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An Experimental Investigation of a Small-scale Solar Updraft Tower in the Sultanate of Oman

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ABSTRACT

Solar updraft towers (SUT) continue to attract investigations as to their viability as a technology for energy generation. In this study, the experimental method is used to investigate the behaviour of airflow in a small-scale solar updraft tower structure in the Sultanate of Oman. A prototype solar updraft tower with a collector diameter of 1.7 m and a chimney height of 2.14 m has been built. The chimney is a 0.023 m PVC pipe with a collector inlet height of 0.07 m. The temperature distribution in the SUT and the velocity of air at the chimney base were investigated and the impact of collector inlet opening on temperature and velocity was also explored. Results indicated that heating generally occurs as air flows through the collector and cooling happens as air exits the chimney. Also, a reduced collector inlet resulted in improved temperature difference and consequently an increase in air velocity.

1. Introduction

Solar chimney power technology was invented for heating applications as early as 1903. In the early 1980s, a working prototype of a solar chimney was developed in Manzanares, Spain [1]. A schematic of a typical solar chimney power station is shown in Figure 1(a). A solar updraft tower, (SUT) consists of a chimney and a transparent solar collector that heats air close to the ground and sends it into the chimney's inlet. The basic concept behind constructing a solar chimney power plant is to convert solar radiant energy to thermal energy, which is then transformed to mechanical energy by a rotating turbine, and finally coupled to an electric power station to generate electrical energy for use in a variety of applications. The work of Kasaeian *et al.,* [1] gave a comprehensive and up-to-date overview that covers the majority of experimental studies, analytical and simulation work, and solar chimney applications. Zhou and Xu [2] conducted a comprehensive assessment of solar updraft tower power plant (SUTPP) technology's history, characteristics, and principles. In addition, recent cost analyses, experimental research, and major parts of theoretical modeling are also presented. A novel non-conventional solar updraft tower's environmental impact and power production parameters are also detailed. In a number of studies, authors discussed about how solar updraft

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towers have changed over the years, as well as how new technology has made the process more efficient.

They also presented SUT challenges and limitations, with changes being made to close the gap and allow the SUT system to improve even more [3-6]. The theory, practical experience, and economy of solar updraft towers are also examined [9]. Between July and September of 1982, the highest power output for a constructed prototype of SUT was generated at 41 kW. The collector's radius was 122 meters and the chimney was 194.6 meters tall and 5.08 meters wide. Under no load conditions, this plant produced an upwind velocity of 15 m/s [7,8]. At the University of Zanjan, Iran, Kasaeian *et al.,* [10], built a solar chimney pilot plant. Temperature, air velocity, and power factors were measured on separate days for this pilot model. Temperature inversion events arose on chilly days in this study, and the inversion effects vanished as the day temperature rises. A similar SUT concept with a transpired solar collector was investigated in Turkey in 2014. The transpired solar collector's efficiency was found to be between 60 and 80 percent. On hot summer days, the maximum temperature rose by 16–18°C. When compared to a typical solar tower glazing collector, this study indicated a threefold increase in efficiency. As a result, the area of solar collectors is reduced by half [11]. A detailed thermodynamic numerical model was used to predict solar updraft tower plant power production for a wide range of design and operational characteristics. The performance of this model was assessed using performance-inducing important factors such as power output and power output per cost. According to the research, the optimum pressure drop ratio is dictated by the collector and chimney radius, but not by chimney height, ambient temperature, or insolation. The dimensions of the major components must be well-matched to provide optimal performance [12,13]. Turbulence characteristics, air temperature, pressure, and velocity profiles all play a role in the SUT solar systems' optimization. Both numerical and experimental models are used to examine the behavior of air flow throughout the solar updraft tower. Temperature, velocity, pressure, and turbulence are all affected by the height of the chimney [14]. To optimize the solar chimney power plant and get further experimental data, a pilot setup consisting of a chimney with a 3 m height and a 3 m collector diameter was developed. Two major effective characteristics, absorber material and geometric dimensions, were investigated using thermal and velocity data [15]. An experimental study by Kinan and Sidik [16] on small size SUT with different shape of collectors concluded that the circular collector gives higher velocity output than the square collector. To improve the performance of the SUT, Ramakrishna *et al.,* [17,18] looked at the material properties needed for the turbine, chimney, and solar collector. The optimal chord length of turbine blades was calculated in this study to obtain maximum power output. A study by Nasraoui *et al.,* [19] proposed a novel collector design with a double-pass counter flow mode to improve even more the efficiency and reduce the large plant area. CFD approach was used to assess three models for these purposes: a conventional collector, a double-pass collector with parallel flow, and a double-pass collector with counter flow. Also, many previous works contributed to the development of a mathematical model for a small chimney power plant in an experimental setting. Using dimensional analysis, Bejalwar and Belkhode [20] and Belkhode *et al.,* [21] measured and estimated the performance of an experimental solar power plant with the collector, chimney, and turbine positioned within a 15-degree slope on top of collector sheets. A parametric study by Too and Azwadi [22] investigated the effect of inclined solar collector and inclined chimney. Their result showed a notable improvement in the power by sloping the collector and without inclining the updraft tower. Despite extensive investigation, the bulk of published studies have demonstrated profiles of air velocity and temperature in a specific location. These profiles, on the other hand, can be misinterpreted at times. In actuality, a number of researchers ignored the air's temperature, velocity, pressure, and turbulence qualities. These factors are critical for the solar updraft tower (SUT) system's optimization. A larger prototype is dealt with in the majority of published works, such as the Manzanares prototype.

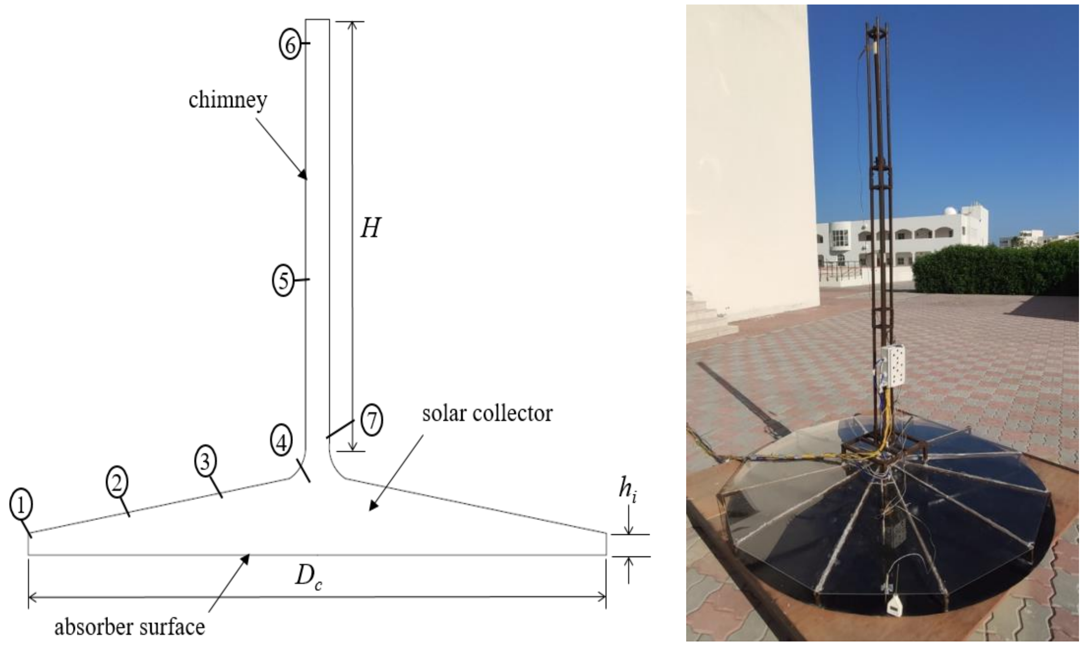
The majority of previous research did not focus on bridging the gap between larger and smaller solar chimney power plants. In this study, the experimental method is used to investigate the behavior of air flow within a small scale solar updraft tower structure in Oman. The impact of collector inlet height with GI sheet as an absorber surface on local variables such as temperature and velocity were explored.

2. Experimental Set-Up

A small scale SUT consisting of a solar collector with a dimeter of 1.7 m and a chimney with a height of 2.15 m was fabricated. The solar collector includes the absorber surface which is made of 0.7 mm thick galvanized iron sheet painted black and the collector roof made of 3 mm thick transparent acrylic panels. Acrylic was used due to its strength, UV resistance and high transmittance to sunlight. The chimney on the other hand is made of 23 mm diameter PVC pipe located at the center of the solar collector. The structural support of the SUT is fabricated from square steel bars. The collector inlet opening is varied by covering the topmost portion of the inlet with board and tape. A calibrated RTD PT 100 thermocouple with three wires, which can measure temperature in the range of -40° to 1000 °C with an accuracy of 0.1°C, was used to measure the temperature at various points in the SUT. The temperature of air in the SUT was monitored at six places, from the collector inlet to the chimney outlet. The thermocouple readings were recorded using an 8-channel data recorder. A schematic diagram of the SUT and the position of thermocouples is depicted Figure 1(a). The geometric dimensions are shown in Table 1. A TES-132 portable solar meter with an accuracy of ±10 W/m^2 and a spectral range of 400 to 1000 nm was used to measure the irradiation. An air flow sensor with an analog output which operates as a hot-wire anemometer is used to measure the air velocity at the base of the chimney. This type of sensor excels at low to medium air speed where cup anemometers are typically ineffective. This sensor is integrated to Arduino to show digital reading of the air velocity. The actual experimental setup is shown in Figure 1(b). The solar meter and air velocity sensor used in the experiment are shown in Figure 2.

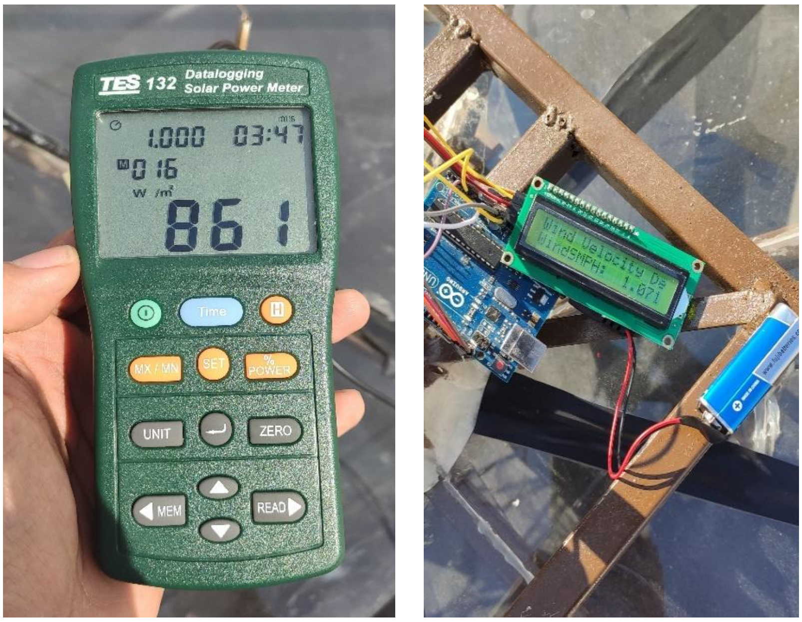
Table 1
Geometrical dimension of SUT and sensor locations

Geometric Parameters	Designation	Values
D_c	collector diameter	1.7 m
h_i	height of collector inlet	0.07 m
H	height of chimney	2.15 m
d	internal diameter of chimney	0.023 m
1,2,3,4,5, 6	location of temperature sensors	along the collector roof and chimney
7	location of velocity sensor	at chimney base



(a) (b)

Fig. 1. (a) Schematic and (b) actual experimental setup of a solar updraft tower



(a) (b)

Fig. 2. (a) Solar meter and (b) air velocity sensor used in the experiment

3. Results

In this study, the primary SUT parameter measured were the air temperature and velocity. The experimental investigation focused on the temperature variation with respect to location in the SUT and the time of the day as well as the resulting induced air velocity near the base of the chimney. Furthermore, the effect on temperature and velocity is also investigated under different collector inlet opening. The experimental investigation was undertaken in December at the campus grounds of the University of Technology and Applied Sciences- Al Musannah, Sultanate of Oman, under the month's prevailing climatic conditions. Experimental data was gathered between 9 AM and 3 PM. To minimize meteorological variability and ensure repeatability, the experiment was conducted within five consecutive days.

3.1 Solar Radiation

Figure 3 shows the variation of the average horizontal solar radiation measured several days in a row as a function of time. The solar meter is placed in two locations; (1) on top of the collector roof to measure incident solar radiation and (2) directly below the collector roof to measure the reduction in solar radiation as it passes through the acrylic roofing. The graph shows that the solar radiation incident at the top of the roof increases in the morning, peaks at about 912 W/m^2 at around 11 AM and steadily decreases towards the afternoon. The measured radiation below the roof follows a similar trend. On the average, the magnitude of solar radiation decreases by about 12.5% as it passes through the acrylic roofing. This is mainly due to the small reflectance and absorptive property of the acrylic roof material. There is a marginal variation in the daily irradiance measurements on the top of the roof as shown by the error bars indicating that the meteorological condition is consistent throughout the data gathering period. Likewise, there is minimal variation in the measured irradiance under the collector roof indicating that cleanliness of the roof is maintained.

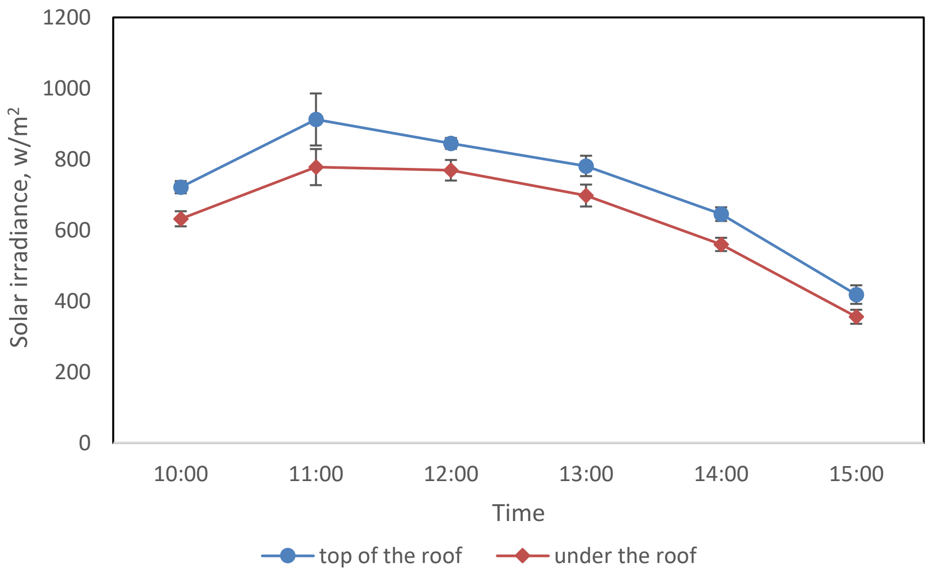
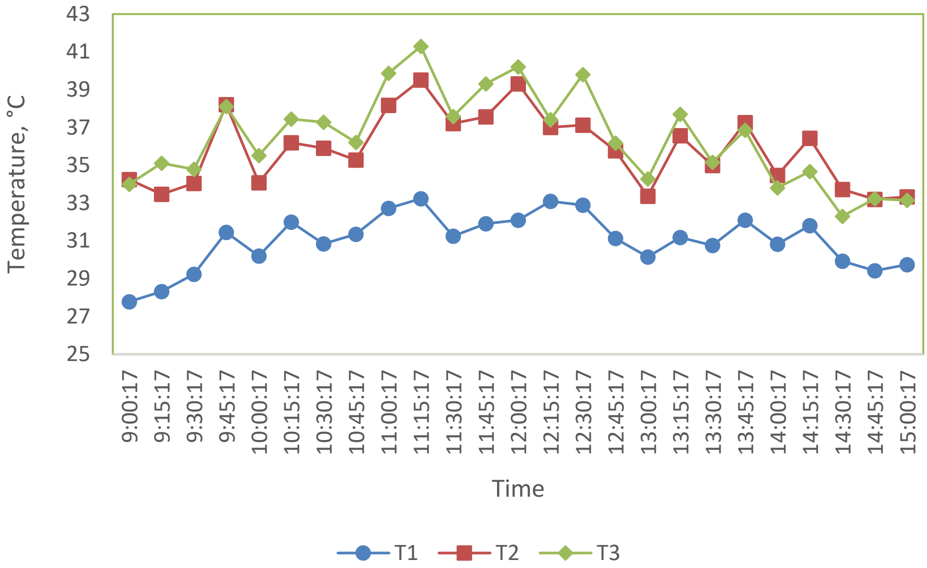


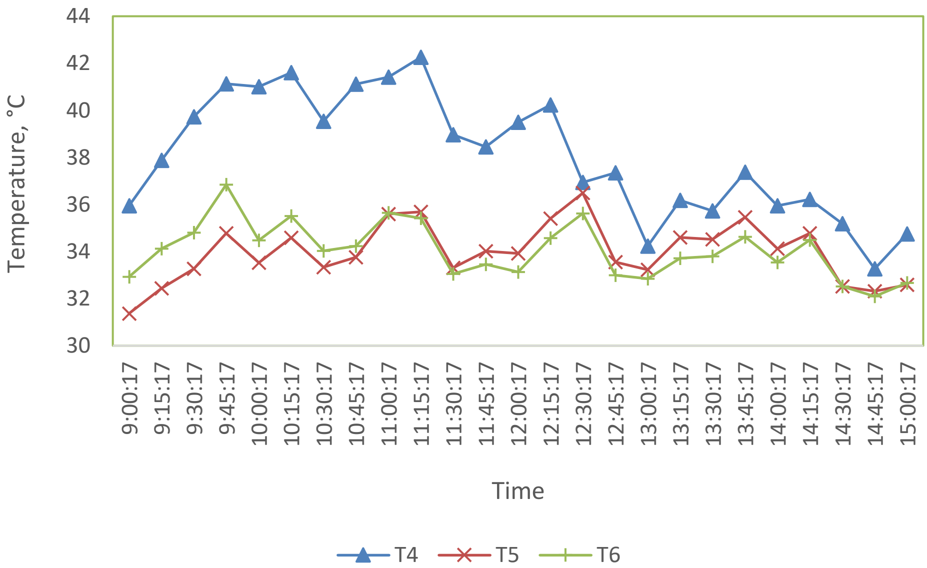
Fig. 3. Solar radiation measured on top and below the collector roof

3.2 Variation of Temperature with Time

Figure 4 depicts the variation of air temperature with time of the day in 6 locations. In the solar collector, as illustrated in Figure 4(a) the air temperature is slowly heated in the morning until it reaches a maximum at past 11 AM. This is about the same time where the maximum solar radiation is measured. The temperature then progressively decreases with time. The lowest temperature is monitored at the collector inlet, T1 while the highest recorded temperature measured is near the chimney base, T3. This is due to air convective heat transfer which is consistent with temperature changes at three measurement locations. The maximum temperature difference reached in the solar collector is about 8.1°C at noon. In Figure 4(b) a similar trend of temperature variation with time occurs in the solar chimney particularly near the chimney base, T4. The variation of temperature with time however is less pronounced further up into the chimney at T5 and T6. While heating is occurring as the air flows in the solar collector, on the contrary, cooling is taking place as the air rises and exits the chimney. The maximum temperature difference reached in the solar chimney is about 6.9°C which is the difference between T4 and T6. Over-all in the SUT, the maximum rise in temperature reached up to 10.8°C corresponding to 35% which occurs between the collector inlet, T1 and the chimney base, T4.



(a)



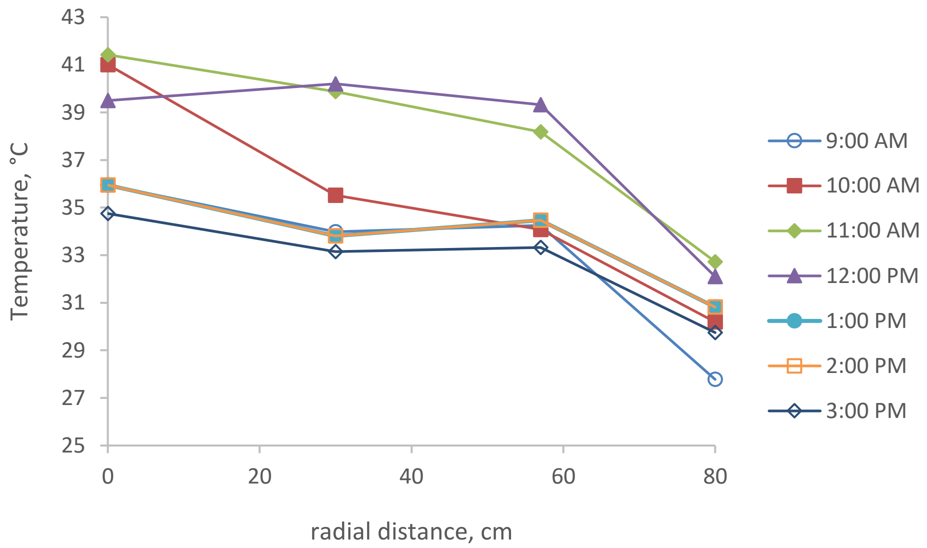
(b)

Fig. 4. Variation of temperature with time (a) in the collector and (b) in the chimney

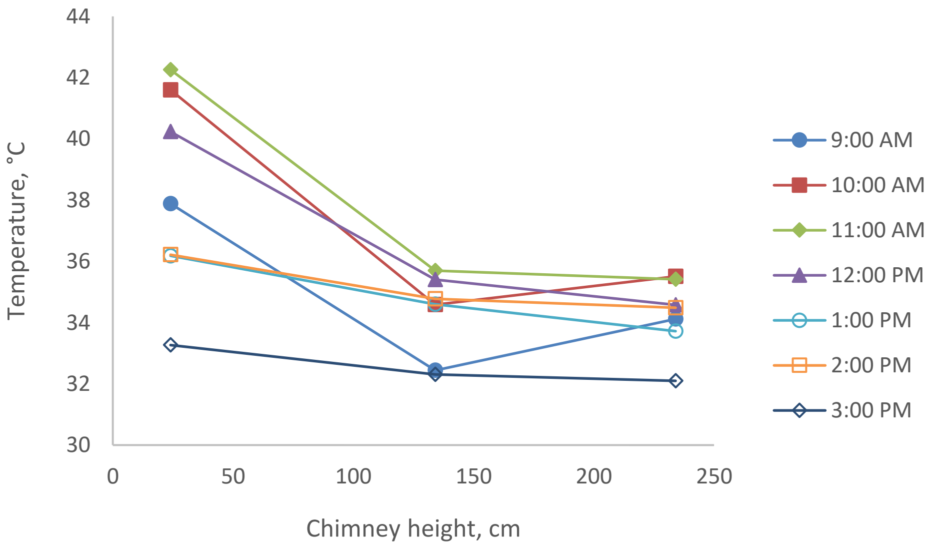
3.3 Variation of Temperature with Location

A plot of the temperature variation with respect to location is shown is Figure 5. Figure 5(a) shows the profile of temperature along the collector radius. In general, heating of air occurs from the collector inlet as air flows towards the center. As the absorber surface is heated by solar radiation, in some instance up to 50°C, the air inside is heated by convection causing it to rise and move towards the center where it is further heated as it moves. Peak temperature at the center is reached about

41°C occurring between 10 to 11AM which was initially 30°C at the inlet. This corresponds to a maximum temperature difference of about 11°C. Figure 5(b) depicts the change in temperature as the air is buoyed vertically up in the chimney. Generally, as the air exits the chimney its temperature decreases. The largest drop in temperature occurs between the chimney inlet at the center and further downstream where the next sensor location is. This can be explained by the stagnation of air at the center thus temperature is increased and eventually this thermal energy is converted to kinetic energy as air flows upward, thus reducing its temperature. The biggest drop in temperature in the chimney is 6.8°C occurring at 11 AM. While the temperature profile describes the thermodynamic overview in the SUT, however additional experiments using additional velocity sensors are warranted to better describe the velocity profile in both the collector and chimney in order to explain the direct effect of the heating and cooling to the flow dynamics.



(a)



(b)

Fig. 5. Variation of temperature with (a) radial distance from collector and (b) with chimney height

3.4 Variation of Difference in Temperature with Time for Different Inlet Openings

The effect of changing the collector inlet opening to the temperature was experimentally investigated. The collector inlet opening was set to fully open, 50% open and 25% while temperature and velocity in the SUT are recorded. Figure 6 shows the variation of the maximum difference in temperature in the SUT with time under different inlet openings. As depicted, the difference in temperature fluctuates within the day. For fully open inlet, the maximum occurs before noon while for 50% and 25% inlet opening, it occurs past noon. Among the three inlet openings, a maximum temperature difference of 15.2°C is achieved for an inlet opening of 25%. This is an additional of 40% increase in temperature difference compared to that of a fully open inlet. This can be explained by less air mass flow rate into the collector inlet due to reduced area and thus increasing the temperature differential at the same heat transfer rate. Also, as the inlet opening is significantly reduced, there is less disturbance of the incoming air from ambient wind. The temperature difference between the collector inlet and chimney base generally describes the performance of the SUT. Theoretically, higher flow velocities can be achieved as the difference in temperature increases.

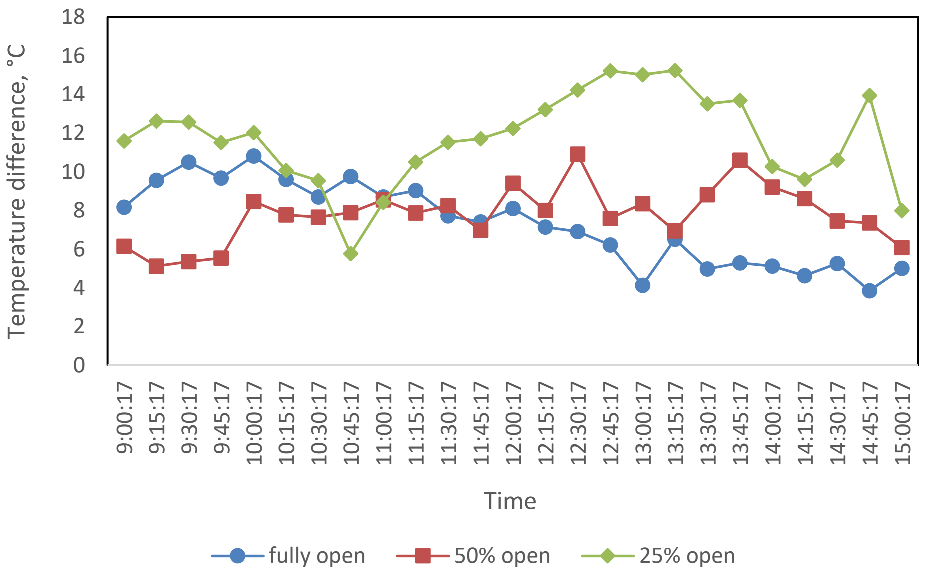


Fig. 6. Increase in air temperature with time for different collector inlet opening

3.5 Variation of Air Velocity for Different Inlet Openings

Velocity reading are recorded at the chimney base for different times of the day under different collector openings. This is shown in Figure 7. Excluding the 3 PM readings, which is observed to be windy during the time the measurement is taken, the peak air velocity occurs at around 1 AM for all inlet openings. There is a strong correlation between the increasing temperature of the air and the measured induced air velocity at the chimney inlet. As air temperature increases with time, the air velocity also increases. In terms of inlet opening, it is observed that a slight increase in air velocity is measured for an inlet opening of 50% and 25% as compared to a fully open inlet. The highest velocity was measured for an inlet opening of 25%. This is consistent with the maximum temperature difference occurring when the inlet opening is reduced to 25% as previously shown in Figure 6 which enforces the principle that temperature difference has a direct positive influence to air velocity and hence to efficiency.

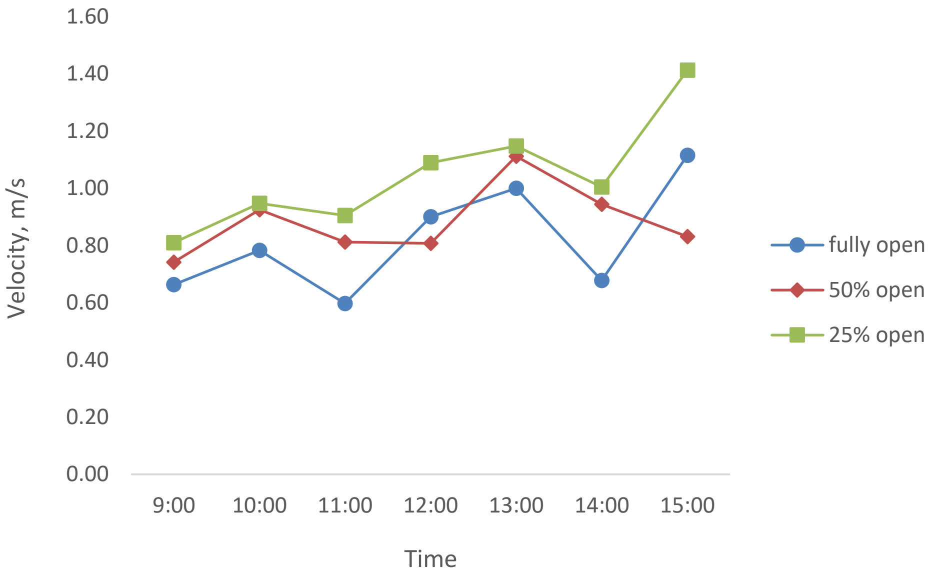


Fig. 7. Variation in velocity with time for different collector inlet opening

4. Conclusion

This study presented an experimental investigation of a small scale SUT under meteorological conditions of the Sultanate of Oman. A small-scale SUT was fabricated and air temperature and velocity measurements were collected at certain locations of the SUT and analyzed. The impact of collector inlet opening to the temperature and velocity was also investigated. In the solar collector, heating occurs as air flows from the inlet towards the base of the chimney. The maximum temperature is measured at the center of the collector near the chimney inlet. As air moves up the chimney, cooling meanwhile ensues. The temperature drops drastically from the collector exit towards the chimney section and continues to cool as air exits the chimney. However, additional experiments are warranted to describe the velocity profile in the SUT to explain the direct effect of the heating and cooling to the flow dynamics. In terms of collector inlet opening, a larger temperature difference is measured when the collector opening is reduced with 25% opening offering the largest temperature difference. Velocity measurements indicate that reducing the inlet opening enhances the flow velocity also. It can be surmised that a reduced collector inlet can have a positive impact on the temperature difference and consequently on air velocity. Additional experiments are warranted to describe the velocity profile in the SUT to explain the direct effect of the heating and cooling in the collector and chimney.

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