Energy Conversion and Management 128 (2016) 343–360

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Parametric study of efficient small-scale axial and radial turbines for solar powered Brayton cycle application

Ahmed M. Daabo [a,b,*], Ayad Al Jubori [a], Saad Mahmoud [a], Raya K. Al-Dadah [a]

[a] The University of Birmingham, School of Engineering, Edgbaston, Birmingham B15-2TT, UK
[b] The University of Mosul, Mechanical Engineering Department, Ninawa, Iraq

ARTICLE INFO

Article history:
Received 30 June 2016
Received in revised form 30 August 2016
Accepted 18 September 2016

Keywords:
Small scale turbines
Axial and radial
Brayton cycle
Preliminary design and CFD
Compressed air

ABSTRACT

The researchers' main target in this work is to demonstrate the performance of small-scale (5–45 kW) axial and radial compressed air turbines which are able to operate at specific boundary conditions. These boundary conditions were chosen to be compatible with a small-scale solar powered Brayton cycle. The evaluation is dependent on the turbines' efficiency, compactness and output power. Firstly, preliminary design work was completed in order to figure out the turbines' shapes and find initial information about the impact of various factors on their efficiency values and output powers. Factors considered were: inlet pressure, inlet temperature, pressure ratio, rotational speed and the mass flow rate. Their performance during the off design conditions was also recorded. Subsequently, three-dimensional computational fluid dynamics modelling was completed for each turbine and at every single studied case in order to study in depth the effect of other factors and have accurate results. The results show that the radial turbine is superior when the main concern is working with low mass flow rate. On the other hand, the axial turbine is more desirable when the low rotational speed is of interest. The cycle results showed that an improvement in the cycle's thermal efficiency ranging from 6% to 12% can be achieved with a turbine efficiency increase from 80% to 90% respectively for fixed cycle boundary conditions. Finally, two different data sets from the previous experimental work have been used to examine the accuracy of the current work and the outcomes were highly accurate.

1. Introduction

Small-scale turbines are considered as a promising technology because of their low initial costs, low maintenance, durability and simple construction. The need for an efficient small-scale turbine, which can operate at low mass flowrates, relatively low pressure ratios and moderately high temperatures, was the driving force for investigating the Small-scale Axial Turbine (SSAT) and Small-scale Radial Turbine (SSRT). There are varying opinions about what characterises a small-scale turbine, however the significance of the power output is commonly agreed upon. Many of the references [1] give ranges from 5 to 500 kW. Several studies investigated separately different components of the cycle: such as the thermal cavity receiver of a small-scale solar Brayton cycle [2]; the effect of some boundary conditions on the overall cycle efficiency [3]; and the optimum performance of the cycle [4]. However, they neglected the turbines' performance. The off-design performance of a small-scale humid air turbine cycle was studied by Wei et al. [5]. An evaluation of the microturbines and their application in the dual cycles was carried out in [6]. The lack of literature published that studied this range of turbine power outputs was the impetus for investigating the suitable boundary conditions for this range. In this study a comparison, with a range of around 5–45 kW was considered. From the perspective of the application, it is necessary to have a suitable turbine from the mentioned SSAT and SSRT which is able to work efficiently at some off-design conditions.

It is stated that the axial flow type has been used specifically in aircraft gas turbine engines and they are also usually engaged in industrial and shipboard purposes [7].

Evaluation of the performance of micro gas-turbine for small-scale hybrid solar power plants using the thermodynamic analysis was achieved by Aichmayer et al. [8]. Klonowicz et al. [9] designed a small-scale single stage turbine uses R227ea as a working fluid. They revealed a good mutual agreement between the theoretical and measured values of the efficiency (55% and 53% respectively). However, they also concluded that it is unknown whether this model would be valid for different values of size parameter, expan-

---

* Corresponding author at: The University of Birmingham, School of Engineering, Edgbaston, Birmingham B15-2TT, UK.

E-mail address: axd434@bham.ac.uk (A.M. Daabo).

http://dx.doi.org/10.1016/j.enconman.2016.09.060

Nomenclature

Symbols

A	area
b	blade width (m)
B	axial chord (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)
r	mean radius of curvature
R_c	compressor pressure ratio
Re	Reynolds no. (–)
R	degree of reaction
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)
x	pressure loss coefficient
Z	blade number in radial turbine (–)

Greek symbols

α	absolute flow angle (deg.)
β	relative flow angle (deg.)
θ	tangential/circumferential direction
ε	clearance (m)
η	efficiency (%)
γ	specific heat ratio
υ	velocity ratio (–)
ρ	density (kg/m^3)
φ	flow coefficient (–)
ψ	loading coefficient (–)
ω	acentric factor (–)
ζ	losses (–)
ζ^*	nominal loss factor

Subscripts

1–6	station
c	compressor
G	gained
hyd	hydraulic
m	meridional direction
r	radial, rotor
Rej	rejected
rel	relative
s	isentropic, stator
t	total, stagnation, turbine
th	thermal
ts	total to static
x	axial

Acronyms

BCs	boundary conditions
CFD	computational fluid dynamics
PD	preliminary design
RMS	root mean square
S.S.A.T	small-scale axial turbine
S.S.R.T	small-scale radial turbine
SST	small-scale turbines

sion ratio or specific speed. Furthermore, a radial turbine was investigated by Fu et al. numerically [10] and then experimentally [11]. They developed an optimisation design approach to the aerodynamic performance, structural strength, and wheel weight of the radial turbine. The optimisation results showed high aerodynamic activity and satisfactory stress distribution. The influence of ambient temperature on the performance of micro gas turbine, for cogeneration system applications in the cold region, has been studied by Basrawi et al. [12]. The results showed that increasing the ambient temperature leads to a reduction in the electrical efficiency and an increase in the exhaust heat recovery. It was also found that by increasing the ambient temperature, the exhaust heat to mass flow rate and exhaust heat recovery to mass flow rate increased. Rahbar et al. [13] utilised the mean-line modelling and CFD techniques in order to develop a small-scale radial turbine, around 5 kWe. Then CFD techniques were used to evaluate the mean-line approach and improve the blade loading by some adjustment of the angles of the blades. Their results showed that achieving a high power output required a higher inlet temperature, mass flow rate and pressure ratio. The results also showed that the minimum number of rotor blades, which was suggested by mean-line modelling, was overestimated. Different types of losses that are associated with turbines were included in the literature. For example, the impact of tip-gap losses on the stage efficiency was intensively studied in [14]. Furthermore, an assessment of different loss correlations for a small-scale impulse turbine working on ORC cycles was conducted in [15]. Enhancing the performance of a small-scale nozzle-less radial turbine with some detailed analysis for loss was achieved in [16]. However, only the VISUAL BASIC program was considered during their study. The flow losses of radial turbines with and without vanes were studied in [17]. An experimental study, using a laser Doppler velocimeter, for measuring the internal flow losses of small turbochargers was carried out in [18]. The study revealed that these losses occurred because of the fluid low energy suction surface of the blade, specifically on the shroud side. The secondary flow losses in the nozzle of a radial turbine were investigated, using both numerical and experimental studies, in [19].

A single stage small-scale radial inflow turbine with a rotor of 4.58 in. was studied by Jones [20]. A simple cycle gas turbine with 50 hp as a nominal power output with a capability to reach up to 100 hp minimal modification was used during his study. Their results showed that small inflow radial turbines were able to have good efficiencies: 86% total to static and 88% total to total, at high stage pressure ratio of 7. The researcher claimed that this level is higher than that of the multistage axial turbines can provide at the same boundary and design conditions. An optimisation procedure was established with the aim of determining the main dimension of the rotor (60,000 rpm and 60 kW electrical power) by Ebaid et al. [21]. In their research they developed a computer program to find the optimum dimensions of the rotor with the relevant number of blades.

Optimizing the blade passage was also achieved by Mistry et al. [22] by designing a nozzle-less small capacity (20 kW) radial inflow gas turbine. They concluded that the maximum efficiency was achieved at the values of 0.54 and 0.41 absolute and relative