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Effect of Divergent Chimneys on the Performance of a Solar Chimney Power Plant

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Abstract

This paper numerically examined the performance of divergent chimneys in solar chimney power plants with two shape-controlling parameters, that is, the area ratio of the chimney exit over the entrance and the divergent angle. Compared with the conventional cylindrical chimneys, a higher power output in the divergent-chimney system could be achieved. This enhancement effect, however, increased first and then declined with increasing the area ratio or the divergent angle. Furthermore, subsequent parametric studies indicated that the area ratio and the divergent angle have different impacts on this enhancement effect: the area ratio may dominate the strength of the enhancement effect while the divergent angle may dominate the change rate of the enhancement effect along the varying shape-controlling parameters.

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Keywords: Solar chimney power plant; Divergent chimney; Area ratio; Divergent angle; CFD.

1. Introduction

A solar chimney power plant (SCPP) utilizes the air heated by sunlight to generate a buoyancy-driven updraft inside a gigantic chimney which can drive one or more wind turbines for power generation (as shown in Fig. 1). The chimney works as a thermal engine converting the internal energy of the air into mechanical energy, which is known as the stack (or chimney) effect. Hence, it is easy to understand that the chimney is one of the critical components in a SCPP. Earlier theoretical analysis revealed that both the height and the radius of the chimney have a critical role in determining the power output of SCPPs [1-2]. Furthermore, an optimal height-to-radius ratio of the chimney was claimed based on a 10MW SCPP with an 800m-high chimney [3]. At the same time, for commercial application of SCPPs of MW size, several designs of the chimney with heights varying from 500 to 1500 m were proposed in previous studies [4].

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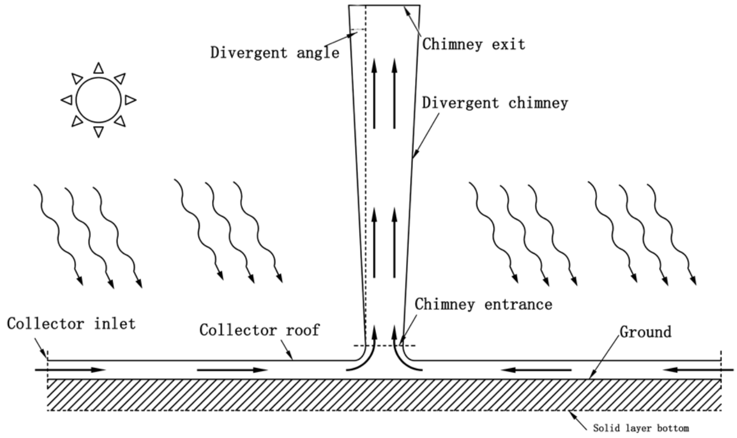

Fig. 1. A schematic of divergent solar chimney power plant.

In recent years, the chimney shape has been discussed from the perspective of system performance. Table 1 summarizes publications in which the cylindrical-chimney SCPPs was compared with the divergent-chimney SCPPs. Obviously, the divergent chimneys showed a better performance compared with the cylindrical chimneys in the numerical and the experimental outcomes. Besides, the numerical simulation indicated that the performance of the divergent solar chimney was governed by some shape-controlling parameters, that is, the Divergent Angle (DA) [6, 7] and the Area Ratio (AR) of the divergent chimney exit over its entrance [1, 5]. Notably, the power output of the divergent chimneys in Table 1 varied very much in different studies, which may be attributed to two issues: (1) authors used different dimensions of SCPPs for testing the divergent chimneys; and (2) different shape-controlling parameters were adopted for defining the shape of the chimneys. Nevertheless, based on the results of previous studies, the better performance of the divergent chimneys should be distinctly stated.

Table 1. Publications on the chimney shape impact on the performance of SCPPs.

Paper	System dimension	Chimney shape	Power output*
Koonsrisuk *et al.* (2013) [5]	Collector dia.: 200 m; chimney height: 100 m	Area ratio: 0.25 to 16.0	0.06 to 179.16
Ming *et al.* (2013) [3]	Collector dia.: 2000 m; chimney height: 800 m	Area ratio: 0.25 to 2.25	0.80 to 1.07
Patel *et al.* (2014) [6]	Collector dia.: 0.6 m; chimney height: 10 m	Divergent angle: 0° to 3°	1.0 to 9.8
Okada *et al.* (2015) [7]	Collector dia.: 0.66 m; chimney height: 0.40 m	Divergent angle: 4°	~3.0

* Normalized by the power output in the cylindrical-chimney SCPPs

The aim of this study is to numerically investigate the enhancement in the SCPP performance of using divergent chimneys through a serial of parametric studies. The discussed parameters included the dimensions of the SCPPs and two shape-controlling parameters, namely the Divergent Angle (DA) and the Area Ratio (AR). Three chimney heights were considered in the numerical study. For each chimney height, the shape of the divergent chimneys was further defined with the AR and the DA, respectively. By this, we supposed to discuss whether the variation in the performance of the divergent chimney along the two shape-controlling parameters would be independent of the chimney heights or not. On the other hand, the parametric studies may also reveal the dynamic features governed by the shape-controlling parameters that would benefit for optimizing the system power output.

2. Methodology

2.1. Physical configuration

For comparing the conventional cylindrical chimney with the divergent chimneys, the first large-scale prototype of SCPP in Manzanares of Spain was selected as the benchmark case. The operation status of this SCPP was reported by Haaf *et al.* [8], so that it is easy to evaluate the numerical results of the divergent chimneys with the performance of the practical system.

Referring to the Manzanares pilot, all the simulated cases have a consistent structure on the ground, that is, the solar collector that was in the radius of 122 m and the height of 1.8 m. Simultaneously, the divergent chimney was designed in terms of three topics: (1) the enhancement effect of divergent chimneys; (2) performance governed by the area ratio; (3) performance governed by the divergent angle. Detailed configurations are shown in Table 2. For each group of the divergent chimneys, there was a corresponding benchmark case that has a cylindrical chimney with the same entrance radius and height.

Table 2. Configurations of the simulated chimneys.

Topic	Group	Height	Entrance radius	Shape-controlling parameter
Enhancement effect	1	200 m	5 m	Area ratio: 1, 1.25, 1.5, 2, 3, … …, 31, 32.
Area ratio impact	2	100 m	5 m	Area ratio: 1, 4, 8, 10, 16, 32.
	3	200 m	5 m	Area ratio: 1, 4, 8, 10, 16, 32.
	4	300 m	5 m	Area ratio: 1, 4, 8, 10, 16, 32.
Divergent angle impact	5	100 m	5 m	Divergent angle: 0.0°, 1.5°, 2.7°, 3.2°, 4.4°, 6.8°.
	6	200 m	5 m	Divergent angle: 0.0°, 1.5°, 2.7°, 3.2°, 4.4°, 6.8°.
	7	300 m	5 m	Divergent angle: 0.0°, 1.5°, 2.7°, 3.2°, 4.4°, 6.8°.

2.2. Numerical model

The air movement inside the 200m-high SCPP was a buoyancy-driven turbulent flow [1]. Thus, the 2-equation k-ε turbulence model was implemented for obtaining numerical results from the commercial CFD software, ANSYS FLUENT 14.0. Koonsrisuk [5] observed a degradation in the performance of divergent chimneys that might be caused by the boundary layer separation near the chimney wall (similar results was obtained in Section 3.1). Hence, the Realizable k-ε turbulence model was used in our simulation which has better performance with flow involving separations [9]. The near-wall treatment adopted the enhanced wall treatment for the separation issue as well. The buoyant effect was only considered in the body force term in the Navier-Stokes equations by using the Boussinesq Approximation. The potential power output of the simulated SCPPs was estimated by a mathematical model [6]:

$$P_{out} = x \cdot (1-x)^{0.5} \cdot \eta_t \cdot \Delta p \cdot m / \rho_0 \tag{1}$$

Given $x = 2/3$, we obtained the potential power output of the system [5]. The turbine generator efficiency, η_t, was set to 80%. The driving potential, Δp, was quantitatively equal to the absolute value of gauge pressure at the chimney entrance.

Table 3 shows the settings at the critical boundaries of the flow domain. To simplify the computation, the 3D structure of SCPP was converted into a 2D asymmetric structure by selecting the centerline of the chimney as the symmetry axis. Structured grid was used in the simulation. As enhanced wall treatment was implemented, the near-wall grid was further refined for acquiring the y+ of ~5. With the tests on grid independence, the cell quantity in the grid reached ~500,000. The second-order schemes and the SIMPLE algorithm were utilized for the numerical solution.

The 200m-high cylindrical chimney case was first evaluated with the record of the Manzanares SCPP for examining the validity of our numerical model. The calculated velocity at the chimney entrance was 16.4 m/s, which is 7.4% higher than the measurement (~15 m/s). This overestimation in velocity may be attributed to the higher air temperature rise (21.8 K V.S. 20 K) relative to the practical system. Considering that the uncertainties in the soil properties and the adiabatic assumption at the solid boundaries may contribute to the overestimation, this error should be acceptable, and thus the model was valid for the subsequent study on the divergent chimneys.

Table 3 Boundary conditions of the numerical simulations.

Surface	Type	Value
Collector roof	Wall	Mixed; T_{ext} = 302 K, h_s = 10 W/m^{2}K, ε_{ext} = 0.89
Ground	Wall	Coupled; Q = 7200 kW/m^3; $D_{thickness}$ = 0.0001 m
Inlet of collector	Pressure-inlet	T_{ext} = 302 K, p_{gauge} = 0 Pa
exit of chimney	Pressure-outlet	T_{ext} = 300 K, p_{gauge} = 0 Pa

3. Results and discussion

3.1. Enhancement effect of divergent chimneys on SCPP

The performance of the divergent chimneys was examined by the 1st-group configurations, that is, the 200m-high SCPPs within a range of the ARs from 1.25 to 32. The numerical results are normalized by the cylindrical benchmark case (as shown in Fig. 2). Obviously, a higher power output could be achieved in the divergent chimneys. The divergent chimneys have an enhancement effect on the performance of SCPPs. However, the power output of divergent chimneys first increases until AR = 10 at which the peak power output is 13.5 times of that of the benchmark case. After that, the power output declines with further increasing the AR, which may be caused by the separation of the boundary layers at the chimney walls [5]. These changes should be attributed to the analogous tendencies in the driving potential and the mass flow rate which were also observed in other simulations [5, 6]. Meanwhile, it can be inferred that similar tendency should be observed along the DAs as the AR can be converted into the DA with the chimney height.

Notably, the temperature rise, ΔT, in the divergent systems has the smallest variation compared with other parameters. ΔT reaches 21.4 K in the cylindrical chimney while it is ~12.0 K in majority of the divergent cases. Even the lower temperature is meant to decrease the driving potential, the driving potential in the divergent chimneys is larger due to the pressure recovery mechanism of the diffusor-like shape.

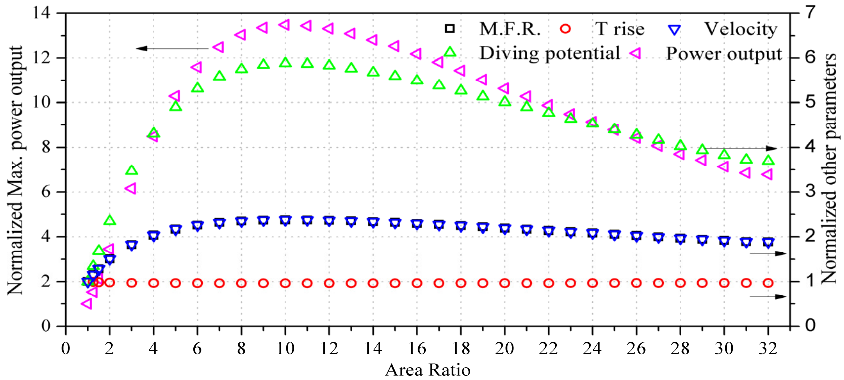

Fig. 2. Normalized results of the simulated divergent chimneys with area ratio from 1.25 to 32.

3.2. Performance of divergent chimneys governed by shape-controlling parameters

Figure 3(a) illustrates the normalized power outputs in three groups of the divergent chimneys that have different heights but the same ARs (Groups 2 to 4 in Table 2). Significantly, there is not a consistent tendency in power output along the ARs in the three groups. Relative to the 200m-chimney group, the peak power output is higher (18.0) and attained at a larger AR (=16) in the 300m-chimney group while the degradation of power output is much slower as well. In contrast, poorer performance is observed in the 100m-chimney group. The highest normalized power output is only 7.9 at AR = 4. With AR > 4, the power output decreases much faster than the other two groups and consequently the case of AR = 32 even achieves a lower performance than the cylindrical benchmark case.

Figure 3(b) illustrates the normalized power outputs in three groups of divergent chimneys that have different heights but the same DAs (Groups 5 to 7 in Table 2). The change rates of the normalized power output in the three groups are fairly close. For instance, the changes of the output in 100m-, 200m- and 300m-chimney group are 3.3, 4.6 and 4.8 when the DA increases from 1.5° to 2.7°. The power output declines a little faster in the 300m-chimney from 4.4° to 6.8° but the agreement on the decreasing rate is still better than that in Fig. 3(a). Meanwhile, the peak power output may locate in the same range of 3.2° to 4.4 ° in all the three groups controlled by the DAs, which also indicates a similar change rate of the three groups.

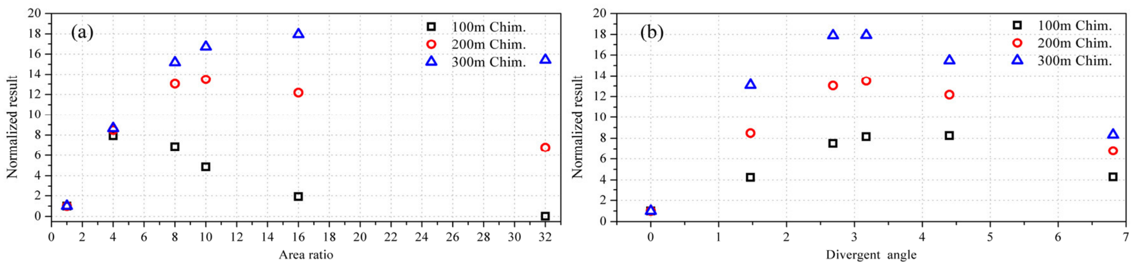

Fig. 3. Normalized power output of the divergent chimneys with various (a) area ratios and (b) divergent angles.

The results in Fig. 3(b) indicated that the DA could control the change rate of the enhancement effect of the divergent chimneys on the performance of SCPPs. With this point, we can further explain why the degradation speed varies significantly in Fig. 3(a). Given a constant AR, the taller chimneys had smaller divergent angles. For instance, the cases of AR = 4, the DAs of the 100m-, 200m- and 300m-high chimney are 1.25°, 0.61° and 0.4°, respectively. Correspondingly, the enhancement effect of the 100m-high chimneys starts to degrade since AR > 4.0 while taller chimneys have a slower degradation in the performance.

On the other hand, with the similar performance of the cases of AR = 4 in Fig. 3(a), we also inferred that the AR may determine the strength of the enhancement effect in power output. If the DA is fixed, a taller chimney has a larger AR. Therefore, the 300m-high chimneys (having larger ARs) have the highest normalized power output while the 100m-high cases have the lowest in Fig. 3(b).

4. Conclusion

In this study, we have numerically examined the performance of divergent chimneys in SCPPs with two shape-controlling parameters, that is, the AR and the DA. Higher power output has been observed in the simulation for the chimneys with ARs from 1.25 to 32, which demonstrated an enhancement effect of the divergent chimneys on the performance of SCPPs. Furthermore, this enhancement effect shows a parabolic trend with increasing AR (or DA).

Different impacts of ARs and DAs on the enhancement effect have been revealed by the parametric studies with multiple chimney heights. The results indicate that the AR determines the strength of the enhancement effect while the DA controls the change rate in the parabolic trend. Notably, the two impacts co-existed in the divergent-chimney systems, and thus, if we want to obtain a replicable performance of the divergent chimneys for different scales of SCPPs, a consistency in the overall geometry of the chimney, that is, the similarity in geometry is required. Subsequent works on divergent chimneys with similar geometry are currently undertaken.

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Biography

Prof. Dennis Y.C. Leung received his Ph.D in 1988 from the Department of Mechanical Engineering at the University of Hong Kong. He joined the same department in 1993 and is now a full professor of the department specializing in renewable energy and energy conservation. He has published more than 400 articles including 210+ peer reviewed SCI journal papers. Prof. Leung is one of the top 1% highly cited scholars in energy field from 2010 to 2015.