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Experimental and numerical analysis of a Pump as Turbine (PaT) in micro Pumped Hydro Energy Storage (μ-PHES)

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Abstract

In the last decade, the power generation mix and the energy markets have been affected by the growing development of distributed and renewable energy sources. Nevertheless, a significant drawback of solar and wind energy is their intermittent and weather-dependent production, which often leads to a mismatch between renewable energy production and its use. Thus, the need for energy storage is recently emerging and becoming more relevant in this era of the energy transition.

Among several technologies, today, pumped hydro energy storage (PHES) represents the largest share of the energy storage systems in the world. However, possible new investors, who might be attracted by potential profit in PHES, are repelled by the long payback period and the scarcity of adequate site topology for such power plants. Relevant design decisions can be taken to reduce the costs and improve the performance or to escape the PHES topographical requirements. For this reason, the first part of this PhD thesis reviews and provides potential assessments of some unconventional PHES systems, applied in synergy with existing infrastructures. Such is the standpoint of micro facilities near waterway locks, or underground cavities used as lower reservoirs (UPSH), or the use of pump-turbines at variable geometry to cope with fluctuating loads. Moreover, important information on PHES in micro-scale is largely missing and their potential in distributed energy systems still needs to be unveiled. In the attempt to fill this gap, this thesis provides a techno-economic overview of the design and characterization of a first-of-its-kind PHES micro facility. In micro-scales hydropower projects, the initial capital cost of a conventional hydroelectric unit is hard to be determined and often economically prohibitive. Interestingly, in order to cut the total capital investment, the micro-PHES prototype runs with a single centrifugal pump for both pumping and generating phases and exploits existing stormwater reservoirs. The variable speed regulation is also implemented and it allows the pump to constantly operate at the maximum hydraulic efficiency in order to deal with load variations. In the same way, the pump working in reverse, namely pump as turbine (PaT), runs at the most suitable speed and it keeps a high efficiency over a wide load range. In addition, the analysis of the techno-economic parameters for such a system provides an important dataset for micro-PHES feasibility breakdown.

PaTs are a legitimate cost-effective option in micro hydropower but an universal performance prediction does not exist. Their hydraulic efficiency can possibly shift from the higher efficiency of traditional hydraulic turbines. Nowadays, these reasons restrict PaTs exploitation. In this thesis, a multivariate regression method is applied to the CFD results to build a surrogate model of the PaT hydraulic characteristics as a function of the cutwater geometrical modifications. Based on this model, an optimization problem is solved to identify the most advantageous geometrical asset of the PaT cutwater to maximize the hydraulic efficiency. The presented methodology and design optimization of the cutwater in PaTs, which are extremely suited to our current energy generation needs, provides a unique and much sought guide to its performance, improvements, and adaptation to hydropower.

Contents

Abstract **i**

Acknowledgments **iii**

Contents **vii**

List of Figures **xiii**

List of Tables **xvi**

Nomenclature **xvii**

1 Introduction **1**
- 1.1 Context and motivation 1
- 1.2 Thesis objectives and strategy 3
- 1.3 Thesis structure 4
- 1.4 Publications 6

2 Literature review and state-of-the-art **7**
- 2.1 Introduction 7
- 2.2 Pumped hydro energy storage system (PHES) 9
  - 2.2.1 Traditional hydro power station 9
  - 2.2.2 Unconventional PHES 11
  - 2.2.3 Underground Pumped Storage Hydroelectricity 12
- 2.3 Turbomachinery options for hydropower and PHES 14
  - 2.3.1 Characteristic curves 14
  - 2.3.2 Hydraulic turbines for hydropower and PHES 16
  - 2.3.3 Variable speed regulation 22
- 2.4 The Deriaz pump-turbine 24
  - 2.4.1 Variable geometry regulation 25
  - 2.4.2 Deriaz in PHES plants 28
- 2.5 Pump as Turbine (PaT) 31
  - 2.5.1 Variable speed regulation applied to PaTs 37
  - 2.5.2 PaT efficiency improvements 38

3 Definition of a framework **41**
- 3.1 Introduction 41
- 3.2 Micro PHES design: the Tucurui case study 45
  - 3.2.1 Introduction to the project 45
  - 3.2.2 Characteristics of Tucuruí locks 46
  - 3.2.3 The facility 47

3.2.4 The selection of the machines . . . 48
3.2.5 Operation scheme . . . 49
3.2.6 Energy payback time . . . 50
3.2.7 Perspectives for the micro PHES design in tucuruí . . . 51
3.3 UPSH case studies in Belgium . . . 52
3.3.1 Towards PHES solutions in Belgium . . . 52
3.3.2 The slate quarry of Martelange case study . . . 56
3.3.3 The coal mine of Péronnes-lez-Binche case study . . . 63
3.3.4 UPSH in Belgium - Discussion . . . 69
3.4 Deriaz pump-turbine . . . 72
3.4.1 Deriaz hydraulic model . . . 72
3.4.2 Selected model case . . . 76
3.4.3 Numerical analysis . . . 77
3.4.4 Final remarks on Deriaz pump-turbine . . . 85
3.5 Chapter conclusions . . . 87

4 Micro-PHES prototype **91**
4.1 Introduction . . . 91
4.1.1 Goals of the analysis . . . 92
4.2 Micro-PHES in the "*Quartier Negundo*" . . . 94
4.2.1 Pipeline and pressure losses . . . 98
4.2.2 Turbomachinery selection . . . 99
4.2.3 Set-up and instrumentation . . . 105
4.2.4 Error measurement propagation . . . 108
4.2.5 Experimental methodology . . . 110
4.3 Results . . . 115
4.3.1 Experimental characterisation . . . 115
4.3.2 Variable rotational speed efficiency gain . . . 118
4.3.3 A simulated day of the micro-PHES . . . 121
4.4 Cost-benefit analysis . . . 123
4.4.1 Sector description of smart-grid business model . . . 123
4.4.2 μ-PHES prototype in the *Quartier Negundo*. . . . 130
4.4.3 μ-PHES case study . . . 133
4.4.4 Economic-evaluation methods . . . 134
4.4.5 Analysis results . . . 136
4.5 Conclusions on micro PHES solution . . . 140

5 Numerical investigation **141**
5.1 Introduction . . . 141
5.2 Problem statement . . . 142
5.3 Methodology . . . 143
5.3.1 Experimental setup . . . 143
5.3.2 Hydraulic domain modelling . . . 144
5.3.3 Mesh generation . . . 151

5.3.4 Numerical Modelling 155
5.3.5 Multivariate regression model 157
5.3.6 Optimization problem 159
5.4 Results 160
5.4.1 Validation of PaT numerical simulations 160
5.4.2 Performance evaluation 162
5.4.3 Surrogate model of the PaT hydraulic performance 168
5.4.4 Optimal cutwater design 171
5.4.5 Unsteady verification of the PaT optimum 178
5.4.6 Development of speed adjustment 183
5.4.7 Pump performance 185
5.4.8 Unsteady verification of the pump performance in Λ_{opt} 191
5.5 Chapter conclusions 194

6 Conclusions and perspectives 197
6.1 Achievements 197
6.1.1 Review of the objectives 197
6.1.2 Work novelty 200
6.2 Future work and perspectives 201
6.2.1 Variable geometry Deriaz pump-turbine 201
6.2.2 UPSH 202
6.2.3 μ-PHES design recommendations 203
6.2.4 Optimal cutwater design finalisation in PaT 205

Appendices 207

A Hydraulic design of a diagonal pump 209
A.1 Introduction 209
A.1.1 Scaling laws 210
A.1.2 Impeller inlet 213
A.1.3 Impeller outlet 214
A.1.4 Blade profile 217

B Fundamental notes on cavitation 221

Bibliography 225

List of Figures

1.1 Objectives of the PhD thesis. 5

2.1 World growth in renewable electricity generation 8
2.2 The operation principle of a PHES: it stores energy in pump operation and it generates energy in turbine operation. 10
2.3 Seawater-based pumped storage plant in Okinawa 11
2.4 Hydraulic gravity storages (HGS) 12
2.5 Simplified schematic diagram of an UPSH facility 13
2.6 Representation of variable head during pumping water in a tall and narrow tank 15
2.7 Representation of variable head during turbine generation 15
2.8 Types of hydraulic turbines in their application area Q-H 17
2.9 Turbine runners 18
2.10 Centrifugal pump in normal and inverse mode. 20
2.11 Pump characteristic curves for different rotational speeds 23
2.12 Internal view of Deriaz pump-turbine runner 25
2.13 Turbine runners 25
2.14 Diagram of hydraulic turbines 26
2.15 Shapes of Deriaz pump-turbine casing 27
2.16 Deriaz runner normally open and closed 27
2.17 Normalised efficiency and discharge of Deriaz-pump-turbine 28
2.18 Radial view of Deriaz turbine guide vanes 30
2.19 Pump four quadrant characteristics 32
2.20 Representations of the operating regimes in four quadrants 32
2.21 Reliability impact of operation away from BEP 33
2.22 Types of hydraulic turbines and PaT for micro-hydropower 34
2.23 PaT discharge and head ratios 36
2.24 Qualitative representation of variable speed adjustments 37
2.25 PaT hydraulic efficiency comparison 39

3.1 "Demand will follow generation" vision 43
3.2 Mine and quarry exploitation in the Walloon region 44
3.3 Overview of the Tucuruí hydropower dam and its locks. 46
3.4 Schematic representation of the Tucuruí locks and of the installation. 47
3.5 Pump mode system operation in Tucuruí micro PHES. 48
3.6 Power production in the hybrid system. 49
3.7 Hybrid system operation scheme. 49
3.8 Comparison of energy alternatives payback. 51
3.9 Belgian electricity generation by source, 1990-2019 52
3.10 Representation of Coo-Trois-Ponts PHES plant and its location . . . 55

3.11 The slate mine on the Martelange site 56
3.12 View of Martelange location and topography 57
3.13 Contingencies costs in percentage of the plant total cost 59
3.14 Discounted cash flow evolution and NPV of the Martelange case study. 60
3.15 Evolution of the gross head, hydraulic efficiency and power for three turbomachinery configurations 62
3.16 PaTs performance estimation for Martelange case study 63
3.17 Scheme of the coal mine of Péronnes-lez-Binche 64
3.18 Schematic representation of Francis turbines in series 65
3.19 SIMSEN components to simulate the Péronnes-lez-Binche power plant. 67
3.20 Gross head, available head and discharge of each Francis 68
3.21 Operating sequence of the three Francis turbines in series 68
3.22 Gross head, available head and discharge of each Francis turbine . . 69
3.23 Overall cross-section of a Deriaz pump turbine in Naussac II powerhouse. 74
3.24 Deriaz CFD research domain 77
3.25 Flow streamlines at the pump inlet and flow speed distribution at the leading edge. 81
3.26 Head and efficiency of Deriaz pump-turbine in pump mode 82
3.27 Experimental and numerical data of Deriaz turbine 84
3.28 Efficiency map of Deriaz turbine at $\delta\beta + 5$ blade angle 84
3.29 Hill chart of Deriaz turbine at fixed runner blade angle 85
3.30 Torque map of Deriaz turbine at fixed runner blade angle 85
3.31 Types of hydraulic turbines and Deriaz turbine in their application area Q-H for μ-hydropower 86

4.1 Schematic representation of the implemented μ-PHES, integrated in its micro smart grid. 93
4.2 Overview of the *Quartier Negundo* in Froyennes, Tournai 94
4.3 Interconnection scheme of *Quartier Negundo* smart grid. 95
4.4 View of the upper reservoir in *Quartier Negundo*. 96
4.5 Internal view of the lower reservoir of the μ-PHES. 97
4.6 Traversal view of the reservoirs and the technical room in *Quartier Negundo* 97
4.7 Photo of protection grid at the pipeline inlet at the upper reservoir . 98
4.8 Estimation of h and q ratios by different methods 100
4.9 Regression for head ratio h and discharge ratio q of available PaT experimental data 101
4.10 Decision tree for PaT selection. 102
4.11 Sectional view and photo of the pump/PaT of the μ-PHES 103
4.12 Powerhouse in μ-PHES of the *Quartier Negundo* 104
4.13 Schematic view of the micro-hydropower station and location of the measurement devices 105
4.14 Pressure transmitted manifold practise 106

4.15 Measuring instrumentation . . . 107
4.16 Control instrumentation . . . 107
4.17 Error propagation in function of the dimensionless discharge number. 109
4.18 Schematic layout of the set-up . . . 110
4.19 Pressure measurements for sensor A, B and C facing PaT run-up, opening valve, normal operation, closing valve and shut-down. . . . 111
4.20 Human-machine interface developed on the LabView for real time control and analysis. . . . 112
4.21 Experimental results of the pump characteristics and its hydraulic efficiency. . . . 115
4.22 Experimental results of the pump and its power consumption. . . . 116
4.23 Experimental results of PaT characteristics in Q-H plot limited by the runaway curve. . . . 116
4.24 Experimental results on PaT efficiency over the variable head, H. . . 117
4.25 Electrical efficiency and torque over the variation of the rotational speed for turbine and pump modes. . . . 117
4.26 Gain in hydraulic efficiency in pump mode by using variable speed over the variation of the head . . . 119
4.27 η_{PAT} normalized to its maximum over H at different speed regimes . 120
4.28 Gain in hydraulic efficiency in turbine mode by using variable rotational speed over the variation of the head. . . . 120
4.29 Absorbed and produced power by the storage system according to the load profile and RES production . . . 122
4.30 Imbalance power (SI) and prices of 30/04/2020 at a quarter-hourly basis . . . 128
4.31 Schematic representation of reducing the consumption at peaks and load-shifting. . . . 129
4.32 Wind turbines capacity factor during the month of April, 2017 in Froyennes . . . 130
4.33 PV panels capacity factor in Tournai, Belgium 2017 . . . 131
4.34 Samples of the weekly load consumption of *Quartier Negundo* . . . 132
4.35 illustration of the μ-PHES prototype in the *Quartier Negundo* (left) and a second case study (right) . . . 133
4.36 Discounted cash flow and NPV of the μ-PHES in the *Quartier Negundo* (left) and in the second case study (right). . . . 137
4.37 Estimations of the NPV of the μ-PHES of two further scenarios: without VFD but coupled with a gear-box and with a progressive electricity price raise (+ 0.5%/year) . . . 137
4.38 LCOE sensitivity analysis using the μ-PHES in *Quartier Negundo*. . 138
4.39 LCOE comparison of the μ-PHES with other storage technologies . . 139

5.1 Numerical investigation workflow and used tools in the methodology 143
5.2 Overview of the simulated domain . . . 144

5.3 Detail of the geometry in CATIA V5 R25 for the baseline cutwater and a tested configuration 145
5.4 Domain geometry improvements by rebuilding the cutwater 145
5.5 Flow path in a centrifugal pump volute 148
5.6 Qualitative representation of a volute with a tangential exit 148
5.7 Variation of the cutwater rounding variable R. 150
5.8 Variation of the cutwater length variable S. 150
5.9 Variation of the cutwater tilt angle variable A. 150
5.10 Velocity triangles at the entrance and exit of the PaT runner 151
5.11 Blade to blade topology map of the mesh blocks and cell point distributions 151
5.12 Full mesh illustration of the pump impeller and blade to blade topology 152
5.13 View of the wall surfaces of a volute and cut-view of a volute mesh . 153
5.14 Mesh convergence test conducted to assess the independence of the grid on the accuracy of the solution. 153
5.15 Evaluation of non-dimensional wall distance y^+ for the volute and impeller in the baseline case. 154
5.16 Examples of fitted regression of two-variables relationship 158
5.17 Numerical simulations and experimental data comparison for the pump specific energy coefficient Ψ and pump efficiency η_h over the relative discharge number. 161
5.18 Numerical and experimental comparison for the PaT specific energy coefficient Ψ and PaT efficiency η_h over the relative discharge number. 161
5.19 Flow field for the baseline cutwater at φ_{BEP}. 162
5.20 Illustrations of three different cutwater at $\varphi = 0.0152$ 163
5.21 Head and efficiency characteristics for cutwaters with $S = 2L$ as a function of the discharge number and the cutwater angle, A. 164
5.22 Head and efficiency characteristics for cutwaters with $S = 3L$ as a function of the discharge number and the cutwater angle, A. 165
5.23 Head and efficiency characteristics for cutwaters with $S = 4L$ as a function of the discharge number and the cutwater angle, A. 166
5.24 Numerical error for mass-flow mismatch between the inlet and outlet over the relative discharge number φ/φ_{BEP} for 224 simulations. . . . 167
5.25 Test model accuracy for $\hat{\eta}_{PAT} = f(S, R, A, Q_{11}, n_{11})$. 169
5.26 Test model accuracy for $\hat{Q}_{11} = g(S, R, A, n_{11})$. 170
5.27 Ψ and η of the baseline and optimal cutwater designs at N_{PAT}. . . . 172
5.28 Velocity streamline and velocity magnitude [m/s] contour for the baseline geometry and the optimal asset at different discharge number 173
5.29 Static pressure profiles at mid-flow span and Cp contour for the rotor/stator interface in both baseline and optimized cutwater geometry. 174
5.30 Contours of the absolute velocity angle [rad] across the volute cut-view and on the R/S used in Fig. 5.29. 175
5.31 Contours of the turbulence kinetic energy k distribution [m^2/s^2] across the volute cut-view. 175

5.32 3D overview of the absolute velocity vector profiles [m/s] in the baseline geometry. 176

5.33 3D overview of the absolute velocity vector profiles [m/s] in the optimized geometry. 176

5.34 Through-flow vorticity contours over the volute cross-sections at BEP for the baseline and optimized geometry. 177

5.35 RANS and URANS characteristics of Λ_{opt} in PaT mode. 178

5.36 URANS α_2 fluctuations in points P1, P2, P3, and P4. The coordinates (x, y) of stations exhibited in Figure are as follows: P1(0, 0.162), P2(0.162, 0), P3(0, -0.162), and P4(-0.162, 0). 179

5.37 URANS α_2 fluctuations in points ad different span angles 179

5.38 Comparison of α_2 for steady and unsteady states at $\varphi/\varphi_{BEP} = 0.87$. 180

5.39 Comparison of α_2 for steady and unsteady states at $\varphi/\varphi_{BEP} = 0.77$. 181

5.40 Comparison of α_2 for steady and unsteady states at $\varphi/\varphi_{BEP} = 0.97$. 182

5.41 PaT performances with the baseline and optimal cutwater designs for $\Omega = [0.85, 1.28]$. 183

5.42 Detail of the PaT efficiency in Fig. 5.41 for the optimized geometry under speed variations Ω. 184

5.43 CFD velocity streamline of the pump 186

5.44 Absolute pressure distribution along the volute cross-section for five representative cases. 187

5.45 CFD velocity streamline and Cp contour of pump cutwater 188

5.46 Pump hydraulic efficiency at $\varphi/\varphi_{BEP} = 1$ 189

5.47 Pump hydraulic efficiency at $\varphi/\varphi_{BEP} = 0.9$ 190

5.48 Pump hydraulic efficiency at $\varphi/\varphi_{BEP} = 1.1$ 190

5.49 Comparison of the numerical pump characteristics with the baseline geometry and Λ_{opt}. 191

5.50 RANS velocity magnitude iso-surface ($V = 2$ m/s) downstream the cutwater of Λ_{opt} in pump mode. 192

5.51 Water flow streamlines of the pump at $\varphi/\varphi_{BEP} = 1$ under Λ_{opt} asset. 192

5.52 URANS velocity magnitude iso-surface ($V = 1$ m/s) downstream the cutwater of Λ_{opt} in pump mode. 193

5.53 URANS velocity magnitude iso-surface ($V = 2$ m/s) downstream the cutwater of Λ_{opt} in pump mode. 193

6.1 Achievements of the PhD thesis. 198

A.1 Slip factor effect on velocity triangle 215

A.2 Schematic representations of the overlap angle. 217

A.3 Trailing edge parameters of the pump 218

A.4 Single-arc method of constructing blade profile 219

B.1 Static head of the pump minimum pressure point 222

B.2 Critical $\sigma_c r$ for pumps, Kaplan turbines, Francis turbines and PaTs . 223

List of Tables

2.1 Available turbomachinery solutions for PHES and UPSH 21
2.2 Pumped storage plants using Deriaz pump-turbine. 29
2.3 Performance prediction methods for PaT. 35

3.1 Energy infrastructure trends summary 42
3.2 Energy tariff in the Amazon region (US$/kWh) in 2018 [National Electric Energy Agency 2018]. 50
3.3 Existing pumped hydro storage plants in Belgium. 54
3.4 Breakdown of the total initial investment cost expressed in k€ 58
3.5 Data and NPV results for a preliminary economic evaluation of UPSH in Martelange. 61
3.6 Mechanical data of Deriaz prototype working in Naussac II. 75
3.7 Operational data in pumping and generating Deriaz prototype in Naussac II power-plant 75
3.8 Mechanical data of the downsized Deriaz pump. In Figure a downsized model of a Deriaz pump-turbine 76
3.9 Mesh convergence test on the same project case at $\delta\beta = 5°$, a_0= 56 % and mass flow of 0.18 [m^3/s] 78
3.10 Mesh quality summary for turbine case at $\delta\beta = 5°$ and closing runner blade at $\delta\beta = 0°$ 79
3.11 Turbulent model test for an assigned mesh 80
3.12 Adopted boundary conditions for the CFD simulations. 82
3.13 Inlet condition for the flow direction in turbine mode. 83

4.1 Extract of the pump data-sheet Main parameters of the pump installed at the micro pumped storage facility plant. 106
4.2 Instrumentation range and accuracy summary. 108
4.3 Summary of PHES control and command actions. 113
4.4 Value for green certificate in Brussels, Belgium, from June 2020. . . . 125
4.5 List of the main players in the electricity market in Belgium. 126
4.6 Averaged capacity factor for the PV panels and wind turbines in Belgium 2017. 130
4.7 Capital costs for μ-PHES in *Quartier Negundo* and cost estimation for the second case study. 134
4.8 Data and NPV results for a economic evaluation of μ-PHES. 137

5.1 List of independent variables describing the cutwater. 149
5.2 Mesh details for the baseline case study domain 154
5.3 Turbulent model test applied to a PaT: Spalart-Allmaras (SA), k-ε models, k-ω with or without Extended Wall Function (EWF). 156

5.4 Adopted boundary conditions for the CFD simulations. 157
5.5 Basis functions for $\hat{\eta}_{PAT}$ by the variables S, R, A Q_{11}, and n_{11}. . . . 169
5.6 Basis functions for $\hat{Q}_{11}$ by the variables S, R, A, and n_{11} for third degree maximum fit spline. 170
5.7 Predicted optimal cutwater geometry and the resulting efficiency by varying n_{11}. 171
5.8 Divergence of the absolute velocity angle α_2 in RANS and URANS. . 179

6.1 SWOT analysis of μ-PHES. 204

A.1 Mechanical data of Deriaz prototype working in Naussac II. 212
A.2 Design values along five main streamlines. 216

Nomenclature

Latin symbols

a_0	Guide vane opening	mm
A	Cutwater inclination angle	deg
b	Passage depth	m
B	Systematic error	-
c	Absolute velocity	m/s
c_{mix}	Celerity of the sound in a fluid mixture	m/s
C	Cost	€
C_d	Discharge coefficient	-
Cp	Static pressure coefficient	-
d	Yearly discount rate	-
dx	Average element size	m
D	Diameter	m
e	Specific hydraulic energy	J/kg
E	Energy	kWh
f	Grid frequency	Hz
g	Gravitational acceleration	m/s^2
h	Head ratio	-
h_i	Hinge function factor	-
H	Head	m
i	Incidence deviation	deg
k_i	Constant	-
K	Project duration	year
L	Length	m
m	Mass flow rate	kg/s
M	Torque	Nm
n	Rotational frequency	rot/s
np	Number of poles in a generator	-
n_{11}	Unit speed	-
N	Rotational speed	rpm
N_s	Specific speed	rpm, m^3/s, m
p	Pressure	Pa
P	Power	kW
q	Discharge ratio	-
Q	Discharge	m^3/s
Q_{11}	Unit discharge	-
r	Nominal cutwater radius	mm
R	Radius	m
Re	Reynolds number	-

S	Cutwater stretching	m
t	Time	s
u	Peripheral velocity	m/s
U	Uncertainty	-
v	General speed vector	m/s
V	Volume	m^3
V_r	Energy loss fraction	-
w	Relative velocity	m/s
W	Direction flow	-
y^+	Non-dimensional wall distance	-
z	Number of blades	-
Z	Altitude	m

Greek symbols

α	Absolute velocity angle	deg
β	Relative velocity angle	deg
γ	Blade pivot angle	deg
η	Efficiency	-
Θ	Angular coordinate	deg
λ	Blade inclination	deg
Λ	Domain	-
μ	Dynamic viscosity	Pa s
ν	Dimensionless turbine specific speed	-
ξ	Efficiency ratio	-
π	Power number	-
ρ	Density	kg/m^3
σ	Thoma number	-
τ	Slip coefficient	-
φ	Discharge number	-
ψ	Correction coefficent	-
ω	Angular speed	rad/s
Ω	Rotational speed ratio	-
Ψ	Specific energy coefficient	-

Subscripts

11	Unit factor
1	Pump inlet
2	Pump outlet
a	Available
ad	Normalised value
CFD	Numerical
cr	Critical
$curt$	Curtailment
exp	Experimental
eff	Effective
fit	Fitting
g	Geodetic
geo	Geometrical
h	Hydraulic
i	Index
in	Injected
l	Loss
L	Liquid
m	Mechanic
m	Meridional
max	Maximum
min	Minimum
md	Model
n	Nominal
opt	Optimal
p	Pump
pty	Prototype
r	Radial
rw	Runaway
syt	System
t	Turbine
th	Theoretic
u	Circumferential direction
v	Volumetric
vp	Vapour
vol	Volumetric

Acronyms

AGV	Adjustable Guide Vanes
AR	Aspect Ratio
ATM	Aero-Thermo-Mechanics
BEP	Best Efficiency Point
BF	Basis Function
CAD	Computer Aided Design
CFD	Computational Fluid Dynamic
CFL	Courant-Friedrich-Levy number
CPU	Central Processing Unit
DES	Decentralized energy sources
DNIT	National Department of Transport Infrastructure
DSO	Distribution system operator
EEX	European Energy Exchange
EES	Electrical Energy Storage
ER	Expansion Ratio
EWF	Extended Wall Function
FEA	Finite Element Analysis
FS	Factor of safety
HGS	Hydraulic Gravity Storage
IDETA	Agence de Développement Territorial
LCOE	Levelised Cost Of Energy
LCOS	Levelized Cost of Storage
MARS	Multivariate Adaptive Regression Spline
MTBF	Mean Time Between Failures
NPV	Net Present Value
OPEX	Operating Expense
O&M	Operations and Maintenance
PaT	Pump as Turbine
PHES	Pumped Hydro Energy Storage
μ-PHES	Micro Pump Hydro Energy Storage
PLC	Programmable Logic Controller
PV	PhotoVoltaic
RES	Renewable Energy Source
RPT	Reversible Pump-Turbine
SA	Spalart-Allmaras model
SPS	Seawater Pump Storage
SST	Shear Stress Transport
TSO	Transmission System Operator
UPHS	Underground Pumped-Storage Hydroelectricity
UPS	Uninterruptible Power Supply
VFD	Variable Frequency Drive