the C_P and the coefficient of determination (R^2) was found to be 97.4%.

Keywords: 6-DoF, response surface methodology, Archimedean screw hydrokinetic turbine, central composite design, numerical optimization.

Material and methods

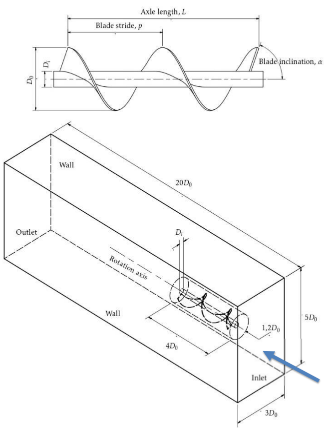


Figure 1. Computational domain in 3D analysis.

Objective

The effect of the three design parameters on the AST performance using the design of experiments (DoE) tool is discussed. In this regard, the relationships between the C_P and the design parameters, such as D_i/D_o, L and p, were obtained utilizing a CCF experimental design combined with a second-order RSM and CFD analysis.

$$TSR = \frac{\omega R}{V}$$

$$C_P = \frac{P}{\frac{1}{2}\rho V^3 \pi R^2}$$ → **Response variable**

$$\omega = \int \frac{M_F - M_A}{J} dt$$

$$P = M_A \omega$$

Table I. Factors, codes and levels for the CCF experimental design

Variables	Unit	Symbol	Levels		
			-1	0	1
D_i/D_o	-	X_1	0.20	0.40	0.60
L	m	X_2	0.30	0.32	0.34
P	m	X_3	0.12	0.16	0.20

Parameter (units)	Description
The blade inclination with respect to the longitudinal axis of the screw (α)	60°
Outer diameter (D_o)	0.1 m
Radius (R) rotor	0.79 m
Fluid	Water at 25 °C
Turbulence model	$k-\omega$ SST
Inlet	Velocity inlet (1.0 m/s)
Outlet	Pressure outlet
Wall of the external domain	No-slip wall
Surface of the AST	No-slip wall

Table II. Parameters involved in the CFD analysis.

Table III. Matrix domain concerning the CCF experimental design

Run	Axle length, L (m)	Blade stride, p (m)	Diameter ratio, D_i/D_o	Maximal power coefficient ($C_{P_{max}}$)	
				CFD results	Predicted results
1	0.30	0.12	0.2	0.5113	0.5063
2	0.34	0.12	0.2	0.4572	0.4713
3	0.30	0.20	0.2	0.3865	0.3990
4	0.34	0.20	0.2	0.4263	0.42435
5	0.30	0.12	0.6	0.1446	0.1555
6	0.34	0.12	0.6	0.1286	0.1205
7	0.30	0.20	0.6	0.1280	0.1229
8	0.34	0.20	0.6	0.1389	0.1482
9	0.30	0.16	0.4	0.3154	0.3098
10	0.34	0.16	0.4	0.3106	0.3049
11	0.32	0.12	0.4	0.3253	0.3134
12	0.32	0.20	0.4	0.2883	0.2736
13	0.32	0.16	0.2	0.509	0.4641
14	0.32	0.16	0.6	0.1831	0.1506
15	0.32	0.16	0.4	0.2778	0.3074
16	0.32	0.16	0.4	0.2778	0.3074
17	0.32	0.16	0.4	0.2778	0.3074

The use of these statistical techniques facilitated the evaluation of several independent geometric parameters, such as L, P and D_i/D_o, on the response variable (C_P).

Results and discussion

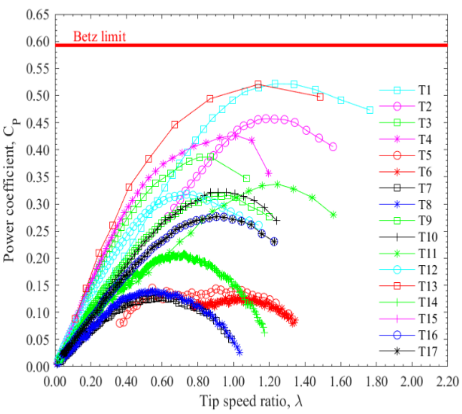


Figure 2. Power coefficient (C_P) *vs.* tip speed ratio (λ) for all the treatments.

Table IV. Statistical analysis of variance (ANOVA)

Term	SS*	Df*	MS*	F-ratio	p-value
Axle length, L (m)	5.8564x10^{-5}	1	5.8564 x10^{-5}	0.09	0.7751
Blade stride, p (m)	0.0039601	1	0,0039601	5.83	0.0364
Diameter ratio, D_i/D_o	0.24558	1	0.24558	361.41	3.52x10^{-9}
$L*p$	0.00182408	1	0.00182408	2.68	0.1324
$p*p$	0.00079067	1	0.00079067	1.16	0.3060
$p*(D_i/D_o)$	0.00279004	1	0.00279004	4.11	0.0702
Residuals	0.00679501	10	0.00067950		
Total	0.261799	16			

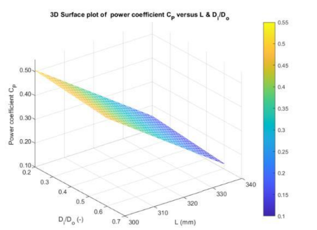
*Df: Degrees of freedom; SS: Sum of squares; MS: Mean square.

$$C_P = 1.6332 - 3.141L - 4.6998p - 1.1571\, D_i/D_o + 18.8750L*p + 2.3344p*D_i/D_o - 8.6607p^2$$

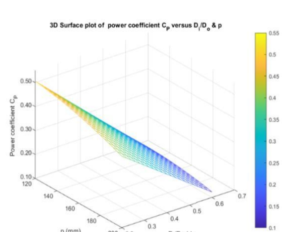
R^2 =97.4%
R^2_{adj} = 95.8%

The variables L, $L*p$, $p*p$ and $p*(D_i/D_o)$ were non-significant parameters, while D_i/D_o and p were significant factors.

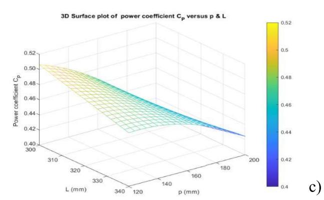
The assumptions of normal distribution, independence and homoscedasticity of the residuals were checked to validate the quadratic regression model. The results from Shapiro-Wilks, Durbin-Watson and studentized Breusch-Pagan tests were 0.3059, 0.9239 and 0.2571, respectively.



a)



b)



c)

The C_{Pmax} was calculated and resulted to be 0.5063 when L, p and D_i/D_o were equal to 0.30 m, 0.12 m and 0.2, respectively.

Figure 3. Response surface plots of C_P *vs.* the effect of the variables, including a) L and D_i/D_o, b) P and D_i/D_o, and c) L and P.

Conclusion

The AST performance was evaluated using numerical simulations through ANSYs Fluent software combined with RSM. The use of these statistical techniques facilitated the evaluation of several independent geometric parameters, such as L, P and D_i/D_o, on C_P. The significance of the independent variables and their interactions were studied and tested through ANOVA.

A second-order quadratic model was built to predict the responses. The regression analysis results revealed that the most significant factors for the measured response were D_i/D_o and p. With regard to the model terms L, $L*p$, $p*p$ and $p*(D_i/D_o)$ were found to not affect in a significant way the C_P of the AST. R^2 and R^2_{adj} values for the regression model were found to be 97.4% and 95.8%, respectively. In turn, the *p-value* associated with the regression model (*p-value* lower than 0.05) indicated that the second-order regression model was highly significant and reliable at a confidence interval of 95%. By understanding the interaction between variables is helpful to achieve the largest C_P. The optimal geometric values for L, p, and D_i/D_o were 0.30 m, 0.12 m, and 0.2, respectively. Under these optimal conditions, the maximal C_P was 0.5063.

The results showed that DoE coupled with RSM was a suitable statistical technique for optimizing the geometric parameters involved in the design of an AST to maximize the turbine C_P.

References

[1] A. Yoosef Doost and W.D. Lubitz. "Archimedes Screw Turbines: A Sustainable Development Solution for Green and Renewable Energy Generation—A Review of Potential and Design Procedures", Sustainability (2020). Vol. 12 (18), pp. 7352.

[2] G.L. Zitti, A. Brunoric and M. Brocchinia. "Efficiency evaluation of a ductless Archimedes turbine: Laboratory experiments and numerical simulations", Renewable Energy (2020). Vol. 146, pp. 867-879.

[3] S. Waters and G.A. Aggidis. "Over 2000 years in review: Revival of the Archimedes screw from pump to turbine", Renewable and Sustainable Energy Reviews (2015). Vol. 51, pp. 497-505.

[4] K. Shahverdi, R. Loni, B. Ghobadian, S. Gohari, S. Marofi and E. Bellos. "Numerical Optimization Study of Archimedes Screw Turbine (AST): A case study", Renewable Energy (2020). Vol. 145, pp. 2130-2143.

[5] G. Dellinger, P.A. Garambois, N. Dellinger, M. Dufresne, A. Terfous, J. Vazquez and A. Ghenaim. "Computational fluid dynamics modeling for the design of Archimedes Screw Generator", Renewable Energy (2018). Vol. 118, pp. 847-857.

[6] A. Stergiopoulou, V. Stergiopoulos and E. Kalkani. "Computational Fluid Dynamics study on a 3D graphic solid model of Archimedean screw turbines", Int. Conf. Environ. Manag. Eng. Planning, Econ. (2014). Vol. 23(11), pp. 7-14.

[7] A. Stergiopoulou, V. Stergiopoulos and E. Kalkani. "Experimental and theoretical research of zero head innovative horizontal axis Archimedean screw turbines", International Journal of Energy and Environment (2015). Vol. 6 (5), pp. 471.

[8] A. Stergiopoulou, V. Stergiopoulos and E. Kalkani. "Greece beyond the horizon of the era of transition: Archimedean screw hydropower development terra incognita", International Journal of Energy and Environment (2015). Vol. 6(6). pp. 527.

[9] D.C. Montgomery. Introduction to statistical quality control. USA. John Wiley & Sons (2019).

[10] F.R. Menter. "Two-equation eddy-viscosity turbulence models for engineering applications", AIAA journal (1994). Vol. 32(8), pp. 1598-1605.

Nomenclature

D_i/D_o is diameter ratio between the inner (D_i) and the outer (D_o) diameters
p is the blade stride
L is the axle length
C_P is the power coefficient
ρ is the fluid density
α is the blade inclination with respect to the longitudinal axis of the screw
P is the mechanical power output
V is the incoming velocity
ω is the angular velocity
M_F is the total hydrodynamic moment acting on the turbine blade
M_A is the applied moment on the rotational axis for determining the power of the turbine