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# Enhancing the Performance of a Laboratory-scale Solar Chimney by Geometric Modifications

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**ABSTRACT**

High energy demand and severe environmental pollution due to extensive use of fossil fuels are among the most important issues that modern human has encountered recently. Renewable energies can mitigate the energy and pollution crisis to an extent. Solar energy is the most promising form of renewables for the countries with high levels of solar radiation. Among the solar energy technologies, solar chimney represents a simple and relatively low-cost concept of energy conversion. However, the major drawback of such a technology is its low performance and efficiency. A lot of geometric modifications have been made to the solar chimney systems. In this paper, the effect of radial guide vanes were tested on the overall performance of a laboratory-scale solar chimney. A solar simulator was developed for this study and the chimney was tested at three radial vane configurations: no-vane, 4-vane and 8-vane. The experimental data were utilized to find the suitable curve fitting models. After extracting the best fitted curves, they were used to calculate velocity and power in 3 different temperature difference levels for each vane configuration. The results of this study indicated that the 8-vane configuration had the highest effect on power and could averagely increase it by 75%.

## 1. Introduction

The scarcity of available energy resources has been further aggravated by the ever-increasing of the world energy demand. In addition, current energy production from coal and oil is damaging to the environment and non-renewable [1]. Solar energy is one of the most promising solutions, especially considering its technological advancements and its growth in the recent years [2].

A Solar Chimney Power Plant (SCPP) offers interesting opportunities to use pollution free resources of energy. SCPP technology, designed to produce electric power on a large-scale, utilizes solar energy to generate buoyancy flow that drives wind turbines to produce electric power [3].

The main components of a SCPP are: a) a transparent collector which enables the sunlight to pass through and heat up the ground; b) a chimney (or tower) to produce the stack effect and induce a buoyancy-driven airflow and; c) a turbine to convert the airflow energy to electricity.

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Fig 1. The solar chimney prototype plant in Manzanares, Spain [4].

This original idea of solar power generation was first proposed in 1903 by the Spanish engineer I. Cabanyes and then it was described in the futurological work of the German H. Günther in 1931. Starting in 1982, the German engineering professor J. Schlaich erected the first prototype SCPP in Manzanares/Spain (Fig. 1) [5].

The results from the conducted tests showed that the prototype plant operated reliably and the concept was technically viable. Since then several studies on solar chimney power plants have been carried out. One common finding in the literature is that the plant efficiency is very low, and that it increases with the plant size [6]. In other word, power production is a function of collector radius and tower height. However, the efficiency is very much related to chimney height only.

Many researchers have attempted to tackle this drawback. They started to modify and optimize the geometry of the collector and chimney in order to have an enhanced airflow and higher updraft velocity. Here is a brief review on the geometric modifications conducted on solar chimney power plants.

In 2013 Koonsrisuk and Chitsomboon used CFD technology to investigate the changes in flow properties caused by the variations of flow area (Fig. 2). It was found that the sloping collector roof affected the plant performance. The divergent-top chimney led to augmentations in kinetic energy at the chimney base significantly. The proper combination between the sloping collector roof and the divergent-top chimney could produce the power as much as hundreds times that of the conventional solar chimney power plant [6].

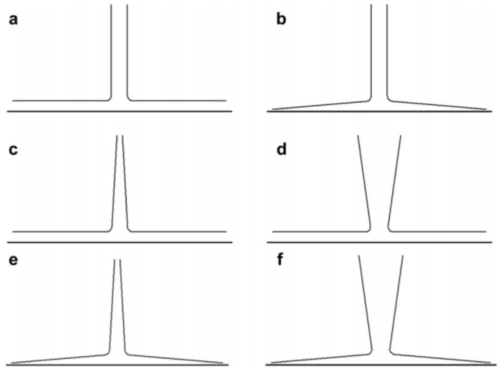


Fig 2. Schematic layout of a reference plant (a) and various geometries (b-f) studied in [6].

In 2016 Hu *et al.* examined the impact of the guide wall (GW) geometry on the power output of a solar chimney. A reduction in mass flow rate after adding a GW in the system was observed in a small-scale experimental prototype. Numerical simulations on a large-scale SCPP further found that the mass flow rate was linearly and inversely proportional to the increase of GW height. The driving force, however, nonlinearly increased with increasing the GW height. Subsequently, the potential maximum power output, which was mainly governed by the driving force, increased with increasing the GW height [7].

In 2016 Ohya *et al.* developed a diffuser-type tower instead of a cylindrical tower (Fig. 3), and investigated a suitable diffuser shape for practical use. After changing the tower height and diffuser open angle, with a temperature difference between the ambient air aloft and within the collector, various diffuser tower shapes were tested by laboratory experiments and numerical analyses. As a result, it was found that a diffuser tower with a semi-open angle of 4° is an optimal shape, producing the fastest updraft at each temperature difference in both the laboratory experiments and numerical analyses [8].

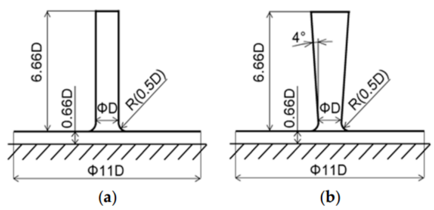


Fig 3. (a) Cylindrical type tower; (b) Diffuser type tower [8].

In 2016 Cottam *et al.* studied the impact of different collector canopy designs (Fig. 4) on the performance of the solar chimney. Their results showed that the height of the canopy had a significant effect on plant performance and that the canopy required to be sufficiently high at the junction to the chimney to ensure maximum kinetic energy in the flow at the chimney inlet can be reached [9].

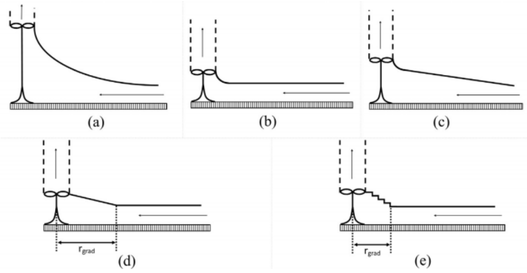


Fig 4. SCPP collector canopy profiles: (a) exponential; (b) flat; (c) constant-gradient sloped; (d) segmented; and (e) segmented & stepped [9].

In 2016 Ming *et al.* developed three numerical models to explore the impact of ambient cross wind on large-scale SCPPs. Three large-scale SCPPs with similar configurations were investigated: one with a conventional horizontal canopy; one with a familiar sloped canopy design; and one with eight radial partition walls (RPWs) uniformly distributed under the collector canopy. The models were used to evaluate the effects of cross wind on the fluid flow and heat transfer processes under various environmental conditions. The results indicated that both the sloped canopy with a lower collector inlet and the RPWs designs were effective in improving the performance of a SCPP by reducing the amount of heated air escaping from the collector under cross wind [10].

In 2018 Hassan *et al.* conducted a parametric three dimensional computational fluid dynamics (CFD) analysis for a solar chimney power plant to illustrate the effects of collector's slope and chimney diverging angle on the performance of Manzanares prototype. Based on the computed results of their CFD model, it was discovered that both velocity and temperature increased with increasing collector's slope due to enhanced heat transfer and mass flow rate, but simultaneously higher collector slopes also deteriorated the smooth air flow by developing vortices and recirculation of air, which obstructs the air flow and may reduce the overall performance. In addition, chimney diverging angle = 1° rose the velocity from 9.1 m/s to a remarkable value of 11.6 m/s; therefore, this diverging chimney approach is conceived to be a beneficial tool in improving performance of solar chimney power plant [11].

The previous studies indicate that the geometric modification of collector and chimney can have significant effects on the flow and performance enhancement of the solar chimney power plants. In this experimental study, the effect of radial guide vanes, which form converging tunnels under the collector's canopy, was investigated.

It is assumed that those tunnels act like nozzles and help to have an enhanced airflow with higher velocity inside the chimney inlet.

## 2. Materials and Methods

In order to test a laboratory-scale solar chimney in a controlled environment and investigate the effect of radial guide vanes on its performance, a low-flux solar simulator system was designed and constructed in the Department of Biosystems Engineering at Ferdowsi University of Mashhad (Fig. 5).

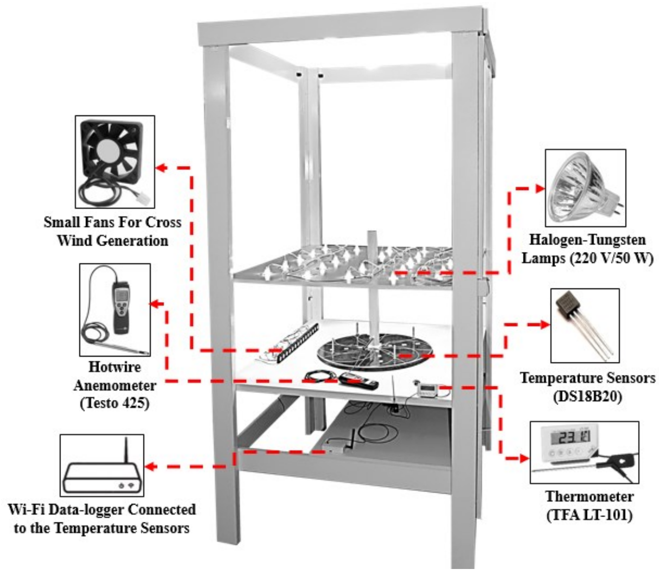


Fig 5. The solar simulator system (developed by authors) and its measuring units

This solar simulator system utilizes an array of halogen-tungsten lamps to simulate the sunlight. This type of lamps was chosen since they produce a light spectrally similar to sunlight, they have excellent light output and relatively low cost [12].

In this simulator, the lamps elevation can vary between 0-150cm. Increasing the elevation results in a lower *nonuniformiy* and weaker *irradiation*. An optimum elevation of 45 cm was chosen to test a solar chimney. A Solarimeter (Standard 1307) was used to measure the irradiation at different points of the test surface at this elevation. The optical properties of the simulator are listed in Table 1.

- Non-uniformity [13]

$$\tau = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \times 100 \quad (1)$$

- Conversion Efficienrcy [12]

$$\eta_c(\%) = \frac{Total\ output\ flux}{number\ of\ lamps \times \frac{lamp\ power}{target\ area}} \times 100 \quad (2)$$

Table 1. Optical propeties of the simulator

| Average Irradiation | Nonuniformity (Eq. 1) | Conversion Efficiency (Eq. 2) |
|---|---|---|
| $I = 224\left(\frac{W}{m^2}\right)$ | $\tau$ =16.41 (%) | $\eta_c$=18.7 (%) |

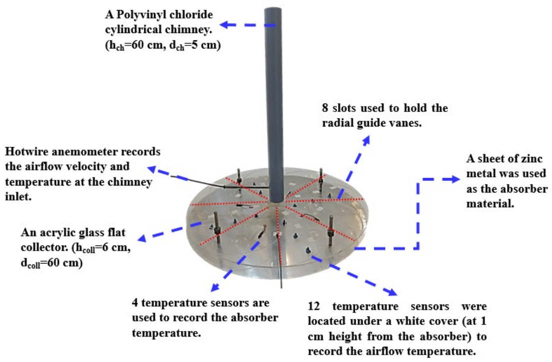


Fig 6. The solar chimney setup

A laboratory-scale solar chimney setup (Fig. 6) was also developed to investigate the effect of radial guide vanes on the overall performance of solar chimney. Its chimney has 60 cm height and 5 cm diameter, which is in agreement with the height-to-diameter ratio ($h_{chimney}/d_{chimney}$=12) proposed by Kashiwa *et al.* [14].

The collector has 8 radial slots to hold the radial guide vanes. These slots are distributed around the collector with equal angular distance = 45° (dotted red lines in Fig. 6).

Airflow and absorber temperatures were measured with 16 temperature sensors in the collector's canopy. A hotwire anemometer was also used to measure the airflow velocity and temperature at the chimney inlet.

Schlaich *et al.* [4] showed that in a solar chimney without turbine, the whole pressure difference is used to accelerate the air and is thus converted into kinetic energy, so the total power, $P_{tot}$ , equals to:

$$P_{tot} = \frac{1}{2}\dot{m}v_{chimney,max}^2 \quad (3)$$

Where $v$ is the maximum airflow velocity and $\dot{m}$ is the mass flow rate inside the chimney and is calculated by:

$$\dot{m} = \rho_{air}.A_{chimney}v_{chimney,max} \quad (4)$$

then, the total power is calculated as follows:

$$P_{tot} = \frac{1}{2}\rho_{air}.A_{chimney}v_{chimney,max}^3 \quad (5)$$

In this experimental study, the buoyancy flow is driven by the temperature difference, $\Delta T$, between the absorber plate temperature, $T_2$, and ambient temperature, $T_1$, ($\Delta T = T_2 - T_1$).

The solar chimney setup was tested at three radial vane configurations: no-vane, 4-vane and 8-vane for an hour under the solar simulator system.

Airflow velocity inside the chimney, average absorber plate and ambient temperatures were recorded and the total power was calculated using Eq. 5.

## 3. Results and Discussion:

Fig. 7 and 8 show velocity and power vs. temperature difference. From these diagrams, it is evident that the radial guide vanes had significant effect on the overall performance.

Using the curve fitting tool in MATLAB, the best curves that fitted the data points were found.

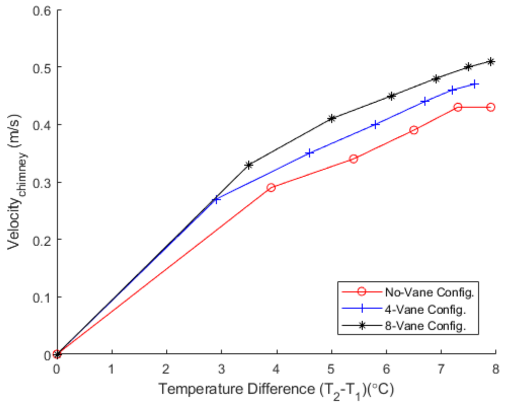


Fig 7. Airflow Velocity at chimney inlet vs. Temperature Difference at three vane configurations.

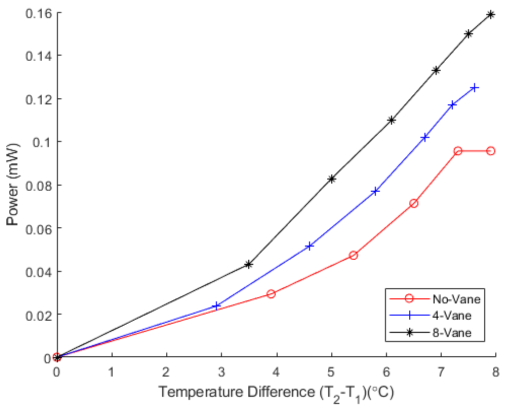


Fig 8. Variations of power in terms of temperature difference at three vane configurations.

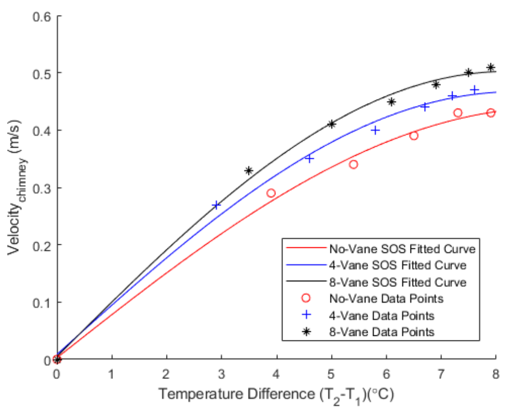


Fig 9. Sum of Sine curve fitted on the velocity-temperature difference of data points.

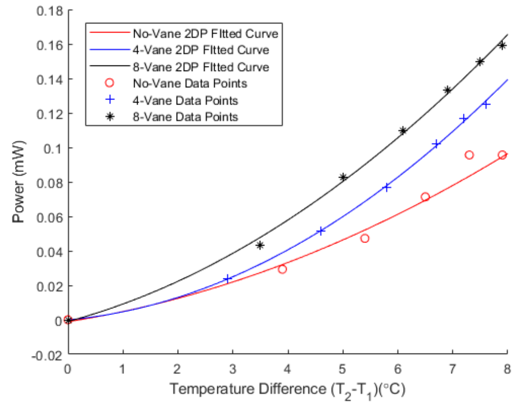


Fig 10. Second Degree Polynomial curve fitted on the power-temperature difference data points.

The best models that fitted the velocity-temperature difference and power-temperature difference data points were found to be Sum of Sine and Second Degree Polynomial, respectively (Fig. 9 and 10).

Table 2. Equations of the best fitted curves

| | | |
|---|---|---|
| **Velocity vs. temperature difference** | No-Vane | $V0 = 0.4401\sin(0.172\Delta T + 0.006148)$ |
| | 4-Vane | $V4 = 0.467\sin(0.1855\Delta T + 0.01842)$ |
| | 8-Vane | $V8 = 0.5022\sin(0.1905\Delta T + 0.009866)$ |
| **Power vs. temperature difference** | No-Vane | $P0 = 9.035e-4\Delta T^2 + 4.967e-3\Delta T - 1.09e-3$ |
| | 4-Vane | $P4 = 1.82e-3\Delta T^2 + 2.879e-3\Delta T - 3.644e-05$ |
| | 8-Vane | $P8 = 1.524e-3\Delta T^2 + 8.619e-3\Delta T - 9.738e-4$ |

The equations of the best fitted curves (Table 2) were used to calculate the performance parameters (i.e. velocity and power) in 3 temperature difference levels (2, 4, 8 °C) for each vane configuration (Table 3.).

Table 3. Velocity and power for each configuration at 3 temperature difference levels

| Performance Parameters | No. of Vanes | $\Delta T = 2$°C | $\Delta T = 4$°C | $\Delta T = 8$°C |
|---|---|---|---|---|
| **Velocity (m/s)** | No-Vane | 0.1510 | 0.2815 | 0.4323 |
| | 4-Vane | 0.1773 | 0.3219 | 0.4659 |
| | 8-Vane | 0.1913 | 0.3503 | 0.5019 |
| **Power (mW)** | No-Vane | 0.0125 | 0.0332 | 0.0965 |
| | 4-Vane | 0.0130 | 0.0406 | 0.1395 |
| | 8-Vane | 0.0224 | 0.0579 | 0.1655 |

Since power is a more critical performance parameter, its increase percentage was calculated for the 4 and 8 vane configurations in reference with the no vane configuration. Results indicated that the 8 vane configuration could averagely increase the power by 75% (Fig. 11).

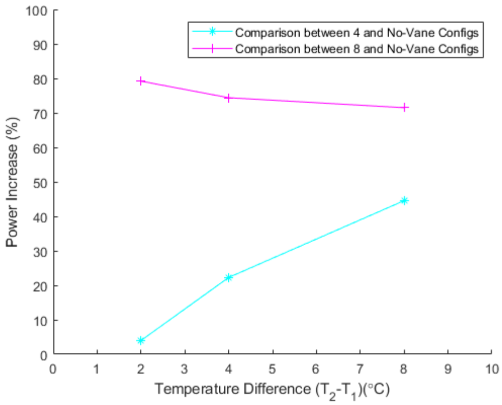


Fig 11. Power Increase (%) vs. Temperature Difference for 4 and 8-vane configurations in reference with the no-vane configuration.

## 4. Conclusion

The objective of this study was to investigate the effect of radial guide vanes on a solar chimney performance parameters (i.e. velocity and total power). A solar simulator and laboratory-scale solar chimney was developed fot this purpose.

The solar chimney was tested in 3 configurations: no vanes, 4-vane and 8-vane. The test results were used to find the best curve that fitted the velocity and power vs. temperature difference diagrams, where Sum of Sine (SOS) and Second Degree Polynomial (2DP), respectively, were chosen as the suitable fitting models.

These models were implemented to extract the velocity and power at 3 different temperature difference levels for different vane configurations.

Results indicated that the 8-vane configuration had the highest effect on the performance parameters and could averagely increase the power by 75%.

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