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Effect of guide wall on the potential of a solar chimney power plant

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ABSTRACT

A solar chimney power plant (SCPP) converts solar thermal energy into electricity by generating a buoyant flow in a chimney. To assist the air flow in shifting its direction from horizontal to vertical, a guide wall (GW) is usually set in the collector-to-chimney transition region. The primary objective of this study is to examine the impact of the GW geometry on the power output of a SCPP. A reduction in mass flow rate after adding a GW in the system was observed in a small-scale experimental prototype. Numerical simulations on a large-scale SCPP further found that the mass flow rate was linearly and inversely proportional to the increase of GW height. The driving force, however, nonlinearly increased with increasing the GW height. Subsequently, the potential maximum power output, which was mainly governed by the driving force, increased with increasing the GW height. Furthermore, a divergent-chimney system which can improve the performance of SCPPs had different reactions with the geometry of GWs compared with a cylindrical-chimney system. Under the optimal GW configuration, the power output of the SCPP increased by ~40% in a cylindrical-chimney system and by ~9.0% in a divergent-chimney system with respect to the system without a guide wall.

1. Introduction

A solar chimney power plant (SCPP) is a system that converts solar energy into electricity with a chimney, a greenhouse-like solar insolation collector and a wind turbine. The system utilizes the greenhouse effect in the collector to generate a buoyant updraft in the chimney which can drive wind turbines for electricity generation. SCPP has advantages in its low cost of construction and operation, and providing renewable energy to communities without aggravating environmental pollution and intensifying climate change. SCPP is believed to have a high application potential in developing countries with large available lands and abundant solar insolation [1].

Studying the impact of different components in a solar chimney is a primary task for designing a solar chimney power plant. Haaf et al. [2,3] indicated that the critical roles of chimney height and air temperature in determining the system power output. Pasumarthi et al. [4,5] established a mathematical model for estimating the heat transferring process and the air flow in a SCPP. They reported that system efficiency of the SCPP was determined by the chimney height as well as the solar insolation. Dos S. Bernardes et al. [6] presented an analysis of a solar chimney under natural laminar convection condition and emphasized the effects of geometric characteristics on the performance of the SCPP. Dai et al. [7] reported that the increasing trend of system performance along the modification in dimensions should be faster in small-scale systems than that in large-scale systems. Pretorices [8] revealed that the collector diameter can also determine the power output of a SCPP and optimized the structure of collector with a multiple-layer roof. Shahreza et al. [9] reported an innovative SCPP in which an air tank coupled with two intensifiers replaced the collector and successfully enlarged the heat flux to the working air. Nia et al. [10] introduced the passive flow control approach by locating a set of obstacles at the ground surface for adjusting the heat transfer process in the thermal collector. A theoretical model established by Ming et al. [11] comprehensively considered the impact of different parameters (i.e. collector diameter, chimney height, solar radiation and other ambient conditions) on the system's power output. Koonsrisuk et al. [12,13] extended a mathematical model for a new SCPP with slope-collector and investigated the impact of flow area changes in both the collector and the chimney on the system's potential. The later study found a remarkable enhancement in the potential of SCPP with divergent chimneys (as shown in Fig. 1). Von

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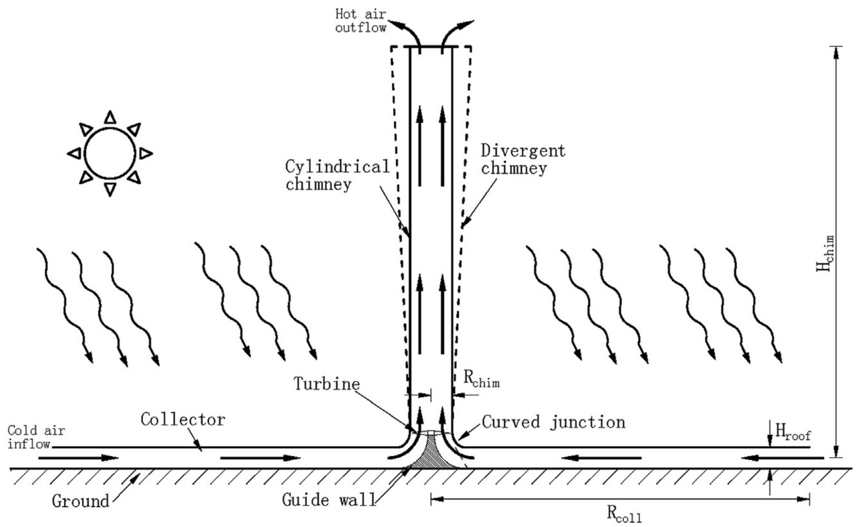

Fig. 1. A schematic of solar chimney (assembled with a cylindrical or a divergent chimney) with a guide wall subset (in shadow) located at the chimney entrance and holding the blades of a turbine.

Backstrom [14] implied that a diffusor-like flow channel for the updraft would lower the kinetic energy loss and thus improve the system power output. OKada et al. [15] reported a similar improvement in a small-scale divergent chimney prototype. Patel [16] examined multiple opening angles of divergent chimney and found that the power output cannot be enlarged infinitely with increasing wall angles. On the other hand, Ming et al. [17] presented a negative attitude towards the divergent chimneys, arguing that although there would be slight improvement, the additional difficulties and cost in construction of the divergent chimneys do not justify its contribution as compared with conventional cylindrical chimneys.

The guide wall (GW) is another prominent subset located at the collector-to-chimney transition region as it can be used to shift the horizontal air flow to the updraft and be the holder of a turbine for power generation (as shown in Fig. 1). Several previous studies have reported this subset would have influence on the SCPP's performance. Dos S. Bernarders [6] emphasized the care for designing the collector-to-chimney region after examining the flow with and without a guide wall or a curved junction. Inlet guide vanes (IGVs) and guide wall were all built but less attention was paid to the later component in the experiments conducted by Van Backstorm et al. [18]. Ming et al. [11] compared the flow in the collector-to-chimney domain before and after adding a guide wall subset and found that the subset was capable of modifying the velocity of the flow with ~18% which might significantly improve the potential of the SCPP. However, there was only one configuration of the GW examined in their study. Hence, the knowledge on the impact of the GW geometry on system performance is still limited.

Considering that the presence of GWs may have significant impact on SCPP's performance but evaluation of this issue is superficial and ambiguous, this study aimed to investigate on the role of GW in a SCPP more comprehensively through examining the flow under the influence of GWs with variant heights and radii. This can help us better understand the characteristics of the local flow in the collector-to-chimney transition domain with GWs. For these purposes, this study was mainly conducted by numerical simulation approach, while a small-scale experimental prototype was used to verify the mass flow rate degradation observed in simulations. Furthermore, a remarkable improvement in the flow velocity in divergent chimneys was reported in several articles. Thus, both the groups of a cylindrical chimney and a divergent chimney coupled with different GWs will be studied as different reactions from the divergent-chimney SCPP compared with the cylindrical one with varying GW configurations would be expected.

2. Methodology

2.1. Experiments in a small-scale prototype

A small-scale prototype of the SCPP was built in the laboratory for investigating the chimney shape impact on the performance of the SCPP (as shown in Fig. 2). A moveable guide wall was added into the prototype initially aimed for reducing the loss caused by the flow direction shifting. As more than suppressing the loss, the guide wall may have further contribution in improving the system potential as reported by Ming et al. [11], the moveable wall provided chances to examine preliminarily the variation in the buoyant flow caused by the GW subset: one additional group of experiments without the GW was conducted for the small-scale prototype and compared with the earlier experiments with the GW. The following sections presented a brief introduction on the configurations of the experiments. More details can be found elsewhere.

2.1.1. Geometry of prototype

The small-scale prototype consisted of two fundamental components of a SCPP, that is, the collector and the chimney. A transparent chamber of 3 m (L) x 3 m (W) x 0.1 m (H) composed of steel frames and organic glass, was used as the thermal collector. Two types of chimney, made in PVC material, were used. The two chimneys were all 2 m high and 0.1 m in their entrance diameter while the exit diameter of the divergent chimney was set to 0.2 m. As to the heat source, we utilized an electrical infra-radiation film heater instead of direct solar radiation in the prototype in order to keep the input heat consistent for different cases. The film heater, with a fixed total power of 1520 W, overlaid the bottom of the collector and covered by several thin aluminum sheets for producing a more uniform heating surface. The moveable GW, placed below the chimney entrance, was 0.15 m high and 0.4 m in its base width.

2.1.2. Data measurement

Two parameters, that is, the air temperature and the flow