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Experimental Investigation of Thermal Performance of a Solar Chimney Provided with a Porous Absorber Plate

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ABSTRACT

Experimental investigation of the influence of inserting the metal foam to the solar chimney to induce natural ventilation are described and analyzed in this work. To carry out the experimental test, two identical solar chimneys (without insertion of metal foam and with insertion of metal foam) are designed and placed facing south with dimensions of length× width× air gap (2 m× 1 m× 0.2 m). Four incline angles are tested (20^o,30^o,45^o,60^o) for each chimney in Baghdad climate condition (33.3^o latitude, 44.4^o longitude) on October, November, December 2018. The solar chimney performance is investigated by experimentally recording absorber plate and air temperatures and velocity of air. Results indicated that the using metal foam absorber plate lead to reducing the mean temperature of absorber plate by 6.7 °C as a result, the values of chimney outlet air temperature increased. The daily solar chimney efficiency enhanced by 58.7% and the useful energy received also increased. The existence of metal foam caused higher air velocity at the exit and increasing in the ventilation rate that the maximum ventilate rate obtained from the solar chimney is 5.96 1/hr for 27 m^3 volume of room at solar irradiance of 730 W/m^2 for chimney incline angle of 60^o. The results of the experimental work show that the addition of metal foam to the solar chimney as an absorber plate is an efficient method to enhance the characteristics of heat transfer and the thermal performance of the solar chimney in the weather condition of Iraq.

Key words: solar chimney, metal foam, natural ventilation.

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دراسة تجريبية للأداء الحراري لمدخنة شمسية مزودة بسطح ماص مسامي

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الخلاصة

تم أجراء دراسة تجريبية في تأثير أدخال الرغوه المعدنية الى المدخنة الشمسية في أنتاج التهويه الطبيعية حيث وضحت وحللت في هذا البحث الحالي. لكي يتم تنفيذ التجربة، نوعين من المداخن الشمسية (بدون أضافة رغوة معدنية و مع أضافة رغوة معدنية) صممت وتم تثبيتها مواجهه للجنوب بأبعاد طول x عرض x عمق فجوة الهواء (2م x 1م x 0.2). أربع زوايا ميلان مقدارها (60°, 45°, 30°, 20°) لكل مدخنة في ظل الظروف المناخية في بغداد (خط العرض 33.3° ، خط طول 44.4°) في شهر تشرين الاول وتشرين الثاني وكانون الاول من سنة 2019. أختبر أداء المدخنة الشمسية بواسطة تسجيل درجات حرارة الهواء و السطح الماص و سرعه الهواء عملياً.اظهرت النتائج أنه بأستخدام الرغوة المعدنية كسطح ماص يؤدي الى انخفاض في متوسط درجة حرارة الصفيحة الماصة للاشعاع االشمسي بمقدار 6.7 درجات مئوية ونتيجة لذلك، قيم درجات حرارة الهواء الخارج من المدخنة تزداد. الكفاءة الحرارية اليومية للمدخنة الشمسية ازدادت بنسبة 58.7% والطاقة المفيدة المحصلة ايضاً تزداد. أن وجود الرغوة المعدنية يسبب سرعة هواء اعلى عند منطقة الخروج و زيادة في معدل التهوية حيث اعلى معدل تهوية تم تحصيله من المدخنة الشمسية هو (5.69) 1/ساعة لحجمم غرفة 27م^3 عند اشعاع شمسي مقداره 730 واط/م^2 عند زاوية ميلان 60°. أظهرت النتائج العملية أن أدخال الرغوة المعدنية الى المدخنة الشمسية كسطح ماص طريقة فعالة لتحسين خصائص أنتقال الحرارة والأداء الحراري للمدخنة الشمسية في ظل الظروف المناخية في العراق.

الكلمات الرئيسية: مدخنة شمسية، رغوة معدنية، التهوية الطبيعية.

1. INTRODUCTION

To minimize the buildings heat gain, also decrease the electrical energy requirement by operating non-consuming systems for ventilation presented as solar chimney **(Chaichan and Kazem, 2011)**. The solar chimney device that naturally ventilate the space that can enhancing the buildings energy efficiency. Various investigation covers this domain experimentally, numerically and mathematically.

Full scale experimental study was made by **(Arce et al., 2009)** to investigate solar chimney thermal performance of 0.3m air gap, 1m wide and 4.5m length under actual weather conditions at day and night time. The results showed that highest temperature air increase by 7˚C through the designed chimney was obtained for maximum irradiance of 604 W/m² occurred on 15th of September,2007, around 13:00h at Tabernas Desert, Almeria province southeastern Spain. As well on same day rate of air-flow was calculated from range 50 till 374 m^3/h. Hence, an average of 177m^3/h air flow rate was obtained at range 0:00 h till 24:00 h and experimental coefficient of discharge found 0.52, C_d for solar chimney. It was discovered that the wind velocity and thermal gradients caused a difference in pressure between output and input that influence the solar chimney air flow rate. A numerical and experimental study was presented by **(Karima and Saif, 2012)** to conduct solar chimney heat transfer enhancement in unsteady conditions with inserting phase change material. Three entrance positions of air was tested for two chimney inclination angles 75^o and 90^o of dimension 2.25m length x 0.97m width and 0.15m air gap. The results indicated that the behavior of solar chimney influence by the entrance position and the best results found with side opening. It was found the inserting of phase change material enhance the behavior of solar chimney and expanded the hours of ventilation after the absence of solar irradiance through releasing the energy stored.

(Jianliu and Weihua, 2013) performed an experimental and numerical study to conduct the solar chimney behavior that inserted into one story building to specify the best inclination angle that gives maximum ventilation rate. Three types of sizes of solar chimneys were used in the case study and located in Nanjing at 60˚,45˚,30˚ tilt angles. The results showed that the numerical simulation was close to the results found experimentally, the glass temperature, the absorber temperature and the flow-channel temperature all were increased with the increasing of solar radiation intensity. It was found that the 45˚ tilt angle the optimum for getting maximum ventilation rate in Nanjing, it was conducted that the mass flow rate at 45˚ tilt angle greater than the mass flow rate at 30˚ and 60˚ tilt angles by 8%, also conclude that the ventilation rate rise with the increasing of air gap to the height of absorber ratio. **(Seytier and Naraghi, 2013)** develop an analysis of convection and radiation heat transfer for solar chimney where the air flow was predicted for different solar irradiations and structures. A CFD modeling utilizes in the software FLUENT that the designed solar chimney was 2m height, air gaps 0.1 and 0.2 meters and the inclinations were chosen 60˚,45˚,30˚. The result showed the delivered rate of air flow will be higher for the thicker chimney, that for doubled air gap thickness there will be increase of 1.7 in flow rate depend on the considering inclination. A solar chimney model was studied experimentally and numerically **(Ahmed et al., 2015)** to investigate chimney performance for various geometric feature under weather condition of Iraq. The tested model of 2m height and 2m wide was attached to room of $12m^3$ volume at the roof, three thickness of air gap (0.05, 0.1 and 0.15m) was examined at tilted angles 15^o to 60^o. results showed that 60^o was the optimum incline angle to achieved highest ventilate rate, which it higher by 20% from 45^o incline angle. The highest produced ventilate rate from the designed solar chimney was 30 ACH at 750 W/m^2 solar irradiance for 60^o incline angle with 0.8 m/s maximum velocity of air for 0.05 m air-gap thickness, also no air-flow reverse was noticed in 0.15 m gap thickness.

In this research, the heat transfer improvement of solar chimney is tested experimentally and the improvement is accomplished by adding metal foam to the solar chimney as an absorber plate. Two identical solar chimneys are designed (without inserting of metal foam and with inserting of metal foam) examine for different chimney inclination angle and the impact of inserting metal foam is observed through comparing the collected data from both chimneys.
To the most useful of authors knowledge, the heat transfer improvement of solar chimney with the integrate of metal foam that investigated experimentally is not showed in the previous work, specifically in Iraq.

2. EXPERIMANTAL APPARATUS

To carry out the experimental test, two solar chimneys are designed and placed facing south. These chimneys manufactured from convenient material that available in the market with dimensions of length× width (2 m× 1 m) and tested for incline angles of (20^o,30^o,45^o,60^o), each chimney consists of glass cover, absorber plate and insulation on the sides and bottom. The chimney gap is 20 cm, considered based on estimate the thickness of boundary layer (δ) and the displacement thickness(δ^*) from the following relation **(Eckert and Jackson, 1950)**:

$$\delta = 0.565y(Gr)^{-1/10}(\mathrm{Pr})^{-8/15}[1 + 0.494(Pr)^{\frac{2}{3}}]^{1/10} \tag{1}$$

Where: the prandtl number is (Pr) and the grashof number is (Gr) of the air. The temperature difference of 20, 30 and 40 ^oC was taken between surface and intel air temperature.
The displacement thickness can be determined by the following equation **(Eckert and Jackson, 1950)**:

$\delta^{*} = 0.272\,\delta$ (2)

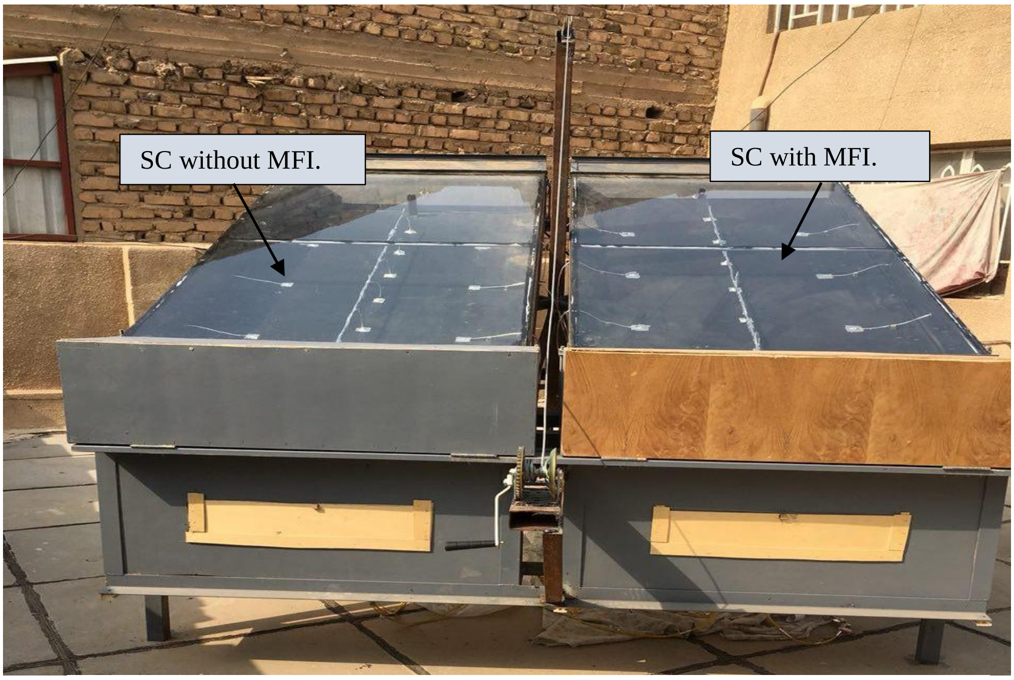
The chimney gap is found double the displacement thickness, for that the proportion of (height/ gap) is roughly equal to eleven (11). That corresponding to the result of proportion indicated from **(Bouchair, 1994)** that (the height/chimney gap) ratio was equal (10), to receive highest flow rate experimentally throughout the structure. The experiment system is shown diagrammatically and photographically in **Fig. 1**.

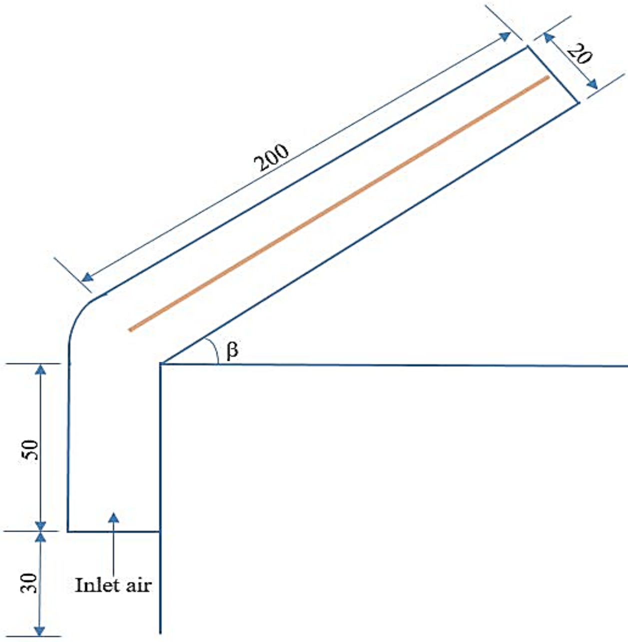
2.1 Solar Chimney

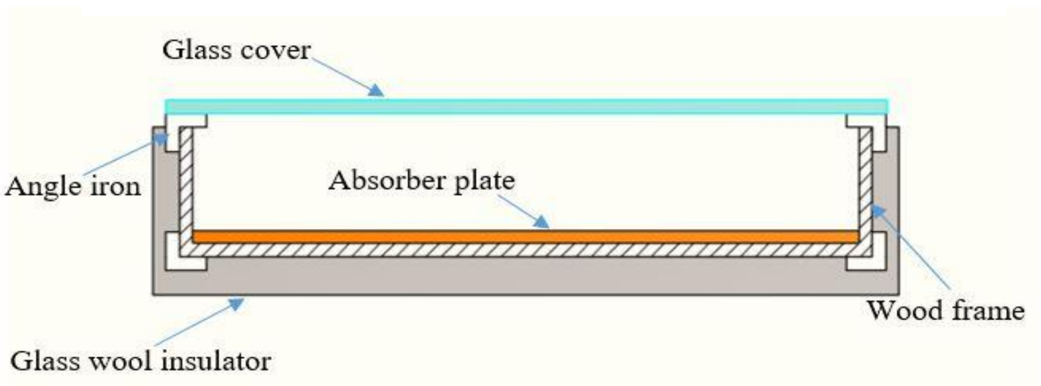
Two solar chimneys are identically designed the first solar chimney with metal foam and the second chimney without metal foam insertion(conventional) with 10 cm space in between. The structure of solar chimney is formed by using iron frame of 3 mm thickness with an area of (2×2.10)m^2 , provided at its end with stud to connect the iron frame. The chimney room at the sides and bottom of each chimney layout is constructed from wood and covered at the top with glass.

A copper plate of 2.5 mm thickness is used as a solar radiation absorber with an area of (2×1)m^2, and coated with a black matte color to enhance the solar chimney thermal behavior. Absorber copper plate is riveted to the bottom side of the chimney applying sixteen rivets. The structure is well insulated by using a glass wool insulator of 2.5 cm thickness at the bottom and sides and reinforced from the bottom by using a fiber wood of 3 mm thickness. The chimney is installed on a stand of iron with the same area of the entire structure of (2×2.10)m^2 and 80 cm high from the ground. Initially the chimney is set up at 20^{o} incline angle from the surface, the incline angle is changed by hand using pulley. A single glass cover of 4 mm thickness is used for each chimney with an area of (2×1)m^2 fitted in the iron frame. The air inters to the chimney room from the bottom 30 cm above the ground. A wood box is assembled and welded to the iron stand that the box height 50 cm.

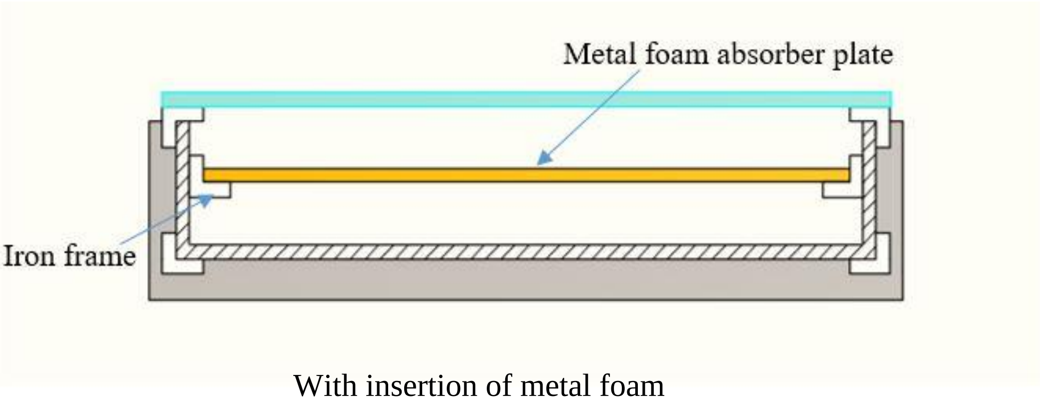
To obtained the anticipated enhance in thermal characteristics of the solar chimney that caused by inserting metal foam, twelve thermocouples (K-type) are fixed by drilling (2.5mm) V-hole on the copper absorber wall and soldered to measure the absorber plate temperature for each chimney (without insertion of metal foam and with insertion of metal foam). Also to obtain the air temperature variation along the flow direction (K-type) thermocouples are utilized placed in the mid line of copper plate, six thermocouples located at 10 cm from the glass cover for solar chimney without insertion of metal foam and twelve thermocouples for solar chimney with insertion of metal foam are installed above and below the copper foam absorber plate located 5cm from the glass cover and 5cm from the back wall as shown in **Fig. 2**.


SC without MFI.
SC with MFI.


200
20
β
50
30
Inlet air


Glass cover
Angle iron
Absorber plate
Wood frame
Glass wool insulator

Without insertion of metal



With insertion of metal foam

Figure 1. Experimental Apparatus and Dimension in (cm) .

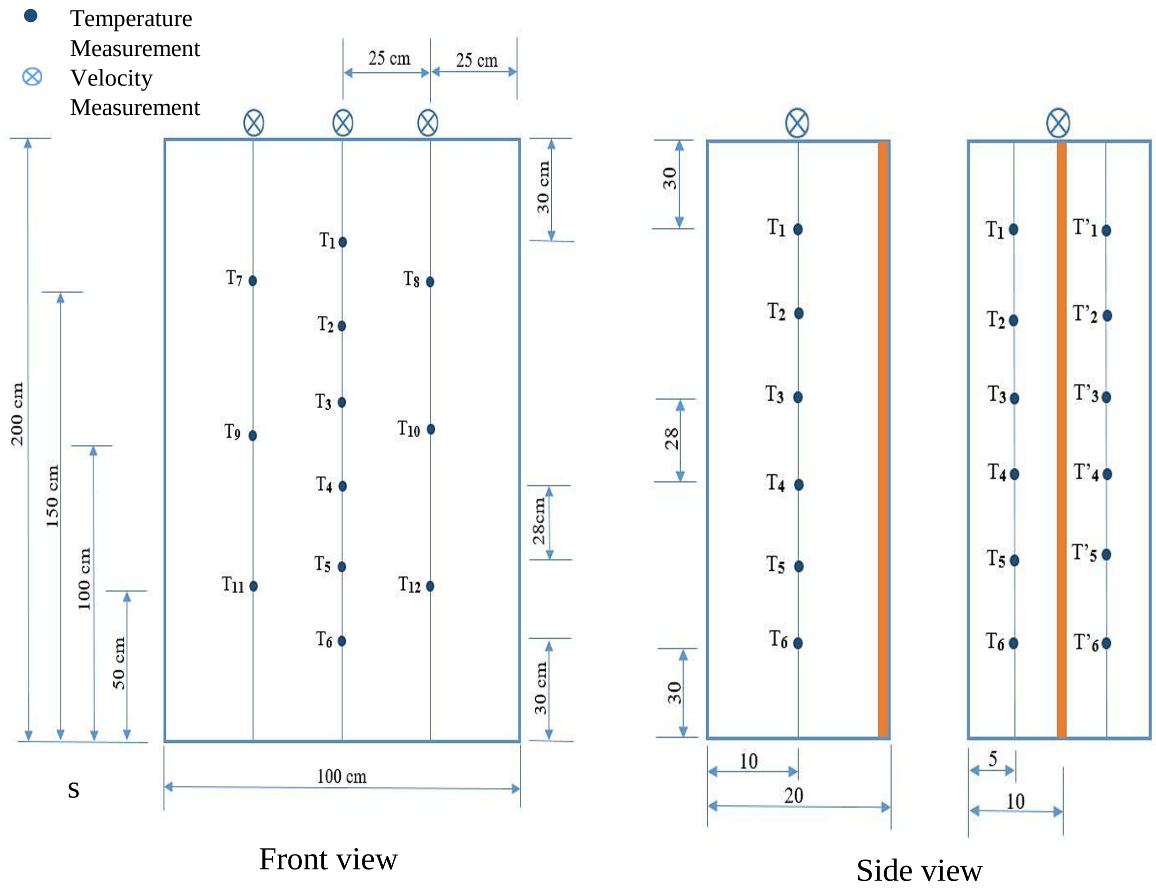


Figure 2. Location of thermocouples for absorber wall and air temperatures.

Measurement of temperature also involved: the air inlet and outlet temperature and cover temperature. A Data Logger device with an accuracy of ± 0.4^o C over a range of - 50 to 999.9 ^{o} C is used for measuring the temperature where the thermocouples attached to, consisted 12-channel thermocouple input model BTM-4208SD with a SD card to save the temperature readings along with time information.

The wind is induced reverse flow that have a significant impact on the chimney air flow rate. To minimize the wind effect, an extension of wood is constructed at the top with the same area of chimney gap. The air velocity measurement is achieved by using Hot Wire Anemometer model DT-8880 that use for low measurement of air velocity with range of 0.1~25 m/s and accuracy ±0.05 m/s. The velocity measurement for exit air flow is taken average of three point for each chimney. A box of wood setup is assembled to make ensure that the sensor head of the device is in the correct position and direction. It is installed at the exit with dimension of (10 cm×5 cm×5 cm), a slot is made along the wood box with the same diameter of hot wire probe.

2.2 Construction of Metal Foam, Bonding and positioning.

The absorber plate of 40 PPI copper foam is used with thickness of 1 cm as shown in **Fig. 1**. The copper foam absorber plate is formed by assembling four metal foam sheets that coated with black matte color. The cross sectional area of (1×0.5)m^2 for single metal foam sheet. To accomplish good contact between the metal foam sheets an overlap original bonding method is utilized to interfere the pieces in appropriate way, that does not influence the metal foam thermal characteristics and its thermal resistance contact. The sheet is overlap with distance of 2 cm over the other sheet by using sharp blade and thirty-two aluminum rivets with 15 cm distance between two consecutive rivets is used to make sure that the copper foam sheets are located in the correct position. **Fig. (3 and 4)** shows the elements which previously mentioned.

Figure 3. Overlapping the metal foam.

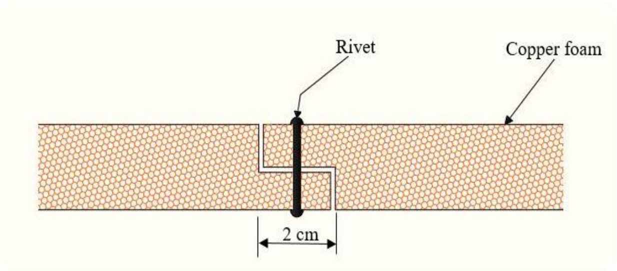


Figure 4. Schematic drawing for overlapping the metal foam.

2.3 Procedure of Experimental Test

The experimental test was take place in Baghdad (33.3° latitude, 44.4° longitude) for this solar chimney system from October to December 2018. Hourly the data of solar radiation and ambient temperature are obtained from the Science and Technology Ministry for Baghdad city. For every half hour the data is obtained where the test started from 09:00 AM and finished at 04:00 PM and. There is some preparatory work that required to be done Before each test start as followed:

1) Clean chimneys glass covers from dust and humidity.
2) Set the incline angle of chimney by using the system that made for changing the angle.

3) Experimental data is recorded from 9:00 AM to 4:00 PM, the temperature and velocity is recorded every 30 min.
4) During each test day the same angle is used for both solar chimneys.

For every test case from (09:00 AM) to (04:00 PM), recorded the following measurements:
1- Thermocouples measurement in ^{o}C.
2- Solar intensity in W/m^2.
3- Air velocity in m/s.

3. HEAT TRANSFER AND THERMAL PERFORMANCE CALCULATIONS

3.1 Air Change Per Hour

The air change per hour can be established as the ratio of the volume flow rate to the total room volume:

$$ACH = \frac{V'}{V} \tag{3}$$

The volume flow rate can be given as,

$$V' = A_o * v_o * 3600 \tag{4}$$

Where the total room volume is taken 27 m^3 by ASHRAE stand of an actual room size. The air change found is indicated the ventilation rate in actual life condition.

3.2 Calculation of Thermal Efficiency

The solar chimney efficiency (η_{sc}) established from the proportion of the provided chimney useful energy to the solar energy incident rate on its area at specified time **(Duffie and Beckman, 2013)**:

$$\eta_{sc} = \frac{Q_u}{Q_i} \tag{5}$$

The useful energy of the solar chimney is determined as follow:

$$Q_u = \dot{m} * C_P * (T_{fo} - T_{fi}) \tag{6}$$

The amount of incident solar energy on the solar chimney area can be obtained from the product of the chimney area and the total solar intensity as follow:

$$Q_i = I_T A_{sc} \tag{7}$$

Where:

$$A_{sc} = W * L \tag{8}$$

The properties of air were evaluated at air average temperature, which it can be obtained as follow **(Bansal et al, 1993)**:

$$T_f = \varepsilon T_{fo} + (1 - \varepsilon) T_{fi} \tag{9}$$

Where: ε is taken (0.74)

For the characteristics of air between 300 and 350 K, the following relation is used **(Incropera and DeWitt, 1996)**:

$$C_p = \left[1.007 + 0.00004\left(T_f - 300\right)\right] * 10^3 \tag{10}$$

$$\rho_f = [1.1614 - 0.00353\left(T_f - 300\right)] \tag{11}$$

4. RESULTS AND DISCUSSION

The experimental studies are established for selected days in October, November and December 2018 to examine the thermal performance of the designed solar chimney and the impact of using metal foam for different inclination angles. The weather condition that involve the solar irradiance intensity and ambient temperature are presented in **Fig. (5 and 6)**. The parameters that are investigated: temperature of mean absorber plate (T_p), mean air temperature inside the solar chimney gap, outlet air temperature, absorber wall temperature, air temperature distribution in the mid space of the gap, mean exit air velocity, air volume flow rate, ACH (air change per hour), chimney thermal efficiency as well as useful energy.

4.1 Overall Characteristics of Chimneys Temperature

The variation of the mean temperature absorber plate (T_p) for the two chimneys without and with metal foam insertion presents in **Fig. 7.** with time at chimney inclination angle (20^o, 30^o, 45^o, 60^o) respectively on the 29^{th}, 13^{th}, 31^{th} and 23^{th} of October. It is clear that the behaviour of the absorber plate temperature similar to that of solar irradiance. With the increase of the intensity of solar irradiance, the temperature of absorber plate increases then the absorber plate temperature decreases due to the declination in the intensity of solar radiation as shown in **Fig. 5** that started afterward 01:00 PM. The maximum value of absorber plate mean temperature $T_{\mathbf{p\text{-}with}}$ with metal foam and $T_{\mathbf{p\text{-}without}}$ for without metal foam are (69 and 75.9) ^{o}C at a tilted angle equal 60^o. It clear that the temperature of metal foam absorber plate is lower when it compares to the temperature of absorber plate without metal foam. The airflow across the metal foam absorber plate caused a decreasing in the mean absorber plate temperature, because the air is passed over, through and lower the metal foam plate while without metal foam the air is passed upper the absorber plate only. The maximum mean plate temperature variance that obtained between the chimneys attained to 4.1 ℃ at 20^o, 5.5 ℃ at 30^o , 6.7 ℃ at 45^o and 6.4 ℃ at 60^o chimney inclination angle.

Fig. 8. shows the variation of mean temperature absorber plate for the chimneys without and with metal foam insertion for various dates (October, November and December) with time for 60^o chimney tilted angle. The absorber mean temperature variance between the two solar chimneys attained to 6.6 ℃ on the 22^{th} of October, 6.7 ℃ on the 1^{st} of November and it reached to 6.2 ℃ on the 11^{th} of December. It is clear that the influence of metal foam presence inside the chimney is more effectual in weather condition with high solar radiation intensity that happens in October and November. When the intensity of solar irradiance increases the buoyancy effect is increased, the metal foam presences will help with the mixing procedure in the chimney and cause the convection heat transfer that occurs in the chimney gap to increase and established the required heat transfer enhancement.

Figs. 9. shows the variation of the mean air temperature measured inside the chimney gap for both solar chimneys without ($T_{without}$) and with insertion of metal foam (T_u and T_L), with time for various chimney inclination angle and different dates. The general behavior of the chimney gap air temperature is proportional directly to the intensity of solar radiation. Highest temperature of air flow for the chimney without insertion of metal foam attained to 49.2 ℃ for 60^o and 48.6 ℃ for 45^o ,although with the insertion of metal foam the solar chimney produces air flow with temperatures of 44.9 ℃ for 60^o and 45.9 ℃ for 45^o for period of time 1:00 PM on 23^{th} and 31^{th} of October. It seems that the air flow temperature in the chimney gap is higher in the case of conventional chimney (without metal foam) than with insertion of metal foam. The absorber plate in conventional chimney is placed at the bottom and have the space to develop the thickness of thermal boundary layer while metal foam absorber plate divides the air flow upper and lower inside the chimney gap **(Karima and Khawla, 2013)**.

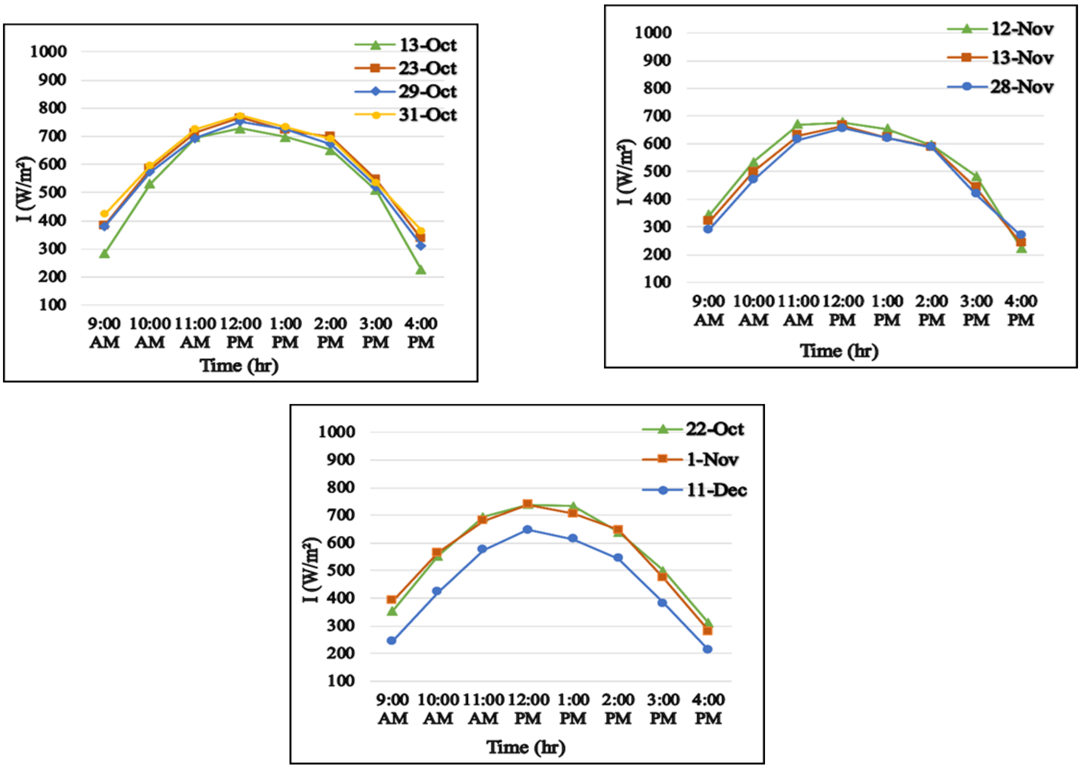


Figure 5. Solar irradiance intensity at various dates.

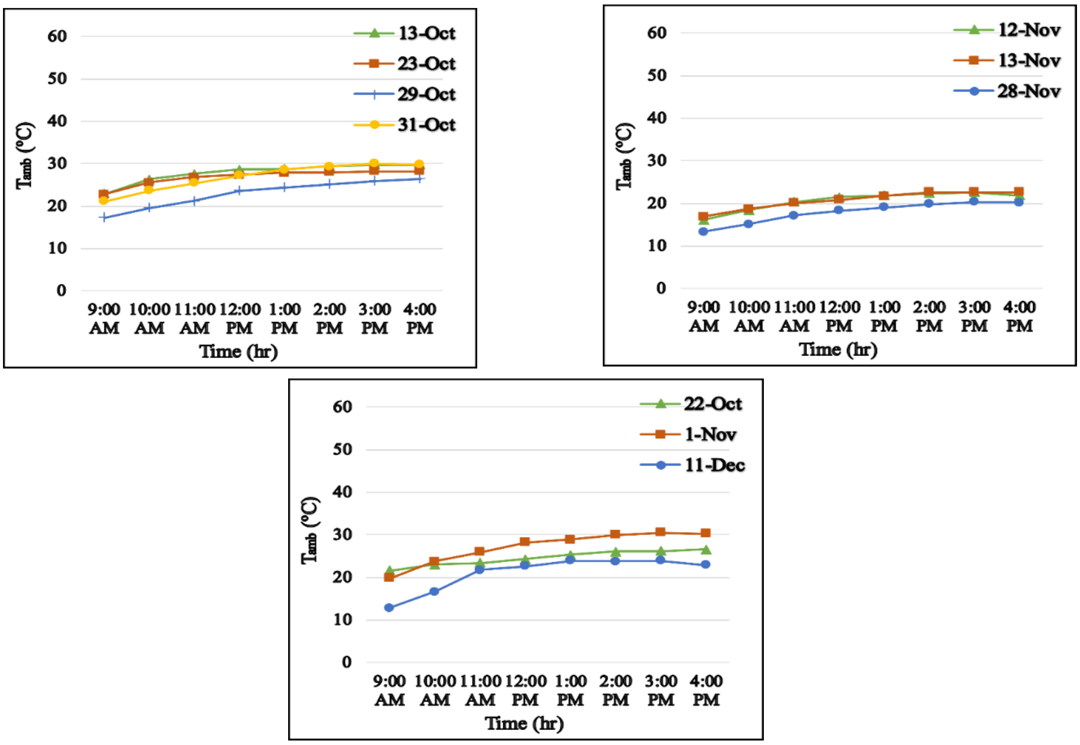


Figure 6. Ambient air temperature at various dates.

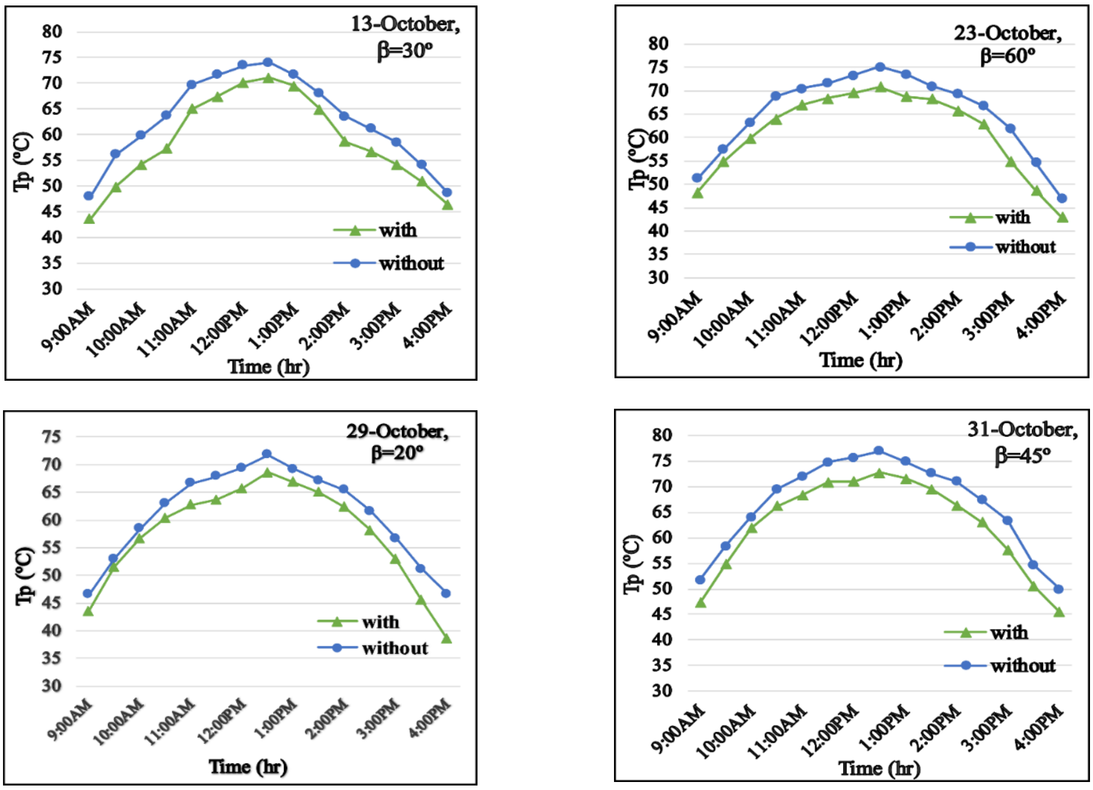


Figure 7. Mean temperature of absorber plate variation with Time for Different Inclination Angles.

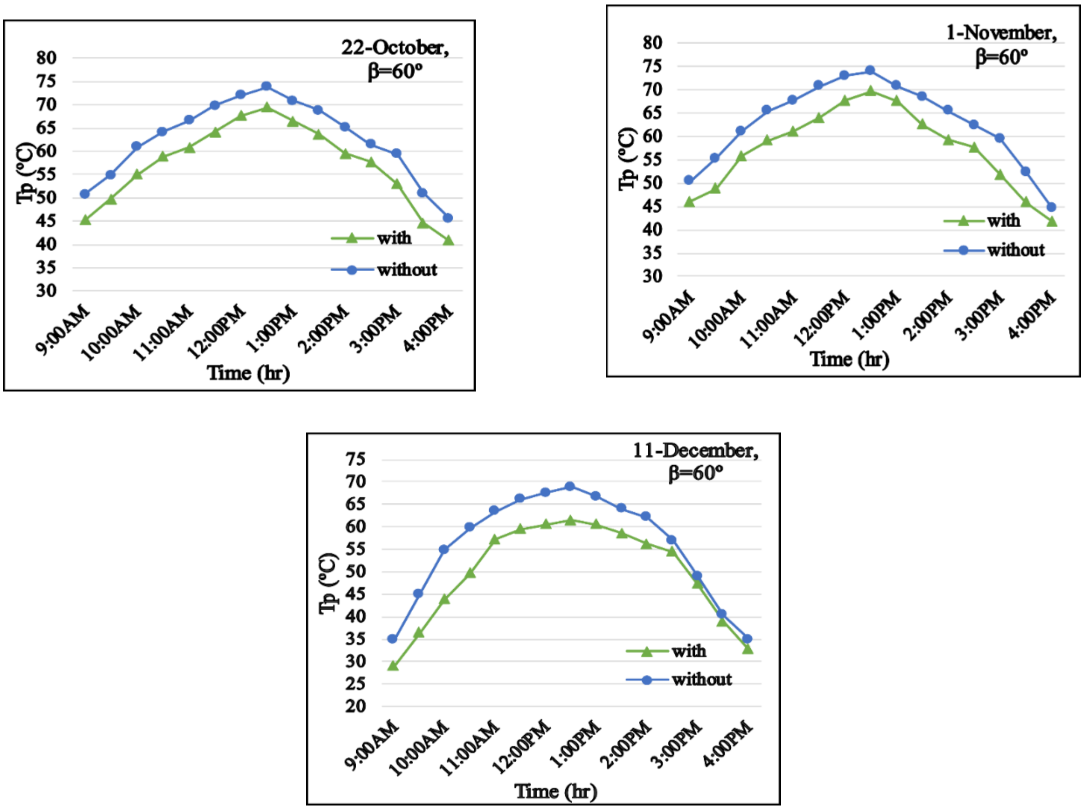


Figure 8. Variation of Mean Temperature Absorber Plate of the Chimneys without and with MFI at 60° tilted Angle with Time on 22th of October, 1st of November and 11th of December.

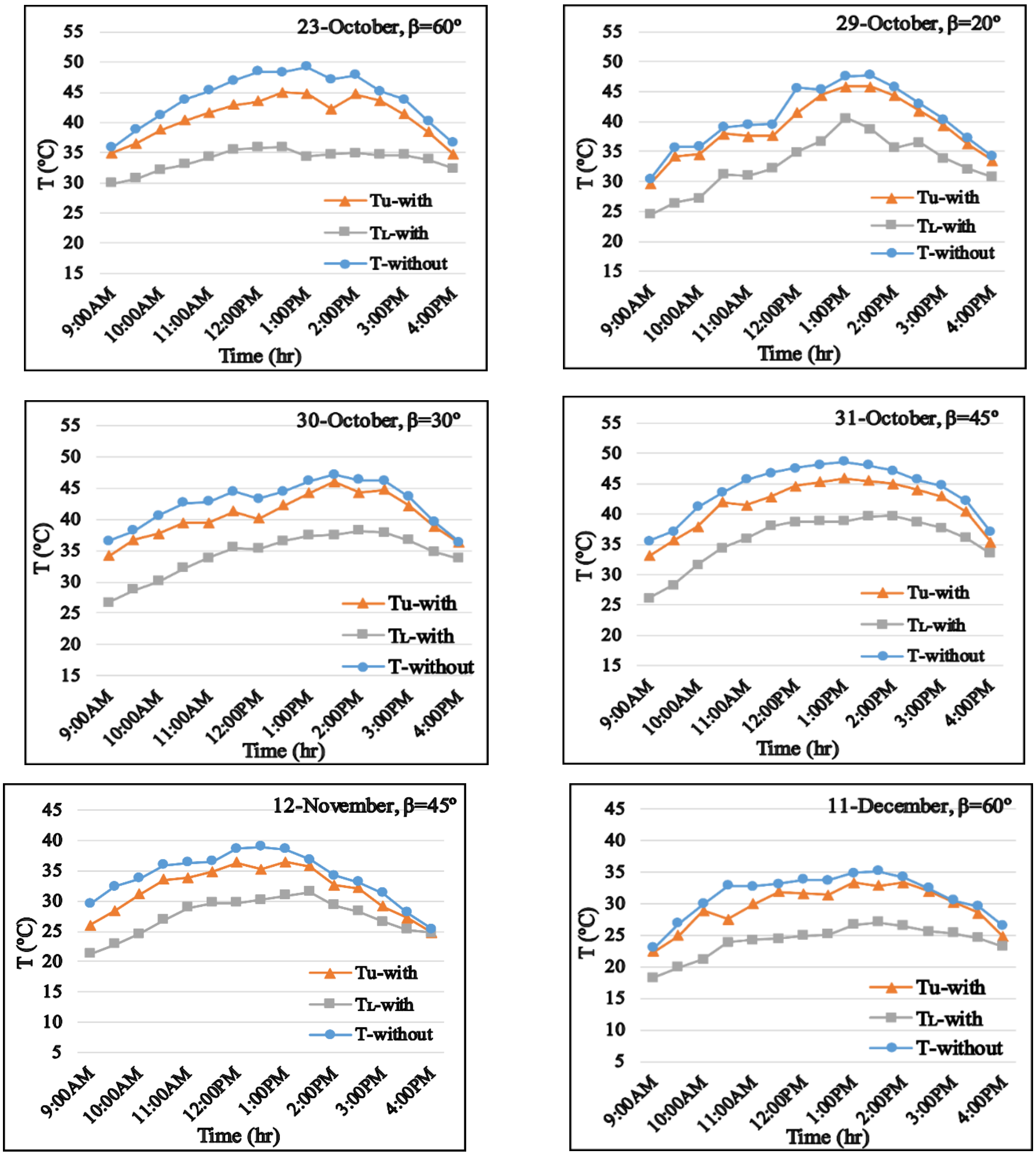


Figure 9. Variation of Air Mean Temperature Inside the Chimney without and with MFI with Time for Various Chimney Inclination Angle.

The variation of measured outlet chimney air temperature (T_o) present in **Fig. 10.** for different inclination angles for each solar chimney without and with insertion of metal foam with time for selected test periods. The trend of outlet chimney air temperature is increasing with time until 1:00 PM then its decreases gradually following the solar radiation intensity. The maximum temperature value of the outlet air for the chimney without insertion of metal foam rise to 46.6 °C for 60^o and 44.2 °C for 45^o and for the solar chimney with insertion of metal foam the temperatures of outlet air are 52.4 °C for 60^o and 47.9 °C for 45^o for the periods of time in between 12:00 PM to 2:00 PM.

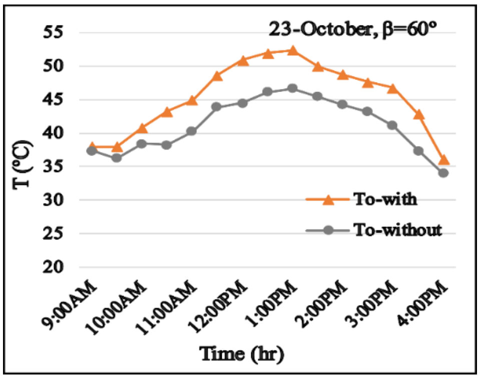
It is clear that the outlet air temperature for solar chimney with metal foam insertion higher from solar chimney without metal foam insertion at any inclination angle. The value of the outlet chimney air temperature at 60^o incline angle gives the maximum difference of 5.8 °C between the chimney of without and with insertion of metal foam. From **Fig. 10.** it can be concluded that the impact of metal foam produced an increment in the chimney outlet air temperature. This behavior presents the proof of enhancement in thermal performance that accomplished when adding the metal foam to the system.

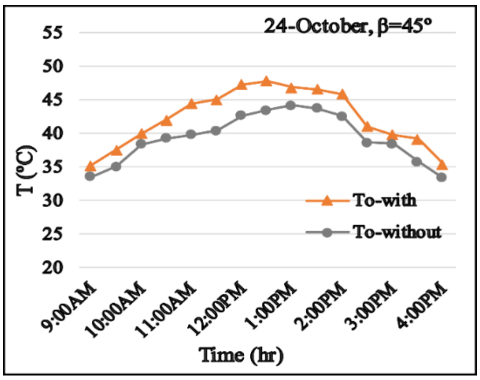
4.2 Distribution of Wall and Air Temperatures

The behavior of distributed temperature of the wall along the centre line ($T_{p1}, T_{p2}, T_{p3}, T_{p4}, T_{p5}$ and T_{p6}) present in **Fig. 11.** For both chimneys without and with insertion of metal foam for 60° incline angle on 8th of December. It is clear that due to the continuous heating and increasing in the temperature of the flowing air throughout the solar chimney, the temperature of wall rises in the direction of flow. The highest values obtained are 69 ℃ for the chimney without metal foam and 64 ℃ for the chimney with metal foam at afternoon and, respectively. It can be concluded that the variance between the temperatures wall along the centre line for each solar chimney increases with the increase of solar irradiance intensity and the influence of adding metal foam in the chimney is more phenomenal. The metal foam existence has influence to rise the ventilate rate of the solar chimney and this causes a higher temperature difference value in the afternoon compared with the earlier morning.

Fig. 12 shows the distribution of the temperature of wall chimney absorber plate along the centre line for each solar chimney, without and with insertion of metal foam for various chimney inclination angle (20°,30°,45° and 60°) on the 29th and 30th of October and 13th and 28th of November.

Fig. 13 shows the distribution of the temperature of air for the chimney along the centre line at six point for each solar chimney without insertion of metal foam ($T_{without}$) and with insertion of metal foam for upper air temperature (T_u) and lower air temperature (T_L) for various chimney inclination angle (20°,30°,45° and 60°) on the 29th and 30th of October and 13th and 28th of November. It is clear that the temperature of air increases in the direction of flow due to the continuous heating throughout the solar chimney. It can be noticed that the air temperature values at the end higher compared to the air temperature at entrance. The metal foam divides the air flow inside the chimney gap and it can be seen that the temperature of air at upper space is higher compared with the temperature of air at lower space. This is because the upper air subjected directly to the fallen solar irradiance while the lower air partially exposed to the sunlight.





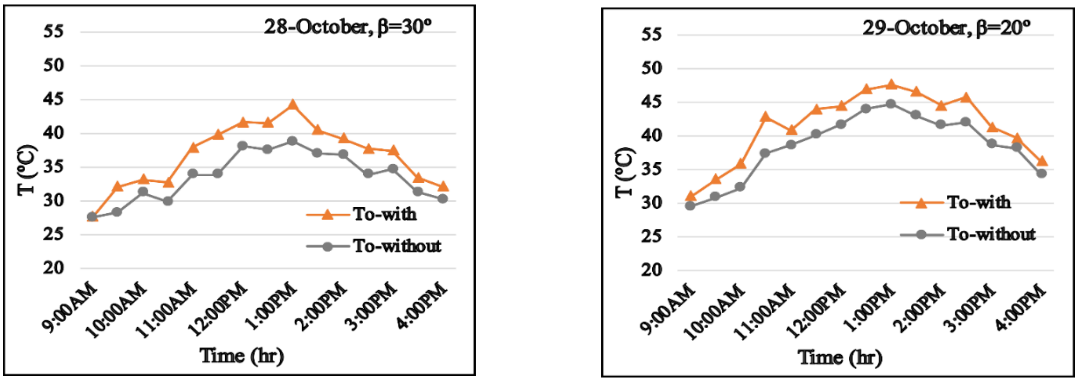


Figure 10. Variation of Outlet Air Temperature of the Chimney without and with MFI with Time for Different Chimney Inclination Angle on the 23rd ,24th, 28th, and 29th of October.

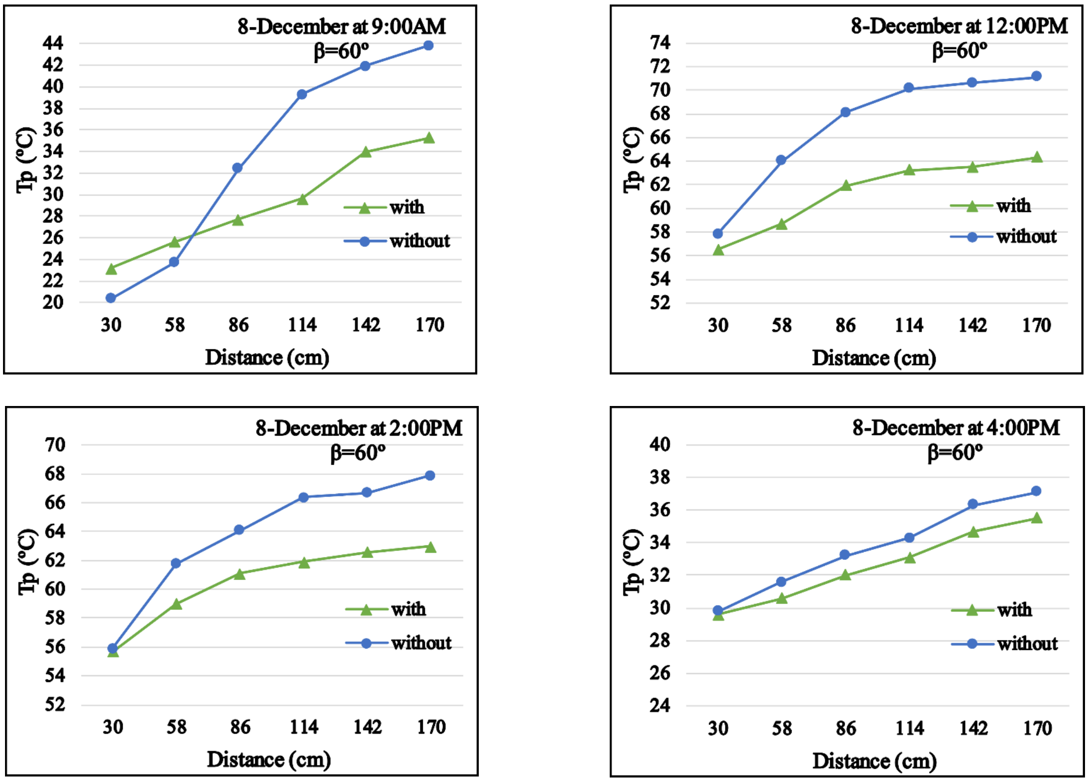
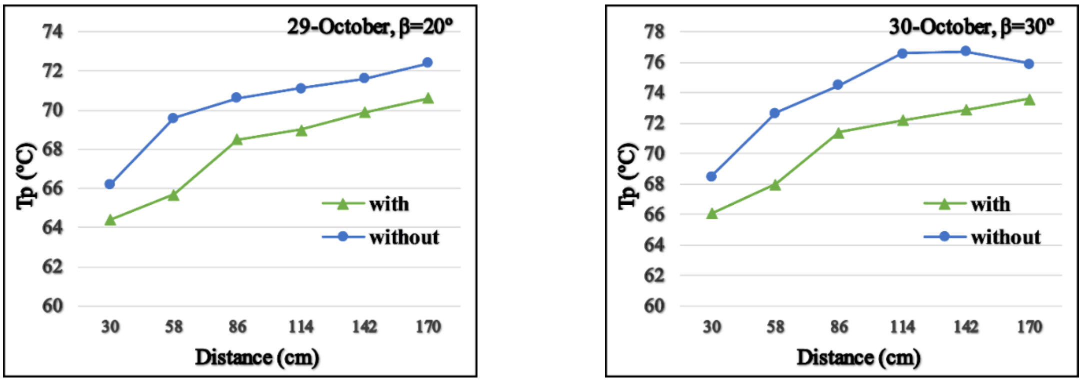


Figure 11. Wall temperature distribution along the mid line of the chimney without and with MFI for different time for 60° inclination angle.



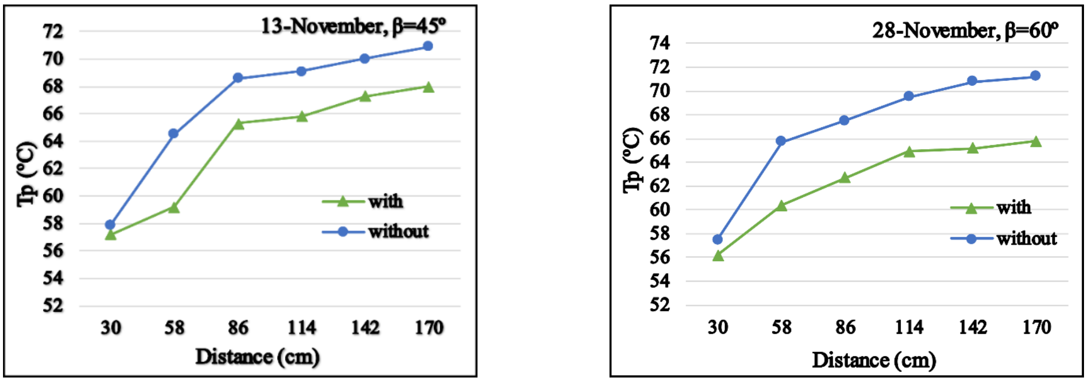


Figure 12. Wall temperature distribution along the mid line of the chimney without and with MFI for Different Chimney Inclination at 12:30 PM.

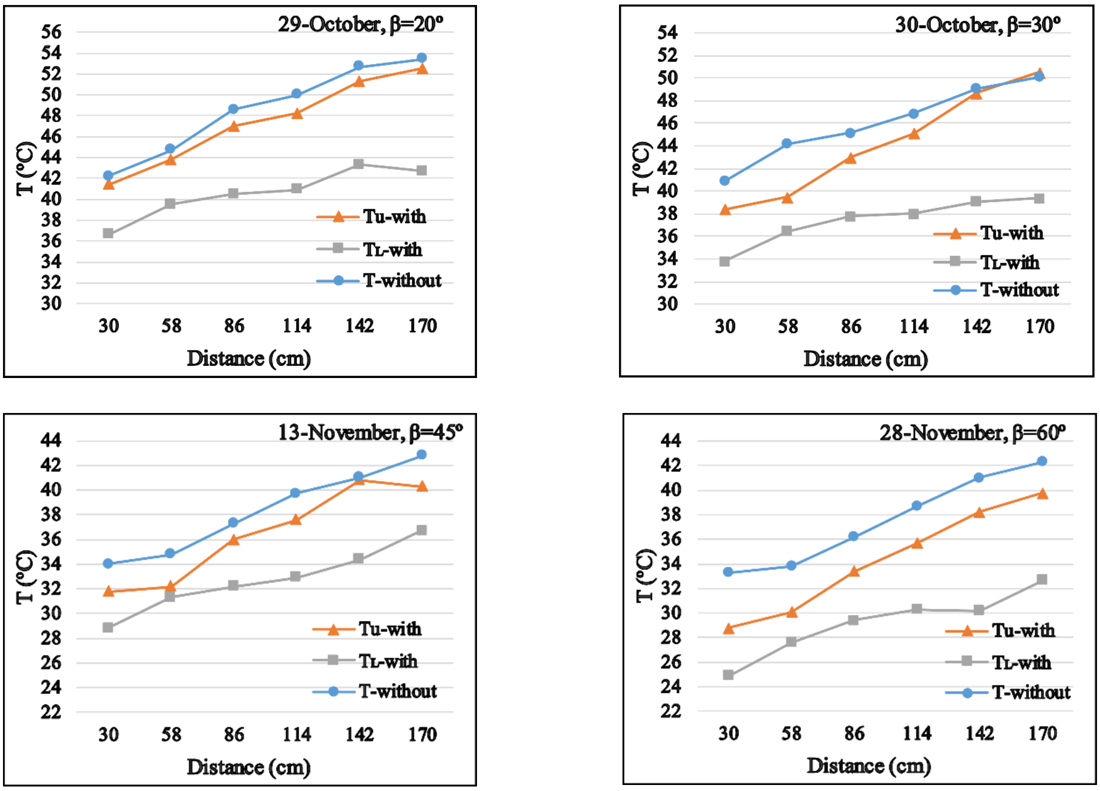


Figure 13. Air temperature distribution along the mid line of the chimney without and with MFI for Different Chimney Inclination at 1:00 PM.

4.3 Velocity Distribution and Ventilate Rate

The mean air velocity (v) behaviour at the exit of the solar chimney is shown in **Fig. 14** for the two chimneys without and with insertion of metal foam, with time for chimney inclination angle (20^o, 30^o, 45^o, 60^o) respectively for different dates. It can be noticed that the trend of the air velocity increase with time until its reach 1:00 PM then it begins to decline following the solar irradiance and the absorber plate temperature. When the solar irradiance intensity increases the temperature increases that cause a reduction in density of air that make the air move upward and drawing air from the ambient and ventilate the space. It clear that the air velocity with insertion of metal foam is higher than for without metal foam solar chimney. The maximum values of solar chimney mean air velocity without insertion of metal foam are 20 cm/s for 60° and 19.3 cm/s for 45° and for solar chimney with insertion of metal foam the mean air velocity are 22.3 cm/s for 60° and 22cm/s for 45° on the 23th and 31th of October. The disturbance that made by existence of metal foam, additionally the increase in the surface-area lead to increase heat transfer among the surface area with the moving fluid (air) inside chimney room. That cause a higher air velocity at the exit and increasing in the ventilation rate that the enhancement can be conducted from the insertion of metal foam.

Fig. 15 presents The variation for the volume flow rate (V') for the two chimneys without and with insertion of metal foam, with time for 60° chimney inclination angle on 23th of October and 1st of November. It noticed from the figure that the ventilate rate (air volume flow rate) is greater for solar chimney with metal foam insertion compared with the solar chimney without metal foam insertion. The maximum value of mean air volume flow rate obtained for solar chimney with insertion of metal foam that reaches 160.5 m^3/hr for 60° on the 1st of November as result, 5.96 1/hr air change per hour is achieved.

4.4 Solar Chimney Thermal Efficiency and Useful Energy

The difference between each solar chimney without and with insertion of metal foam thermal efficiency shows in **Fig. 16,** with time on 23th and 31th of October. The trend of the thermal efficiency can be noticed its follows the solar radiation that the thermal efficiency of solar chimney increases with the increase of intensity of solar radiation. Because of the ambient temperature rise continuously and that lead to decrease in the losses of heat. It clearly noticed in **Fig. 16** the enhance accomplished by using the metal foam in the solar chimney. That the maximum value of chimney thermal efficiency for solar chimney without insertion of metal foam attained to 42% for 60° and 30.9% for 45° on the 23th and 31th of October, respectively at 01:00 PM and for with insertion of metal foam solar chimney the maximum values of chimney thermal efficiency are 53.6% for 60° and 48.8% for 45° on the 23th and 31th of October.

Fig. 17 present the distribution of useful energy received from the solar chimneys without and with insertion of metal foam for every hour. The trend of the useful energy follows the solar irradiance that increases with the increase of solar irradiance and start to decrease due to the solar irradiance decreasing. It can be noticed that the energy obtained from the solar chimney with the insert of metal foam higher than from the solar chimney without metal foam. It is clear the effect of inserting the metal foam as an absorber plate to the solar chimney where the energy achieved from the solar chimney has been effected by the heat transfer characteristics enhancements. The highest values of chimney useful energy without insertion of metal foam are 540.8W for 60° and 477 W for 45° and for with insertion of metal foam the useful energy received are 812.5 W for 60° and 892.7 W for 45° on the 23th and 31th of October

The highest daily solar chimney efficiency enhancement present in **Fig. 18**. That the values of daily solar chimney efficiency enhancement for 20° and 30° chimney inclination angles 41.2% and 47.8%, respectively and in the case of 45° and 60° chimney inclination angles the enhancement rise to 53.6% and 58.7%, respectively.

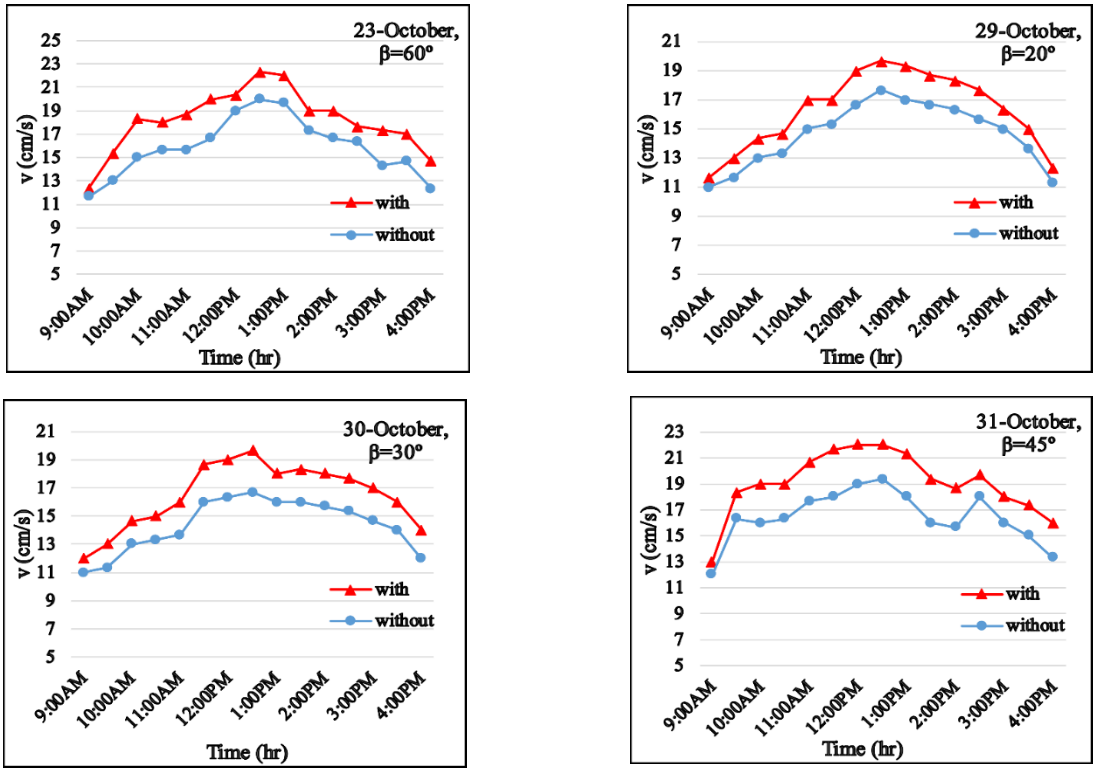


Figure 14. Variation of air velocity for the solar chimney without and with MFI with Time for Different Inclination Angles on October.

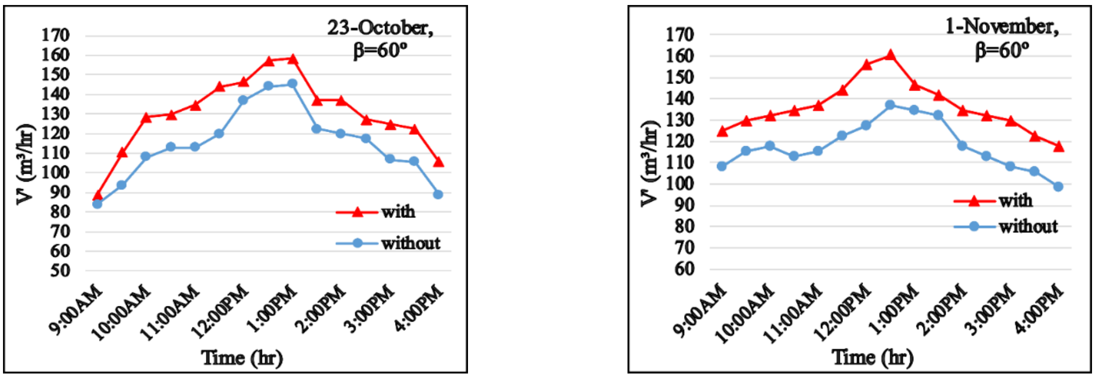


Figure 15. Variation of volume flow rate for the solar chimney without and with MFI with Time for 60^o Inclination Angles on 23th of October and 1st of November.

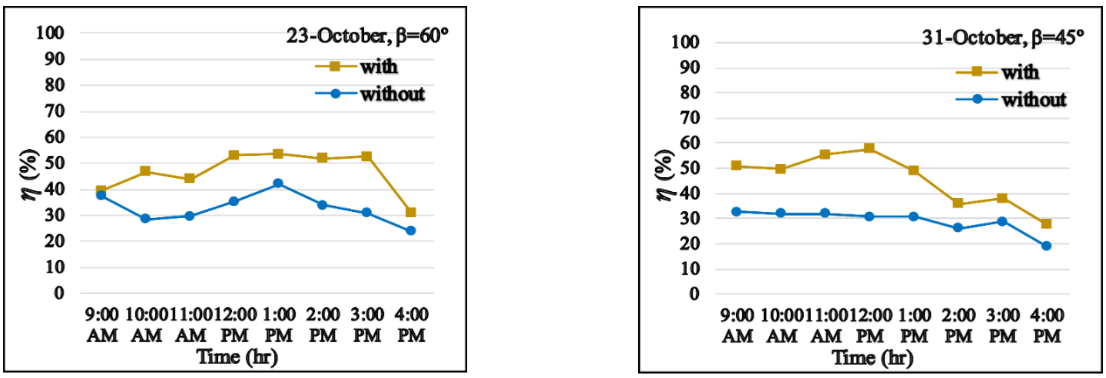
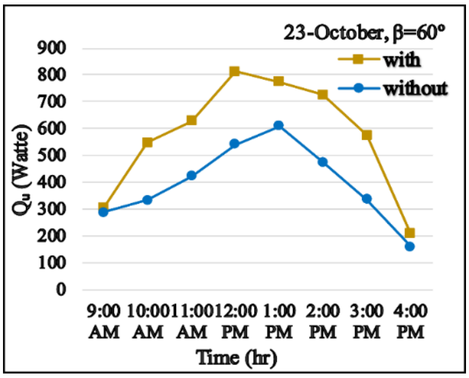


Figure 16. Variation of chimney thermal efficiency of the solar chimney without and with MFI with Time for 60^o and 45^o Inclination Angles on 23th and 31th of October.



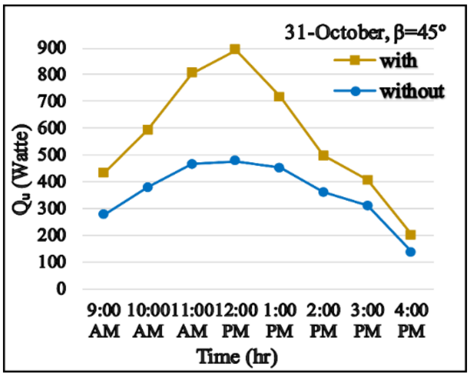


Figure 17. Variation of chimney useful energy of the solar chimney without and with MFI with Time for 60° and 45° Inclination Angles on 23th and 31th of October.

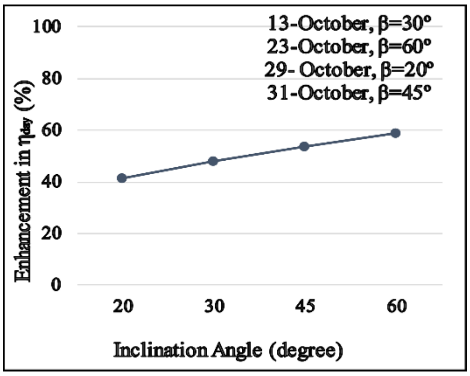


Figure 18. Chimney thermal efficiency enhancement per day with chimney inclination angles.

5. CONCLUSION

The solar chimney has been studied experimentally to conduct natural ventilation and investigate the enhancement in the characteristics of heat transfer and the solar chimney thermal performance that was achieved by integrating the copper foam absorber plate in the solar chimney. The study is carried out on two solar chimneys with insertion of metal foam and without metal foam under Iraqi weather condition with different chimney inclination angles in October, November and December 2018. The following conclusions are summarized from the present investigation.

1- Thermal performance of solar chimney is greatly influenced by the solar irradiance and the incline angle, especially at higher tilted angle.
2- A comparison for the data that obtained from the two chimneys with insertion of metal foam and without insertion of metal foam. The addition of metal foam produced the following effects:
   a) Reducing the mean temperature of absorber plate value and an increment in the values of chimney outlet air temperature. The highest reduction in the plate temperature that obtained experimentally is 6.7 °C at 45° chimney inclination angle. The highest increase in the air temperature that obtained through the whole experimental is 5.8 °C at 60° chimney inclination angle.
   b) Increase the mean outlet air velocity through the whole experimental by 4 cm/s on 1st of November for 739 W/m^2 solar irradiance intensity at 12:00 PM for 60° incline angle. That enhance by 22.6%

c) An increasing in the air volume flow rate and air change per hour that the highest values obtained are 160.56 m^3/hr and 5.96 1/hr, respectively at 60^o incline angle on 1st of November.
d) An increasing in the chimney thermal efficiency and useful energy that the maximum enhancement by 87.14% on 31th of October at 12:00 PM for 45^o inclination angle.
e) Enhance the daily chimney thermal efficiency that for 20^o and 30^o chimney inclination angles 41.2% and 47.8%, respectively and in the case of 45^o and 60^o chimney inclination angles the enhancement rise to 53.6% and 58.7%, respectively.

3- The enhancement that achieved by the existence of metal foam is decreased as the chimney inclination angle is decreased and as the solar radiation intensity decreased.

4- The results of the experimental work show that the addition of metal foam to the solar chimney as an absorber plate is an efficient method to enhance the characteristics of heat transfer and the thermal performance of the solar chimney in the weather condition of Iraq mainly for higher intensity of solar irradiance and higher chimney inclination angle.

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NOMENCLATURE

Symbols	Description	Units	Symbols	Description	Units
Latin Symbols					
A_{sc}	Solar chimney surface area	m^2	T_f	Air average temperature	^oC
A_o	Outlet cross area	m^2	T_{fi}	Inlet air temperature	^oC
b	Chimney depth	m	T_{fo}	Outlet air temperature	^oC
Gr	Grashof number	/	T_u	Air temperature upper the copper foam	^oC
I	Total solar incident	W/m^2	T_L	Air temperature lower the copper foam	^oC
L	Chimney length	m	T_p	Mean absorber plate temperature	^oC
$\dot{m}$	Mass flow rate	Kg/s	v_o	Exit air velocity	m/s
Pr	Prandtl number	/	V	Volume	m^3
Q_i	Incident solar energy	W/m^2	V'	Volume flow rate	m^3/hr
Q_u	Useful energy	W/m^2	w	Chimney width	m
T_{amb}	Ambient air temperature	^oC	y	chimney's height	m
Greek Symbols					
β	Chimney inclination angle	degree	η	Thermal efficiency	/
ε	Constant in mean temperature approximation	/	ρ_f	Density of air	Kg/m^3
			δ	thickness of the thermal boundary layer	m
Abbreviations					
ACH	Air Change per Hour				
MFI	Metal foam insertion				
PPI	Pore per inch				
SC	Solar chimney				