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Numerical Modelling of the Compressible Airflow in a Solar-Waste-Heat Chimney Power Plant

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Abstract

A Solar-Waste-Heat Chimney Power Plant (SWHCPP) is similar to a solar chimney power plant (SCPP) but uses both the solar insolation and the waste heat from industries to heat the working air. To model the variation of the air density due to the high temperature rise, a 3D numerical model, in which the air density is modelled by the ideal gas law, is established for the SWHCPP in this study. Comparing with the conventional CFD model and the experimental benchmarks, the new model can suppress the overestimation in the simulated results and generally indicates an acceptable accuracy in the performance determination of the SWHCPP. In addition, a method of directly integrating the air density profiles captures the right variation in the system performance during the numerical experiment with multiple flue gas injection flow rates and it would be more suitable to be used for the modelling research about the SWHCPP. The simulations indicated that more than 50% higher power output was achieved due to multiple-stage heating with the waste heat while the existence of the waste heat slightly influenced the absorption of solar insolation.

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Keywords: Solar chimney; Waste heat recovery; Compressible airflow; Ideal gas law; CFD.

1. Introduction

Solar Chimney Power Plant (SCPP) uses solar insolation to generate a buoyancy-driven updraft in a chimney driving a wind turbine for electricity generation. In recent years, this system has been developed with the idea of

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coupling with the waste heat sources from industries to increase the temperature of the working air and thus improving the power output. For instance, Al-Kayiem et al. [1,2] and Chikere et al. [3] channeled hot flue gas into some tubes in or underneath the solar collector so that the working air was simultaneously heated by the solar insolation and the flue gas. Zandian et al. [4] and Zou et al. [5] put heat exchangers containing the hot recycling water from a thermal power plant at the solar collector entrance. The working air was firstly warmed by the water and then kept increasing its temperature when passing through the collector. In the design of Ghorbani at el. [6], both recycling water and flue gas were used: heat exchangers were located at the collector entrance and flue gas was injected into the chimney and mixed with the warm air from the collector. Positive outcomes were widely achieved in the studies above: the driving potential of the system was strengthened by the solar-waste-heat hybrid mode.

The studies, so far, have mainly utilized numerical simulations to illustrate the thermal-hydraulic dynamic behaviors of the Solar-Waste-Heat Chimney Power Plant (SWHCPP) and the numerical models adopted were much similar to the SCPP because the SWHCPP shares the same fundamental mechanism with the SCPP. However, a critical issue that attention should be drawn attention to is that, the incompressible Boussinesq approximation, which is widely used in the simulation on SCPPs, has a limitation on the temperature rise (ΔT) in the system, which is $\beta \cdot \Delta T << 1$ [7], where β is the thermal expansion coefficient of the air. However, the temperature rise in a SWHCPP would be higher than in a SCPP, especially under the scenario of injecting the flue gas into the chimney. Hence, the conventional models with the Boussinesq approximation might increase errors in the numerical outcomes. In this paper, we are going to introduce a numerical model in which the compressible air flow is simulated by using the ideal gas law to calculate the air density instead of any approximations. So that, the robustness of the model of the SWHCPP is supposed to be enhanced for a much wider ΔT range. Moreover, the simulating performance of the new compressible-air model was compared to the incompressible Boussinesq one to discuss the importance of the compressibility of the working air. Simultaneously, a novel method of estimating the driving potential of a SWHCPP is also demonstrated and found to be more suitable for the scenario of SWHCPPs.

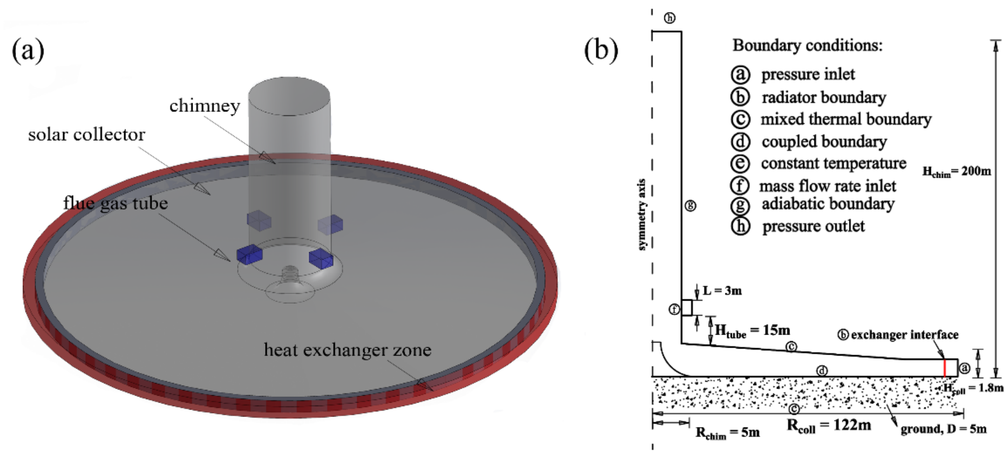

Fig. 1. The SWHCPP under simulation. (a) Schematic diagram, (b) geometry and boundary conditions in the model.

2. Methodology

2.1. The physical model of the SWHCPP

In this study, the SWHCPP used both hot recycling water and hot flue gas as the waste heat sources. Referring to the design of Ghorbani at el. [6], the heat exchangers containing the water were set in front of the solar collector but were simplified as an interface without any physical depth inside the flow domain as suggested by Zandian et al. [4], Ghorbani at el. [6] and Zou et al. [8]. The flue gas was injected directly into the chimney through four square tubes on the chimney wall. On the other hand, the solar collector and the chimney were kept consistent to the SCPP prototype