Experimental assessment of energy tower performance

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Research Article

Keywords: Energy Tower, Humidafication, Solar Chimney, Airflow velocity, Chimney effect

Posted Date: October 28th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-2110242/v1

Abstract

Solar energy is one of the most feasible options to produce energy in countries where unexploited desert areas or solar radiation are abundant. An energy tower is an effective system for electrical power generation that can perform more efficiently along with solar radiation. in this study, the efficiency of the energy tower system is investigated experimentally by an indoor fully adjustable apparatus. In this regard, a comprehensive set of influencing parameters like air velocity, humidity, and temperature and the effects of tower height on the performance of the energy tower is individually assessed. Based on the obtained results, by increasing humidification, the temperature difference increased between the inlet and outlet of the energy tower. In addition, the more the temperature difference between the inlet and outlet, the higher the airflow velocity in the outlet. The kinetic energy increases in the direction of airflow from top to bottom, and as the height of the tower lengthens, the kinetic energy enhances and subsequently increases the overall efficiency of the tower. Although the energy tower performs efficiently in the nighttime, airflow velocity increases averagely about 8% during the daytime and at the peak of the solar radiation, the airflow velocity enhances by 58% compared to nighttime.

1. Introduction

With the rapid world population growth, the consumption of fossil fuels for energy production has increased, which has led to an escalation in pollution from fossil fuel burning. Due to the limitations of fossil fuel usage and the resulting problems, developing countries, in recent years, have considered substituting fossil fuels with new energy references. The purity and renewability of these resources are their most important advantage. Solar chimneys and energy towers are new methods for generating power based on changing air density.

The main concept of the solar chimney was introduced in 1931 by Hans Günter(Kasaeian, Ghalamchi, and Ghalamchi 2014). The first solar chimney prototype with a height of 195 meters and a collector radius of 120 meters was designed and built by Huff et al.(Haaf 1984; Haaf et al. 1983) in Manzanares, Spain, and in 1990 and 1995, Schlaish discussed the generalizability of the results obtained from the Manzanares Prototype(Schlaich 1995). As shown in Fig. 1.a the sun radiates to air and ground under the collector, which heats the trapped air and subsequently decreases air density. Due to the air density difference between the inlet and outlet of the chimney and the buoyancy effect, the hot air moves upwards and causes the implemented turbine to move and generates energy.

Various studies have been performed to evaluate the effect of different parameters on solar chimney efficiency. The effect of different collector angles on the solar chimney's performance has been done mathematically(Hoseini and Mehdipour 2018) and experimentally(Hoseini and Mehdipour 2020). In addition, the effect of chimney height on different geometries(R Mehdipour, Golzardi, and Baniamerian 2020) and the effect of humidity in collector inlet(Ramin Mehdipour et al. 2020) has been reviewed, and solar chimneys' thermal and exergy evaluation has been studied using an experimental model(Ramin Mehdipour et al. 2021). These shreds of evidence show that the solar chimney in its typical geometry is not efficient, so another model for solar chimney has improved its performance(Golzardi, Mehdipour, and Baniamerian 2020). Contrary to the existing theoretical modeling, which shows that the solar chimney had an excellent performance, in the experimental samples, the proper performance of the solar chimney has not been reported. As a result, another technology (energy tower) has been presented, and its performance is analyzed in this study (Fig. 1).

Energy tower is another technology of energy production utilizing air density alteration. Unlike other solar technologies that require solar collectors and function in limited hours of a day, energy tower can be employed 24 hours a day at different efficiencies(Omer et al. 2008; Zaslavsky 1999). The temperature difference between the inlet and outlet and the humidity of the surrounding air are the essential parameters in this system that significantly impact its efficiency. Independency on direct solar radiation is the advantage of an energy tower over a solar chimney(Lucier 1979).

The resemblance of the energy tower and SCPP are geometrically identical, and the function of the chimney is the same in both technologies, while functional principles are not alike. Unlike the solar chimney, cold and heavy air and its downward flow produce power in this method. As shown in Fig. 1-b, the airflow in the energy tower is in the opposite direction of the solar chimney from top to bottom. The hot air is cooled by the water sprayed above the tower, leading to downward airflow due to increased air density. The warmer the water spray generates the air above the tower, the more current and energy are generated, so the temperature difference significantly affects system performance. This current downward moves the turbine inside the tower and generates electricity.

After Carlson, who first introduced energy tower technology(Carlson 1975), Asaf and Bruniski et al.(Assaf and Bronicki 1989) in 1989, and Zaslawski et al.(Zaslavsky et al. 2003) in 2003 provided models and investigated the tower's performance, and the airflow in and around the tower was numerically simulated(Mezhibovski 1999). This technology has been used in other areas such as desalination(Altman et al. 2005) and evaporative cooling towers(Pearlmutter, Erell, and Etzion 2008), which are efficient in air conditioning and cooling. No greenhouse gas emissions and dust(Zwin 1997) made the energy tower one of the promising technology to generate electricity compared to other existing systems. It is demonstrated that the best performance of energy towers is in arid and semi-arid places(Altmann et al. 2005) and is not dependant on direct sunlight(Omer et al. 2008; Zaslavsky 1999).

Due to the lack of experimental study on the energy tower, the novelty of the present study is to examine the experimental performance of the energy tower. In this study, all experiments were performed in in-door conditions to control the environmental condition, and solar radiation was simulated with a heater installed at the bottom of the grand. In the present study, the impacts of three diverse independent parameters, tower height, temperature difference alongside the tower, and humidity level, on the total performance of the energy tower were investigated.

2. Method And Materials

2.1 Energy tower structure and equipments

An experimental model was designed and built to meet the purpose mentioned in the last section, as shown in Fig. 2. The Two-Part chimney was designed to enable users to adjust chimney height at their desire. A humidity tank was placed at the top of the chimney to spray water at different inputs. Four heaters were embedded in the system's bottom under the aluminum plates to simulate solar radiation (day condition). To lessen the energy loss, all heaters were placed on adiabatic plates. Twelve sensors (Sunward 15-T1) with an accuracy of 0.1 were utilized to monitor the heat map on the aluminum plates, as shown in Fig. 2. The velocity and temperature were measured using a speedometer (ANEMOMASTER LITE model 6006-0G) with an accuracy of 0.01, a thermometer (ST-1A) with an accuracy of 0.1, and a thermometer (HTC-2) with an accuracy of 1 degree. The HTC-2 hygrometer measures the humidity created on the top of the chimney with an accuracy of 1%. All the measuring points are demonstrated in Table 1.

2.2 Experiments procedures

In this study, the experiments were adjusted and executed according to the environmental conditions. Two critical parameters of the environment are the specific humidity in the air and the ambient temperature. The lower the humidity of the environment, the more the humidity of the ambient air is absorbed. Also, different ambient temperatures, which cause differences in temperatures of the system, cause changes in system efficiency due to the direct effect of the temperature difference between the inlet and outlet. The experiments were performed at various set-ups at different humidifying powers, heating inputs, and chimney heights (Table 2 & Fig. 3). The effects of alteration in tower height, inlet moisture flow rate, and amount of solar radiation have been studied to inspect the changes in the generated kinetic energy. Three sets of experiments have been performed.

Table 1
Used sensors and their location in present energy tower model

Sensor Type	Specification	Sensor Location (Fig. 2)
Speedometer	ANEMOMASTER LITE model: 6006-0G	A,B,C,D
Thermometer	ST – 1A	A,C
	Sunward 15-T1	Points: 1 to 12
Hygrometer	HTC-2	E,F

Since a closed space (In-door) was considered for the system, a controllable set of heaters has been used to simulate the solar radiation emitted to the energy tower system. As long as the heater was on, the solar energy conditions simulated day time, and when the heater was off, we mimicked the night time. These experiments were performed at a constant height, humidity flow, and variable heating power. These experiments were performed at intervals of 30 minutes, and the data was recorded until the system reached a steady state.

Experiments on changes in humidifier flow, which cause different volumes of moisture to enter the system inlet, have been performed at a constant height to measure the alteration in kinetic energy due to changes in the amount of moisture entering the system. In each test, the time interval between each data set measured from the system to the convergence stage is 5 minutes. All data were recorded at these intervals until the system reached a steady state.

Chimney's height-related experiments, which cause different suctions in the system, have been performed at a constant flow rate of the humidifier at different chimney heights to observe the effects of height change on kinetic energy. At each chimney's height, the time interval for recording different variables was 5 minutes, and the test was continued until the alteration of airflow velocity was fully converged.

In the present study, effective parameters such as air humidity, chimney height, and the amount of solar radiation on the efficiency of the energy tower are investigated. The system's performance in both transient and steady states is investigated in the following.

Table 2
Three sets of experiments

Experiments	Tower Height (cm)	Humidifier Power (mL/s)	Heater Power (W)
Variable Height	180–207–225–250	0.0605	1000
Change in Humidifier Power	207	0.0460 – 0.0186–0.0123	1000
Change in Heater Power	207	0.0605	600–800–1000

3. Results

3.1 Transient Stage

In energy tower technology, the airflow is from the top of the chimney to the bottom, which is caused by the temperature difference created at the inlet and outlet due to the spray of water on the air. This current reaches a steady state in a short time, which is much less than solar chimney technology and is about 15 to 20 minutes (Ramin Mehdipour et al. 2021). In the transient stage, as it is shown in Fig. 4, the temperature difference between the inlet and the outlet gradually increases and as a result the air velocity increases continuously. The system efficiency is not sufficient until the air velocity reaches its maximum.

As shown in Fig. 4, at the beginning of the experiment, as the humidity increased, the temperature difference at the inlet and outlet of the chimney increased and continued until the heaters were turned off. After the heaters were turned on at the chimney outlet (bottom of the system), the humidity rose less intensely while no noticeable change in temperature difference. After turning the heaters on, humidity increased about 7% until system reached the steady state condition.

3.2 Simulation of day and night condition and effects of different radiation power

As stated earlier, the presence and absence of the heaters simulate solar radiation in day and night. As a result, by turning the heaters on, we simulated the solar radiation emitted to the collector of the energy tower, and when they were off, we mimicked the night condition. As it is obvious from Fig. 5.A, by moving along the chimney, airflow velocity gradually increased regardless of the status of the heaters (day and night condition). In addition, when the time passes and it reaches the steady state, airflow velocity was higher compared to the experiment initiations (Fig. 5.A). It is also shown that in day condition, and difference between initial and steady points decreased compared to night condition. In the nighttime, the airflow velocity difference between the initial and steady-state point measured 27.6%, while it was 6.5% in the daytime. Afterward, we investigated the difference in airflow velocity during day and night. It is demonstrated in Fig. 5.B that existence of solar radiation leaded to an increase in airflow velocity. Airflow velocity in the outlet of the chimney was higher about 8% compared to night condition in steady state (Fig. 5.B). Furthermore, we studied the impact of different solar radiation power on airflow velocity. It was found that the more solar radiation power, the more airflow velocity at all parts of the chimney (Fig. 5.C & 5.D). It was measured that airflow velocity increased about 58% for maximum heaters' power (1000 W) compared with nighttime. Figure 5.E indicates that more solar radiation power increased the temperature difference between the inlet and the oulet of the chimney which can be the main factor for increase in airflow velocity shown in Fig. 5.C. For maximum heaters' power, it is shown that temperature difference between the inlet and the outlet increased about 25%.

3.3 Synergistic effects of humidity and solar radiation

To study the effect of humidifying and solar energy on the function of energy tower, airflow velocity in the inlet (point A in Fig. 2), the outlet (point C in Fig. 2), and the middle of the chimney (point B in Fig. 2) were measured when the heaters were off and on. An increase in the humidifier's power means that more water will enter the airflow in a shorter time. As shown in Fig. 6.A, airflow velocity reached higher value for higher waterflow rate. To investigate the impacts of humidifier in day and night, airflow velocity was measured in two different status of the heaters (on & off). Similar to Fig. 5, existence of solar radiation decreased the difference between initial and steady points of the experiments. However, it is shown that airflow reached higher velocity in the presence of solar radiation (Fig. 6.C). In addition, the temperature difference between the inlet and the outlet of the chimney was increased in day condition (Fig. 6.B). As shown in Fig. 5, in both conditions (Heaters Off & Heaters On), airflow velocity in the outlet and the middle point is approximately the same and is much higher than the airflow velocity in the inlet. When the heaters were off, the temperature difference increased by raising the humidity in the inlet, which led to an increase in airflow velocity in the outlet and the middle point of the chimney. However, these increases in temperature difference did not affect the airflow velocity in the inlet. It has been seen that airflow velocity increased about 27.6% in the outlet of the chimney. When the heaters were on, no significant changes were seen in temperature difference as demonstrated in Fig. 5. In addition, there was no noticeable alteration in airflow velocity in these circumstances in all three points on the chimney (Fig. 5).

3.4 Airflow velocity alters dependent to the chimney's height

Previously, we investigated the impacts of solar radiation and humidifier powers on airflow velocity for a constant height of the chimney. In this case, we studied the effect of height alteration on energy tower efficiacy in day conditions for fixed power of humidifier, and the results were reported in the steady-state.

Although a gradual increase in the chimney's height slightly influenced the airflow velocity, it did not significantly change. As demonstrated in Fig. 7.A, Temperature difference between the inlet and the oulet of the chimney remarkably decreased by an increase in chimney's height. In addition, airflow velocity approximately increased about 2.7% for an increase in the chimney's height from 180 cm to 250 cm (Fig. 7.B).

4. Concluding Remarks

Energy tower was introduced as new candidate and proper alternative for fossil fuel since it can overcome solar chimney's downfalls. Unlike SCPP technology, solar energy is not a necessity for energy tower to function and this technology can operate in day and night with proper efficiency. In present study, we designed a similar prototype to actual energy tower system and evaluated its function experimentally in diverse situation. We chose the airflow velocity as dependant variable which directly impacts the kinetic energy of airflow velocity. Higher airflow velocity means higher kinetic energy utilized for turbine movement and subsequently means a higher potential for electricity production. It is well-established that temperature difference is a vital factor for airflow generation. On the other hand, we aimed to investigate the effect of humidity on airflow generation and velocity due to the nature of energy power. To investigate the energy tower function in day and night condition, four heaters were installed at the bottom of the chimney, and by altering the power of the heaters, we controled the amount of solar radiation emitted to the energy tower's collector.

We showed (Fig. 5) that in the absent of solar radiation, energy tower can operate properly which is an experimental proof that energy tower can operate suffiently for 24 hours. In addition, for higher heaters' power, the airflow velocity in the inlet, the middle, and the chimney outlet increased. Hence, existence of solar radiation increases the kinetic energy, which can improve the efficiency of the energy tower.

The use of humidifiers to increase the humidity above the chimney (the inlet) is one of the main requirements of energy tower technology. This creates an airflow from the top to the bottom of the chimney. As a result, the amount of water entering the airflow at the chimney inlet can affect the total performance of the energy tower. Hence, we executed the experiment for different humidifier powers to survey the humidity effect on airflow velocity and also studied the synergic effects of solar radiation and humidity on total efficiency of the energy tower. It is demonstrated (Fig. 6), by increasing the humidity in the air, the temperature difference between the inlet and the outlet increased, and subsequently, the airflow velocity increased at different points of the chimney with and without the presence of solar radiation. It means that regardless of day or night condition, energy tower has higher efficieny for higher humidifier powers. Besides, we witnessed that the existence of solar radiation impacts the effects of humidifier flowrate on the efficiency of the energy tower. In other words, solar radiation and humidifier had synergic effect on airflow velocity and energy tower efficiency.

Since the airflow developes through the chimney embedded at the center of the system, any changes in its length may affect the airflow regime and velocity. We demonstrated that for higher chimney's length, airflow reached more value for a constant humidifier and solar radiation power while, it decreased the temperature difference between the inlet and the outlet. This contrary result showed that chimney height have higher impact on airflow velocity than temperature difference.

To conclude, three parameters (solar radiation, humidity, chimney's height) are the most important and foremost reason for changing the airflow velocity. we also witness that airflow velocity alters through changes in temperature difference (between the inlet and the outlet of the chimney) and airflow regime (caused by chimney's height alteration).

Declarations

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

Conceptualization: Ramin Mehdipour, Zahra Baniamerian ; Methodology: Ramin Mehdipour; Formal analysis: Ramin Mehdipour, Mojtaba Habibi, Mohammad Eydiyan and Ehsan Mohammadi; Writing - original draft preparation: Ramin Mehdipour and Ehsan Mohammadi; Writing - review and editing: Ramin Mehdipour, Ehsan Mohammadi and Zahra Baniamerian; Funding acquisition: Ramin Mehdipour; Resources: Ramin Mehdipour; Supervision: Ramin Mehdipour

Ethical approval

The present Research doesn't involve Human Participants and/or Animals.

The authors consent to participae and publish.

The corresponding data and material are available if necessary.

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Figures

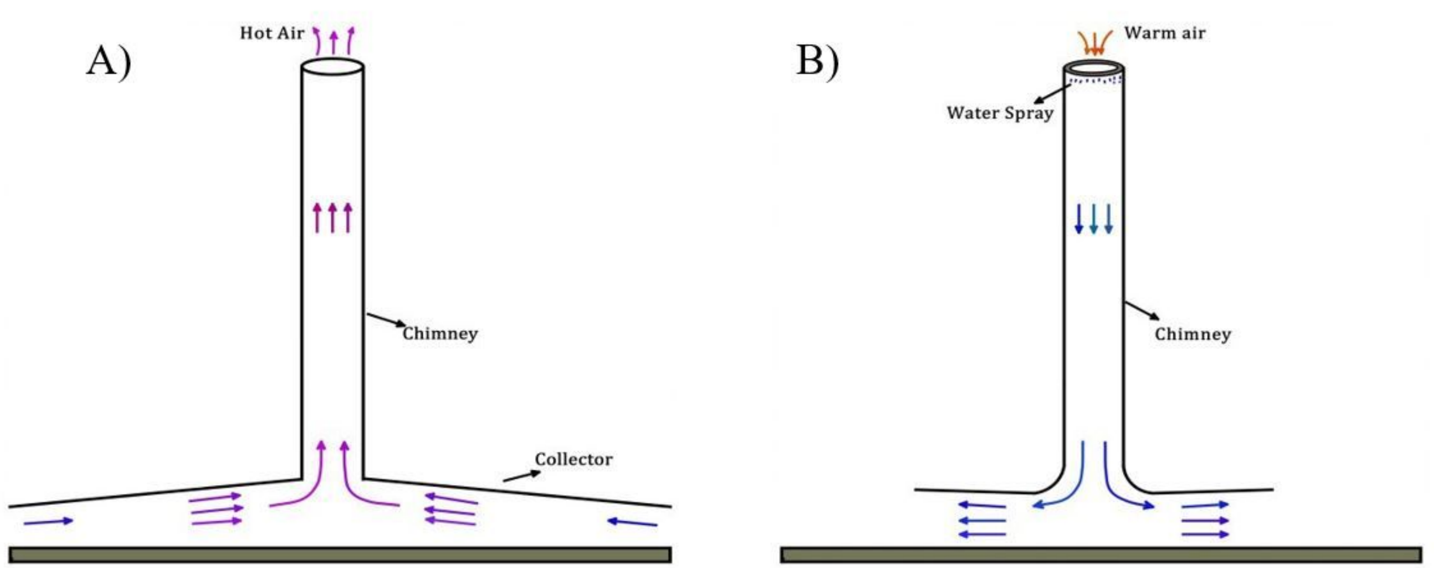
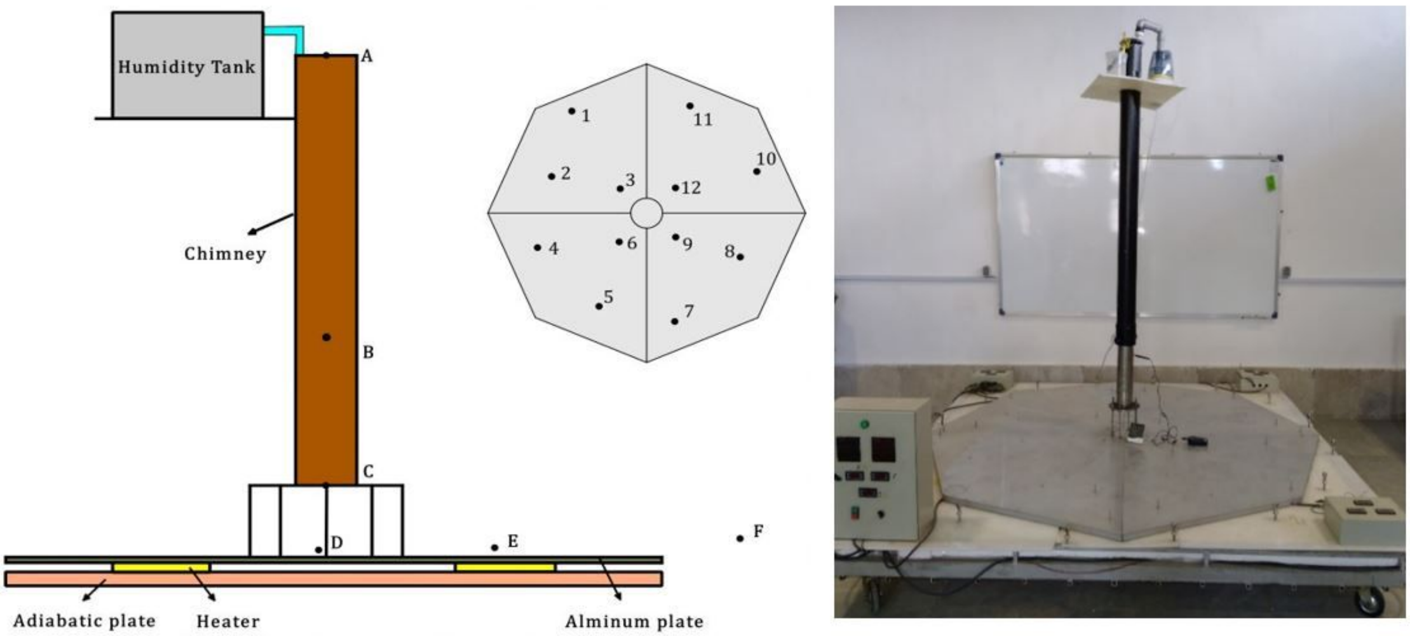


Figure 1

Schematic presentation of **A)** Solar Chimney Power Plant **B)** Energy Tower



	Points	1	2	3	4	5	6	7	8	9	10	11	12
Coordinate	X (cm)	140	175	155	205	175	145	85	65	95	40	65	90
	Y (cm)	25	65	95	145	175	155	195	175	140	95	65	85

Figure 2

Schemcatic and actual presentation of energy tower prototype used in present study and the location and coordination of 12 sensors on the aluminium plates

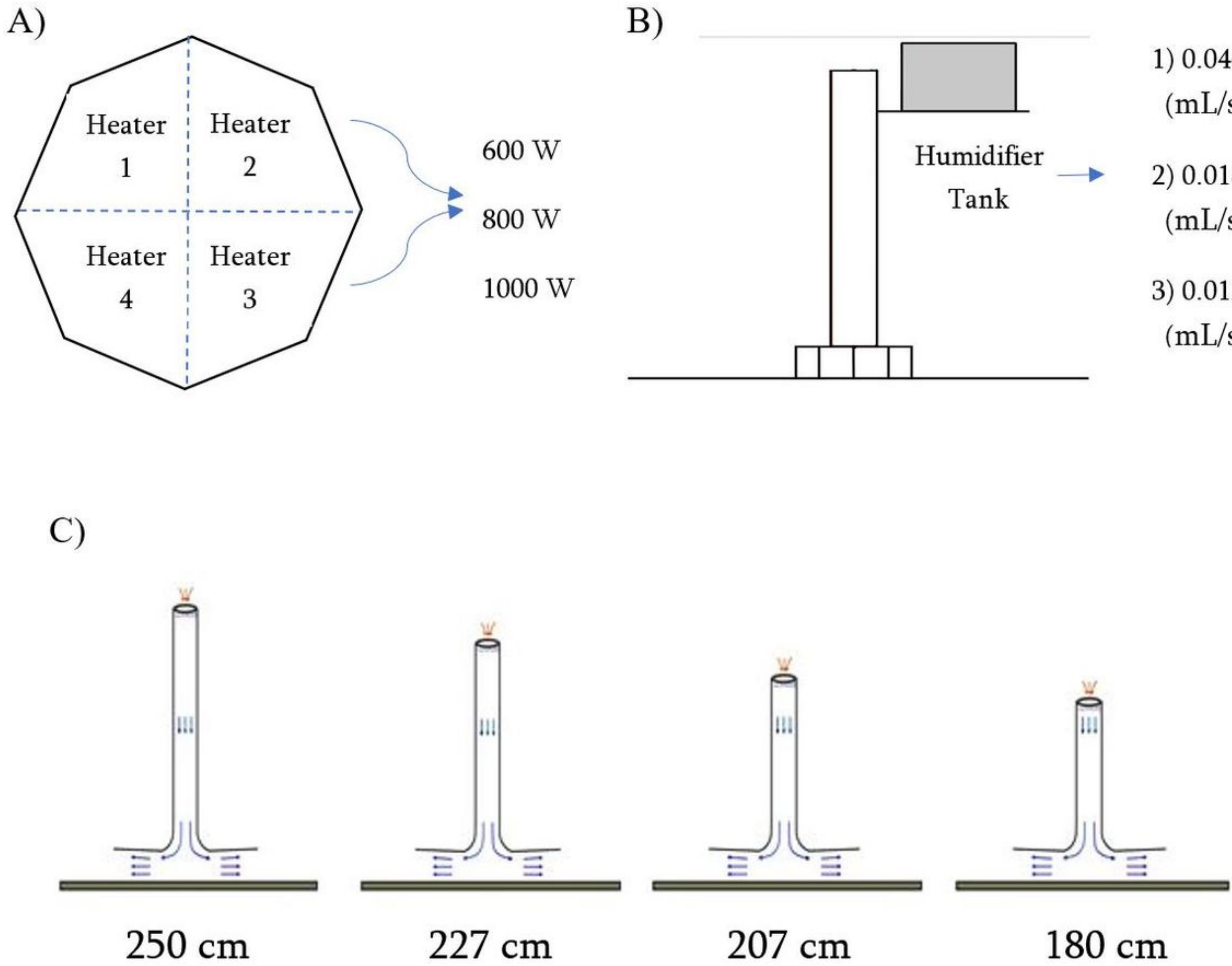


Figure 3

Representation of three different set-ups performed in the present study **A)** Three different heater's power **B)** different humidifier power **C)** Different chimney's height

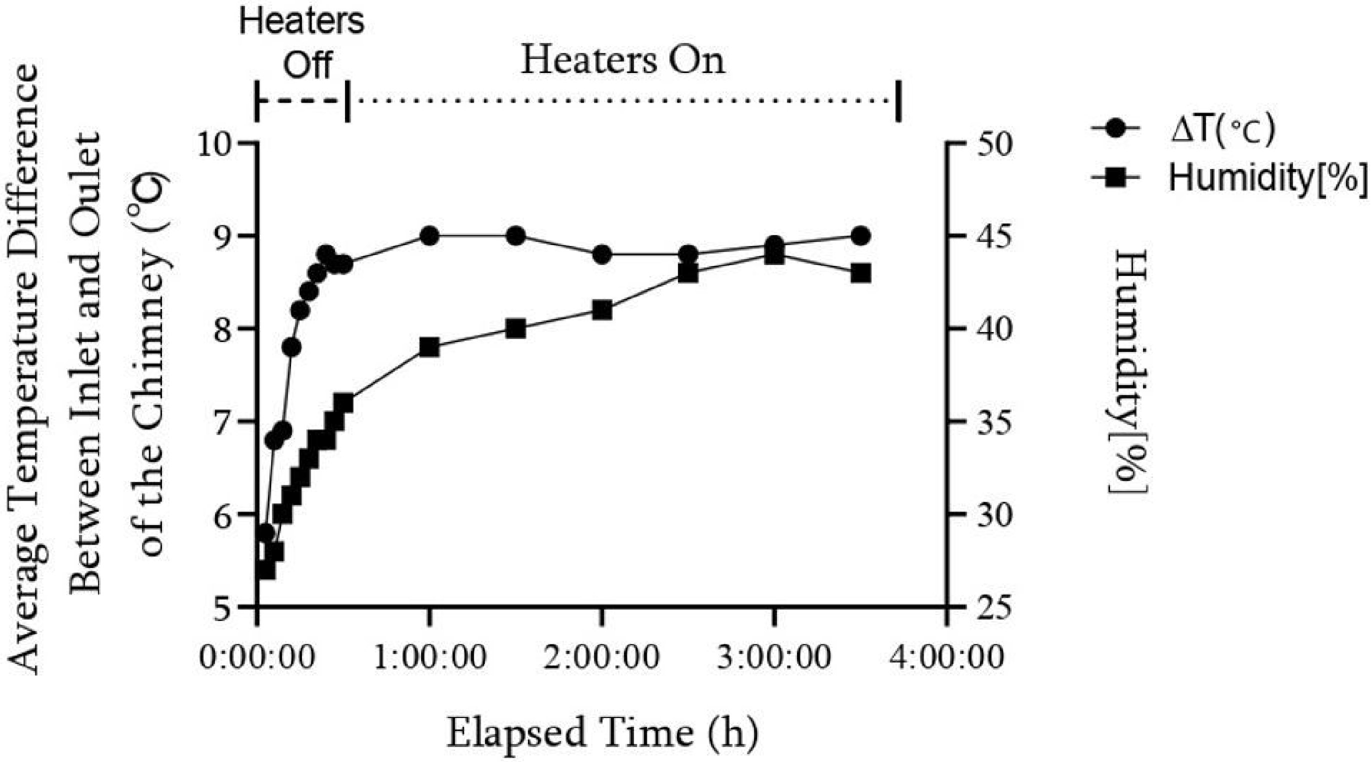


Figure 4

Humidity and temperature difference alteration from transient stage to steady stage

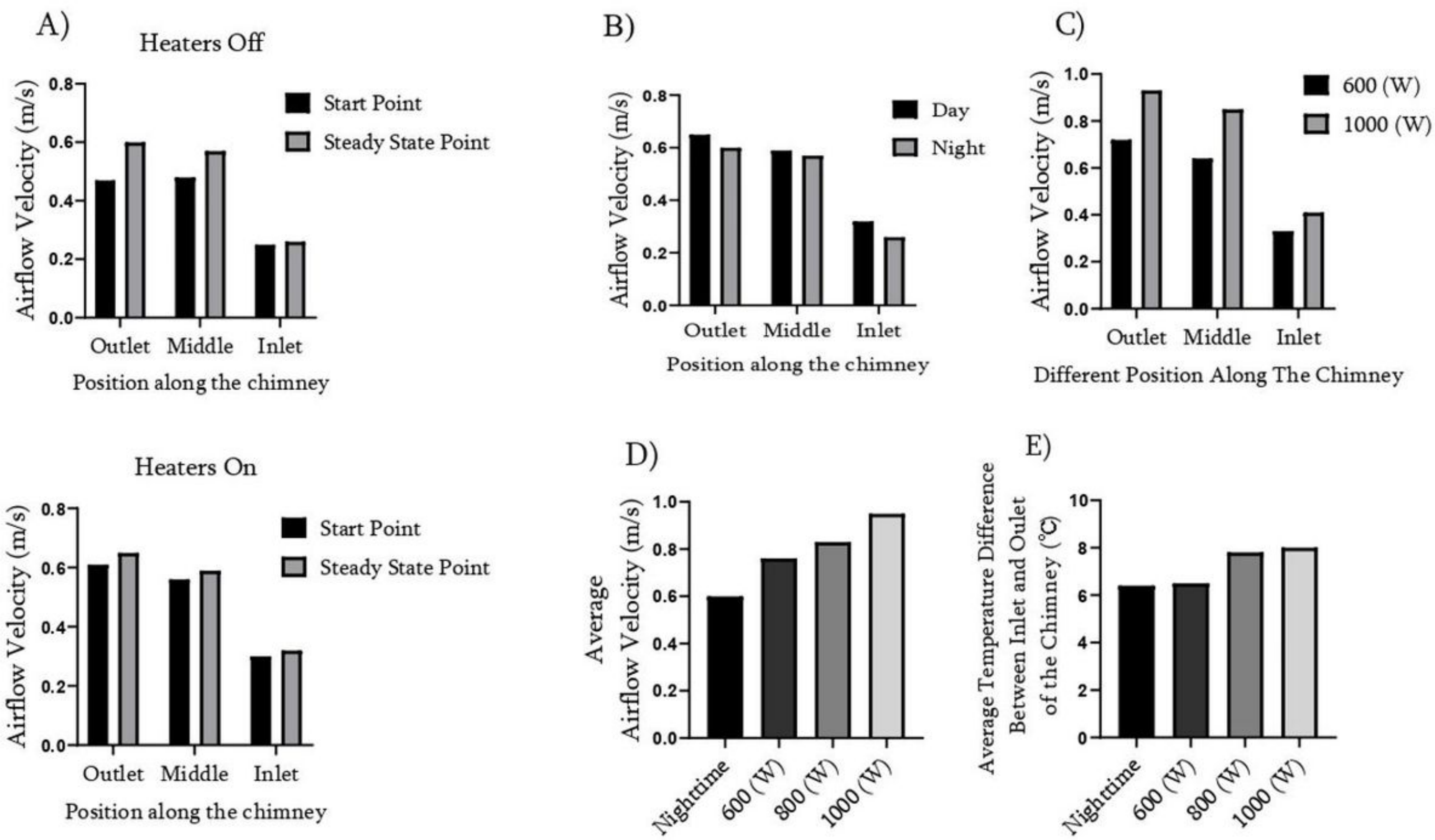


Figure 5

The investigation of the impact of different solar radiation status on airflow velocity, and temperature difference along the chimney. **A)** Comparing the airflow velocity at the initiation and end points of the experiment in both day and night condition **B)** Airflow velocity along the chimney in day and night condition **C)** The impacts of different solar radiation power on the airflow velocity along the chimney **D)** Airflow veloctity for three different solar radiation power **E)**Alteration in temperature difference for different solar radiation power

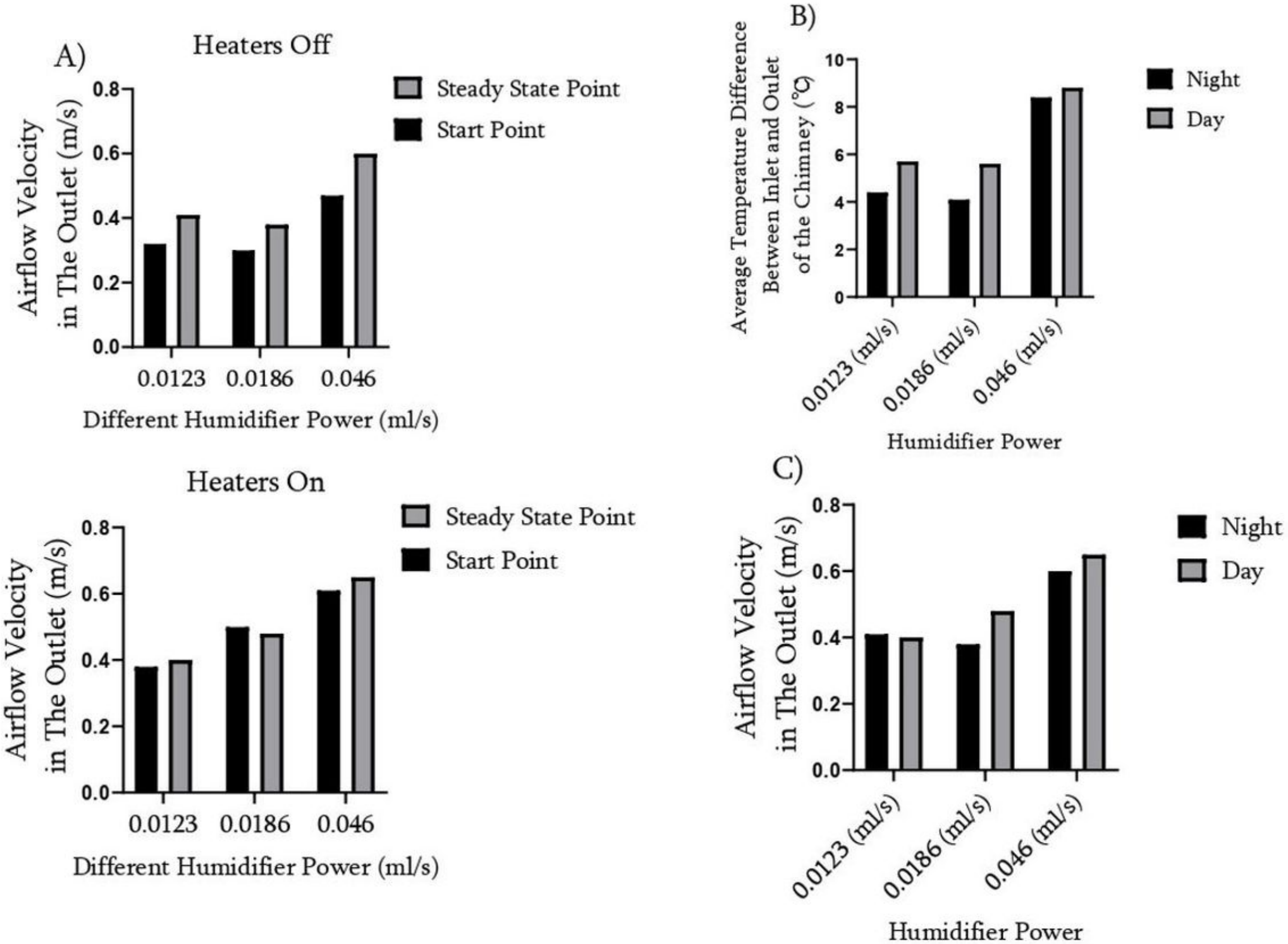


Figure 6

A) Comparing airflow velocity of initial and steady points in day and night condition. **B)** average temperature difference between the inlet and the outlet of the chimney in both day and night condition **C)** Alteration in airflow velocity in the outlet of the chimney for different humidifier powers and solar radiation status

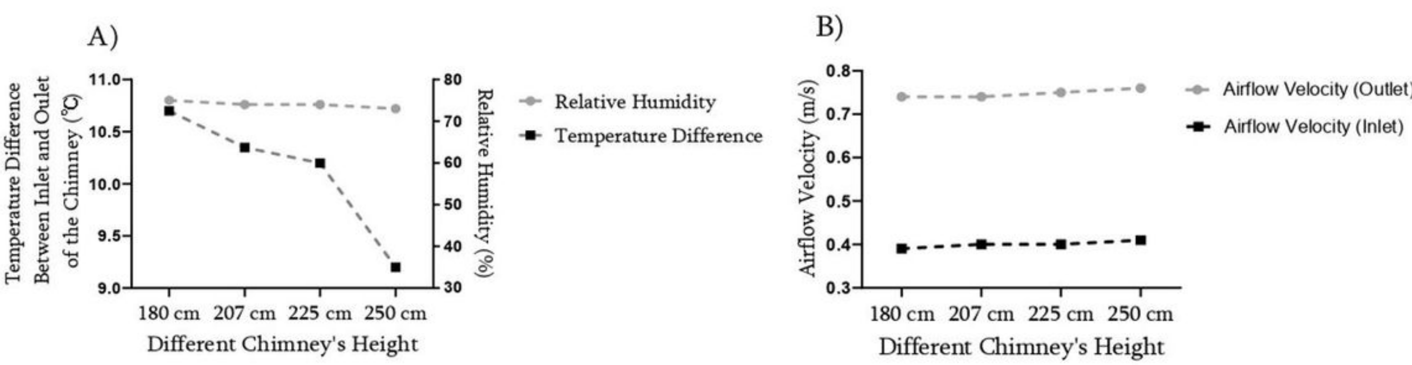


Figure 7

Impacts of changes of chimney's height on airflow velocity, humidity, and temperature difference

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