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Optimum dimension of geometric parameters of solar chimney power plants – A multi-objective optimization approach

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Abstract

In this communication, a multi-objective optimization method is implemented using evolutionary algorithm techniques in order to determine optimum configuration of solar chimney power plant. The two objective functions which are simultaneously considered in the analysis are power output and capital cost of the plant. Power output of the system is maximized while capital cost of the component is minimized. Design parameters of the considered plant include collector diameter (D_{coll}), chimney height (H_{ch}) and chimney diameter (D_{ch}). The results of optimal designs are obtained as a set of multiple optimum solutions, called 'the Pareto frontier'. For some sample points of Pareto, optimal geometric is presented. In addition, effect of changing design variables on both objective functions is performed. This multi-objective optimization approach is very helpful and effective for selecting optimal geometric parameters of solar chimney power plants. The results show that, power output of the plant increases linearly when solar irradiation increases and increase in ambient temperature causes slight decrease in power output of the plant.

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Keywords: Solar chimney; Geometric parameters; Optimization; Capital cost

1. Introduction

Continual increase in energy demands, due to world population growth and depletion of fossil fuels, has revealed importance of renewable energy sources more than ever. Solar tower (chimney) is one of the technologies which utilizes the sun's energy for power generation. The idea of generating electricity by a solar tower was suggested by Haaf et al. (1983). Also, they presented preliminary experimental results of a small scale (50 kW) prototype in Manzanares, Spain (Haaf, 1984; Schlaich et al., 2005; Schlaich, 1996).

Sangi proposed a mathematical model for predicting electric power of a solar chimney in southern and central areas of Iran, in which collector diameter was 1000 m and chimney had height of 350 m (Sangi, 2012). His performance analysis of the solar chimney power plant (SCPP) in different ambient conditions (solar radiation of 400–750 W/m^2 and ambient temperature of 270–315 K) demonstrated potential electricity generation of 1–2 megawatt (Sangi, 2012). Nizetic and Klarin (2010) discussed

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Nomenclatures

A	area (m^2)
C	currency unit (U)
CC	capital cost (U)
CC_{SC}	specific capital cost (U/m^3)
c_p	specific heat capacity ($kJ\,kg^{-1}\,K^{-1}$)
D	diameter (m)
F'	collector efficiency factor
F''	collector flow factor
F_R	collector heat removal factor
g	gravitational acceleration (m/s^2)
G	solar radiation (W/m^2)
H_{ch}	chimney height (m)
H_{coll}	collector height (m)
$\dot{m}$	mass flow rate (kg/s)
P_{cl}	power loss of exit kinetic energy (W)
P_{el}	electric power output (kW)
pt	percentage (%)
P_{tc}	power of theoretical air cycle (W)
T	temperature (K)
T_{ma}	mean air temperature (K)
T_{mp}	mean plate temperature (K)
V	velocity (m/s)

Greek letter

α	effective absorption coefficient
β	convective energy loss coefficient ($W\,m^{-2}\,K^{-1}$)
Δ	differential
η	efficiency (%)
η_{ge}	blade, transmission and generator efficiency (%)
η_p	plant efficiency (%)
ρ	air density (kg/m^3)

Subscripts

1	inlet of solar collector
2	outlet of solar collector| inlet of wind turbine
a	ambient
ch	chimney
coll	collector
p	plant
t	turbine
tg	turbo-generator

Acronyms

CFD	computational fluid dynamics
PCU	power conversion unit
SCPP	solar chimney power plant

simplified thermodynamic analysis for evaluating pressure drop ratio across turbines as well as optimal velocity of air at the chimney inlet in SCPP. Based on the optimal velocity of air at the chimney inlet (Nizetic and Klarin, 2010), Gholamalizadeh and Mansouri (2013) introduced an analytical and numerical model for analyzing performance of the SCPP built in Kerman, Iran. The Kerman pilot plant had a collector diameter of 40 m. With chimney height and diameter of 60 m and 3 m, respectively, it was capable of generating about 400 W power in solar radiation of 800 W/m^2 (Gholamalizadeh and Mansouri, 2013). Bernardes et al. (2003) developed a mathematical model to investigate effect of various construction conditions on the power output. Their model was validated with the experimental data from the Manzanares prototype. Petela studied a simplified model of the SCPP based on the derived energy and exergy balances to develop analysis of total SCPP process (Petela, 2009).

Hamdan (2011) and Asnaghi and Ladjevardi (2012) investigated SCPP performance and quantity of electric energy generation throughout the Persian Gulf region and Iran, respectively. Moreover, Nizetic et al. (2008) studied feasibility of applying SCPP in Mediterranean zone. Moreover, an approximate cost evaluation including a total investment approximation was carried out. In this literature, other works have been studied by Dai et al. (2003), Onyango and Ochieng (2006), Ketlogetswe et al. (2008), Maia et al. (2009), Alawin et al. (2013) and Asnaghi et al. (2012). Koonsrisuk and Chitsomboon (2013) used a mathematical model to investigate relationship between pressure ratio and mass flow rate of system as well as influence of temperature rise across collector on the generated power in a large scale solar chimney. And, for a SCPP with constant driving pressure, optimum pressure drop of the turbine was calculated as 2/3 in references Koonsrisuk and Chitsomboon (2013) and von Backström and Fluri (2006). Moreover, Bernardes and Backstrom have shown that the optimum pressure drop ratio is not constant during the whole day and it is dependent of the heat transfer coefficients applied to the collector (Bernardes and Backstrom, 2010).

The performance of the power conversion unit (PCU) and its interaction with the plant is analyzed by Fluri and Von Backström (2008). Furthermore, they compared three PCU configurations, (i) the single vertical axis, (ii) the multiple vertical axis and (iii) the multiple horizontal axis turbine configuration. Moreover, they compared different layouts of turbogenerators and evaluated the performance of these layouts using analytical models (Fluri and Backstrom (2008)).

Koonsrisuk and Chitsomboon (2009a) presented a solar chimney model (a model which is partially geometrically similar to the prototype) to maintain dynamic similarity for a prototype and its models while using the same heat flux. They showed that, to achieve the same-heat-flux condition, the roof radius between the prototype and its scaled

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