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Research Paper

Development of three-dimensional optimization of a small-scale radial turbine for solar powered Brayton cycle application

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HIGHLIGHTS

- 1D and 3D CFD analysis for compressed air radial turbine was carried out.
- Small scale radial turbine with high efficiency.
- 3D MOGA optimization for the radial turbine was achieved.
- Enhancing the performance of both the turbine and the solar powered Brayton cycle.
- Excellent agreement between the current CFD results and two experimental works from literatures.

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ABSTRACT

Numerical simulation was carried out to optimize the design of a small-scale radial turbine. One-dimensional (1D) Mean Line (ML) approach and three-dimensional computational fluid dynamic (3D CFD) simulations, using 3D Reynolds-Averaged Navier-Stokes (RANS) models with the shear stress transport (SST) turbulence model in ANSYS®15-CFX, were employed to achieve the best turbine performance and consequently cycle efficiency. For the current study, a new methodology that integrates the Brayton cycle analysis with modelling of a highly efficient small-scale radial turbine at a wide range of inlet temperatures was developed. A multi-objective function was utilized for optimizing the designed radial turbine power in the range of 1.5–7.5 kW. This method has been developed in order to find the optimum design, from an aerodynamic point of view. After applying a well-designed range of parameters for both the stator and the rotor, the results demonstrated an excellent improvement in the turbine efficiency from 82.3% to 89.7% for the same range of output power. Moreover, the effect of the turbine inlet temperature, rotational speed and pressure ratio was further studied and presented in this paper. Finally, the overall cycle efficiency showed an excellent improvement of about 6.5% for the current boundary conditions; and it yielded more than 10% with the increase in the inlet temperature and the pressure ratio. Such results highlight the potential and the benefits of the suggested methodology to achieve a high performance (i.e. turbine efficiency and cycle efficiency).

1. Introduction

The demand for energy is continually increasing day after day, but at the same time, investigations around the world into sustainable sources of power are growing in number. Solar energy is considered one of the main renewable energy sources which can play an important role in decreasing CO_2 emissions. It can be efficiently used to generate electricity using different types of thermal power cycles, such as the Brayton cycle.

Moreover, small scale turbines are considered as a promising technology because of their low initial costs, low maintenance, durability and simple construction. Furthermore, they can offer a solution for the power generation demand in domestic or even remote areas. In order to increase the cycle efficiency, one of the main effective ways is to improve the turbines' performance.

Much research has been carried out regarding both the solar Brayton cycle thermodynamic analysis and the selection of the appropriate boundary conditions of energy as heat sources such as [1–4]. For example, an attempt to enhance the overall efficiency

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Nomenclature

Symbol

A	area (m^2)
b	axial chord (mm), blade width (mm)
c	absolute velocity (m/s)
d	diameter (m)
f	friction factor (–)
h	enthalpy (J/kg)
H	blade height (mm)
i	incident angle (deg.)
k	loss coefficient (–)
l	length (m)
m	mass flow rate (kg/s)
p	pressure (Pa)
PR	pressure ratio (–)
r	radius (m)
Re	Reynolds no. (–)
s	entropy (J/kg K)
SC	swirl coefficient (–)
T	temperature (K)
U	rotor blade velocity (m/s)
w	relative velocity (m/s)
W	power (W)
Z	blade number in radial turbine (–)

Greek symbols

α	absolute flow angle (deg.)
β	relative flow angle (deg.)
ε	clearance (m)
η	efficiency (%)
υ	velocity ratio (–)
ρ	density (kg/m^3)
φ	flow coefficient (–)
ψ	loading coefficient (-)
ω	acentric factor (–)
ζ	losses (–)

Acronyms

BL	base-line design
BCs	boundary conditions
CFD	computational fluid dynamics
DoE	Design of Experiment
GA	Genetic Algorithm
LE	leading edge
ML	mean line design
MOGA	multi-objective genetic algorithm
ORC	organic rankine cycle
O.S.S.R.T	Optimized Small Scale Radial Turbine
RANS	Reynolds-Averaged Navier-Stockes
RSA	response surface approximation
SST	Shear Stress Transport
TE	trailing edge

Subscripts

1–6	station
m	meridional direction
r	radial
rel	relative
s	isentropic
x	axial
t	total, stagnation
ts	total to static
th	thermal
θ	tangential/circumferential direction

of the small-scale solar Brayton cycle, by optimizing both the receiver and the parabolic concentrator, has been achieved by Le Roux et al. [5]. Riazi and Ahmed [6] studied the effect of specific heat ratios for three different working fluids and for air, helium and tetrafluoromethane, on the efficiency of small scale solar energy. A regenerative closed Brayton cycle was analysed in terms of the influence of temperature ratio and the minimum to maximum gas temperature. Their results showed that the higher the specific ratio of the analysed fluid, the higher the cycle efficacy. Moreover, they also suggested that for small-scale Brayton cycles, the performance of lower specific ratios is better as this scale only accumulates a small amount of heat. However, the performance of turbines

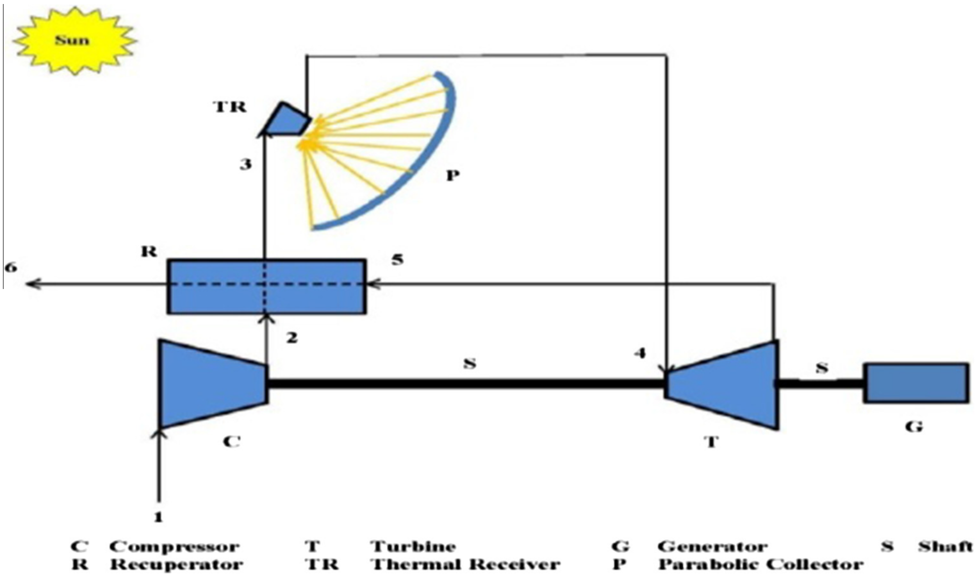

Fig. 1. Schematic diagram of CSP-BC system.