Experimental Investigation for a Laboratory Solar Chimney; A Practical Study in Iraq

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Abstract- The solar chimney is a type of passive solar system, used for power and ventilation purposes. For the past decade, a lot of theoretical and experimental studies have been done to improve the thermal performance of a solar chimney by changing some design parameters.The aim of the present work is simulating the thermal performance of a solar chimney system that was investigated based on two parameters, such as heat flux and air gap height under monitored operating conditions in the laboratory. For this purpose, a small solar chimney was built in the laboratory/Kirkuk Technical College. Experiments were conducted on the chimney by choosing three air gap heights 3, 4.5 and 6 cm, and the heat flux variation from 125 to 1000 W/m^2 in eight steps. The simulation results show that the maximum air velocity entering the chimney obtained at a 3 cm air gap height, which is about 2.29 m/s at a heat flux of 1000 W/m^2, it was higher than the velocity of air gaps (4.5 and 6) cm by (3.6% and 10.6%). The average temperature of the hot plate was also affected by the width of the air gap, as the maximum temperature at the air gap was small. The results also indicate that the maximum thermal efficiency of the system obtained at the height of 3 cm, which is about 25% at a heat flux of 1000W/m^2. On the other hand, the highest chimney efficiency is obtained at the height of 6 cm.

Keywords: Small solar chimney, Laboratory solar chimney, performance of solar chimney, chimney efficiency, air gap width.

Nomenclature

A	Area, m^2
Cp	Specific heat, J/kg.°C
G	Acceleration m/s^2
Hc	Convection heat transfer coefficient ,W/m^2.°C
Hr	Radiation heat transfer coefficient, W/m^2.°C
I	Current, A
L_c	Characteristic length, m
$\dot{m}$	Mass flow rate kg/s
K	Thermal conductivity, W/m.°C
P	Perimeter, m
$\hat{P}$	Power, W
R	Thermal resistance, m^2.°C/W
T	Thickness, m
T	Temperature, °C
$\bar{T}_b$	Bulk temperature, °C
U	Overall heat transfer coefficient, W/m^2.°C
f	Air
g	Glass
gi	Inside glass surface
go	Outside glass surface
gap	Air gap
l	Loss
o	Outlet
p	Plate
s	Side
u	Useful
st	Storage

Greek symbol

β	Coefficient of volumetric thermal expansion
Δ	Difference
ε	Emissivity
η	Efficiency

Q	Heat transfer rate, W
Q	Individual heat transfer rate, W
V	Voltage, V
$V1$	Air velocity at the entrance of the chimney
$V2$	Air velocity at the mid-height of the chimney
$V3$	Air velocity at the exit of the chimney
Subscripts	
A	Ambient
B	Bottom
C	Collector
C	Convection
Ch	Chimney
ν	Kinematic viscosity, m^2/s
ρ	Density, kg/m^3
σ	Stefan Boltzmann constant (5.669×10^{-8} $W/m.K^4$)
Dimensionless terms	
Gr	Grashoff number
Nu	Nusselt number
Pr	Prandtl number
Ra	Rayleigh number

1. Introduction

The concept of a solar chimney was introduced in 1930 by Hanns Gunther [1-3]. According to this study, the first prototype of a solar system consisting of a chimney height of 195 m and 10 m chimney diameter was built in 1982 under the supervision of Professor George Schlaich in Manzanares, Spain [4-6]. Many researchers considered it a pilot reference to a solar plant to validate the results. Several studies have been conducted in both theory and experiment, but most experimental studies have focused on small models of solar chimneys around the world. Dai et al. [7] analysed a solar chimney power plant that was expected to provide electric power for remote villages in northwestern China. Zhou et al [8] studied the SCPP for different values of the chimney height in order to determine the optimal chimney height which corresponds to the maximum power output. Zheng et al. [9] investigated the effects of various energy storage materials on the power output at different solar insulations. Sangi [10] evaluated the performance of solar chimney power plants in some cities of Iran theoretically to estimate the quantity of the produced electric energy. An energy equilibrium mathematical model was developed to estimate the energy output of solar chimneys in order to examine the effect of different surrounding conditions and the structural dimensions of energy output. Buğutekin [11] studied the distribution of the temperature, ground temperature and air velocity. It found that the performance of the solar chimney system was negatively affected, as the collector was built above ground level, resulting in a loss of part of the energy absorbed from the collector to its bottom by convection and radiation. Tayebi and Djezzar [12] modeled and simulated the SCPP with curved conjunction between tower and collector for different Rayleigh numbers. Motoyama et al. [13] carried out a laboratory solar chimney by studying the effect of the tower shape on the performance of the system by measuring the air velocity inside the tower. Two tower shapes were chosen for the chimney, cylindrical and diffuser. The results indicated that the chimney with a diffuser tower performed better than the chimney with a cylindrical tower. Al-Azawie et al.[14] studied empirically and numerically the potential of six ground materials in Malaysia, such as ceramic, sawdust, sand, dark green painted wood, black stone, and pebble. The results showed that the black stone and ceramic had better function, in comparison with other materials. Okada et al. [15] studied the power that improving produced from the solar chimney by using a diffuser tower instead of a cylinder. The results showed that the improving system increased power production 2.6 to 3 times higher than a conventional solar chimney. Ghalamchi et al. [16] constructed a solar chimney pilot power plant with 3 m collector diameter and 2 m chimney height The air velocity and temperature distributions were evaluated, and it was found that the solar chimney had a better performance at a reduced entrance size. Ming et al. [17] studied the distribution of heat and the rate of airflow inside the chimneys, and the variation of air over time, by a small-scale prototype of the solar chimney inside the laboratory. Two types of experiments were performed: continuous heat flux and variable heat flux. The result showed that the air velocity and temperature are higher in winter compared with summer, in addition to a good agreement between experimental and theoretical results. Shyaa et al. [18] investigate a numerical and experimental effect of the air gap area on the thermal performance of the solar chimney. Three widths were chosen for the air gap, namely 3.8, 2.6 and 1.28 cm. The results showed that the minimum height gave the maximum performance among other heights, and there is a good match between theoretical and experimental results. Ohya et al. [19] studied the effect of environmental factors such as ambient temperature, the clarity of the sky and solar radiation on the performance of collectors. The result shows that the outlet air temperatures from the solar collector and the velocity at the junction are dependent on the ambient temperature and solar radiation, the differences in air temperature at the solar collector ranging between 8^oC to 24^oC. Ayadi et al.[20] investigated the thermal performance of a laboratory solar chimney, using two different forms of a chimney, cylindrical and diffuser, where the angle of diffusion varies from 2^o,4^o and 6^o. This shows 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. Zhou et al.[21] studied the experimental and numerical analysis of the collector roof height effect on solar chimney performance. As a result, they have noted that the effect of the collector roof height on the local characteristics, such as the temperature, the velocity, the pressure and the turbulence characteristics.

The goal of the present work is to simulate the impact of change in both the heat flux and the height of the air gap on the thermal performance of the solar chimney. A small solar chimney was built in the laboratory to conduct experiments under controlled working conditions. The experiments will be performed according to a pre-drawn scheme, which is the height of the air gap between 3 and 4.5 and 6 cm, and in each height, the heat flux ranges from 125 to 1000 W/m^2 in 8 steps. Through this study, temperature, air velocity, air mass flow rate, thermal efficiency and chimney efficiency will be studied for two months (May and June 2019) at Kirkuk Technical College - in Iraq.

2. Experimental setup:

A small solar chimney was built in the higher education aboratory at the Kirkuk Technical College, to conduct the experiments required in the current study. It consists of two main parts: a collector and chimney. Fig. 1. illustrates a photo of the components of the test system. The structure of the collector is made of MDF wood with dimensions (2× 2 × 0.18m); it contains two insulating layers of polystyrene and glass wool to prevent heat loss from the collector to the surrounding area. It also contains five electrical elements with a capacity of 2 kW per element; they are submerged in a layer of fine sand 4cm thick, to dissipate heat uniformly upwards. The collector structure is covered with an aluminum plate of 1mm thickness, and its exterior surface is painted black. A 12mm thick thermal glass is used to cover the collector at a variable height ranging from 3 to 6 cm. A PVC pipe 3m long and 75 mm diameter is used as a chimney in the system and fixed in the center of the glass plate. The system is supplied with electric power through the power supplies to set the power supply for the electrical elements. Two data recorders are used to record experimental data anytime automatically. The first is the AT4532 type temperature data logger, used to record temperature in the 32 positions in the system by type K thermocouples, and the other is three hot wire anemometer types AR866A, use to measure air velocity at three positions in the chimney. Fig. 2. shows a schematic diagram of a test system, the names of the components and their technical specifications listed in Table 1 Three sets of experiments were performed in May and June 2019 on the solar chimney, and each set lasted ten days, during which the tests were repeated in the same procedure to obtain the accuracy of the results as possible. In order to perform experiments well, the following procedure can be followed:

a. Ensure that all electrical elements are well connected to the power supply, and the measuring devices are working correctly.

b. Adjust the height of the air gap initially (3 cm).

c. Set the power supply at the beginning of each experiment at 60 W/m^2 for 1hour to obtain heat dissipation stability inside the collector's heating part.

d. Set measuring devices in 15 minutes to record data.

e. Begin experiments with a heat flux of 125W/m^2 and are raise to 1000W/m^2 in eight steps. The duration of each specific step is 30 minutes.

f. Repeat These processes for 10 times.

g. Follow the same procedures for the 4.5 and 6 cm air gap upon completion of experiments at the height of 3 cm.

Fig. 1. A photo of a small laboratory solar chimney

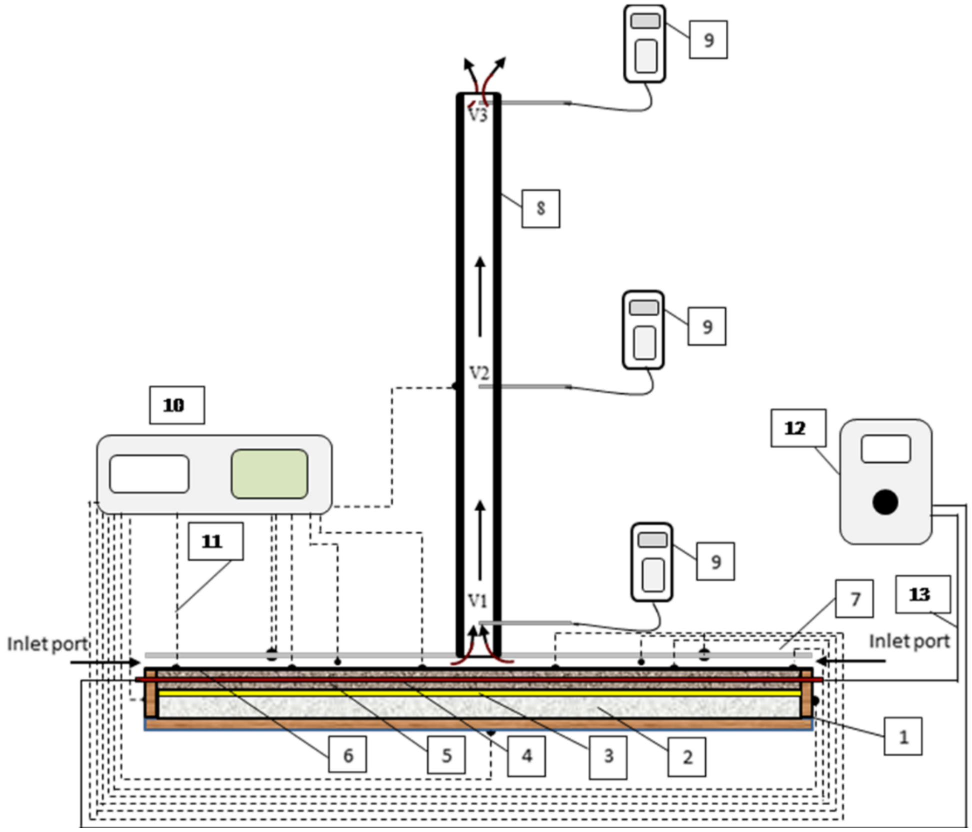

Fig. 2. Schematic diagram of solar chimney and measuring devices used

Table 1. List of solar chimney components and technical specifications

Part No.	Part name	Material	No.	Description
1	Frame	Wood type MDF	1	2×2×0.12 m
2	Insulation 1	polystyrene	1	1.96×1.96×0.05 m
3	Insulation 2	Glass wool	1	1.96×1.96×0.01 m
4	Heater element	Copper	5	(L=2 m × d=18 mm)
5	Sand layer	Sand	-	1.96×1.96×0.04 m
6	Plate	Aluminium		2×2×0.001 m
7	Glass layer	Thermal glass	1	2×2×0.012 m
8	Chimney	PVC pipe	1	L=3m. di= 63.5mm, do=74.3mm
9	Hotwire	-	3	Resolution(0.01 m/s), accuracy (±1%±0.1)
10	Temperature data logger	1	1	Resolution (0.1°C), accuracy (0.2%+1°C)
11	Thermocouple wire type K		32	2 m length/ part
12	Power supply	-	4	(0-220v),(10A)
13	Connection wire	Copper	8	5 m length /part, 2.5 mm

3. Calculations

Experimental data are analysed to assess the thermal performance of the solar chimney in different environmental conditions, based on basic heat transfer equations. Fig. 3. represents the heat transfer mechanism in the collector portion, which includes conduction, convection, and radiation. It can be expressed by thermal resistance, as shown in Fig. 4. In order to bring the calculation results close to reality, we assume that the system is in a steady-state, that the air is an ideal gas, and that airflow in the collector is a flow between two parallel plates: we also neglect heat exchange with surrounding radiation [22]. Procedures for analysing thermal energy in solar chimneys are followed:

3.1 The heat loss from the hot plate to the surrounding area.

The amount of heat loss from the hot plate to the ambient is expressed as [23-25]:

$$q_{p-a} = U_{p-a} \times A_c \times (T_p - T_a) \quad (1)$$

where

$$U_{p-a} = 1/(R_{gap} + t/k_{gl} + 1/hc_{go-a}) \quad (2)$$

$$R_{gap} = R_1 \times R_2/(R_1 + R_2) \quad (3)$$

$$R_1 = 1/hc_{p-gi} \quad (4)$$

$$R_2 = 1/hr_{p-gi} \quad (5)$$

The radiation and convection heat transfer coefficient can be calculated from [26-27]:

$$hr_{p-gi} = \sigma(T_p^2 + T_{gi}^2)(T_p + T_{gi})/(1/\varepsilon_p + 1/\varepsilon_{gl} - 1) \quad (6)$$

and

$$hc_{p-gi} = N_u k_f / L_c \quad (7)$$

Nusselt number (Nu) is calculated from the following experimental correlations [28-29]:

$$N_u = 0.54\, Ra^{1/4} \qquad 10^4 \le Ra \le 10^7 \quad (8)$$

$$N_u = 0.15\, Ra^{1/3} \qquad 10^7 \le Ra \le 10^{11} \quad (9)$$

Ra is a Rayleigh number and is defined as a product of the Grashof and Prandtl numbers, expressed [30]:

$$Ra = Gr.Pr \quad (10)$$

where

$$Gr = g\beta\Delta T\, L_c^3/\nu^2 \quad (11)$$

$$\Delta T = \begin{cases} T_{go} - T_a \\ T_p - T_{gi} \end{cases} \quad (12)$$

and

$$\beta = 1/T_f \quad (13)$$

$$T_f = \begin{cases} (T_{gi} + T_p)/2 \\ (T_{go} + T_a)/2 \end{cases} \quad (14)$$

wher L_c is represented a characteristic length can be calculated from [29]:

$$L_c = A_c/P \quad (15)$$

3.2 Heat loss from the bottom and sides of the collector to the surrounding.

Part of the thermal energy stored in the sand layer is lost to the ambient through the base frame, as shown in Fig. 4. is expressed [28-29]:

$$q_{b-a} = hc_{b-a}\, A_c(T_b - T_a) \quad (16)$$

where

$$hc_{b-a} = N_u K_f / L_c \quad (17)$$

and

$$N_u = 0.27\, Ra^{1/4} \qquad 10^5 \le Ra \le 10^{10} \quad (18)$$

$$q_{s-a} = hc_{s-a}\, A_s(T_s - T_a) \quad (19)$$

where

$$hc_{s-a} = N_u k_f / L_c \quad (20)$$

$$N_u = 0 \cdot 68 + \left[0.670 R_a^{1/4} / \left[1 + (0.492/Pr)^{9/16}\right]^{4/9}\right] \quad (21)$$

Thus, total heat loss is,

$$Q_l = q_{p-a} + q_{b-a} + q_{s-a} \quad (22)$$

3.3 Calculation of useful energy

The useful energy resulting from heating the air in the air gap through free convection and forcing it to move to the chimney, determined on the basis of the energy conservation law [31]:

$$Q_u = \dot{m}\, c_P(T_o - T_a) \quad (23)$$

where

$$\dot{m} = \rho V_1\, A_{ch} \quad (24)$$

The physical properties of the air evaluated at $\bar{T_b}$ from the Table (A-5) [24]:

where

$$\bar{T}_b = (T_a + T_o)/2 \quad (25)$$

3.4 Calculation of energy stored within the collector

Figure 3. shows the location of the heat source elements in the collector, which covers in sand layer. The sand layer is initially heated, and it dissipates energy to the plate and other components of the collector, and it stores a part of energy. In order to determine the amount of energy stored in the sand layer, energy balance has been applied to the collector, as follows:

$$\hat{P} = Q_{st} + Q_u + +Q_l \quad (26)$$

where

$$\hat{P} = \eta_h \times V \times I \quad (27)$$

Thus,

$$Q_{st} = \hat{P} - (Q_u + +Q_l) \quad (28)$$

3.5 The efficiency of the collector

The heating process in the complex is done using a group of electrical elements immersed in the sand layer. Thus the part of the generated energy will be dissipated to the plate, and the rest will be stored in the sand. Therefore, the net energy received by the board from the elements can be calculated as:

$$Q_p = \eta_{elec} \times V \times I - Q_{st} \quad (29)$$

So, the practical efficiency of a laboratory chimney can be evaluated from:

$$\eta_{coll} = Q_u/Q_p \quad (30)$$

3.6 The efficiency of the chimney tower

The efficiency of the chimney tower is defined as the ratio between the energy content of the constant air current going up to the useful energy produced by the chimney and is expressed [31-32]:

$$\eta_{ch} = gH_{ch}/\left(C_p \times (T_a + 273)\right) \quad (31)$$

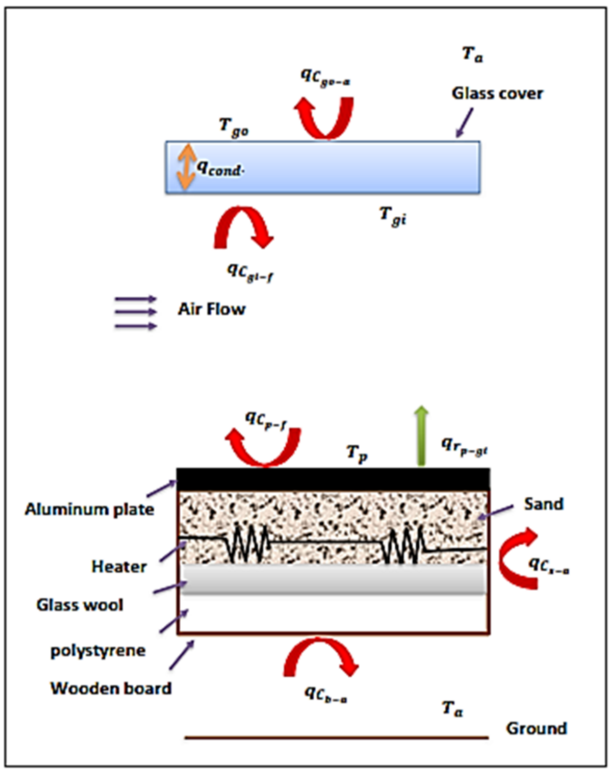

Fig. 3. Schematic diagram of the heat transfer method in the collector.

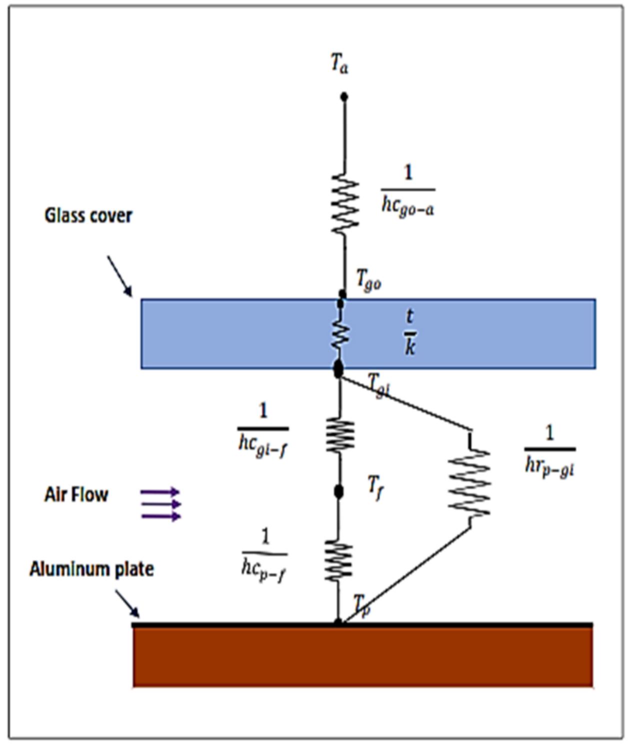

Fig. 4. Schematic diagram of the thermal resistance network

4. Results and Discussion

The experimental data obtained from a set of tests were analysed on the small size lab solar chimney during two months of May and June 2019. The effect of both the height of the collector air gap and the change in heat flux on the chimneys thermal performance was studied. Data analysis was based on average values for ten tests. System performance was compared based on the following parameters:

4.1 The effect of the air gap width on the plate temperature

Figure 5 shows the variation of pale temperature (Tp) versus heat flux at air gap heights (3, 4.5, 6). It is noted that Tp is inversely proportional to the height of the air gap, which depends on the thermal resistance in the heat transfer zone: it is a resistance summing of convection, conduction, and radiation, which is related proportionally to a height of air gap. For this reason, we saw a higher level of Tp in the 3 cm air gap than other air gaps.

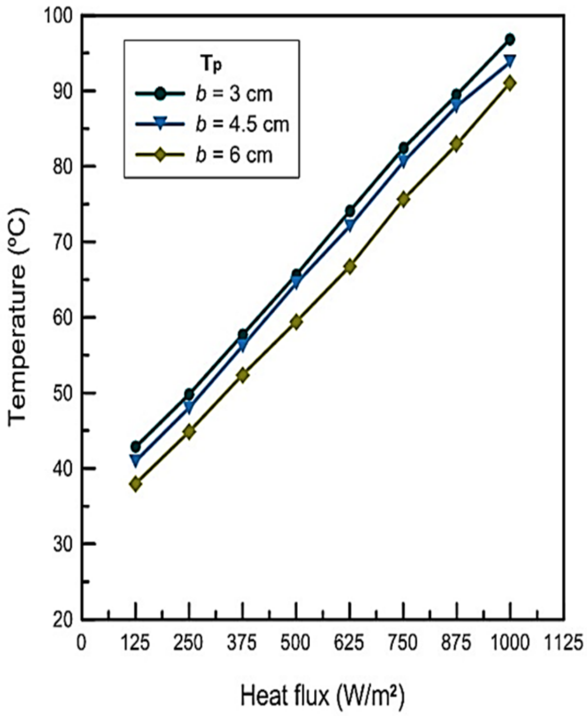

Fig. 5. The effect of heat flux on temperatures of the hot plate surface of the air gap (6, 4.5, 3) cm

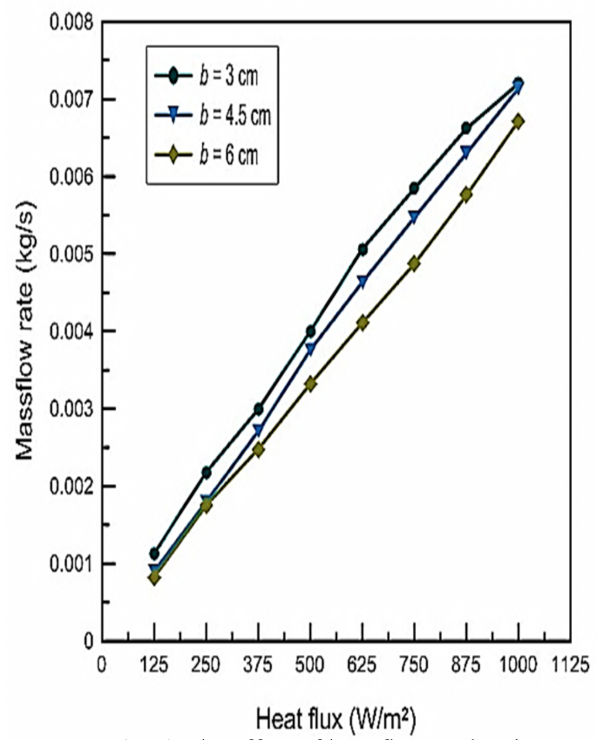

Fig. 6. The effect of heat flux on the air mass flow rate of the air gap (6, 4.5, 3) cm.

4.2 The effect of air gap width on mass flow rate

The mass within two parallel plates is strongly dependent on its temperature levels, as it affects the physical properties of the liquid occupied in the air gap. In the present work, the heating process is carried out by free convection, in this case, the increase in temperature increases the velocity of the air, which leads to an increase in the flow rate of the air mass. Based on the above concept, it is noted that in Fig. 6 presents a change in the mass rate of air flow versus the rate of heat flux in the air gap height of 3, 4.5, and 6 cm. This indicates that the mass flow at all heights of the air gap is sim-linear related to the heat flux, as in Tp relation with heat flux. It also indicates that it is inversely related between the mass flow rate and the heat flux. A curve of 3 cm is observed, and a decline in the curve after the heat flux is 750 W/ m^2, that due weather changes during the experiments, especially have been conducted in April. On the other hand, it noticed that there is a convergence between the curve of heights 4.5 and 6 cm through a heat flux values of 125 to 250 W/m^2. Because both experiments carried out in May, and the weather was almost the same, especially in the early hours of the day. However, the results showed that the highest mass flow rate occurs in the case of 3 cm in all heat flux rates, which ranged from $(1.131 \text{ to } 7.199) \times 10^{-3}$ kg/s. The average mass flow rate was higher than the other two heights of 4.5 and 6 cm by 10% and 20%, respectively.

4.3 The effect of the air gap height on the air velocity of the chimney

The height of the chimney was divided into three positions (V1, V2, and V3), as shown in Fig. (2). The airflow's behaviour through the chimney has been studied, keeping in mind the local air velocity at these locations. The air velocity through the chimney in the three experiments was significantly similar in appearance but resulted in different values. Fig. (7) shows the variation of local air velocity versus the heat flux at the air gap height of 3 cm in the chimney tower, and an increase in the velocity drop over the length of the chimney has been observed when the heat flux increases. This energy loss comes from the sum of kinetic energy loss due to increased losses in friction, and heat in the surrounding area as well as the effect of gravity. The maximum local air velocity has been recorded at the site of V1 with a value of 2.29 m/s at a heat flux of 1000 W/m^2. On the other hand, the rate of drop in the velocity at V2 was 51% and 62% for site V3. Fig. (8) shows the change of the local velocity against the heat flux at three locations in the chimney at the height of the air gap 4.5 cm, and it indicates that the local air velocity at V1 becomes linear against the heat flux change, and this indicates that the airflow is becoming stable in this case. The results showed that the velocity gradients in the chimney started with values of (0.24, 0.19, 0.18) m/s and ended in (2.21, 1.06 and 0.85) m/s for the locations V1, V2 and V3, respectively. It noticed that the velocity drop ratio in this experiment at the heat flux of 1000 W/m^2 was 52% and 62 % for locations V2 and V2, respectively. Fig. (9) shows the change in the local air velocity in the chimney versus the heat flux at the locations V1, V2 and V3. It is noted that the velocity entry curve changes in the concave relationship with the change of heat flux, and it is indicated that the air velocity has slowed from a stable range. The maximum air velocity at site V1 is recorded at 1000W/m^2 with a value of 2.1m/s, which has dropped by 44.2% at site V2 and 53.4% at site V3. From the results presented, it was observed that increases in the height of the air gap lead to a decrease in air velocity, and this result is consistent with experimental work results [18].

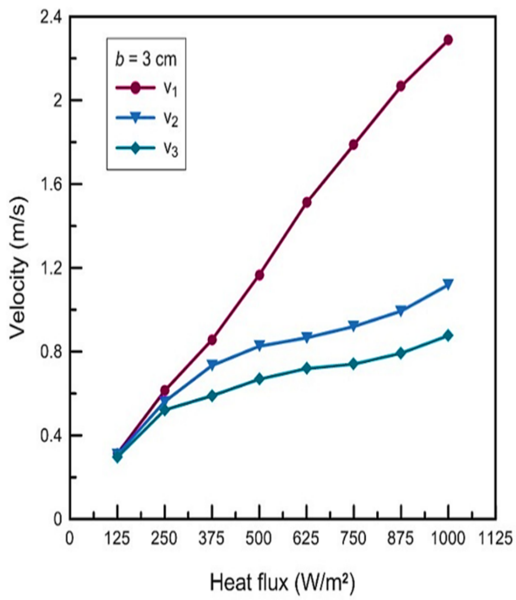

Fig. 7. The airflow velocity varies vs. the heat flux inside the chimney at the air gap (3 cm).

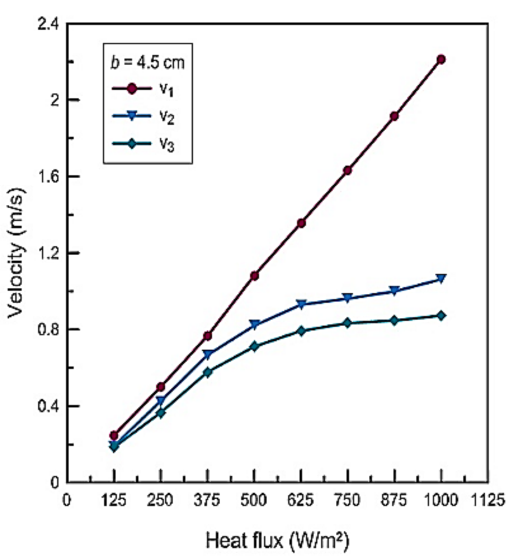

Fig. 8. The airflow velocity various vs. the heat flux inside the chimney at the air gap (4.5 cm).

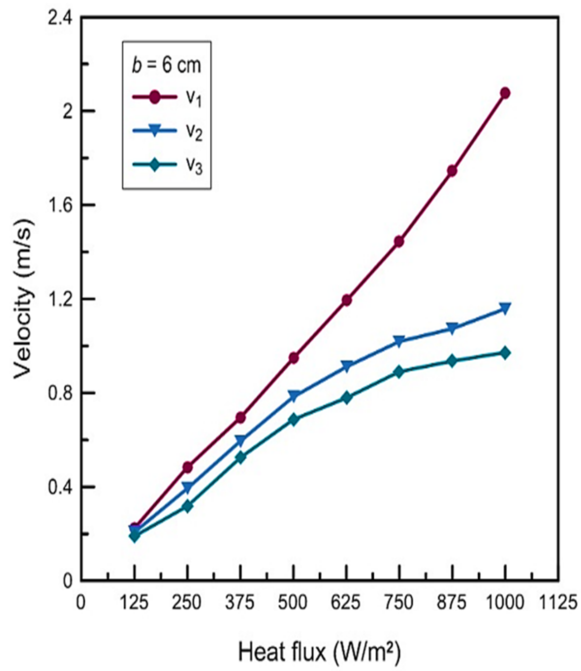

Fig. 9. The airflow velocity varies vs. the heat flux inside the chimney at the air gap (6cm).

4.4 The thermal and tower efficiency of the solar chimney

The lab chimney efficiency was investigated at each air gap height for the values of the heat flux. The result showed that a 3 cm height was the best because it gave the maximum efficiency in all heat flux ranges compared with the heights 4.5 and 6 cm; it ranges from 4% to 25%, as shown in Fig. (10). It is also noted in the figure that there is a convergence in the efficiency of the air gap heights 4.5 and 6 cm in most of the heat flux values; however, the efficiency of 4.5 cm was slightly higher than the efficiency of 6 cm. As for the efficiency of the chimney tower, the result showed that it was inversely proportional to the heat flux and is directly proportional to the air gap heights, as shown in Fig. (11). The reason is the change in the environmental condition through experiments from cold to hot weather, where the sequence of the experiments was performed from a height of 3 cm in April and 4.5 and 6 cm, respectively, in May. The results showed that the highest efficiency obtained at a height of 6 cm ranged between 9.74 and 9.64×10^{-3} % throughout the heat flux ranges, and was higher than efficiency at the heights 3 and 4.5 cm in the rate of 1.2% and 0.9%, respectively at a heat flux 1000 W/m^2.

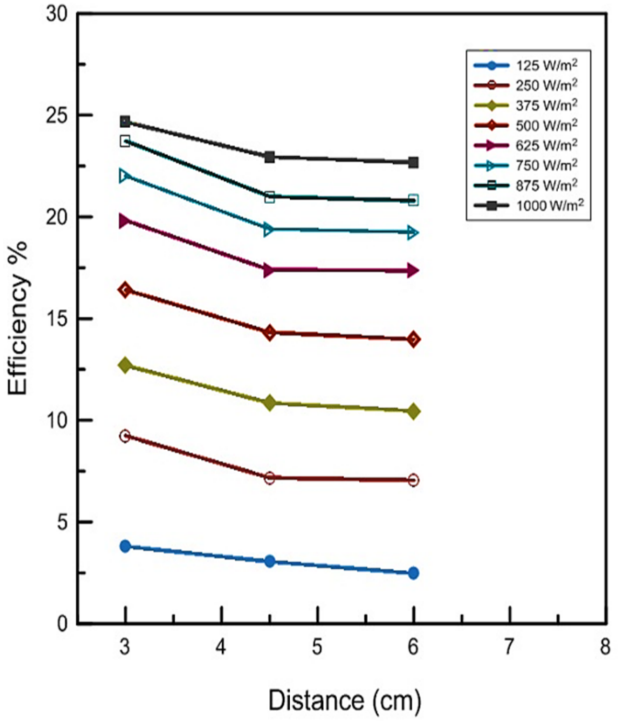

Fig. 10. The collector efficiency versus the air gap for the heat flux ranges

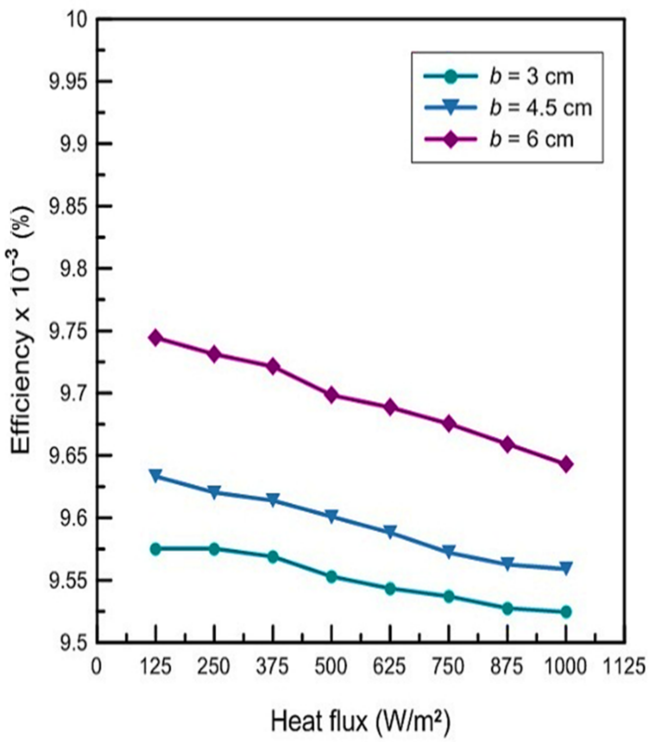

Fig. 11. The effect of heat flux on the tower efficiency of the three air gaps

5. Conclusions

From the simulation results on the data obtained from conducting experiments on the laboratory chimney by changing the height of the air gap from 3, 4.5 and 6 cm and the heat flux range 125 to 1000 W/m^2, the results are expressed as charts between the studied parameters. The smallest air gap heights have considered the best case of the present work, which has the highest thermal performance among other heights; it matches the results Ref. [18]. The main conclusions of this work can be summarised as follows:

- The highest average local air velocity at the entrance to the chimney was obtained at the height of 3 cm. It was about 2.29 m / s at a heat flux of 1000 W/m2, which exceeds the highest velocity of the other two air gaps (4.5, 6) cm by (3.6 and 10.6) %, respectively. The results have good agreement with the result of Ref. [18].
- The velocity drop in the chimney is inversely related to the air gap height.
- The average thermal efficiency of the experimental chimney is 25% in the case of 3 cm, which is 17.6 and 19.6 % larger than in both heights 4.5 and 6cm, respectively.
- The high efficiency of the tower (chimney) was obtained in the height of the air gap 6 cm because it was performed at colder weather than the other two cases. It is not considered a valid indicator of the performance of the chimney because it depends on the ambient temperature.

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