A parametric simulation of solar chimney power plant

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Abstract. The strong solar radiation, continuous supplies of sunlight and environmental friendly factors have made the solar chimney power plant becoming highly feasible to build in Malaysia. Solar chimney power plant produces upward buoyancy force through the greenhouse effect. Numerical simulation was performed on the model of a solar chimney power plant using the ANSYS Fluent software by applying standard k-epsilon turbulence model and discrete ordinates (DO) radiation model to solve the relevant equations. A parametric study was carried out to evaluate the performance of solar chimney power plant, which focused on the temperature rise in the collector, air velocity at the chimney base, and pressure drop inside the chimney were based on the results of temperature, velocity, and static pressure distributions. The results demonstrate reliability by comparing a model with the experimental data of Manzanares Spanish prototype. Based on the numerical results, power capacity and efficiency were analysed theoretically. Results indicate that a stronger solar radiation and larger prototype will improve the performance of solar chimney power plant.

1. Introduction
Malaysia is situated on the South China Sea that lies between 1° and 7° in North latitude and 100° and 120° in East longitude. The annual climate condition of Malaysia does not have a distinct seasonal variation which results in receiving almost equal amount of sunshine daily throughout the year. Theoretically, Malaysia should have high potential for harvesting solar energy. However, the solar radiation received is generally low due to the high presence of cloud [1].

Malaysia is an ideal country for running large-scale solar power system due to its geographic position being located at the equator of earth. The strong solar radiation, continuous supplies of sunlight, lower carbon emissions and environmental friendly factors have made the solar chimney power plant become highly feasible to build in Malaysia. Research shows that the measured monthly average daily solar radiation of Malaysia falls in the range of 600 W/m² and 1000 W/m² [2]. The average daily sunshine duration was found to be in the range of 4 to 8 hours per day with an average daily temperature of 26.5°C [3]. Hence, solar chimney power plant is very practicable to be developed in the climatic conditions of Malaysia.

Solar chimney produces electrical power from solar radiation. The system combines three components, which consists of a huge greenhouse collector, a chimney that placed in the center, and one or multiple wind turbines that is connected to the generators below the chimney (figure 1). Generally, the principle of solar chimney is based on the idea of natural convection that using hot air produced by sun lights to drive the turbines. The conversion between solar radiations to electricity involves two stages. During the first stage, thermal energy is produced by means of greenhouse effect.
This can be done by placing a collector above the ground to trap the radiant energy. In the second stage, the hot air generated by the radiant energy rise up in the chimney due to buoyancy effect. Thus, the movement of air drives the turbines at the base of chimney to generate the electricity [4-9].

In 1998, Sherif and Pasumarthi have carried out several experiments to examine the velocity and temperature distributions of the airflow inside the chimney [4]. The method of setting up the solar chimney is by modifying the shape and the radius of collector. All experimental results were found to be agreed within the calculation of mathematical model. On the other hand, Schlaich claimed that the output power of solar chimney is proportional to the height of chimney and the area of collector [5]. Besides, it was mentioned that solar chimney has poor efficiency because only a small amount of solar radiation can be converted into useful energy [5].

Nonetheless, many researchers have performed evaluation on the mathematical models of solar chimney power plant based on both theoretical and numerical analysis [6]. Moreover, Ming et al. [7] have developed different types of mathematical models for the solar collector, solar chimney and energy storage layer. The research has analyzed the characteristics of air flow in the solar chimney with energy storage layer. As a result, the effects of several parameters such as static pressure, driving force, output power, and efficiency were evaluated. Results show that the relative static pressure decreased, whereas the velocity increased significantly inside the chimney with the increase of solar radiation.

In recent years, Pastohr et al. [8] have performed study on solar chimney with two dimensional steady state simulations. The research has analyzed the energy flow on the collector, turbine, and the chimney. In the research, the profile of temperature, pressure, and velocity in the collector have been identified. Results show that when the collector radius is constant, the increase of solar radiation will increase the air velocity. Furthermore, the results of analytical calculations have shown a good agreement with the fluent results. Similarly, Sangi et al. [9] have performed two-dimensional axisymmetric numerical simulation of solar chimney using standard k-ε model and standard wall mode to describe the air flow. A good agreement was obtained between numerical results and the experimental data of Spanish prototype. However, further investigation is still needed for different sizes of solar chimney power plant.

In fact, Cao et al. [10] have presented the simulation of sloped solar chimney with respect to different chimney height using the validated numerical model. A conventional Spanish prototype was first simulated to observe the agreement between experimental data and the Fluent result. Accordingly, the numerical model is then used to simulate solar chimney in other conditions.

In this research, parametric study was conducted on solar chimney of different geometrical size to determine the performance of solar chimney power plant under different conditions of solar radiations, so that the power capacity could be evaluated. This study was performed using ANSYS Fluent software.

2. Methodology

As the size of solar chimney power plant will result in significant effect on the velocity and temperature rise, three different dimensions of design have been proposed to observe the difference. It should be noted that the dimensions of solar chimney used in second design (Case 2) were based on the parameters of Spanish prototype [8]. Meanwhile, other designs of solar chimney (Case 1 & 3) have been drawn based on the ratio of Spanish prototype which results in three different geometrical dimensions of solar chimney. The main dimensions of solar chimney prototype are given in table 1. Case 1 & 3 prototypes were drawn to consider minimum and maximum optimum size, respectively.

| Solar Chimney | Chimney Height (m) | Chimney Radius (m) | Collector Radius (m) |
|---------------|--------------------|--------------------|----------------------|
| Case 1        | 100                | 3                  | 75                   |
| Case 2        | 195                | 5                  | 120                  |
| Case 3        | 500                | 15                 | 400                  |
The solar chimney power plant was divided into three parts, which consists of the collector, transition section in the middle, and the chimney tube. In ANSYS Fluent, the meshing process on different part was generated separately and independently. Since the transition section is the most sensitive part in simulation, it requires a finer mesh, which tetrahedral meshes were used. Meanwhile, the collector and the chimney tube were meshed using hexahedral meshes. The grid generation of solar chimney power plant is shown in figure 1. Boussinesq model was selected to describe the air flow. The change of density was only considered in the momentum equation. Besides, the pressure boundary condition was used to simulate the natural convection flow in the chimney. Since both convection and radiation exist in the transparent covering of collector, discrete ordinates (DO) radiation model and convection heat transfer boundary were applied. The mean daily solar radiation in Malaysia was found to be around 800 W/m² with the minimum solar radiation around 600 W/m² and the maximum solar radiation around 1000 W/m². Hence, these values were used to apply in the simulations. On the other hand, the ground is treated as an inner heat source. The setting has considered the transmission absorptivity because the ground surface absorbs solar energy and the energy also converts to the cover of collector. For the turbulent flow conditions, the standard k–ε model and standard wall mode were selected to describe the fluid flow. All the numerical calculations are selected to be performed with double precision by the solver. Table 2 shows the boundary conditions setting for simulation.

![Diagram of solar chimney power plant](image-url)

Figure 1. Solar chimney power plant (a) schematic illustration [9] (b) grid generation overall view (c) grid generation section view
Table 2. Setting of main boundary condition

| Surface             | Type                  | Value                      |
|---------------------|-----------------------|----------------------------|
| Collector inlet     | Pressure inlet        | ΔP = 0 Pa & T = 299.5 K    |
| Chimney outlet      | Pressure outlet       | ΔP = 0 Pa                  |
| Chimney wall        | Adiabatic wall        | Heat flux = 0 W/m²         |
| Transition section  | Adiabatic wall        | Heat flux = 0 W/m²         |
| Collector           | Wall (Semi-transparent)| Heat transfer coefficient = 8 W/m² K |
| Ground surface      | Wall                  | T = 299.5 K                |

3. Results and discussion

To validate the numerical model, the temperature rises in the collector and the upwind velocity at the chimney inlet of Case 2 prototype are compared with the experimental data of Spanish prototype. Experimental data of Spanish prototype shows that when the solar radiation is 1000 W/m², the temperature increase through the collector reaches 20 K, and the upwind velocity at the base of chimney have a value of 15 m/s under no load condition [9]. The temperature, velocity, and pressure distribution of solar chimney power plant are shown in figure 2, figure 3 and figure 4, respectively. Based on the test of validation in table 3, a good quantitative agreement was obtained between the experimental data and the result of numerical simulations. In addition, benchmarking of this simulation results were conducted by comparing to previous work [10] and [11]. It can be concluded that the reliability of the simulation results in this research project is proven. Therefore, the developed method including boundary conditions is feasible to simulate the other prototypes.

Table 3. Comparison between the experimental data and numerical result

| Results                  | Temperature Increase (K) | Upwind Velocity (m/s) |
|--------------------------|--------------------------|------------------------|
| Experimental             | 20                       | 15                     |
| This work                | 21.9                     | 15.7                   |
| Asnaghi and Ladjevardi   | 21.8                     | 16.2                   |
| Cao et al. [10]          | 21.5                     | 14.33                  |

![Figure 2. Temperature distribution of Case 2 solar chimney power plant at 1000 W/m²](image_url)
Figure 2 shows the temperature distribution of Case 2 power plant when the solar radiation is 1000 W/m². The figure shows that the temperature of air rise through the collector reaches about 21.9 K. Figure 3 shows the velocity distribution of the solar chimney. When the solar radiation is 1000 W/m², the maximum velocity inside the solar chimney is about 15.7 m/s. It is illustrated that the velocity of air increases through the collector and the maximum velocity is at the chimney base. The static pressure distribution of the solar chimney is shown in figure 4. Results show that the static pressure decreases through the collector up to -122.3 Pa and starts increasing through the chimney up to 0 Pa. It is observed that the minimum static pressure lies at the bottom of the chimney.

![Figure 3. Velocity distribution of Case 2 solar chimney power plant at 1000 W/m²](image)

![Figure 4. Static pressure distribution of Case 2 solar chimney power plant at 1000 W/m²](image)

Table 4 to 6 shows the influence of different solar radiation and geometrical dimensions of solar chimney on the numerical results (Case 1 to 3). Based on the numerical results of temperature rise in collector, airflow velocity at chimney, and pressure drop inside the chimney as function of the solar
radiation ranging from 600 to 1000 W/m\(^2\), the results show that when the geometrical dimensions are constant, the raising of solar radiation increases the air temperature and velocity while decreasing the static pressure in the chimney. This is because more heat is absorbed and the increase of the heat quantity causing the air temperature to rise while dropping the air density at the same time. The decrease of density increases the pressure difference which results in more air flowing through the chimney. Similarly, when the solar radiation is constant, the increase of geometrical dimensions causes the air temperature to increase which results in the decrease of air density. Hence, the buoyancy differences increases which produces greater driving force and thus the pressure drop. Thereby, the increase of driving forces results in a higher velocity of air inside the chimney. Figure 5 shows the velocity distribution of Case 3 prototype solar chimney power plant (maximum of 27 m/s).

**Table 4. Simulation results of Case 1 prototype**

| Solar Radiation (W/m\(^2\)) | Temperature Rise (K) | Airflow Velocity (m/s) | Pressure Drop (Pa) |
|-----------------------------|----------------------|------------------------|-------------------|
| 600                         | 14.5                 | 9.8                    | 51.1              |
| 800                         | 16.5                 | 11.1                   | 60.2              |
| 1000                        | 18.5                 | 12.1                   | 68.7              |

**Table 5. Simulation results of Case 2 prototype**

| Solar Radiation (W/m\(^2\)) | Temperature Rise (K) | Airflow Velocity (m/s) | Pressure Drop (Pa) |
|-----------------------------|----------------------|------------------------|-------------------|
| 600                         | 16.2                 | 12.4                   | 86.6              |
| 800                         | 18.4                 | 14.3                   | 105.7             |
| 1000                        | 21.9                 | 15.7                   | 122.3             |

**Table 6. Simulation results of Case 3 prototype**

| Solar Radiation (W/m\(^2\)) | Temperature Rise (K) | Airflow Velocity (m/s) | Pressure Drop (Pa) |
|-----------------------------|----------------------|------------------------|-------------------|
| 600                         | 22.2                 | 22.0                   | 250.2             |
| 800                         | 24.0                 | 24.7                   | 301.3             |
| 1000                        | 26.6                 | 27.0                   | 350.4             |

**Figure 5.** Velocity distribution of Case 3 prototype at 1000 W/m\(^2\).
Table 7 to 9 shows the power capacity and efficiency of the solar chimney from Case 1 to 3, respectively. The power generated by turbine and the overall system efficiency are analyzed by,

\[ P_{\text{out}} = \eta_t \Delta P_t V_{ch} A_{ch} \]  \hspace{1cm} (1)

\[ \eta = \frac{P_{\text{out}}}{A_{gro} q} \]  \hspace{1cm} (2)

Where, \( \Delta P_t \) is the driving forces to impel the air flow, and \( A_{gro} \) is the area of ground [10].

| Solar Radiation (W/m²) | Power Capacity (kW) | Efficiency (%) |
|------------------------|---------------------|----------------|
| 600                    | 32.64               | 0.12           |
| 800                    | 43.56               | 0.12           |
| 1000                   | 54.19               | 0.12           |

The mentioned equation was used to analyze the performance of solar chimneys theoretically. Results show that the power capacity of solar chimney increases with higher solar radiations and larger geometrical dimensions. When the chimney height reaches 500 m with collector radius of 400 m, the efficiency surpasses 1%. The solar chimney power plant was estimated to produce power of about 600 kW, under the solar radiation of 1000 W/m². Power generation could further be increased if the chimney height increases, which results in improving the efficiency.

| Solar Radiation (W/m²) | Power Capacity (kW) | Efficiency (%) |
|------------------------|---------------------|----------------|
| 600                    | 70.00               | 0.26           |
| 800                    | 98.53               | 0.27           |
| 1000                   | 125.17              | 0.28           |

| Solar Radiation (W/m²) | Power Capacity (kW) | Efficiency (%) |
|------------------------|---------------------|----------------|
| 600                    | 358.82              | 1.32           |
| 800                    | 485.14              | 1.34           |
| 1000                   | 616.73              | 1.36           |

The main reason that causing the low efficiencies of solar chimney is due to the heat loss in the turbine, whereby the heat energy generated from the solar energy could not transfer well into work energy during the isentropic expansion process. Despite the efficiency of solar chimney is very low, it still able to generate over 100 kW when the efficiency remains less than 1%. Considering that solar chimney power plant does not consume fossil energy, the materials used to build the plant can be easily assessed which initiated the investment for commercial application. From an economic viewpoint, it is well known that these power plants were only considered to be constructing in desert regions where the land price is very cheap. Nonetheless, the power plant is not only used in power production, on the other hand the space under the collector roof can also be planned for agricultural purposes (drying).
4. Conclusion

This paper presents a description of the temperature rise, air velocity, pressure drop, power output and efficiency as dependent on the effects of solar radiations and geometrical dimensions of solar chimney power plant. The distributions of the temperature, velocity and static pressure were illustrated for a solar chimney power plant model, which reported reasonable agreements between the numerical results and experimental data of temperature difference and upwind velocity. Other models result should be validated in future work as well, while more parameters can be explored without time constraint. Based on the results from parametric study, it can be concluded that the performance of solar chimney depends significantly on its geometric dimensions and the intensity of solar radiation to some extent. Further investigations are required to improve the efficiency of the solar chimney power plant. The effectiveness of geometry such as the ratio between chimney height, chimney radius, and collector radius of the solar chimney has to be investigated. The optimization and chimney modification of the solar prototype models are also required. Additionally, the effectiveness of material for the solar chimney need to be examined to improve the airflow velocity and temperature.

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