Rudimentary analysis for solar chimney enhancement

I E Jamil*, C Y Sing and H H Al-Kayiem

Mechanical Engineering Department Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak, Malaysia.

*E-mail: iylia_0008404@utp.edu.my

Abstract. This paper presents fundamental results for solar chimney enhancement. Solar radiation proves to be an important factor in influencing the efficiency of the solar chimney power plant, but its effects on the ambient conditions outside the system has not been considered. Using the Discrete Ordinates radiation model on the semi-transparent collector component of the two-dimensional system, the work presented in this paper simulates the velocity and temperature inside the solar chimney as the ambient temperature of air outside is varied from 307 K to 314 K. At the highest ambient temperature, results show an increase in air velocity of 0.55 m/s at ground level and 1.85 m/s at a height of 1 m along the chimney. To further investigate of this study, a simulation model to include the ambient domain is proposed as a conclusion.

1. Introduction

The solar chimney power plant (SCPP) is an alternative method for electrical power generation. Due to limited resource of conventional energy, the research and development of renewable energy technology has expanded over the decades. An SCPP is a solar thermal system, which converts solar energy into electricity. It consists of typically three main components: a solar collector, a chimney tower and a wind turbine. The working principle of the SCPP is simple (figure 1); solar insolation passes through the semi-transparent collector which heats up the air within. Additionally, it creates a greenhouse effect between the ground and the collector, which further heats the air underneath the collector. The increased air temperature causes difference in buoyancy, which triggers the stack effect. Consequently, continuous updraft is created as hot air leaves through the chimney and ambient air enters from the collector inlet. This flow provides the kinetic energy that runs through the turbine installed at the base of the chimney.

![Figure 1. Schematic of the solar chimney [1].](image)
The first pilot solar chimney system was built in Manzenares, Spain in 1982. With a collector radius of 122 m, chimney height and diameter of 194 m and 10 m respectively, the plant was designed to produce a 50-kW electrical power output. From this point, many studies revolve around the Manzenares plant to investigate the defining parameters of the SCPP efficiency. One investigation on analytical and numerical models that consider the influence of ambient conditions and structural parameters on the power output was performed by Bernardes et al. [2]. The results show that the power output increases by increasing chimney height, collector area and transmittance.

To widen the research, development of small-scale prototype of the SCPP has increased popularity up to this day. In Kota, India, a prototype of 8 m height and 12 m collector diameter has been built [3]. The experiment shows that the solar intensity has an effect on air velocity, and ambient air temperature. Kasaeian [4] presented the effects of ambient condition to the performance of SCPP through a scaled model and dimensional analysis. Roozbeh [5] also proved that increase in solar radiation will increase the power output of the system. In another research, Jiakuan [6] showed that power output of the system increases with global solar radiation intensity, collector area and chimney height. It also concluded that a taller chimney would create a higher air velocity through the system.

In University Teknologi PETRONAS, a small-scale pilot plant have been built with 6 m collector diameter and 6.3 m chimney height. From this model, a series of investigations findings have been published. Al-Azawiey et al [7, 8] presented the influence of the collector geometry on SCPP performance. A larger collector area shows a significant increase in the air velocity inside the chimney. In terms of height, the lower height of the collector will provide a higher overall efficiency. An optimum collector height-to-diameter ratio also suggested for future design. To target the hours with low sun radiation, Azeemuddin et al [9], Al-Azawiey et al [10] and Auryby et al [11] have studied various types of energy storage mediums that can sustain the SCPP performance throughout the day.

To this date, no work has been published to investigate the effect of incoming air temperature into the system. Ambient conditions are investigated mainly to see the effect of solar radiation intensity on system performance. The objective of the work presented in this paper is to investigate the effect of inlet air temperature on the flow inside the system. The proposed method to investigate this is by extending the thermal absorption material on the ground beyond the collector area. In this paper, the investigation was conducted by increasing the preset air temperature at the inlet to be higher than the ambient air temperature.

2. Fundamentals of the design

2.1. Governing equations

The fluid motion inside the model is solved through the conservation equation of mass, momentum and energy in ANSYS Fluent software. Simulation is carried out assuming steady-state, turbulent, 2-D flow. According to the Fluent User Guide [12], the basic equations can be expressed in tensor form for continuity and momentum equation as shown by equation (1) and equation (2).

\[ \frac{\partial}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \]  
\[ \frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \left( \mu \nabla \vec{v} + \nabla \vec{v}^T \right) - \frac{2}{3} \nabla (\vec{v} \cdot \vec{v}) + \rho g \]  

The incompressible flow assumption is justified for the model since the maximum Mach number is much smaller than 0.1. The buoyancy effect was considered by applying the Boussinesq model in equation (3) to allow a variation of density as a function of temperature. This model treats density as a constant value in all solved equations, except for the buoyancy term in the momentum equation. This model accounts for the full bouncy effect, where the density varies with temperature, and the flow is motivated by force of gravity, which influences the change in density.

\[ (\rho - \rho_o)g \approx -\rho_o \beta (T - T_o) g \]  
\[ \rho = \rho_o (1 - \beta \Delta T) \]  

Equation (3) is valid when \((1 - \beta \Delta T) \ll 1\).
Meanwhile, energy equation as shown by equation (4) has been used in this investigation.

\[
\frac{\partial}{\partial t} (\rho E) + \nabla \cdot (\bar{v} (\rho E + p)) = -\nabla \cdot (k_{\text{eff}} \nabla T) - h \bar{f} + \left( \mu \left( \nabla \bar{v} + \nabla \bar{v} \right) - \frac{2}{3} \nabla \cdot \bar{v} \right) + S_h
\]  

(4)

In equation (4), \(S_h\) represents the heat source of the solar radiation. The radiation transfer equation was solved by Discrete Ordinates (DO) model. The DO model solves surface to surface radiation problems and radiation through semi-transparent materials. The radiation equation solved by the software can be written as:

\[
\nabla \cdot (I_k(\vec{r}, \vec{s}) \vec{s}) + \nabla \cdot \left( a_k + \sigma_a I_k(\vec{r}, \vec{s}) \right) = a_k n^2 I_{b\lambda} + \frac{\sigma_a}{4\pi} \int_0^{4\pi} I_k(\vec{r}, \vec{s}) \varphi(\vec{s}, \vec{s}') d\Omega'
\]  

(5)

The solar intensity in each direction \(\vec{s}\) and position \(\vec{r}\) can be written as follows:

\[
I_k(\vec{r}, \vec{s}) = \sum I_k(\vec{r}, \vec{s}) \Delta I_k
\]  

(6)

In equation (6), the summation represents all wavelength bands. In this study, the collector material is specified Perspex and assumed all the Perspex had the same behavior for all wavelength bands.

2.2. Geometry and boundary conditions

An initial model is built based on geometry from experiment [7] to validate the simulation model. Equations presented in the previous section are solved numerically on ANSYS Fluent. The geometries of the model are defined in table 1.

| Parameter                  | Dimension |
|----------------------------|-----------|
| Collector radius (m)       | 3.00      |
| Collector height at inlet (m) | 0.05     |
| Collector angle of inclination from ground (degree) | 15.00 |
| Chimney height (m)         | 6.30      |
| Chimney radius (m)         | 0.08      |

Boundary conditions of the simulation model are taken from [7] and described in table 2. Properties of materials used in the simulation are described in table 3. Velocity and temperature values are obtained from post-processing for comparison with the experimental results. It can be observed by simulation that the maximum velocity occurs at the collector inlet, and at the base of the chimney. Increase in solar intensity raises the temperature of the ground and overall air temperature in the system.

Simulation values for maximum temperature at the ground and velocity observed at the chimney base are compared with experimental values for solar intensity of 200 and 800 W/m² and shown in table 4. With reasonable percentage difference between the values, this model is acceptable to be used in the proceeding simulation.

| Boundary     | Type                   | Condition          | Temperature (K) |
|--------------|------------------------|--------------------|-----------------|
| Ground       | Wall                   | Temperature, \(T_{\text{ground}}\) | 330             |
| Collector    | Wall, semi-transparent | Mixed              | Not applicable  |
| Chimney      | Wall                   | Adiabatic          | Not applicable  |
| Collector inlet | Pressure inlet        | Zero gauge pressure | 307             |
| Chimney outlet | Pressure outlet        | Zero gauge pressure | 307             |
Table 3. Material properties for simulation.

| Physical property          | Collector | Ground     | Chimney    |
|----------------------------|-----------|------------|------------|
| Material                   | Perspex   | Black pebble | PVC        |
| Absorption coefficient     | 0.06      | 0.9        | 0.04       |
| Transmission coefficient   | 0.92      | 0.0        | 0.0        |
| Density (kg/m³)            | 2700      | 2640       | 833        |
| Specific heat (J/kg·K)     | 840       | 820        | 1170       |
| Thermal conductivity (W/m·K) | 0.78  | 1.73       | 0.19       |
| Emissivity                 | 0.9       | 0.9        | 0.91       |

Table 4. Comparison of simulation and experimental results.

| Case                        | Experiment [7] | Validation Model | Difference % |
|-----------------------------|----------------|-----------------|--------------|
| Velocity at chimney base (m/s) | 0.71  | 0.82  | 0.15  |
| 200 W/m²                    | 1.85  | 1.96  | 0.06  |
| 800 W/m²                    | 300.0 | 302.0 | 0.007 |
| Max T at ground (K)         | 321.0 | 332.0 | 0.034 |
| 200 W/m²                    | 1.2   | 1.3   | 0.08  |
| 800 W/m²                    | 14.6  | 16.0  | 0.09  |

The same model is used for other cases presented here with new geometry described in table 5. Figure 2 shows the preliminary model geometry and figure 3 presents the mesh elements at the collector region.

Table 5. Dimensions of the preliminary model geometry.

| Parameter                             | Dimension |
|---------------------------------------|-----------|
| Collector radius (m)                  | 4.00      |
| Collector height at inlet (m)         | 0.07      |
| Collector angle of inclination from ground (degree) | 20.00 |
| Chimney height (m)                    | 14.00     |
| Chimney radius (m)                    | 0.08      |

Quadrilateral elements are used for the mesh and table 6 summarizes the grid independence test. Based on the simulation, mesh model 3 is used for all simulations with the preliminary model.

Table 6. Grid independence test for the preliminary model.

| Mesh model | Number of elements | Velocity at chimney base (m/s) | Error (%) |
|------------|--------------------|-------------------------------|-----------|
| Mesh 1     | 27548              | 1.63                          | 9.2       |
| Mesh 2     | 61164              | 1.88                          | 3.7       |
| Mesh 3     | 111655             | 1.95                          | 0.5       |
| Mesh 4     | 145668             | 1.94                          | -         |

The SIMPLE algorithm available in ANSYS Fluent is employed to solve the system of equations. The convective terms are discretized with a second-order-accurate upwind scheme.
3. Results and discussion

The simulation is carried out assuming ambient temperature at the collector inlet for the preliminary model. Then, the inlet temperature is increased by a range of values to see the effects on the flow inside the system. Velocity for all results is taken at the base of chimney, unless otherwise stated. For all simulations, the solar radiation is set at 800 W/m². The justification of this is when solar radiation is at lower levels, the increase in temperature inside and outside the system is minimal. [3]

From figure 4, it can be observed that air velocity increases with increase in air inlet temperature. As the air temperature at inlet increase by 7 K from ambient temperature, the air velocity doubles from 1.95 m/s to 3.93 m/s.
At the chimney base, temperature can be observed to increase as the air inlet velocity increases. While at ambient inlet temperature, the air inside is 315.21 K. As the ambient temperature goes up to 314 K, the air temperature inside the chimney increases to 320.52 K (Figure 5).

Ground temperature is also observed in the simulation. Figure 6 shows the maximum values of ground temperature as the inlet air temperature is increased from 307 K to 314 K. At the ambient temperature of 307 K, the difference between ground and ambient temperature is 35 K. At 314 K, the difference is 34 K. This shows that the ground temperature is still increasing as the inlet air temperature increases even though the solar radiation level is kept constant.

The velocity values along the chimney height is compared for all values of inlet air temperature. Based on Figure 7, it can be observed that at the base of the geometry (\( y = 0 \)), the difference in air velocity is 0.55 m/s between 307 K and 314 K inlet air temperature. Moving up the chimney height, it is evident that the difference between the lowest and highest velocity increases. At height 1 m from the ground, the difference is 1.85 m/s. It can be concluded that the increase in air velocity along the chimney height is greater as the inlet air temperature increases. As these data are taken at 800 W/m² solar intensity and an assumed range of air inlet temperatures, further investigation is required to see the combined effect of the solar intensity and changes on the air inlet temperature.
Figure 7. Air velocity along the vertical height of chimney at inlet temperature 307 K to 314 K.

In figure 8, velocity vectors for six air inlet temperatures are compared: from 307 K to 312 K. For all cases, velocity is high at the collector inlet, averaging at 7 m/s. A recirculating flow can be observed along one third of the collector radius upon entrance. However, it can be seen that for a higher inlet air temperature, the recirculation velocity increases and a stronger swirl pattern can be witnessed. For all cases, the air flow inside the collector is driven towards the chimney base. At this location, there is a surge or flow and air velocity increases as it enters the chimney.

Figure 8. Velocity vector for all inlet air temperature 317 K to 312 K.

Temperature contour of air under the collector are for all cases can be seen in figure 9. For air inlet temperature 307 K, the maximum temperature observed in this region is 315.2 K for, while for 312 K, the maximum temperature observed is 320.6 K. As observed from the contours, the higher temperature regions start to occur at a distance from the collector inlet. This corresponds with the region of the
swirl formation from figure 8. As air velocity reduces after the swirl, the flow is more settled and convection from the ground increases the air temperature.

![Temperature contour for all inlet air temperature 308 K to 313 K.](image)

**Figure 9.** Temperature contour for all inlet air temperature 308 K to 313 K.

### 4. Conclusion
Solar radiation is one of the most important factors in SCPP performance apart from the design geometry. It influences the ambient condition outside the system by increasing the ambient air temperature. From the results presented, it is apparent that higher temperature of the ambient air result in higher flow velocity in all regions inside the solar chimney. Results show an increase in air velocity of 0.55 m/s at the chimney base and 1.85 m/s at a height of 1 meter from the ground as ambient temperature increases. To further investigate this, a study must be conducted to simulate the SCPP combined with the surrounding ambient domain. Methods to increase the temperature of ambient air are to be included to further enhance the overall SCPP performance. To further investigate this, a simulation model to include the ambient domain is proposed as a conclusion.

### Acknowledgements
The authors acknowledge Universiti Teknologi PETRONAS for the financial and technical support to conduct this work under STIRF research grant; CS: 015LA0-005.

### References
1. Fasel H, Shams E and Gross A 2013 CFD analysis for solar chimney power plants *Sol. Energy* **98** 12–22.
2. Bernardes A S and Weinrebe V A 2003 Thermal and technical analyses of solar chimneys *Sol. Energy* **75** 511–4.
3. Lal S, Kaushik S C and Hans R 2016 Experimental investigation and CFD simulation studies of a laboratory scale solar chimney for power generation *Sustain. Energy Technol. Assess.* **13** 13–22.
4. Kasaedian A, Amirifard M, Ahmadi M H and Kasaedian F 2017 Investigation of the effects of ambient temperature and dimensional parameters on the performance of solar chimney power plants *Int. J. Low-Carbon Technol.* **12** 335–48.
5. Sangi R, Amidpour M and Hosseinizadeh B 2011 Modeling and numerical simulation of solar
chimney power plants *Sol. Energy.*

[6] Zhou X, Yang J, Xiao B and Hou G 2007 Simulation of a pilot solar chimney thermal power generating equipment *Renew. Energy.*

[7] Al-Azawiey S S, Al-Kayiem H H and Hassan S B 2017 On the Influence of Collector Size on the Solar Chimneys Performance *MATEC Web of Conferences.*

[8] Al-Azawiey S S, Al-Kayiem H H and Hassan S B 2016 Investigation on the influence of collector height on the performance of solar chimney power plant pp 12197–201.

[9] Azeemuddin I, Al-Kayiem H H and Gilani S I 2014 Simulation of a collector using waste heat energy in a solar chimney power plant system *WIT Transactions on Ecology and the Environment* p 179.

[10] Al-Azawiey S S and Hassan S B 2016 Heat Absorption Properties of Ground Material for Solar Chimney Power Plants *Int. J. Energy Prod. Manag.*

[11] Aurybi M A, Al-Kayiem H H, Gilani S I U and Ismaeel A A 2017 Numerical assessment of solar updraft power plant integrated with external heat sources *WIT Transactions on Ecology and the Environment.*

[12] Inc. A 2016 ANSYS Fluent Theory Guide v17.1 *ANSYS 17.1 Doc.*