# A Study of the Solar Chimney for Heat Protection in a Hot and Humid Climate

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**Abstract**

This study aims to experimentally investigate a solar chimney that integrates the cool air above the moist earth with the warm air in the chimney to enhance heat protection of a building. The exterior surface of a testing chimney exposed to the simulated moderate and high solar intensity of 10-700 $W/m^2$ and 80-980 $W/m^2$ gives a surface temperature of 30.2-63.2°C. Cool air of 26.0-27.8°C entering the high mass solar chimney reduces the surface temperature of the internal wall by 2.1-16.9°C with delay time of 1-3 hours compared to the exterior wall's temperature. The air temperature at the outflow is higher than that of the inflow by 10°C at 6:00 p.m. , corresponding to the highest air ventilation rate. With similar values of air temperature in the chimney, the surface temperatures with moving air are found to be less than that of the computed stationary air by 8.5-8.9°C during the nighttime. Therefore, the proposed solar chimney performs as an active insulator for both daytime and nighttime. The coefficient of discharge of 0.42-0.67 are derived from the relationships between the values of air velocity and the outflow-inflow temperature differences.

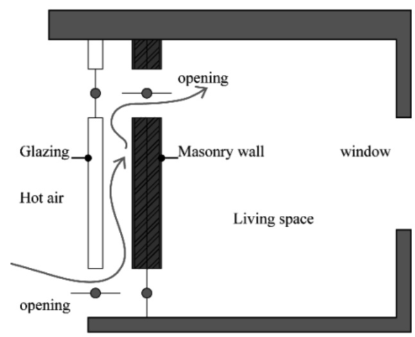
**Keywords:** Solar chimney, Natural convection, Stack ventilation, Coefficient of discharge, High mass buildings

## 1. Introduction

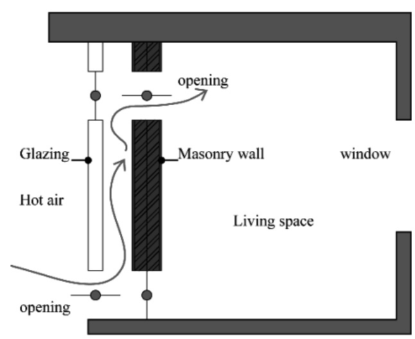
The Trombe wall and the solar chimney have been applied for natural air ventilation for decades in the cold and hot-humid climates. A Trombe wall has vertical double walls used to warm up air in the living space in a cold climate (see Fig. 1a). It consists of a glazing, an air channel, and a masonry wall. There are two openings, one at the bottom of the glazing wall to let the ambient air flow into the channel and the other one at the top of the masonry wall to allow the flow of warm air into the attached living space. The warm air in the channel is created by transmitted sunlight through the glazing and the absorbed heat in the masonry wall. This developed warm air is driven upward (in the channel) through the top opening by the natural buoyancy force, providing thermal comfort for occupants [1]. Besides providing warm air, the heated surface of the internal masonry wall transfers the heat to the living space [2].

Though working with the upward driving force like the Trombe wall, the solar chimney, is different in the utilizing purpose, materials of composition, and the approach of improvement. Unlike the Trombe wall in a cold climate, the solar chimney discharges the warm accumulated air from the living space and draws the cool ambient air into the living space as shown in Fig.1b. The materials of the solar chimney resemble that of the Trombe wall, but it appears with double masonry walls without glazing [3, 4], with a Photovoltaic cell on the glazing [5], with ametals and insulation as the internal wall [6, 7]. The addition of those materials was found to enhance the thermal efficiency, increase the air ventilation and provide electricity. This study aims to investigate the performance on heat protection and air ventilation of the solar chimney. The enhancing thermal and air ventilation performances of the solar chimney in a hot and humid climate were achieved by 1) adjusting of the width and the length of the air channel, (2) changing of the internal and external materials, and (3) increasing the difference of air temperature between the openings.

The experimental and computational results showed that the ratio of channel width (b) to height (L) of 0.02-0.09 brought about high air temperature and airflow rate [8, 9]. A black-painted opaque wall and black painted metal [8, 9] are used in place of glass as they enhance the heat accumulation in the external wall and reduce the direct solar gain on the internal wall. The combination of the vertical solar chimney with the tilted solar collector on the roof also showed the large amount of airflow in the system of 2-15 air changes per hour [10, 11, 12]. These materials and combinations increase the air temperature in the channel, stimulating the hot air to rapidly escape to the relative low ambient air. The enhancement of the airflow rate in the air channel was also obtained by the creation of a temperature difference between the inflow and outflow of the ventilated roof, especially for the very warm ambient air in a hot and humid climate [12].




(a)




(b)

**Fig. 1.** a) The application of a) Trombe wall in cold climate and b) solar chimney in hot and humid climate.

Similar to the previous research, this study employs a width of the air channel of 0.1 m with a height of 3.0 m, but a large mass for external wall and small a mass with 0.15 m-insulator for the internal wall are used. The purposes for the use of the large mass and insulator are to store heat within the external wall and to keep heat away from the internal wall, respectively. Additionally, the vertical air channel in the solar chimney is connected with the cool horizontal channel in order to increase temperature differences between the inflow and outflow, which in turn increase the ventilation. As a vertical black wall was considered unaesthetic [13], the external surface of the solar chimney in this study is light grey mortar cement.

This paper proposes an improved design of solar chimney for heat protection and also shows the effect of warm air in the living space on the thermal performance. There are three objectives in this study: (1) to demonstrate the capability of heat protection of the solar chimney, (2) to use the time-delay in the mass wall in creating ventilation in the appropriate time, and (3) to investigate the effect of warm air on the air velocity.

Through the decades of environmental and energy concerns, the use of low-energy systems have become more appealing. However, the use of the solar chimney is inadequate for human thermal comfort because the ambient air temperature in the hot-humid climate is too high. Therefore, a solar chimney that provides heat protection is suggested in this study. The proposed solar chimney is specifically arranged to induct air from the connected surface of constant temperature such as the shaded moist earth around the house. A typical house in a hot-humid climate is raised above the ground to avoid flood, leaving a shaded crawl space on the ground floor. A wind breeze through the crawl space exchanges heat with the moist earth surface resulting, in a surface temperature around 25-26°C [14]. Air of this temperature could be driven up to the solar chimney and provide insulation for the building envelope.

## 2. Experimental Set up

### 2.1 Experimental apparatus

As shown in Fig. 2, there are two experimental models in this study: 1) the model of solar chimney and 2) the model of solar chimney with heat source near the opening of the inflow. The two models are similar in materials and configuration, but a 300-Watt light bulb is placed in the horizontal channel in the second model. The 16 adjustable halogen light bulbs of 0-500 Watts simulate the solar intensity in the winter and summer and a pyranometer is used to measure the solar intensities. Solar intensities on the south vertical wall in winter are usually higher than that in the summer for the Northern Hemisphere [12]. Solar intensities in winter and summer are shown in Table 1 are hereafter called the high and moderate solar intensities, respectively. Fig. 3 shows a solar chimney of 1-m width and 3.1-m height consisting of the brick wall with 0.1 mortar, air channel and gypsum board of 0.15 m, and 0.01m in thickness, respectively. In addition, the high density polystyrene foam of 0.15 m in thickness is installed on the gypsum board to prevent the heat loss. The horizontal air channel, connected to the solar chimney, consists of polystyrene foam with the dimension of 1.0 m x 2.4 m x 0.35 m. To simulate the earth surface in experiment #1 and #2, an aluminum sheet is placed on the concrete floor of the horizontal air channel. The values of air temperature in the horizontal channel ($T_{Ah}$), varying between 26°C -27.8°C, are always less than the value of ambient temperature ($T_{A\ ambient}$). The air and surface temperatures are measured by using 17 t-type thermocouples and recorded by the U-12 HOBO data logger. The air velocity is measured by a hot-wire anemometer positioned near the outflow of the air channel. The velocity data is recorded by a testo-435-2 data logger with resolution of 0.1 and the average values of velocity within 2 minutes are used for later analysis.

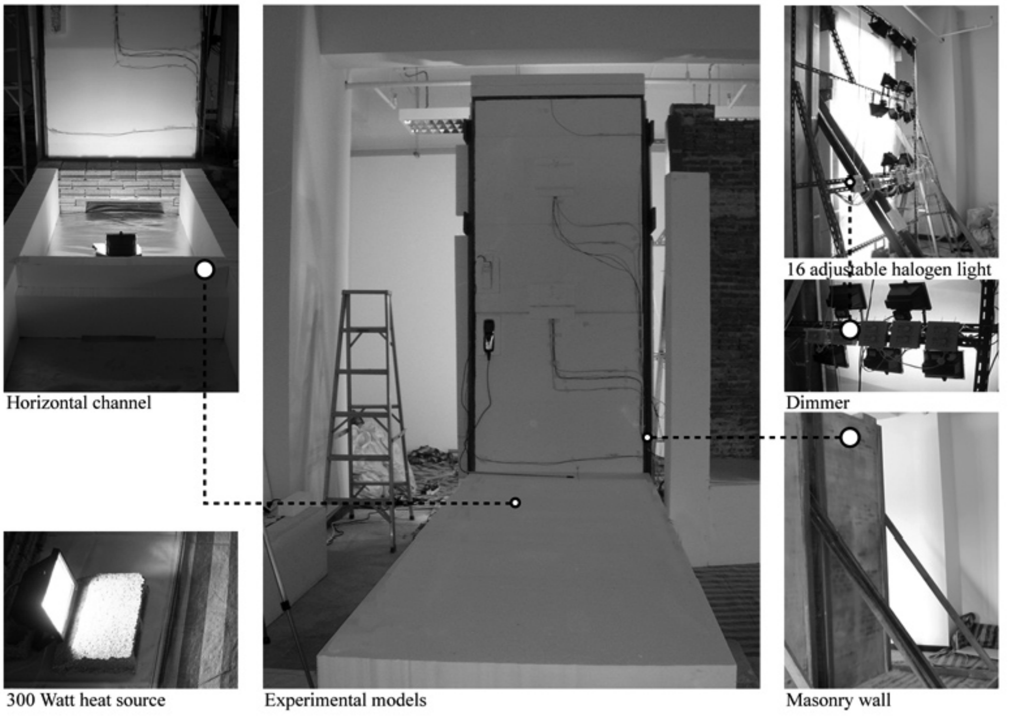



**Fig. 2.** Experimental set up.

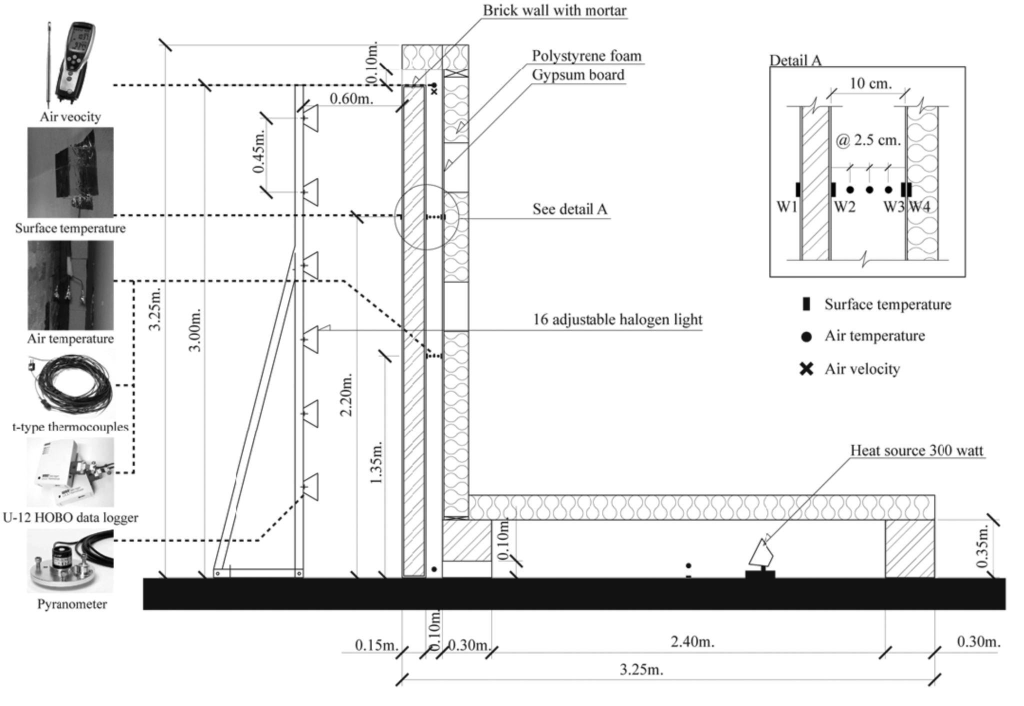



**Fig. 3.** Position of temperature and velocity measurements.

### 2.2 Testing methodology

Three experiments were carried out in the testing room during the cool season where the air temperature in the testing room was kept in the range of 26-30 °C. Experiment #1 included studies of the effect of the solar intensity and the thermal mass on the wall surface temperature and the air flow rate. The experiment began as the halogen bulbs were turned on and adjusted to the first value of the moderate solar intensity. The surface and air temperatures and air velocity were recorded every 15 minutes for one hour before the simulated solar intensity was adjusted to the next value. At the end of the first day, the halogen bulbs were turned off for 12 hours to simulate nighttime. To simulate the second day, all procedures were repeated again for the next 24 hours. Then, experiment #1 was finished and heat in the solar chimney was allowed to dissipate for 24 hours before starting of the experiment #2. Experiment #2 covered the same procedures of experiment #1 with the values of high solar intensity. Temperature in the experiment #2 is lower than the ambient temperature in experiment #1 by 1-2°C. Experiment #3 studies the effect of solar intensity the thermal mass and the inflow air of with high temperature on the air flow rate.

**Table 1.** Solar intensity in this study.

| Time (hr) | Solar intensity moderate | (Watt/m$^2$) high |
|---|---|---|
| 5.00 | 10 | 0 |
| 6.00 | 180 | 80 |
| 7.00 | 345 | 345 |
| 8.00 | 490 | 590 |
| 9.00 | 590 | 790 |
| 10.00 | 650 | 920 |
| 11.00 | 700 | 980 |
| 12.00 | 650 | 980 |
| 13.00 | 650 | 880 |
| 14.00 | 560 | 700 |
| 15.00 | 440 | 500 |
| 16.00 | 290 | 240 |
| 17.00 | 130 | 0 |

As shown in Fig. 2 and Fig. 3, a 300-Watt halogen bulb was placed in the horizontal air channel to represent the heat source in the room such as humans, lighting, kitchen stove and electronic devices. The halogen bulb in the horizontal channel was turned on during 8:00-18:00 to simulate the heat source during the daytime.

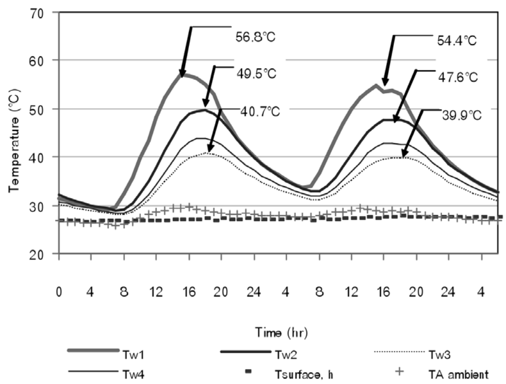
## 3. Results and discussion

### 3.1The insulation characteristic of a solar chimney

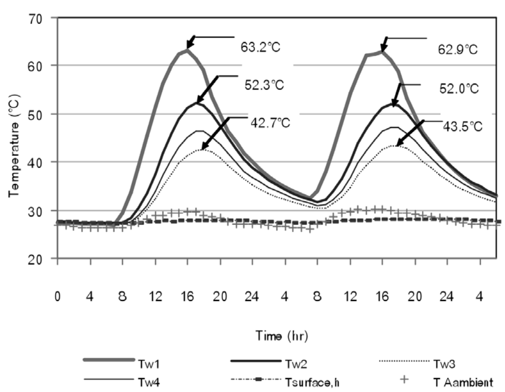
The results of wall temperatures from experiments #1 and #2 are shown in Fig. 4a and 4b, respectively. On the first day of experiment #1, the maximum value of brick surface temperature ($T_{w1}$) is 57.1°C at 15:00 and the internal surface temperature ($T_{w2}$) is 49.6°C at 18:00. On the second day of experiment #1, the maximum value of $T_{w1}$ is 54.9°C at 15:00 and the maximum value of $T_{w2}$ is 47.0°C at 17:00. Therefore, the maximum difference between the external surface and the internal surface temperatures of the brick is 7.5-7.9 °C with a time delay of around 2-3 hours. For the high solar intensity, the maximum value of temperature difference between $T_{w1}$ and $T_{w2}$ is 10.2°C with a time delay of the maximum temperature of 1 hour. The high solar intensity causes a reduction of delayed time in experiment #2. Fig. 4 also shows that the values of $T_{w3}$ are greater than $T_{w4}$ since the polystyrene insulation of high thickness prevents heat loss through the gypsum board ($W_3$).

Fig. 5 shows the hourly average value of air temperature in the horizontal channel ($T_{A h}$), at the inflow ($T_{A\ inflow}$), in the channel at the height of 1.35 m ($TA_{1.35m}$), in the channel at the height of 2.2 m ($T_{A\ 2.2m}$) and near the outflow ($T_{A\ outflow}$). The result shows that the value of air temperature in the horizontal channel varies from 26.5°C to 28.5°C before it is raised to the temperature of $T_{A\ inflow}$ and eventually reaches the outflow at the air temperature of $T_{A\ outflow}$ The value of $T_{A\ outflow}$. is always higher than the value of $T_{A\ inflow}$ and $T_{A\ ambient}$; thus, there is always air moving upward in the channel. In addition, the free convection due to heat loss from the internal surface to the flowing air always takes place since the surface temperatures ($T_{w2}$ and $T_{w3}$) are higher than the average air temperature ($T_{A\ avg}$). Furthermore, the temperature difference between the inflow and outflow air of 4.0-10.6°C suggests buoyancy driven flow. Therefore, the brick wall of thickness of 0.15 m can slow down the amount of heat transferring from the external surface Tw1 into the internal surface $T_{w2}$ by 1-3 hours depending on the solar intensity. The combined effect of thermal delay togethe with the cool inflow air is a lower internal wall temperature lower than that of the external brick wall by 3.0-10.2°C all of the day.

The thermal performance of the solar chimney can also be explained from the comparison of surface temperature $T_{w3}$ with

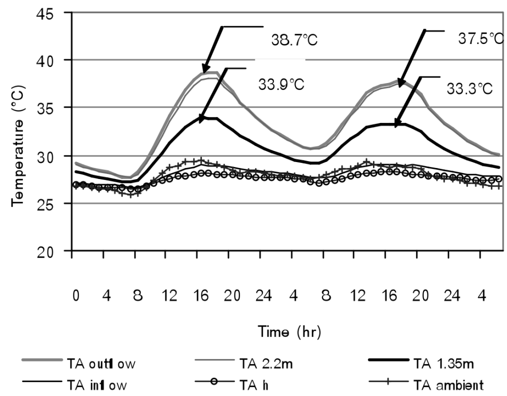



(a) experiment #1

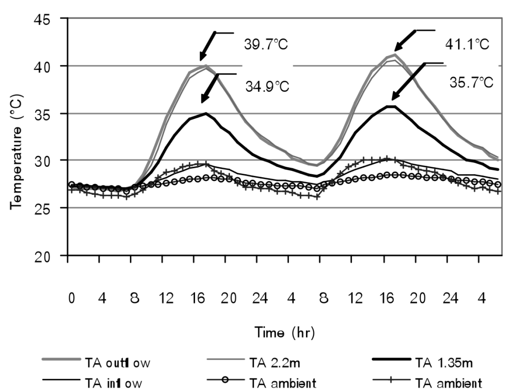



(b) experiment #2

**Fig. 4.** The experimental results of surface temperatures during (a) moderate and (b) high solar intensities in experiment #1 and #2.




(a) experiment #1




(b) experiment #2

**Fig. 5.** The experimental results of air temperatures for (a) moderate and (b) high solar intensities.

and without ventilation. The computed values of surface temperature with ventilation ($T_{w3(cal,\ vent)}$) are calculated from heat balance around the surface w3 in Eq.(1). The steady state without energy storage is assumed since the thickness of gypsum board is only 0.01 m. Calculated results of $T_{w3(cal,\ vent)}$ are compared with the results of $T_{w3}$ inexperiment #1 and #2.

$$h_{w3}(T_{w3(cal,\ vent)} - T_{A2.2}) + k_{gypsum}(T_{w4} - T_{w3(cal,\ vent)})/\Delta x_{gypsum} + \sigma \cdot (T^4_{w2} - T^4_{w3(cal,\ vent)}) / ((1/\varepsilon_2) + (1/\varepsilon_3) - 1) = 0 \quad (1)$$

where $h_{w3}$ is convective heat transfer coefficient at surface W3, σ is the Stefan-Boltzmann constant (5.667e$^{-8}$ W/m$^2$K$^4$), and ε is the thermal emissivity of the masonry wall and the gypsum wall with dark gray color (0.92), $k_{gypsum}$ and $\Delta x_{gypsum}$ are thermal conductivity (0.0873 W/m·K) and thickness (0.01 m) of gypsum board, respectively.

There is no experimental results of closing inflow and outflow openings, therefore the surface temperatures $T_{w3}$ without ventilation $T_{w3\ (cal,\ no\ vent)}$ are computed from the steady energy balance, Eq. (2). For Eq. (2), assumptions of the energy balance of the air control volume are (1) there is conduction heat transfer across the channel of stationary air, (2) the air next to the surfaces $w_2$ and $w_3$ have the temperature of the surface temperature $T_{w2}$ and $T_{w3}$, respectively, and (3) the air in the channel is assumed to be the same value with the experimental result.

$$Q_{cond,\ masonry} = Q_{cond,\ air} + Q_{rad2-3} \quad (2)$$

where $Q_{cond,\ masonry}$ is the conduction heat transfer through masonry wall, $Q_{cond,\ air}$ is the conduction heat transfer through air, and Qrad2-3 is the radiation heat transfer between surface w2 and w3. The values of $T_{w1}$ and $T_{w2}$from experiments #1 and # 2 as well as the material properties are substituted into Eq. (3) as follows:

$$k_{masonry}\ WL\ (T_{w1} - T_{w2})/\Delta x_{wall} = k_{air}\ WL\ (T_{w2} - T_{w3\ (cal,\ no\ vent)})/\Delta x_{air} + \sigma WL\ (T^4_{w2} - T^4_{w3\ (cal,\ no\ vent)})/((1/\varepsilon_2) + (1/\varepsilon_3) - 1) \quad (3)$$

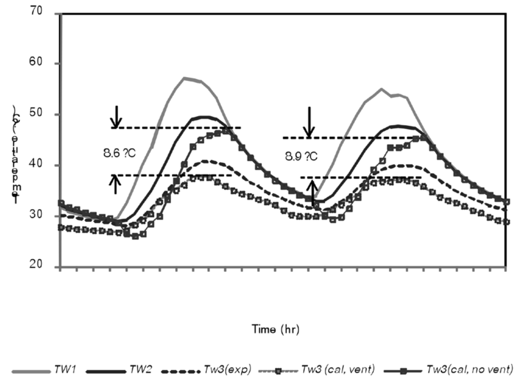
where $k_{masonry}$ is the thermal conductivity of the masonry wall (0.77 W/mK), W is the width of the wall (1.0 m), L is the height of the wall (3.0 m), $\Delta x_{brick}$ is the thickness of the brick wall (0.15 m), $k_{air}$ is the thermal conductivity of the air (0.0262 W/mK), and $\Delta x_{air}$ is the thickness of the air (0.10 m),

Fig. 6 shows the results of computed surface temperatures $T_{w3\ (cal,\ vent)}$, $T_{w3\ (cal,\ no\ vent)}$ and experimented surface temperature $T_{w3}$ together with adjacent surface temperatures $T_{w1}$ and $T_{w2}$. The computed values of $T_{w3\ (cal,\ vent)}$ are lower than those of experimental values $T_{w3}$ starting from 13.00 until 8:00 of the next day. This could be the result of steady state modeling without taking into account the storage heat in the afternoon and night times. However, the computed results follow the experimental results correspondingly. Compared to those surface temperatures without ventilation, $T_{w3\ (cal,\ no\ vent)}$ values are higher than the surface temperatures $T_{w3\ (cal,\ vent)}$ for 15 hours/day. For both of moderate and high solar intensities, the calculated $T_{w3\ (cal,\ no\ vent)}$ values are less than the values of $T_{w3\ (cal,\ vent)}$ during 8:00-15:00 because the heat on surface w1 has not reached the surface w2 yet; therefore, the surface temperature $T_{w2}$ and the calculated $T_{w3\ (cal,\ no\ vent)}$ are not so high during this time. Starting from 16:00 to 8:00 of the next day, the surface temperature $T_{w3\ (cal,\ no\ vent)}$ values are higher than $T_{w3\ (cal,\ vent)}$ by 8.5-8.9°C. Hence, the solar chimney provides better protection against heat transferring to the wall w3 than the insulated façade with stationary air during the evening and night times.

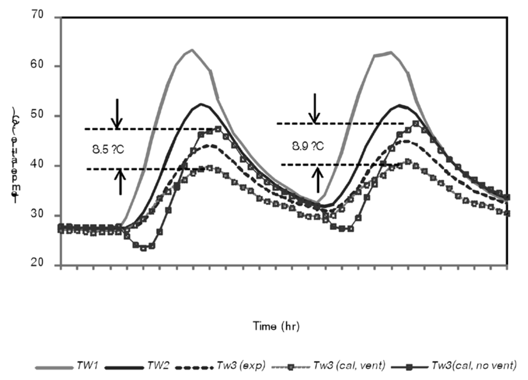
### 3.2. The effect of high air temperature at the inflow

Experiment #3 studies the effect of the high air temperature at the inflow during hour 8.00-18.00 on the surface and air temperatures and on the air ventilation rate. The heat source of 300 watts in the horizontal air channel produces air temperature ($T_{A,\ inflow}$) of 31.5-41.5°C for the ambient temperature of 24.2°C-29.8°C. With the moderate solar intensity, the results of experiment #3 in Fig. 7a shows that the maximum values of surface temperatures $T_{w1}$, $T_{w2}$, $T_{w3}$ and $T_{w4}$ are higher than the results of experiment #1 by 3.6, 1.2, 2.2, and 5.2°C, respectively. Therefore, warm air entering the inflow opening should be avoided as it tends to increase the temperature of the wall attached to the living space. It would result in too high air temperature in the living space all of the day.

Also shown in Fig 7b, the maximum values of air temperatures in the channel are higher than the values in results of experiment #1 by 12.7, 6.3, and 2.9°C for TA inflow, $T_{A\ 1.35\ m}$ and $T_{A\ outflow}$, respectively. Therefore, the too high air temperature at the inflow tends to increase the temperature of the wall attaching to the living space, $T_{w4}$. Since the hot air rapidly moves from the source through the vertical channel, it is additionally heated up in the vertical channel by 0.5-2°C to the value of $T_{A\ outflow}$ of 40.5-42.7°C. In this case the effect buoyancy due to the wall temperature is less than the effect of buoyancy due to air temperature and the ambient temperature.

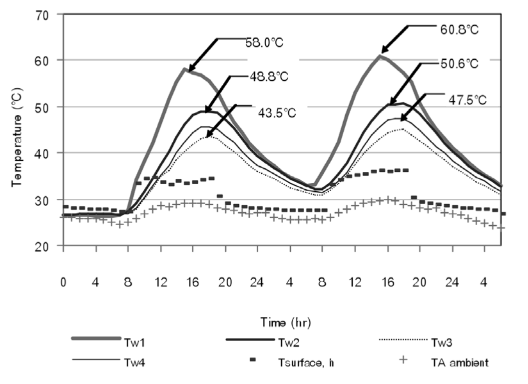



(a) experimaent #1

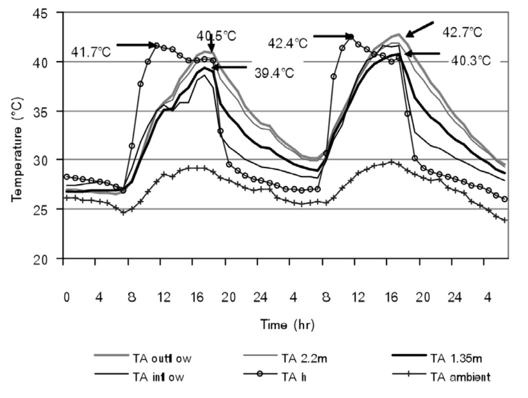



(b) experiment #2

**Fig. 6.** Comparison of the measured surface temperatures $T_{w3}$ and the calculated $T_{w3}$ with and without ventilation for (a) moderate and (b) high solar intensities.




(a) experimaent #1




(b) experiment #2

**Fig. 7.** The effect of high air temperature at the inflow on the surface and air temperatures in experiment # 3.

### 3.3. The results of air velocity

The results of air velocity at the outflow of experiment # 1, #2, and #3 are shown in Fig. 8. Applied with the moderate solar intensities during 6:00-18:00, the thermal mass of brick wall causes the air velocity in experiment #1 to gradually increase until it reaches the maximum value of 0.32 m/s at time 20:00. With the high solar intensity in the experiment #2, the air velocity reaches the maximum value of 0.47 m/s, faster than that experiment #1 by one hour. The results of experiment #3 show that the velocity increases rapidly because of the internal heat source. The highest values of experiment #3 is 0.55 m/s and the values of air velocity keep varying between 0.25-0.40 m/s after application of the heat source during the nighttime. The calculation of volume flow rate from $A \cdot v$, where A is the cross sectional area of the air channel ($m^2$) and v is the air velocity (m/s), gives the results of volume flow rate of 0.013-0.024 $m^3$/s, 0.013-0.048 $m^3$/s and 0.025-0.057 $m^3$/s for experiments #1, #2 and #3, respectively.

According to Fig. 8, it is obvious that the high solar intensity of experiment #2 and the high air temperature at the inflow of experiment #3 result in the high air velocity. However, the too high air temperature at the inflow can causes the high wall temperature and brings discomfort to the living space. In addition, the air with high temperature during 8:00-18:00 in experiment #3 flows up because of the buoyancy of the warm air relative to the cool ambient air that is independent of the wall temperature. Fig.10 and Fig. 11 show the relationships between the square of air velocity and the absolute values of air temperature differences resulting from the experiments #1, #2, and #3. According to the relationships in Eq. (4) [15],

$$v^2 = C_D \cdot gL(T_{A\ outflow,\ abs} - T_{A\ inflow,\ abs}) / (T_{A\ outflow,\ abs} + T_{A\ inflow,\ abs}) \quad (4)$$

where v is the air velocity (m/s), CD is the coefficient of discharge, g is the gravity acceleration ($m/s^2$), TA outflow, abs is the absolute temperature at the outflow (K), TA inflow, abs is the absolute temperature at the inflow (K), the linear relationships between $v^2$ and gL(TA outflow, abs -TA inflow, abs)/ (TA outflow, abs+ TA inflow, abs) are investigated.

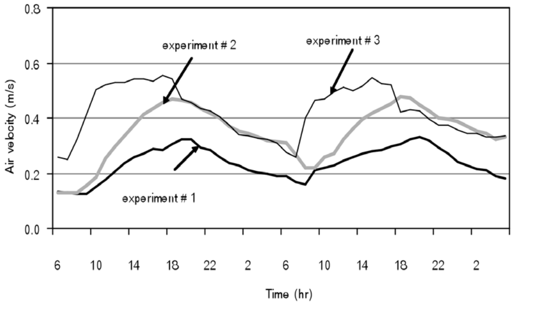



**Fig. 8.** The experimental results of air velocity from experiment #1, #2 and #3.

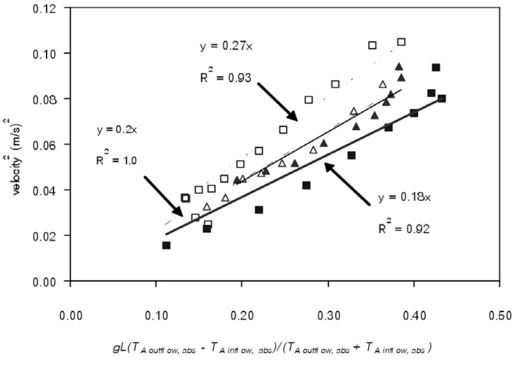



**Fig. 9.** The linear relationships between (air velocity)$^2$ and ($T_{A\ outflow,\ abs}$-$T_{A\ inflow,\ abs}$)/ ($T_{A\ outflow,\ abs}$+$T_{A\ inflow,\ abs}$) for the first day and the second day of the experiment #1.

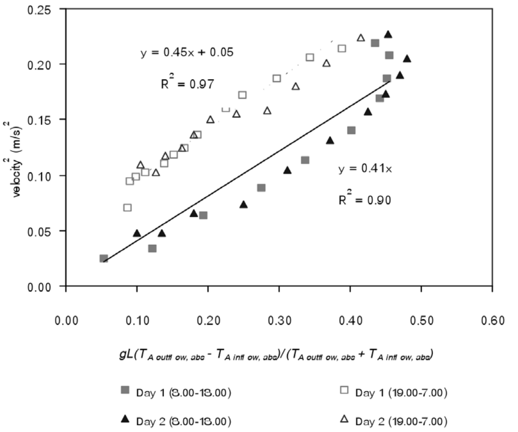
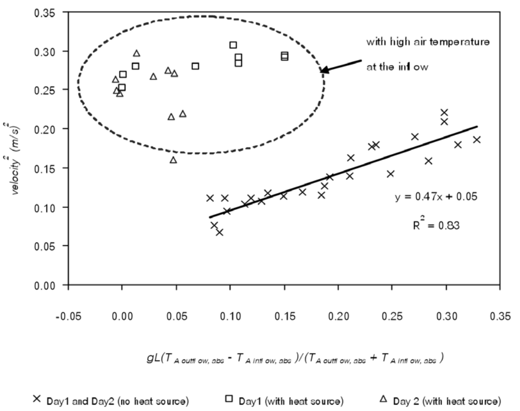
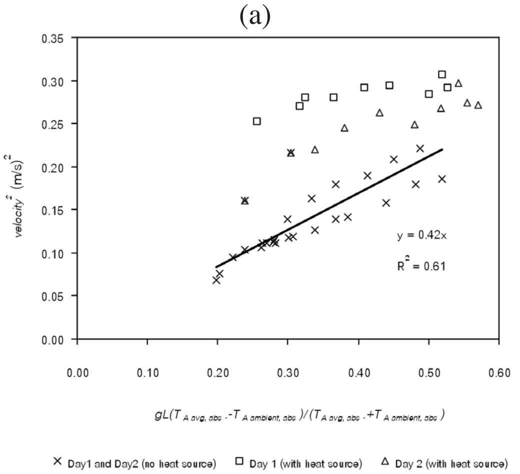



**Fig. 10.** The linear relationships between (air velocity)$^2$ and $(T_{A\ outflow,\ abs} - T_{A\ inflow,\ abs}) / (T_{A\ outflow,\ abs} + T_{A\ inflow,\ abs})$ for the first day and the second day of experiment #2.




(a)




(b)

**Fig. 11.** The relationships between v$^2$ and $gL(T_{A\ avg\ ,\ abs} - T_{A\ ambient,\ abs}) / (T_{A\ outflow,\ abs} + T_{A\ inflow,\ abs})$ of the experiment #3.

Fig. 9 shows the values of slopes of experiment #1. The values are 0.18-0.20 for the daytime and 0.27-0.32 for the nighttime, leading to the values of $C_D$ of 0.42-0.47 and 0.52-0.57, respectively. As the $C_D$ values depend on the Reynolds number [12], varying of velocity leads to different $C_D$ values. The results of experiment #2 depicted in Fig. 10 shows the higher slopes than that of experiment #1 and the corresponding values of $C_D$ of 0.63-0.64 for the daytime and 0.61-0.67 for the nighttime. Therefore, the higher values of solar intensity such as those in winter provide higher temperature difference and air velocity for two days.

For high air temperature at the inflow in experiment #3 during daytime, the relationships between $v^2$ and $gL(T_{A\ outflow,\ abs} - T_{A\ inflow,\ abs}) / (T_{A\ outflow,\ abs} + T_{A\ inflow,\ abs})$ is inconsistent as shown in Fig. 11a. However, the linear relationships are found in experiment #3 between the $v^2$ and the absolute temperature differences $(T_{A\ avg\ ,\ abs} - T_{A\ ambient,\ abs}) / (T_{A\ outflow,\ abs} + T_{A\ inflow,\ abs})$ as shown in Fig. 11 b, where $T_{A\ avg,\ abs}$ is the absolute temperature of air in the vertical channel (K), and $T_{A\ ambient,\ abs}$ is the absolute temperature of the ambient temperature (K).

## 4. Conclusions

This research proposed a solar chimney that integrates cool air near the earth surface and hot air in the building envelope to promote heat protection in a house. The utilization of cool air to enter the solar chimney can delay the time of the internal surface temperature to increase by 3 hours during moderate solar intensity and 1 hour during high solar intensity. The buoyancy driven ventilation occurs all of the daytime and it produces the highest air ventilation in the channel at 6:00 pm.

Compared to of stationary air of the same temperatures, a solar chimney with moving air can reduce the temperature of the surface attached to the living space during the nighttime by 8.5-8.9 °C for both moderate and high solar intensities. There fore, the proposed solar chimney functions as thermal insulation during the daytime and nots as an active solar chimney during the nighttime. Cooling load reduction by a ventilated solar chimney is computed from airflow rates and air temperature differences between the inflow and outflow, i.e. warm air flowing out of the solar chimney. As the air velocity varies between 0.12-0.46 m/s and air temperature differences are 0.16-11.00°C, the cooling load reductions are 0.0-4.17 kW and 0.0-5.11 kW for moderate and high solar intensities, respectively.

The high air temperature at the inflow of the solar chimney causes the reduction of buoyancy driven by the channel surface temperature as well as the increase of temperature of the wall attached to the living space. Thus, the application of a solar chimney as insulation should avoid the direct connection of the inflow to the living space occupied by heat sources such as humans and equipment. On the other hand, the inflow opening of the solar chimney should be connected to cool air such as a shaded earth surface as it can help increase the air ventilation.

From the experimental results, the values of coefficient of discharge are found varying between 0.42-0.67, where the higher value is obtained from the high air velocity during the nighttime. For the experiment with high inflow air temperature, the air velocity keeps correlated linearly with the ambient temperature rather than that of the inflow and outflow temperatures.

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