Solar Energy 170 (2018) 379–387

Contents lists available at ScienceDirect

Solar Energy

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

Performance of divergent-chimney solar power plants

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ARTICLE INFO

Keywords:
Solar chimney power plant
Divergent chimney
Pressure recovery
Performance enhancement

ABSTRACT

Simulations of divergent-chimney solar power plants (DSPPs) are conducted, and the DSPP performance studied by changing chimney outlet-to-inlet area ratios (COAR, representing the degree of divergence) over a wide range of values. Study method involves the use of total pressure potential (TPP) which consists of buoyancy and static pressure recovery in which an effective pressure potential recovery coefficient (EPPRC) is employed. Results show when the COAR is large enough, the boundary layer separation (BLS), flow stall and backflow will occur, vortex be formed, and a part of flow area be blocked. Due to the backflow from the ambient cool air, the temperature greatly decreases above the BLS point, possibly causing the reduction of buoyancy of the divergent chimney. With COAR increasing, the TPP initially increases and reaches a maximum for COAR = 8.7 then decreases. The mass flow rate and the power output have the same variational trend, while the collector temperature rise has the inverse variational trend. A maximum power of 231.7 kW is attained at COAR = 8.7, which is 11.9 times as high as that for COAR = 1. Before the occurrence of flow stall, the EPPRC decreases slowly due to the gently thickening of boundary layer and is higher than 0.91. While after the occurrence of flow stall, mainly due to the vortex and backflow the EPPRC greatly decreases and is found to decrease gradually with COAR. The effective ground heat flux increases the power output, but has little influence on the characteristics of the flow stall in the chimney, specifically the EPPRC.

1. Introduction

As an important component of solar chimney power plants (also called solar updraft power plants), solar chimney (also called solar updraft tower) produces the total pressure potential (TPP), which determines the inflow velocity and then power output. A high chimney is needed for high efficiency of the solar chimney power plant (Zhou et al., 2010; Zhou and Xu, 2016). A high chimney can also be used for other additional purposes (Tan et al., 2017; Zhou et al., 2015). The chimney shape can also influence the performance of the plant (Zhou and Xu, 2016). The conventional solar chimney for power generation is cylindrical in shape in which the cross sectional area doesn't change much with height (Schlaich, 1995, 1999; Pretorius and Kröger, 2006; Zhou et al., 2014, 2017a; Xu et al., 2015; Guo et al., 2016, 2017; Lorente et al., 2010). Optimization of the chimney shape for enhancement of the plant's efficiency is therefore an important and competitive study area.

Von Backström and Gannon (2000) developed a mathematical model based on the properties of compressible gas and found that the flow area in the solar chimney can increase gradually with height from the chimney inlet to its outlet by 14% to keep the through-flow Mach number constant in order to eliminate the pressure drop associated with the vertical acceleration of the indoor air. The pressure drop is about three times the pressure drop associated with wall friction. Few experimental data showed that divergent chimney helped increase the mass flow rate of air in the solar chimney power plant (Koonsrisuk, 2009; Okada et al., 2015; Ohya et al., 2016). Chan et al. (2014) developed a theoretical model of a telescopic divergent chimney for power generation without heat input in the chimney inlet (for example, due to the solar collector) but based on forced air movement, in which the air follows incompressible gas assumptions. Zhou et al. (2017b) developed a theoretical model of solar chimney power plants with variable chimney inlet-to-outlet area ratio based on compressible ideal gas assumptions, and studied the performance of the plants. Researchers focused on performing computational fluid dynamics (CFD) simulations of divergent-chimney solar power plants (DSPPs) based on the incompressible gas assumptions (Okada et al., 2015; Ohya et al., 2016; Koonsrisuk and Chitsomboon, 2006, 2013; Ming et al., 2013; Patel et al., 2014; Vieira et al., 2015; Lebbi et al., 2015; Hu et al., 2016, 2017). Due to the axisymmetric representation of the solar chimney power plants, the computational domain was simplified to a 5-degree pie shape of domain (Koonsrisuk and Chitsomboon, 2013) or a two-

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https://doi.org/10.1016/j.solener.2018.05.068
Received 18 October 2017; Received in revised form 16 May 2018; Accepted 19 May 2018
0038-092X/

Nomenclature

c_p	constant-pressure specific heat capacity (J/kg K)
g	gravitational acceleration, 9.81 (m/s^2)
H	height (m)
k	turbulent kinetic energy (J/kg)
P	power (W)
p	static pressure (Pa)
q	effective ground heat flux (W/m^2)
R	radius (m)
Ra	Rayleigh number
Re	Reynolds number
T	static temperature (K)
V	volumetric flow rate (m^3/s)
v	velocity (m/s)
z	random height above ground (m)

Acronyms

BAR	backflow area ratio
BLS	boundary layer separation
CFD	computational fluid dynamics
COAR	chimney outlet-to-inlet area ratio
CTR	collector temperature rise (°C)
DSPP	divergent-chimney solar power plant
EGHF	effective ground heat flux (W/m^2)
EPPRC	effective pressure potential recovery coefficient
MFR	mass flow rate (kg/s)
TPP	total pressure potential
2D	two-dimensional
3D	three-dimensional

Greek symbols

α	thermal diffusivity (m^2/s)
β	volumetric thermal expansion coefficient (1/K)
ε	turbulent dissipation rate (J/kg s)
χ	turbine pressure drop factor
η	efficiency
μ	dynamic viscosity (Pa s)
ξ	effective pressure potential recovery coefficient (EPPRC in abbreviation)
Δ	difference
ρ	density (kg/m^3)

Subscripts

c	chimney
gauge	gauge
max	maximum
r	roof
ref	reference
tg	turbine-generator
turb	turbine
0	collector inlet
1	chimney inlet
2	chimney outlet
∞	atmosphere

dimensional (2D), axisymmetric domain (Ming et al., 2013; Vieira et al., 2015; Lebbi et al., 2015; Hu et al., 2016, 2017). Whereas, three-dimensional (3D) domains were only used by Patel et al. (2014), Okada et al. (2015) and Ohya et al. (2016), respectively. Out of the studies, it was found out that divergent chimneys can enhance the power output effectively. Optimal divergence degrees (represented by divergence angles or COARs) for the power peak obtained in previous works were summarized in Table 1.

Large COAR can lead to the occurrence of the boundary layer separation (BLS) in the divergent chimneys. Koonsrisuk and Chitsomboon (2013) and Hu et al. (2016, 2017) thought the BLS in the chimneys and the resultant flow recirculation occurring near the chimney outlet can lead to a degradation in the performance of DSPPs. However, they have not analyzed the flow field affected by the BLS mainly due to their simplified models. Based on 3D simulations, Ohya et al. (2016) found the updraft was separated from the inside wall of the chimney. As observed from the results, the flow field is evidently nonaxisymmetric due to the BLS. In this case, 5-degree pie shape of domain or a 2D, axisymmetric domain was not suitable for simulating the DSPP when the BLS occurs. To date, the previous 3D simulation studies have focused on the effects of small COARs on the chimney or DSPP performance. The influencing mechanism of divergent shape especially with large COAR leading to the BLS on the chimney or DSPP performance has not been well understood and there exist few reports on the effects of large COARs and the resultant BLS based on 3D simulations.

In this paper, 3D numerical simulations of DSPPs are conducted, the flow in divergent chimney studied, the effects of COARs over a wide range of values on the DSPP performance examined and a new formula for the TPP of DSPPs developed where an effective pressure potential recovery coefficient (EPPRC) is introduced.

2. Mathematical model

The schematic of a divergent-chimney solar power plant is shown in Fig. 1. The flow in the plant is a typical buoyancy-driven flow. The Boussinesq approximation used in the field of buoyancy-driven flow is applicable for modeling the DSPP where the density difference in the air is small. The strength of the flow can be indicated by Rayleigh number (Ra) based on the Boussinesq approximation:

$$Ra = \frac{g\beta\Delta T H_r^3 \rho}{\mu\alpha} \tag{1}$$

where g is the gravitational acceleration (9.81 m/s^2), β is the volumetric thermal expansion coefficient, ΔT is the maximum difference of

Table 1
Optimal divergence angles obtained in previous works.

Optimal divergence angles (°)	Studied divergence angles (°) or COARs	Chimney height[a] (m)	Chimney radius (m)	References
53.7 for peak (COAR = 16)	COAR = 2, 4, 6, 8, 16 and 32	100	8	Koonsrisuk and Chitsomboon (2013)
2	angle = 1, 2 and 3	10	0.25 and 3	Patel et al. (2014)
12.7 (COAR = 3.52)	COAR = 1.76–7.04	10	0.125	Vieira et al. (2015)
4	angle = 2, 4 and 6	2[b]	0.32	Ohya et al. (2016)
13.7 (COAR = 10)	angle = 2, 3, 4, 6, 8, 10, 12 and 14	–	–	Hu et al. (2017)

[a] Not sure whether the chimney height includes the collector height/the chimney throat height or not.
[b] From the chimney inlet or throat to the outlet.