Experimental and numerical study on ground material absorptivity for solar chimney power applications

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Abstract

A solar chimney power plant utilizes the ground as its energy conversion medium from solar radiation to kinetic energy in the adjacent air stream. In this work, the conversion capability of six different ground materials, that are potentially available in Malaysia, were studied experimentally and numerically. An experimental setup was constructed to acquire measured data. A numerical model was constructed in the FLUENT software environment to model and simulate the energy conversion process. The selected materials were ceramic, black stone, sawdust, dark green painted wood (DGPW), sand and pebble. The simulation results showed good consistency with the experimental results in terms of the air stream velocity and the energy conversion efficiency. The ceramic and black stone have shown better performance upon the other materials. In particular, the ceramic medium has shown another advantage to its solar radiation absorptivity – its heat storage capability. However, due to its availability, black stone is recommended for use as the absorbing material in the solar chimney in Malaysia and regional countries.
Keywords: absorptivity, absorption materials energy conversion, convective heat transfer, solar chimney, solar energy.

1 Introduction

The solar energy reaching the earth's surface can be harnessed and utilized for power generation by two methods. The first method is by directly being converted to electrical energy using photovoltaic cells. The second method is to convert the

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solar radiation into thermal energy using a collector or concentrator for heating of working fluids to drive prime movers, turbines, for electrical generation. A solar chimney power plant (SCPP) works by the second method. Solar radiation is captured at the ground surface which heats up air as the working fluid. In general, the efficiency of the SCPP is low. Some enhancement techniques are proposed. Chikere *et al.* [1], reviewed the proposed enhancement of the SCPP and they suggested modified SCPP integrated with flue gas as added source of heat. Al-Mustafa *et al.* [2] reported review of the enhancement of the solar power updraft systems. Al-Kayiem [3] and Al-Kayiem *et al.* [4] presented experimental and numerical results of modified SCPP integrated with external auxiliary thermal source. They concluded that considerable enhancement was achieved in the performance of the integrated system and the SCPP became able to produce electricity all the day and night due to the continuous heat supply to the absorber.

Many studies about solar energy applications have been carried out, some of which have become true, yet others are still in the process of development. The studies have also aimed to achieve several interesting applications. These studies have been executed in different methods: Experimental and Numerical.

An experimental and theoretical studies of solar chimney power plant was conducted in Baghdad by Shyia [5] using 7 m diameter and 6 m chimney height. Times of measuring were 12 am, 2 pm, and 4 pm in July year (2002) for five kinds of absorbing ground: aggregates, soil, sand underneath, asphalt soil and asphalt aggregate. The important conclusions are. The high air velocity and temperature are at 2 pm, (3.12 m/s and 52.5°C), respectively. Asphalt aggregate was the best absorption floor. Bernardes [6] investigated the possibility of using water-filled tube on the collector floor as heat storage device and found increases in the power output after sunset. Another study was carried out in Baghdad by Chaichan and Hussein [7] focusing on the chimney basement's kind and its effect on collected air temperatures. Three ground bases were used: concrete, black concrete and black pebble. The results showed that the highest temperature difference reached was with the pebble ground.

The effect of storage parameters, such as the solar radiation, ambient temperature, and heat storage capacity for ground materials on the power plant operational time were also investigated. Abdulcelil [8] experimentally investigation a special layered soil as absorbing medium. The chimney has a 15 m height and 0.8 m diameter. The ground floor was 27 m diameter and 0.5 m deep pit. He investigated the temperature and air velocity distribution along the day. The results showed that the temperature and velocity were influenced by the heat stored in the ground.

Azeemuddin *et al.* [9] and Azeemuddin *et al.* [10] suggested an enhancement technique using waste heat energy as a flow of flue gases passing through conduits in the solar collector, Fig. 8. By using ANSYS software the process of the heat flow was simulated then validated with Manzanares prototype results. The simulated model shown good enhancement for the performance and gives contributes to the reduction of global warming. The proposed hybrid technique befits to generate electricity 24 hours.

Ming *et al.* [11] performed unsteady numerical simulations to analyze the characteristics of heat transfer and air flow in the solar chimney power plant system with an energy storage layer. The numerical simulations showed that it is beneficial for the utilization of soil, with a comparatively higher heat capacity, as the material of the storage layer. The results showed that the larger the conductivity of the energy storage layer, the lower the surface temperature of the energy storage layer. A Numerical study to analyze the performance of a solar chimney with an energy storage layer was carried out by Zheng *et al.* [12] using different energy storage materials. This study had shown that soil and gravel could be used as energy storage materials for solar chimney systems. Fanlong *et al.* [13] adopted the hybrid energy storage system with water and soil in their research to decrease the fluctuation of the solar chimney power generating systems. The authors established mathematical models of the fluid flow, heat transfer and power output features of the solar chimney including an energy storage layer. Also, the influence of the material and the depth of the energy storage medium upon the power output was analyzed. The results demonstrated that hybrid energy storage systems with water and soil can effectively decrease the power output fluctuation. Zhou *et al.* [14] chose Paraffin as the material of the energy storage layer. An unsteady conjugate numerical study of the system was performed by FLUENT software. The operational condition of the system was simulated when the solar radiation value was changed with time according to the actual situation. Due to the energy storage effect of the phase change materials, the system had an output of power at night. Moreover, because of the conditions of the workings of the heat storage layer, in the same condition of the solar radiation, the air velocity and maximum output of power increased with the system's operational days being extended. Hurtado *et al.* [15] analyzed the thermodynamic behavior and the power output of a solar chimney power plant over a daily operation cycle taking into account the soil as a heat storage system, through a numerical modeling under non-steady conditions. The influence of the soil thermal inertia and the effects of soil compaction degree on the output power generation are studied. A sizeable increase of 10% in the output power is obtained when the soil compaction increases. It is found a clear relationship (essentially linear) between the updraft temperature difference and the updraft velocity, for any time of day. The behavior of the soil as cold focus (storing energy) during the rising solar radiation period, but as hot focus during the falling solar period (releasing energy), causes a sizeable hysteresis loop in the evolution of updraft temperature and velocity as a function of solar radiation. The higher compaction of soil causes a relevant increase on total energy generation.

The SCPPs are unfeasible unless they are established with an absorbing area on a scale of hundreds of meters. The common practice is to utilize the ground as the absorbing media of the solar energy. The absorptivity is of high importance in the performance of the solar chimney. Accordingly, it is vital to select a suitable type of ground material from what is potentially available.

In the present work, the absorptivity of different types of ground materials were studied, experimentally and numerically. These materials are readily available locally to be used as ground material for the solar chimney application to convert radiation energy into thermal energy. Different types of ground materials are subjected to a similar environment and setup, and their absorptivity is measured based on the temperature and velocity of the outlet air at the top of the chimney. The experimental results are compared numerically with FLUENT software. The present work investigates the most practical type of ground material to suit the solar chimney application in Malaysia for sustainable power generation due to the material's capability in efficiently absorbing solar radiation and converting it into thermal energy.

2 Experimental implementations

In the beginning, the rig is constructed after drawing a simple design of a semi-model for the solar chimney system without load. Its contents several greenwood slides of a 10 mm thickness to represent the collector and chimney walls for any one of the six channels, whilst the top surface for the chimney is made from a glass (3 mm thickness) and is tilted at 4° from the ground level. Figure 1 shows the schematic diagram of the experimental apparatus.

Six basement materials are used in these channels (dark green painted wood (DGPW), stone, pebble, ceramic, sand, and sawdust) at a thickness of 20 mm for any material. Nineteenth of the calibrated thermocouples are fixed to measure temperature; some of them are fixed on the top face of the ground materials. The recorded temperatures in the collector and chimney are taken at various times (8:00 am–6:00 pm) over a period of five days. The radiation intensity and the outlet air velocity from the chimney are also measured.

The set of equations used to predict the results from the experimental measurements are presented as follows:

Energy absorbed by the ground material and transferred to the air:

$$Q_u = \dot{m}.cp.\Delta T \tag{1}$$

Energy supplied to the system by solar radiation:

$$Q_{in} = I.A_{collector} \tag{2}$$

Energy conversion efficiency in the system:

$$\eta = \frac{\dot{m}.cp.\Delta T}{I.A_{collector}} \tag{3}$$

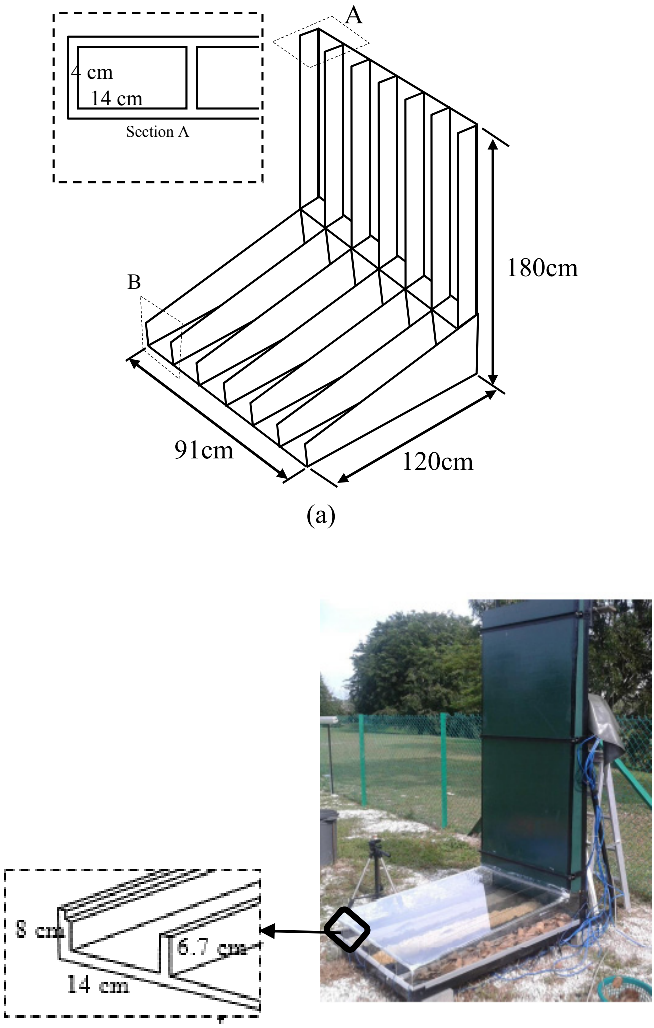


Figure 1: (a) Outlines of the experimental apparatus. (b) The experimental setup.

3 Numerical implementations

This study involves the use of FLUENT software to determine the characteristics of the air flow within the chimney with changing the material for collector foundation as; ceramic, stones, sand, pebbles, saw dust and dark green painted wood (DGPW). The CFD is based on the numerical solutions of the fundamental governing equations of fluid dynamics namely the continuity, momentum, energy, the data that chosen for the numerical analyses are taken from the practical work.

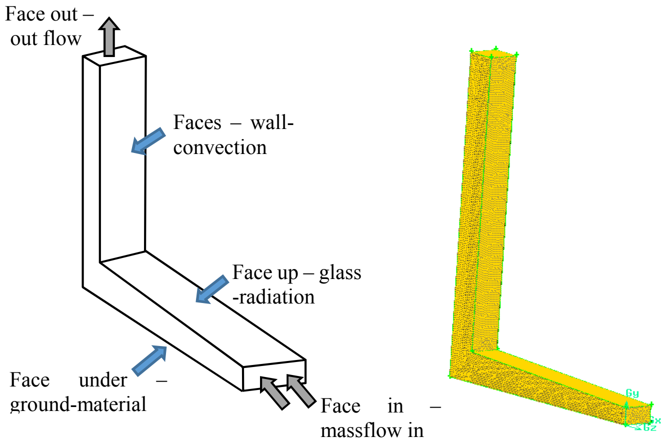


Figure 2: The geometry of the section test drawn and the mesh from the program.

Computational Fluid Dynamics (CFD) FLUENT software using to generate the mash, the number of element was (166764) and select the boundary condition in all faces. The process in the system is steady state. The roof and ground surface create a vertical temperature gradient (active walls). The physical properties of the fluid are constant, apart from the density. Viscous dissipation is neglected, just as the radiation (emissive properties of the two walls being neglected). It was accepted that the problem is bidimensional, permanent and laminar. The equations that are converting the process are as following.

Continuity equation

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \tag{4}$$

Momentum equation, in *x* and *y* directions

$$\frac{\partial(\rho uu)}{\partial x} + \frac{\partial(\rho vu)}{\partial y} = -\frac{\partial \rho}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{5a}$$

$$\frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho vv)}{\partial y} = -\frac{\partial \rho}{\partial y} + \mu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \tag{5b}$$

The energy equation

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{\lambda}{\rho\, Cp}\left(\frac{\partial\, T^2}{\partial\, x^2} + \frac{\partial\, T^2}{\partial\, y^2}\right) \tag{6}$$

The velocity and temperature for each material measured from experimental work with different times during the day (9:00 am, 12:00 pm, 3:00 pm and 6:00 pm).

4 Result and discussion

4.1 Experimental results

Figure 3 shows that the stone have a higher absorptivity from the solar energy during various times (9:00 am, 12:00 pm, and 3:00 pm) and gave the best efficiency with the emitted energy. Whilst one of these materials (ceramic) has a higher emissivity in the intensity of the solar radiation and was lower at 6:00 pm.

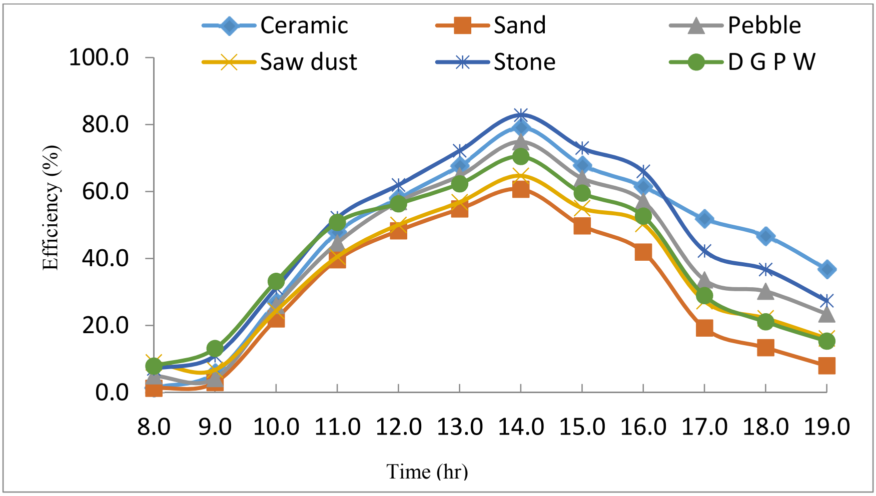


Figure 3: Measured efficiency versus time.

Efficiency results in Figure 3 demonstrate that the stone ground is performing better than the other materials in conversion of solar radiation to kinetic energy in the collector air. Ceramic ground material demonstrated interesting phenomena as it work as efficient storage of thermal energy, which is released to the working fluid after the sunset. Stone has similar trend, but lower than the ceramic

After 4:00 pm, the efficiency started to reduce noticeably, where the solar radiation reduced to a value less than 320 W/m^2 and the maximum energy conversion was achieved around 12:00 pm, and the maximum solar intensity was recorded at 12:00 pm. While the materials are absorbing the solar radiation, they store considerable amount of thermal energy, which is released to the working fluid after a while. The maximum measured efficiency results are presented in table 1 and compared with the system efficiency at 12:00 pm and 4:00 pm.

Table 1: Predicted efficiency from the measurements at three different daytimes.

Radiation	Time	Efficiency (%)					
W/m²	Hourly	Ceramic	Sand	Pebble	Saw dust	Stone	DBPW
529.3	12:00	58.0	48.3	57.0	50.0	62.0	56.4
369.3	14:00	79.1	60.7	74.8	64.7	82.8	70.5
319.3	16:00	61.5	41.9	57.1	50.3	66.0	52.6

4.2 Numerical results

Velocity field: After considered all of the cases, the velocity contours for each ground materials at the various times (9:00 am, 12:00 pm, 3:00 pm, and 6:00 pm) during the day show that there is a change in the air flow. Figure 4 shows a simple example for these contours which represents the velocity distribution in the collector and chimney for stone material at 9:00 am. Whilst, Figure 5 shows the velocity distribution at the chimney inlet (section (A–A)) for each ground material.

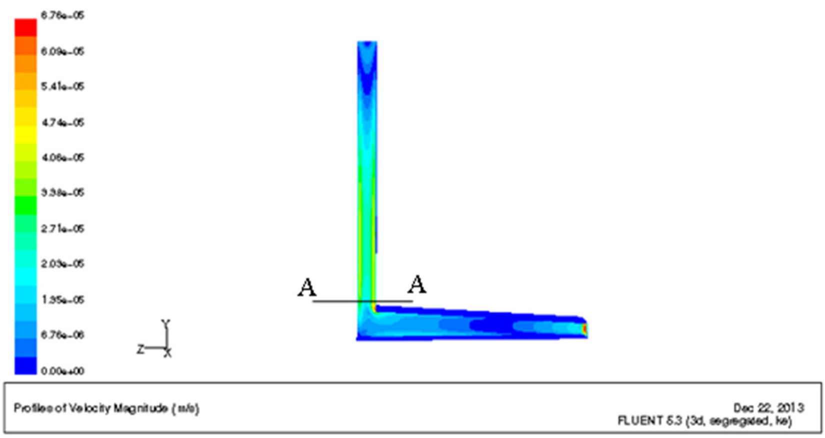


Figure 4: Show the velocity distribution in the collector and chimney for the stone material at 9:00 am.

Figure 5 shows how the velocity magnitude increases within the chimney zone as a result of increasing heat transfer to the air from the energy storage in the ground materials. Noticeable in the section (A–A), the air flow behavior changes as the range growth of the flow from entrance length (developing profile) fully develops.

However, the sequence for the variable velocity through the times of 9:00 am, 12:00 pm, and 3:00 pm is Dark Green Painted Wood (DGPW), Stone-Saw Dust, Stone-Dark Green Painted Wood (DGPW), Ceramic and Stone–ceramic–Pebble, respectively.

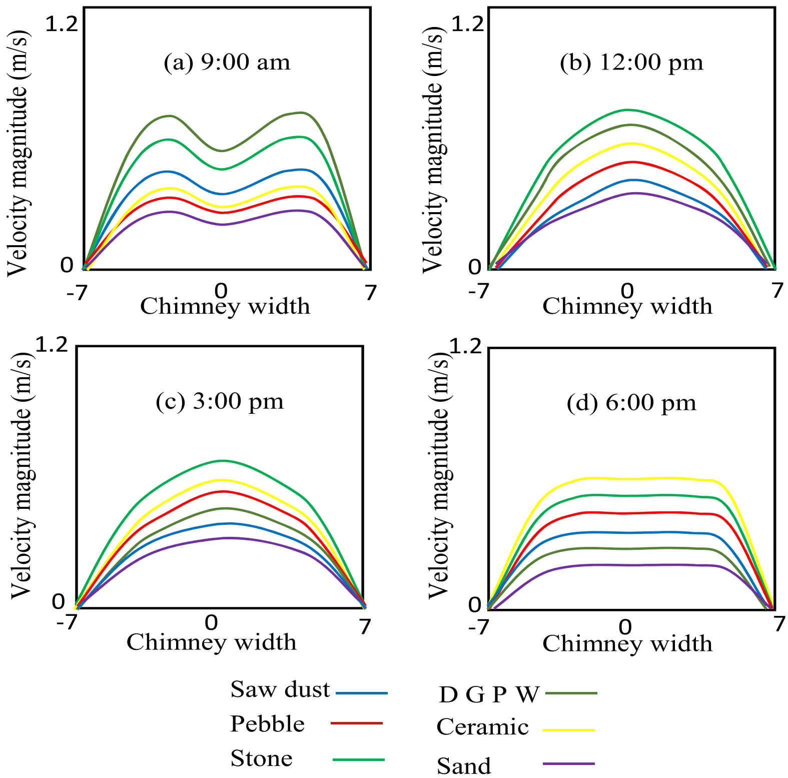


Figure 5: The velocity distribution at section (A–A) in the inlet of the chimney at 9:00 am, 12:00 pm, 3:00 pm, and 6:00 pm.

Noticeably, there is an increase in the efficiency for the materials dark green painted wood (DGPW), ceramic, black stone, and saw dust. Whilst, Figure 5(d) shows the values of velocity at 6:00 pm as a sequence Ceramic-Stone-Pebble. So from these results it can be found that ceramic is the best material for the absorptivity and emissivity of the energy during the length of the whole day.

Temperature field: As maintained above in velocity field the temperature contours for each ground materials show that there is a change in the temperature distribution. Figure 6 shows a simple contour of the temperature distribution in the collector and the chimney with ceramic basement at various times (9:00 am, 12:00 pm, 3:00 pm, and 6:00 pm).

The noticeably for temperature and velocity will be maximum at 12:00 pm at the maximum intensity 529.3 W/m^2, where temperature 40.25°C and the velocity was 0.67 m/s, after that both of them will be decrees at the intensity will be below from 320 W/m^2, as shown in Figure 7, which it illustrate the results for both numerical and experimental for the stone.

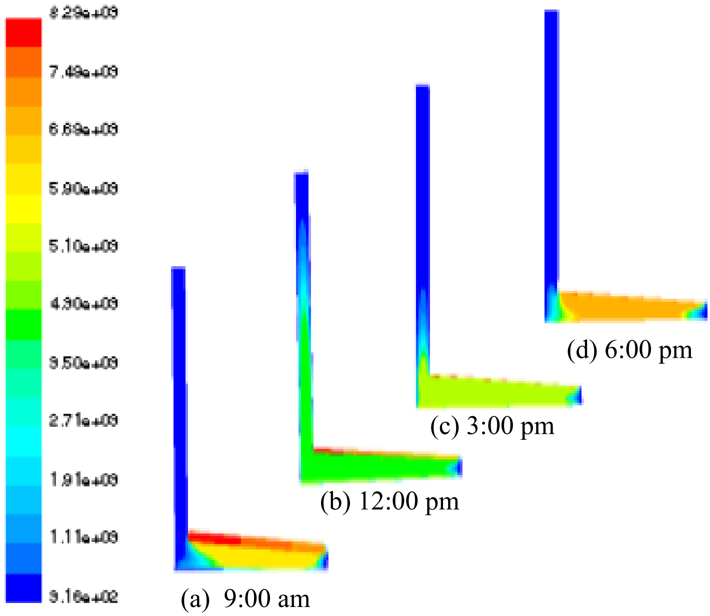


Figure 6: The temperature distribution counters for ceramic.

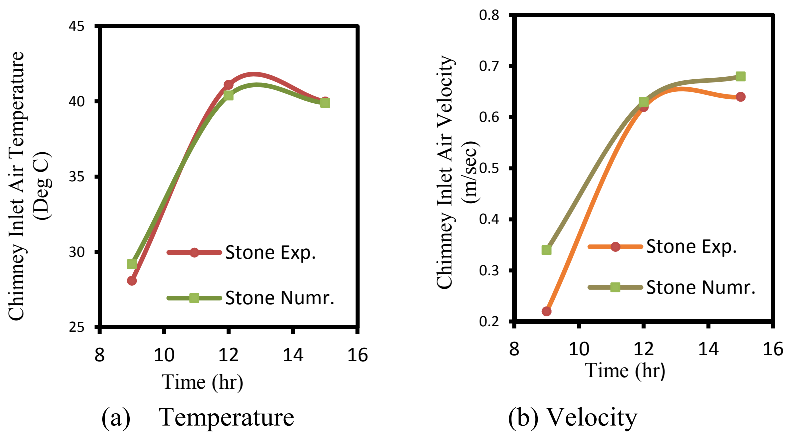
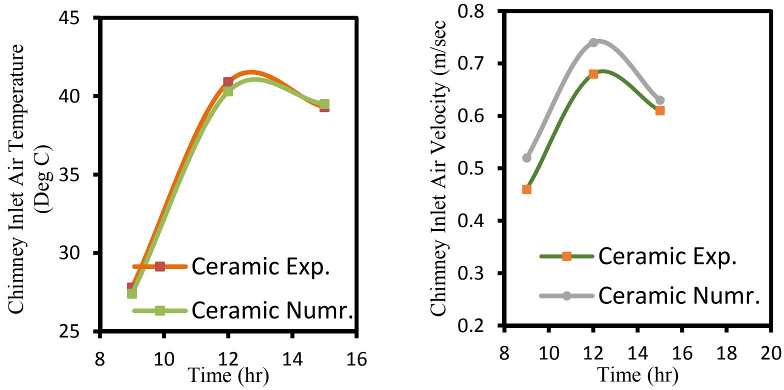


Figure 7: The temperature distribution and the velocity for the stone material at inlet chimney.

Figure 8 illustrates the results for both numerical and experimental work for the ceramic material, where the maximum value of the temperature 40.80°C and the velocity 0.69 m/s at 12:00 pm at the maximum intensity 529.3 W/m^2 and decrease at intensity less them 320 W/m^2.



(a) Temperatures (b) Velocity

Figure 8: The temperature distribution and the velocity for the ceramic material at inlet chimney.

5 Conclusions

During the experimental and numerical analysis of the solar chimney system, the different materials which have different absorptivity properties with the darker material being closer to a black body are considered. In this study different materials are tested in a similar environment and their performances are determined based on the data collected. All of the material candidates to be tested are of natural resources and available locally in Malaysia. These data then analyzed to determine the efficiency of the collector using a particular ground material. This is scaled down experiment as the objective of the experiment is mainly focused on the ground material performance rather than the solar chimney system itself. From the above it can be concluded that.

The different materials that have the same potential energy can be used in a similar environment and their performances are determined based on the data collected. In the mid-day from (12:00 pm–3:00 pm) it can be seen that the stone store the heat and released after a 3:00 pm. The best materials that have higher efficiency in the night is a ceramic as a result of ability of this material to absorb the radiation hitting it without any being reflected or transmitted. From the results, it demonstrated that the numerical and experimental analogues are in good agreement.

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