An enhanced heat collector design and numerical simulation for solar chimney power plant

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Abstract. The solar chimney power plant (SCPP) is a promising renewable energy technology to address energy security and CO₂ mitigation problems. To improve efficiency of energy conversion from solar radiation to electricity, this article changes conventional horizontal heat collector and proposes a partial inclined and convergent collector for SCPP. Utilizing $k-\varepsilon$ turbulence model and computational fluid dynamics (CFD) method, this article implemented a series of numerical simulations to explore the thermodynamic characteristics of airflow in SCPP and power generation efficiency in a way of changing value of design parameters, such as collector convergent angle, slope length and collector radius. The results reveal that, increasing these parameters will decrease airflow pressure, increase airflow velocity and temperature around the chimney base, hence will improve power generation efficiency. Comparing the enhanced convergent collector with conventional horizontal one, the former can improve SCPP performance and energy transformation efficiency.

1. Introduction

With energy security and greenhouse gases (GHGs) mitigation problems[1] being growing concern worldwide, solar chimney power plant (SCPP) is becoming an interesting technology for researchers and practitioners. As a kind of renewable energy generation technology, SCPP utilizes sunlight and buoyancy of heated air to produce electricity[2]. Generally, SCPP is composed of heat collector, chimney pipe, turbine and absorber. The collector usually covers large ground area to collect heat from sunlight, therefore forms gradient air pressure in its covered area to lead horizontal airflow from ambient to center. Utilizing chimney pipe effect to lead vertical airflow, high speed wind propels turbine to generate electricity[3].

Heat collector design can significantly affect the performance of SCPP. Conventional collector roof is horizontally designed and covered by transparent materials, such as glass or plastic membranes[4]. Koonsrisuk[5] does a numerical experiment on a horizontal collector cover and a sloped one for SCPP, the results support that the latter performs better than the former in thermodynamic effect. Gholamalizdeh and Kim[6] employs the computational fluid dynamics (CFD) model to simulate the Manzanares SCPP with an alternative collector of inclination roof, and suggest that this collector design will affect the convection pattern. Aurybi et al.[7] propose an additional layer design between collector roof and ground to save heat and smooth power generation at night and day, their reports show that this installation can raise 23.1% of power generation efficiency.

Chimney geometric shape is also an important factor to influence power generation of SCPP. Ayadi et al.[8] explore features of airflow in SCPP affected by chimney height and support that this parameter design can significantly influence velocity, pressure, temperature and turbulence of airflow.
To further explore the performance of chimney shape, Hu et al.\cite{9} design a divergent tube chimney and corresponding numerical simulations suggest that widening divergent angle increases first and then declines power generation.

Beyond SCPP design factors, solar radiant intensity, determined by local environment conditions, still acts as a key role for evaluating performance of SCPP. Xu et al.\cite{10} does a numerical simulation to build the relationship between solar irradiance and power generation for SCPP. Bernardes and Weinrebe\cite{11} simulate the effect of ambient condition and geometric parameter on power generation, hence support that collector’s optical property and its radius have a significant influence on efficiency of power generation. Through investigating solar irradiance distribution across China, Cao et al.\cite{12} suggest that horizontal collector for SCPP is suitable for southeastern China while sloped collector is more suitable for northwestern China to enhance energy conversion efficiency.

In literature, there also have many articles focusing on the integrated effect of design factors and environment conditions for SCPP. El-Ghonemy\cite{13} does an evaluation on the performance of pressure drop across the turbine, airflow velocity and temperature, power output for a specific SCPP with chimney height 200 m and diameter 10 m, collector diameter 500 m and height 2.5 m, as well as solar radiant intensity 800 w/m$^2$. Based on $k - \varepsilon$ turbulence model, Toghraie et al.\cite{14} hold that power generation for a conventional horizontal collector SCPP has a positive relationship with chimney height and collector radius but a negative relationship with collector height. Generally, the main factors affecting SCPP power generation efficiency contain solar irradiance, heat collector radius and geometric shape, materials of collector cover and absorber plate, chimney pipe height and radius, as well as turbine head design\cite{15-16}.

In line with literature review, many researches on SCPP set collector roof as horizontal plane. Although a few researches explore an inclined roof design, however they almost all focus on a divergent collector. To improve SCPP energy conversion efficiency, this article proposes an enhanced heat collector for SCPP which is characterized as a partial inclined and convergent roof, thereafter utilizes CFD model to simulate airflow features and power generation efficiency to validate its effectiveness.

The rest of this article is organized as, section 2 is the partial convergent collector design for SCPP. Section 3 provides a detail on the CFD numerical simulation model. Section 4 explains the results of simulation, of which thermodynamic features of airflow in SCPP and power generation efficiency are discussed. Finally, a brief conclusion is summarized in section 5.

2. Enhanced heat collector design
Contrast to conventional horizontal heat collector for SCPP\cite{4-5}, this study proposed a partial inclined and convergent collector design to enhance energy conversion efficiency. As seen in figure 1.

![Figure 1. The enhanced collector design for solar chimney power plant.](image)

To explore airflow thermodynamic characteristics and energy transformation efficiency for the enhanced collector design in a numerical simulation and comparison way, this study configures heat collector diameter and height respective equal to 1250 m and 25 m, chimney height and diameter each equal to 200 m and 15 m, collector roof convergent angle and slope length equal to $2^\circ$ and 573 m. The data process is fulfilled in Matlab R2014 environment.
3. Numerical simulation

3.1. Mathematical model

In theory, airflow is regulated by equations of the Reynolds Averaging Navier-Stokes model [17]. The continuity equation, momentum equations, energy equations of turbulent kinetic and its dissipation rate are formed in the cylindrical coordinate [6, 18].

The continuity equation can be written as,

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial z} + \frac{1}{r} \frac{\partial (r \rho u)}{\partial r} = 0$$

Where \( r \) represents the radial coordinate, \( z \) represents the axial coordinate, \( \rho \) signs density of air, \( u \) denotes velocity in the radial direction.

The energy equation can be written as,

$$\frac{\partial (\rho T)}{\partial t} + \frac{\partial (\rho u T)}{\partial z} + \frac{1}{r} \frac{\partial (r \rho u T)}{\partial r} = \frac{\partial}{\partial z} \left( \rho C_p \frac{\partial T}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \rho C_p \frac{\partial T}{\partial r} \right)$$

Where \( C_p \) denotes specific heat capacity of air, \( T \) signs temperature, \( \lambda \) indicates thermal conductivity and \( v \) signs air velocity.

The momentum equations can be written as,

$$\frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho u^2)}{\partial z} + \frac{1}{r} \frac{\partial (r \rho u^2)}{\partial r} = \frac{\partial}{\partial z} \left( \rho \mu \frac{\partial u}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \rho \mu \frac{\partial u}{\partial r} \right) - \frac{1}{\rho} \frac{\partial P}{\partial z}$$

$$\frac{\partial (\rho v)}{\partial t} + \frac{\partial (\rho v w)}{\partial z} + \frac{1}{r} \frac{\partial (r \rho v w)}{\partial r} = \frac{\partial}{\partial z} \left( \rho \mu \frac{\partial v}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \rho \mu \frac{\partial v}{\partial r} \right) - \frac{1}{\rho} \frac{\partial P}{\partial r}$$

Where \( \mu \) represents dynamic viscosity, \( \rho_0 \) signs reference density and \( P \) signs pressure, respectively.

The standard \( \varepsilon - k \) turbulence model equations for turbulent kinetic energy and dissipation rate of turbulent kinetic energy are given below,

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho ku)}{\partial z} + \frac{1}{r} \frac{\partial (r \rho ku)}{\partial r} = \frac{\partial}{\partial z} \left( \rho \mu \frac{k}{\sigma_k} \frac{\partial k}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \rho \mu \frac{k}{\sigma_k} \frac{\partial k}{\partial r} \right) - C_{k1} \rho \varepsilon + C_{k2} \frac{\varepsilon}{k}$$

$$\frac{\partial (\rho e)}{\partial t} + \frac{\partial (\rho e u)}{\partial z} + \frac{1}{r} \frac{\partial (r \rho e u)}{\partial r} = \frac{\partial}{\partial z} \left( \rho \mu \frac{e}{\sigma_e} \frac{\partial e}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \rho \mu \frac{e}{\sigma_e} \frac{\partial e}{\partial r} \right) - C_{e1} \rho \varepsilon + C_{e2} \frac{\varepsilon}{k}$$

Where \( \mu \) denotes turbulent viscosity, \( \sigma_e \) and \( \sigma_k \) each represent turbulent Prandtl numbers for \( \varepsilon \) and \( k \).

Generally, constant parameters \( C_{k1}, C_{k2}, \varepsilon \) and \( \sigma_k \) in standard \( k - \varepsilon \) turbulence model are configured as 1.44, 1.92, 1.2 and 1.0, respectively.

The efficiency of solar chimney power plant can be calculated as,

$$\eta_{collect} = \frac{\phi_{collect} \cdot \phi_{chimney} \cdot \phi_{turbine} \cdot \phi_{generator}}{\phi_{chimney}}$$

$$\eta_{collect} = \frac{Q_{collect}}{Q_{chimney}} = \frac{\dot{m}C_p \Delta T}{\dot{m}C_p \Delta T}$$

$$\eta_{chimney} = \frac{\Delta P_i}{\dot{m}C_p \Delta T} = \frac{gH}{T_0C_p}$$

Where, \( \eta_{collect} \), \( \phi_{collect} \), \( \phi_{chimney} \), \( \phi_{turbine} \), and \( \phi_{generator} \) each denotes efficiency of solar power plant, heat collector, chimney, turbine, and generator. \( Q \) and \( Q_i \) respective signs heat outflow specific rate and solar energy input. \( \dot{m} = \rho_{chimney} A_{chimney} \) is mass flow in chimney. \( \Delta T \) is air temperature incremental between collector inflow and outflow. \( \Delta P_i \) is pressure difference between chimney bottom and chimney outlet. The reached velocity by free convection currents is calculated by \( \nu_{chimney} = \sqrt{2gH \Delta T / T_0} \).

Without turbine, power embodied in airflow can be calculated by \( \Delta P_i = \dot{m} \nu_{chimney}^2 / 2 \).
3.2. **Boundary conditions**
The chimney axis is defined as symmetry axis of the cylindrical coordinate. The collector inlet and chimney outlet are respectively set as the pressure inlet and outlet, both of which are equal to standard atmospheric pressure 101.3 KPa. The heat collector roof is configured as a transparent polymer film wall and solar energy radiant is 700 W/m². The chimney inner surface is composed of a non-transparent polyvinyl chloride pipe, hence cannot receive any solar energy radiant.

4. **Results and discussion**
In line with the configured SCPP scale, thermodynamic features of airflow in the enhanced SCPP and its energy conversion efficiency are reported as follows.

4.1. **Pressure**
Pressure distribution in chimney pipe direction presents an upward trend and reaches standard atmospheric pressure at the top. The same phenomenon still exists along collector radius direction, but decreases very slowly. The minimum relative pressure is found at the bottom of chimney. Concretely, an increase of collector convergent angle, inclination slope, collector radius causes a decrease of airflow pressure around the chimney base. Comparing the enhanced convergent collector to conventional horizontal collector, the former has lower static pressure at chimney bottom area.

4.2. **Airflow velocity**
The maximum airflow velocity is found at the inlet of chimney. Airflow velocity decreases from chimney bottom to its outlet, the same is also true for airflow velocity along the collector radius direction. Sensitivity analysis shows that an increase of collector convergent angle, inclination slope, collector radius will increase airflow velocity, both along the collector radius axis and chimney axis. To keep other parameters the same, airflow velocity in SCPP is increased by 20.3-30.7% for θ=2° convergent collector comparing with conventional horizontal collector.

4.3. **Temperature**
Temperature of airflow decreases in collector radius direction and gets ambient temperature at its inlet area. The same phenomenon is found in chimney pipe direction, but decreases very slowly. The maximum temperature locates near the absorber area. Keeping other parameters the same, enhanced convergent collector has higher airflow temperature at chimney bottom than horizontal heat collector. Furthermore, temperature is increased with an increase of convergent angle and inclination slope.

4.4. **Power generation**
Figure 2 reports that an increase of collector convergent angle enhances power generation performance.

![Figure 2. Relationship between power generation and collector convergent angle.](image)

To keep other parameters the same, generated power is 1100 KW for θ =2° convergent collector SCPP, means that incremental rate is 17.3% comparing with conventional horizontal collector.
Sensitivity analysis also reveals that an increase of collector radius or inclination slope raises power generation.

5. Conclusions
To combat climate change and address energy security problems, solar energy generation is becoming an increasingly concern worldwide. This article explores the improvement of energy efficiency of SCPP by optimizing product design. It proposes a novel heat collector design for SCPP characterizing as partial inclination and convergence. By employing $k-\varepsilon$ turbulence model and CFD method, this article carries out several numerical simulations for different parameter design, including convergent angle, slope length as well as collector radius length, to examine thermodynamic features of airflow in SCPP and its power generation efficiency. The results reveal that an increase of convergent angle, inclination slope and collector radius decreases airflow pressure in chimney inlet region, increases airflow velocity and temperature in this region, also enhances power generation efficiency. Comparing with conventional horizontal heat collector, the enhanced convergent collector may improve energy conversion efficiency of SCPP technology.

Nomenclature

- $\theta$: Convergent angle of heat collector
- $v$: Air velocity (m/s)
- $u$: Velocity in the radial direction (m/s)
- $\varepsilon$: Turbulent kinetic energy dissipation rate ($m^2/s^3$)
- $z$: Axial coordinate (m)
- $\rho$: Density of air ($kg/m^3$)
- $\mu$: Turbulent viscosity (Pa/s)
- $D$: Collector diameter (m)
- $C_p$: Specific heat capacity of air ($J/kg$)
- $H$: Chimney height (m)
- $r$: Radial coordinate (m)
- $P$: Pressure (KPa)
- $k$: Turbulent kinetic energy ($m^2/s^2$)
- $A_{chimney}$: Chimney square ($m^2$)
- $T_0$: Ambient temperature (Kelvin)
- $\rho_{chimney}$: Air specific density at temperature $T_0 + \Delta T$ of chimney bottom ($kg/m^3$)
- $\rho_0$: Reference density of air ($kg/m^3$)
- $\beta$: Thermal expansion coefficient
- $\mu$: Dynamic viscosity (Pa/s)
- $\lambda$: Thermal conductivity ($w/(m.Kelvin)$)
- $\gamma$: Air specific density at temperature $T_0 + \Delta T$ of chimney bottom ($kg/m^3$)
- $\lambda$: Thermal conductivity ($w/(m.Kelvin)$)
- $\theta$: Convergent angle of heat collector
- $l$: Collector roof slope radius (m)
- $v_{chimney}$: Air velocity at chimney bottom (m/s)
- $w$: Velocity in the tangential direction (m/s)
- $\rho_0$: Reference density of air ($kg/m^3$)
- $\mu$: Dynamic viscosity (Pa/s)
- $\lambda$: Thermal conductivity ($w/(m.Kelvin)$)
- $G$: Global radiation ($w/m^2$)
- $h$: Collector height (m)
- $g$: Gravitational acceleration ($m/s^2$)
- $P$: Total pressure (KPa)
- $A_c$: Collector square ($m^2$)
- $T$: Temperature (Kelvin)
- $P_r$: Total pressure (KPa)
- $\Delta+T$: Temperature (Kelvin)

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