Applied Thermal Engineering 116 (2017) 549–583

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Development and experimental study of a small-scale compressed air radial inflow turbine for distributed power generation

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HIGHLIGHTS

- Proposing methodology for developing small-scale RIT as expander of CAES and ORC.
- 1D modelling enables estimation of turbine performance and obtaining key geometry.
- Turbine efficiency improved from 81.3% obtained by 1D model to 84.5% obtained by CFD.
- CFD predicts turbine efficiency and power with accuracy of ±16% and ±13% compared to tests.

ARTICLE INFO

Article history:
Received 4 October 2016
Revised 16 January 2017
Accepted 25 January 2017
Available online 31 January 2017

Keywords:
Radial turbine
Distributed power generation
CFD
Experimental
Additive layer manufacturing (3D printing)
Stereolithography

ABSTRACT

With ever increasing demand on energy, disturbed power generation utilizing efficient technologies such as compressed air energy storage (CAES) and organic Rankine cycle (ORC) are receiving growing attention. Expander for such systems is a key component and its performance has substantial effects on overall system efficiency. This study addresses such component by proposing an effective and comprehensive methodology for developing a small-scale radial inflow turbine (RIT). The methodology consists of 1-D modelling, 3-D aerodynamic investigation and structural analysis, manufacturing with pioneering technique and experimental testing for validation. The proposed 1-D modelling was very effective in determining the primary geometry and performance of turbine based on parametric studies of turbine input design variables. However with CFD analysis, it was shown that more efficient turbine geometry can be achieved that not only provides more realistic turbine performance by capturing the 3-D fluid flow behaviour but also improves turbine efficiency with the aid of parametric studies of turbine geometry parameters. Turbine efficiency was improved from 81.3% obtained from 1-D modelling to 84.5% obtained by CFD. Accuracy of the CFD model was assessed by conducting experiments on the RIT manufactured with stereolithography technique. The CFD model can predict turbine efficiency and power with accuracy of ±16% and ±13% respectively for a wide range of tested operating conditions. Such results highlights the effectiveness of the proposed methodology and the CFD model can be used as benchmarking model for analyses of small-scale RITs. Besides, it was shown that for such applications, the novel manufacturing technique and employed material are very effective for producing prototypes that assist design decisions and validation of CFD model with reasonable accuracy at reasonable cost and in timely manner.

1. Introduction

Nowadays energy is a key factor in the global economy and the effectiveness of energy generation and consumption processes has remarkable impacts on our society and environment. Following the international energy agency (IEA) report [1], extending the current trend of energy consumption and energy efficiency to 2050 yields a growth of 70% and 60% in the global energy demands and emissions respectively compared to 2011. The associated emissions result in a long-term global average temperature rise of 6 °C by 2050 which can result in potentially devastating consequences such as climate change and energy security. IEA (2014) suggested an effective scenario called "2DS" which offers a vision for a sustainable energy system that reduces CO_2 emissions to maintain the global temperature rise within 2 °C by 2050 and to limit increases in energy demand by 25% and cut emissions by 50%. This

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http://dx.doi.org/10.1016/j.applthermaleng.2017.01.100
1359-4311/

Nomenclature

Symbols

A	area (m^2)
b	blade height (m)
BK	blockage factor (–)
C	absolute flow velocity (m/s)
C_{nozzle}	nozzle chord length (m)
C_p	specific heat capacity at constant pressure (J/kg K)
C_s	spouting velocity $(J/kg)^{-1}$
d	diameter (m)
d_{hyd}	hydraulic diameter (m)
ER	expansion ratio (–)
f	friction coefficient (–)
f_{curve}	turbine friction factor (–)
h	enthalpy (J/kg)
Δh_{actual}	actual specific enthalpy drop (J/kg)
Δh_{ideal}	ideal specific enthalpy drop (J/kg)
Δh_{losses}	enthalpy drop due to losses (J/kg)
I	rothalpy (J/kg)
k	coefficient (–)
l	length (m)
l_{hyd}	hydraulic length (m)
$\dot{m}$	mass flow rate (kg/s)
Ma	Mach number (–)
N_s	specific speed (–)
$O_{throat,nozzle}$	nozzle throat width (m)
P	pressure (Pa)
R	gas constant (J/kg K)
R_0	universal gas constant ((J/(k mol))
RR	relative roughness (m)
Re	Reynolds number (–)
r	radius (m)
$\mathbf{r}$	location vector (m)
r_c	mean radius of curvature (m)
S	entropy (J/kg K)
$\mathbf{S}_E$	energy source ($kg/(m\,s^3)$)
$\mathbf{S}_M$	momentum source (($kg/(m^2\,s^2)$)
S_{nozzle}	nozzle blade pitch (m)
T	temperature (K)
t	time (s)
U	rotor blade velocity (m/s)
$\mathbf{U}$	vector velocity $\mathbf{U}_{x,y,z}$ (m/s)
W	relative flow velocity (m/s)
w	molecular weight (kg/mol)
Z	Blade number (–)

Greek letters

α	absolute flow angle with respect to radial (degree)
β	relative flow angle with respect to radial (degree)
γ	specific heat capacity ratio (–)
δ	identity matrix (–)
ε	clearance (m)
ζ	shear stress tensor ($kg/m\,s^2$)
η	efficiency (–)
λ	thermal conductivity (W/m K)
μ	dynamic viscosity (kg/(m s))
υ	isentropic velocity ratio (–)
ρ	density (kg/m^3)
σ	solidity (–)
φ	flow coefficient (–)
ψ	loading coefficient (–)
ω	rotational velocity (RPM)

Subscripts

1–5	stations across turbine
abs	absolute
b	back plate
cfg	centrifugal
Cor	coriolis
f	friction
hub	rotor hub
j	counter
m	meridional direction
r	radial
ref	reference
rel	relative
rms	root mean square
rotor	rotor
s	isentropic
sonic	sonic velocity (speed of sound)
x	axial direction
stage	turbine inlet to turbine outlet
stat	static
t	total, stagnation
tip	rotor tip
ts	total to static
θ	tangential direction

Superscripts

T	matrix transpose
–	average

Mathematical operators

∇	vector operator $\left[\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right]$
$\otimes$	dyadic operator (tensor product)

Acronyms

CAES	compressed air energy storage
CAD	computer aided design
CFD	computational fluid dynamics
CHP	combined heat and power
CPG	centralized power generation
DPG	distributed power generation
DUI	datum universal interface
EES	engineering equation solver
FEA	finite element analysis
GGI	general grid interface,
IEA	international energy agency
LE	leading edge
MOGA	multi-objective genetic algorithm
ORC	organic Rankine cycle
PS	pressure surface
RANS	Reynolds-averaged Navier-Stokes
RIT	radial inflow turbine
RPM	revolutions per minute
SS	suction surface
SST	shear stress transport
TE	trailing edge

strategy creates a framework for a future sustainable energy systems which are expected to be smarter, renewable oriented, integrated, well-regulated and more distributed.

Improvements in energy efficiency have significant contribution to the “2DS” scenario. For example, power in the traditional electrical grid (or centralized power generation) followed one