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# Mathematical modelling of the performance of a solar chimney power plant with divergent chimneys

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**Abstract**

Chimney is a critical component influencing the performance of a Solar Chimney Power Plant (SCPP). An enhancement on the power output of SCPPs with divergent chimneys was observed in a number of experimental and numerical studies using Computational Fluid Dynamic (CFD) models. In this paper, a mathematical model was established to analyse the hydrodynamic features of a series of divergent chimneys in a SCPP. The importance of estimating the loss from the potential diffuser stall in divergent chimneys was especially discussed in this study. The result of the mathematical model was compared with those of CFD simulation to evaluate the validity and the performance of this present model. Subsequently, parametric studies were conducted by using this mathematical model. The performance of divergent SCPPs was found to be governed by the area ratio of chimney entrance over its exit. The result further indicated that the optimal area ratio of divergent chimneys was different when the chimney height varied from 100m to 300m. Besides, several shorter divergent SCPPs showed a comparable power output as the cylindrical SCPPs with taller chimneys, which demonstrated an outstanding advantage of divergent SCPPs for commercial application.

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*Keywords:* Solar chimney power plant; Mathematical model; Divergent chimney; Area ratio; Diffusor stall.

## 1. Introduction

Chimney is a critical component of a Solar Chimney Power Plant (SCPP). It allows warm air from a solar collector move upwards to drive a wind turbine, converting the internal energy of the air into mechanical energy. The shape of

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chimney is usually cylindrical in most studies [1, 2]. Based on this, the hydrodynamic characteristics of cylindrical chimneys were analyzed comprehensively. Multiple studies revealed that chimney height and diameter can govern the power output of the cylindrical SCPP [3-5]. Furthermore, the optimal ratio of height / diameter was also discussed by Ming *et al* [5].

Recently, divergent chimney has been adopted as an alternative for SCPPs (as shown in Fig. 1). Besides, a remarkable improvement on the power output of the SCPPs with divergent chimneys was reported in several publications [5-8]. Interestingly, there is a large deviation in the performance of the divergent SCPPs in different studies: after normalizing the power output of the divergent SCPPs with that of the equal-size cylindrical SCPPs, the dimensionless output varied from 0.7 to 160 [5-8].

The history of studying divergent SCPPs is much shorter than that of the conventional cylindrical SCPPs. Compared with the experimental, theoretical and numerical studies on the cylindrical SCPPs, the divergent SCPPs were mainly examined by numerical simulations with Computational Fluid Dynamics (CFD) models. Indeed, CFD simulation is a powerful tool to analyse the thermo- and hydro- dynamic features of SCPPs. It requires, however, large computing resources and is time-consuming. For the sake of a theoretical analysis on the performance, this study aimed to establish a one-dimensional mathematical model for divergent SCPPs. This model included the formulas for calculating the expansion loss in divergent chimneys, which is seldom considered in previous mathematical models. With this model, we further examined multiple configurations of the divergent SCPP. By this, we hope to have a better understanding on the hydrodynamic features of the divergent chimney and promote the future commercial application of the divergent SCPP.

**Nomenclature**

| | | | | |
|---|---|---|---|---|
| A | area, $m^2$ | | Greek letters | |
| $c_p$ | specific heat of air, J/kg.K | | $\alpha$ | divergent angle of a chimney, degree |
| D | hydraulic diameter, m | | $\beta$ | thermal expansion coefficient of air, $k^{-1}$ |
| f | Darcy friction factor | | $\delta$ | pipe diameter ratio, $D_{in}$ / $D_{out}$ |
| L | length, m | | $\varepsilon$ | loss factor |
| g | gravitational acceleration, $m/s^2$ | | $\rho$ | air density, $kg/m^3$ |
| H | height, m | | $\eta_t$ | turbine generator efficiency |
| $\Delta$H | difference in height, m | | Subscripts | |
| $\dot{m}$ | mass flow rate, kg/s | | 0 | ambient condition |
| p | pressure, Pa | | 1 | entrance of solar collector |
| $\Delta$p | driving potential of a SCPP, Pa | | 2 | exit of solar collector |
| P | power output, kW | | 3 | entrance of chimney |
| q | heat flux into air, $w/m^2$ | | 4 | exit of chimney |
| R | radius, m | | ij | from Section i to Section j |
| T | temperature, K | | a | air |
| $\Delta$T | temperature rise after solar collector, K | | chim | chimney |
| V | velocity, m/s | | coll | solar collector |

## 2. Mathematical model

Some fundamental assumptions of the one-dimensional mathematical model presented are as follows:

- The flow in the SCPP is homogeneous from each direction. After the collector exit, the flow is adiabatic throughout the rest flow domain.
- The variation of air density due to the heating process in the solar collector is modelled by Boussinesq Approximation as shown below
$$\rho_a = \rho_0 - \rho_0 \cdot \beta \cdot (T_a - T_0) \quad (1)$$
- After the solar collector, the air density is assumed to be constant throughout the rest flow domain. As the

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