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A review on the thermodynamic optimisation and modelling of the solar thermal Brayton cycle

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ABSTRACT

Many studies have been published on the performance and optimisation of the Brayton cycle and solar thermal Brayton cycle showing the potential, merits and challenges of this technology. Solar thermal Brayton systems have potential to be used as power plants in many sun-drenched countries. It can be very competitive in terms of efficiency, cost and environmental impact. When designing a system such as a recuperative Brayton cycle there is always a compromise between allowing effective heat transfer and keeping pressure losses in components small. The high temperatures required in especially the receiver of the system present a challenge in terms of irreversibilities due to heat loss. In this paper, the authors recommend the use of the total entropy generation minimisation method. This method can be applied for the modelling of a system and can serve as validation when compared with first-law modelling. The authors review various modelling perspectives required to develop an objective function for solar thermal power optimisation, including modelling of the sun as an exergy source, the Gouy–Stodola theorem and turbine modelling. With recommendations, the authors of this paper wish to clarify and simplify the optimisation and modelling of the solar thermal Brayton cycle for future work. The work is applicable to solar thermal studies in general but focuses on the small-scale recuperated solar thermal Brayton cycle.

Contents

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Nomenclature

a	constant, –
A	cross-sectional area, m^2
b	constant, –
BSR	blade speed ratio, –
c	constant, –
c	specific heat, J/kg K
COP	coefficient of performance, –
C_s	gas velocity, m/s
d	degradation constant, –
D	turbine diameter, m
e	specific exergy, J/kg
E	exergy, J
f	sunlight dilution factor, –
F_D	external drag force, N
g	gravity constant, m/s^2
h	specific enthalpy, J/kg
I	solar irradiance, W/m^2
J	polar moment of inertia, kg m^2
k	gas constant (c_p/c_v), –
k	thermal conductivity, W/m K
l	thread length, m
L	length, m
m	mass of the rotor assembly, kg
$\dot{m}$	mass flow rate, kg/s
N	speed, rpm
N	number of fins, –
NTU	number of transfer units, –
P, p	pressure, Pa
$\dot{Q}$	heat transfer rate, W
r	pressure ratio, –
r	distance from rotational axis to thread's attachment to the rotor, m
R	gas constant, J/kg K
s	specific entropy, J/kg K
S	solar constant, W/m^2
S	entropy, J/K
$\dot{S}$	entropy rate, W/K
t	time, s
T	temperature, K
T_0	environment temperature, K
U	rotor inlet blade tip speed, m/s
V	velocity, m/s
$\dot{W}$	power, W
x	distance in x-direction, m
y	distance in y-direction, m
z	height, m
z	constant, –
ε	heat exchanger effectiveness, –
η	efficiency, –
κ	dilution factor of diffuse radiation, –
λ	dimensionless parameter for longitudinal conduction, –
σ	Stefan–Boltzmann constant, $W/m^2\,K^4$
τ	period time for one oscillation, s
υ	volume, m^3

Subscripts

0	surrounding/loss
0	zero pressure (ideal gas) for c_p
1	at state 1
2	at state 2
1–11	refer to Fig. 1
a	dead (reference) state
acc	acceleration
b	at heat transfer boundary
B	base
BH	Bahnke and Howard
be	beam
c	compressor
col	collector
cv	control volume
d	diffuse
D	destruction
e	exit
eff	effective
eff	efficiency
gen	generation
i	inlet
j	component number
$loss$	loss into the environment
m	mechanical
max	maximum
min	minimum
net	net
opt	optimum
p	for constant pressure
p	planet
r	receiver
reg	recuperator
$rotor$	rotor
R	reversible
s	isentropic
S	Sun
$sngl$	single
t	turbine
v	for constant volume
∞	surrounding area/free stream

Superscripts

*	solar
.	time rate of change
CH	chemical

1. Introduction

Concentrated solar power systems use the concentrated power of the sun, as a heat source in a power cycle, to generate mechanical power. Bejan et al. [1] implied that the solar heat source is more suitable than the isotope and nuclear heat sources when the power plant size is in the range of 2–100 kW. Solar thermal power cycles have potential to be used in many sun-drenched countries. One of these cycles is the solar thermal Brayton cycle. This cycle can be very competitive in terms of efficiency, cost and environmental impact. Chen et al. [2] showed that the Brayton cycle is definitely worth studying when comparing its efficiency with those of other power cycles. Mills [3] predicted that emphasis may shift from Dish–Stirling technology to solarised Brayton micro-turbines due to lower Brayton costs, as a result of high production quantities in the current market. An open solar thermal Brayton cycle uses air as