Impact of Absorbent Surface Type on Thermal Performance of Trombe Wall System

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Abstract:- The absorbent surface of a passive solar heating system plays an important role in improving its performance. Therefore, in this paper, an experimental comparison was conducted between the thermal performances of modified and classic sample of thermal storage wall (Trombe wall) under Kirkuk city climate in January 2018. The absorbent surface of the modified Trombe Wall was treated by adding a layer of copper chips. In general, the Trombe Wall was made of 10 cm thick vented concrete wall south faced, pained black and covered with a glass layer. The samples' performances were investigated by computing the thermal efficiency and Nusselt number along with the air channel. The comparative results showed that the absorbent surface type had a significant effect on the Nusselt number and least effect on thermal efficiency. The average Nusselt number of the modified sample increased by about 10% compared to the classic sample, whereas the thermal efficiency of the classic sample was higher at about 5% than the modified sample.

Keywords:- *Absorbent Surface; Nusselt Number; Thermal Efficiency; Trombe Wall.*

I. INTRODUCTION

The sun emits solar energy in the form of light and thermal energy to earth. Within a year, the thermal energy emitted to earth exceeds many times the world's energy needs [1]. Solar energy can be exploited in many activities especially for heating since 40% of energy consumption is spent on heating buildings [2]. The passive solar heating system seeks to reduce energy bills of buildings since building materials act as thermal blocks that store and distribute solar energy through natural convection, radiation, and conduction. Thermal storage wall (Trombe wall) is one of the passive solar heating systems used for space heating. The first idea of the wall was explored and patented by an architect named Edward Morse in 1881 and in the 1960s, it was developed as an architectural element by a French engineer named Félix Trombe in collaboration with an architect named Jacques Michel [3,4]. The thermal storage wall consists of a massive wall, usually mounted on the south face of the house, built from common building materials such as concrete, bricks, and phase change materials. The outer surface of the wall is painted black and acts as an absorbent surface for solar radiation. The southern faced wall is covered with a single or double glass layers, with a cavity behind the air channel. At the top and bottom parts of the storage wall, there are vents to allow air circulation between the house area and the air channel.

Trombe wall stores solar energy throughout the day and releases it at night to the air space via convection and radiation heat transfer. There are several theoretical and experimental studies conducted on the Trombe wall to improve its performance, namely by changing the parameters, materials, and dimensions of certain parts of the system to reach an optimal module that serve the building occupants. Natural convection process along the air channel can be analyzed by using finite volume method in Trombe [5–7]. In another study by Yakhot and Arad [8], a numerical investigation on combined forced and free convection along the vertical channel for the laminar regime was done. The results showed that the Nusselt number and dimensionless overall heat transfer increased with increasing Reynolds and Grashof numbers. Briga et al. [9] theoretically studied the effect of Trombe wall thickness on the air mass circulating through vents and heat transfer rate. The results indicated that as the wall thickness increased, the amount of thermosiphon energy increased and heat transfer rate by conduction, free convection and radiation decreased. Hussein [10] developed a mathematical model for solving partial differential equations of a porous Trombe wall. The results showed that the Nusselt number was affected and the flow direction decreased as a result of the growth of the thermal boundary layer. A numerical comparison was made by Rabani and Kalantar [11] between the heating performances of the new and classic designs Trombe wall under the Yazd (Iran) desert climate. The newly designed Trombe wall received solar energy from three directions. The simulation showed that the newly designed Trombe wall improved the average daily heating efficiency at about 27%. Burek and Habeb [12] did an experimental investigation on heat transfer and mass flow rate in a test rig comprised of a vertical channel with steady heat inputs ranged from 200–1000 W, and the channel depth was varied between 20 and 110 mm. The results showed that the thermal efficiency was a function of the heat input, and not dependent on the channel depth. Abbas and Azat [13] did an experimental investigation on the effect of varying channel depth on mass flow rate by using the passive solar system (Trombe wall) made of phase change material (PCM). The results showed that the mass flow rate directly affected the channel depth and inversely with the Rayleigh number. The efficiency at depth of 30 cm was about 2.45 times of that of 10 cm.

The absorbent surface of a passive solar heating system plays an important role in improving heat transfer through the wall and air mass flow rate along the channel. In the present study, an experimental investigation was conducted on a thermal storage wall (Trombe wall) built from concrete and its absorbent surface was treated by adding a layer of copper chips. The thermal performance of the system was investigated by computing the thermal efficiency and Nusselt number along with the air channel. It was also compared with a classic sample built from concrete only. The experiment was carried out for one month under the actual weather conditions of the Kirkuk city from January 1st to January 27th, 2018.

II. EXPERIMENTAL SETUP

The experiment was carried out on two identical test rigs containing classic and modified Trombe walls located at Kirkuk Technical College (E44°34' and N34°39') in Kirkuk city, Iraq. Fig.1 shows a photograph of the two test rigs with internal dimensions of *l* =140 cm, *w*=90 cm and *h* = 110 cm constructed from 8 cm thick PVC sandwich insulation panel. Both test rooms had a massive wall with similar dimensions of *W* = 87 cm, *H* = 100 cm, and *t*=10 cm built from a basic building material, i.e., concrete. 7 kg of copper chips were added as a layer to the absorbent surface of the modified sample. The massive wall had two vents of W_v=30 cm and H_v= 7 cm opened normally to the room from the bottom and top parts. The space between the vents' center was 96 cm. The outer surface of the wall was painted black and covered with a 6 mm thick single glass panel and the air gap was 25 cm. The properties of the concrete, copper, and glass are presented in [14].

The AT4532 multi-channel temperature data logger was used to record temperatures at similar locations in both samples. Fig.2 shows the thermocouples' locations. Wireless weather station type HP 2000 was also used to record ambient temperature, solar intensity, and wind speed during the experiment period. The experiment was executed for one month from January 1st until January 27th, 2018. The necessary data were automatically recorded every 10 min at the same time by both data devices.

Fig 1:- Photographic of test rooms.

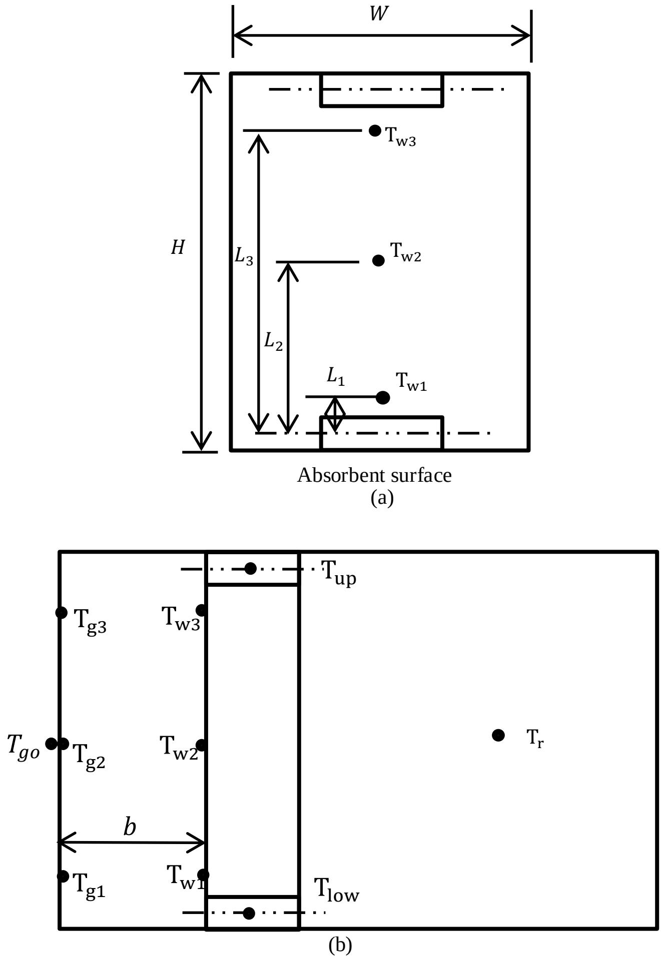

Fig 2:- Sketch of test rig shows locations of thermocouples. (a)Front section and (b) Side section.

III. DATA REDUCTION

A. Nusselt Number

Heat transfer along the channel between the absorbent surface and glass layer occurs via natural convection. The natural convective heat transfer relationships are usually expressed in terms of the Nusselt number. The Nusselt number depends on the Rayleigh (Ra) and the Prandtl (Pr) numbers; the latter is only dependent on the type of fluid. Therefore, it is given as a function of film temperature as follows [15]:

$$Pr = 0.680 + 4.69 \times 10^{-7}(T_f - 540)^2 \quad (1)$$

Other physical properties are also determined at film temperature as follows [15]:

$$\mu = \frac{1.458\times10^{-6}T_f^{1.5}}{T_f+110.4} \quad (2)$$

$$\rho = \frac{P}{R_A\,T_f} \quad (3)$$

$$\vartheta = \frac{\mu}{\rho} \quad (4)$$

$$\beta = \frac{1}{T_f} \quad (5)$$

The Rayleigh number depends on the temperature difference between the absorbent surface and glass layer, and also the channel height, so it can be written as follows [14, 16]:

$$Ra_{\acute{H}} = \frac{g\, \beta\, \Delta T\, \acute{H}}{\vartheta^2} Pr \quad (6)$$

Where ΔT represent temperature difference across air channel side i.e. absorbent surface and glass layer. While, $\acute{H}$ is channel height. More complicated relations provided by Churchill and Chu are applicable over wider ranges of the Rayleigh number as follows [14, 16]:

$$\overline{Nu} = 0.68 + \frac{0.67 Ra_{\acute{H}}^{1/4}}{\left[1+\left(\frac{0.492}{Pr}\right)^{9/16}\right]^{4/9}} \qquad for\ Ra_{\acute{H}} < 10^9 \quad (7)$$

$$\overline{Nu}^{1/2} = 0.825 + \frac{0.387 Ra_{\acute{H}}^{1/6}}{\left[1+\left(\frac{0.492}{Pr}\right)^{9/16}\right]^{8/27}} \quad for\ 10^{-1} < Ra_{\acute{H}} < 10^{12} \quad (8)$$

B. *Thermal Efficiency*

The thermal wall efficiency is defined as the ratio of solar heat gain available from the wall to the solar energy absorbed by the wall, it is given according to the reference as follows [3]:

$$\eta = 0.638 - 1.574\, \frac{T_r - T_a}{I_t} \quad (9)$$

IV. RESULTS

A. *Weather Condition*

During the experiment period, there were many fluctuations in the weather. In order to verify the effect of the absorbent surface on thermal efficiency and the Nusselt number along with the air channel, the experimental data from two different days (January 7th and 8th, 2018) were used since those two days had the best weather conditions among the test days. The weather parameters that affected the operation of the Trombe wall system were ambient temperature and solar radiation. As can be seen in Fig.3, the daily difference of temperature for the selected dates was about 10°C. The maximum ambient temperature during the daytime was around 18.6°C and 19.7°C and the test days represented clear and sunny days with the maximum solar intensity of approximately 368 and 403.2W/m^2 for January 7th and 8th, at 1:30 pm, respectively. Where, each peak represented a day.

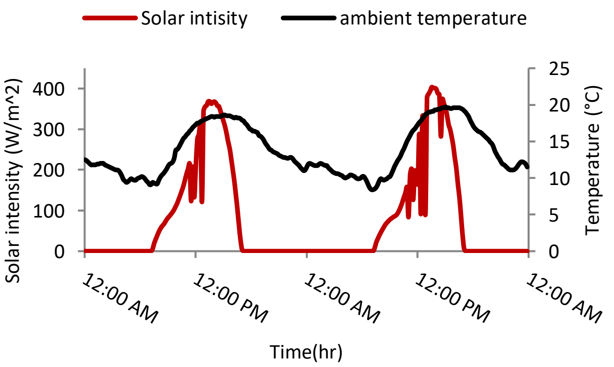

Fig 3:- shows weather condition during 7 and 8 January 2018.

B. *Nusselt number along the channel*

Equations in Section III.A were applied for the readings on January 7th and 8th, 2018, and a relationship was drawn between solar intensity and average Nusselt number at three different levels along air channel L1 to L3. Fig.4 shows the relationship mentioned above for the modified and classic Trombe wall samples. The basis of comparison was chosen according to the range of solar intensity starting from 100 to 360W/m^2. Generally, the Nusselt number (Nu) increased directly with increasing solar intensity and height level along the air channel. The results showed that at L1, Nu ranged from 19 to 37 and there was a large convergence between the classic and modified samples because the temperature at this level was usually lower than other levels and it was approximately equal to the temperature of the indoor test room. At L2, there was a difference between the Nu of samples at approximately 8%. The modified sample gave a high Nu compared to the classic sample along the solar intensity range. Meanwhile, at L3, the Nu of modified sample ranged from 44 to 141, whereas for the classic sample, it ranged from 54 to 122 along the solar intensity range. Generally, the Nu of a modified sample is higher than the classic ones due to two reasons; firstly the thermal conductivity of copper is high, leading to the increase in thermal conductivity of the massive wall. Therefore, the speed of heat transfer through the massive wall increases, leading to reduced absorbent surface temperature as compared to the classic sample. Another reason is because copper possesses emission property which leads to the increase in temperature of the glass layer. These two reasons lead to the increase in temperature difference between the absorbent surface and glass layer, and thus increases the value of $Ra_{H'}$, which is an important factor in computing the Nusselt number.

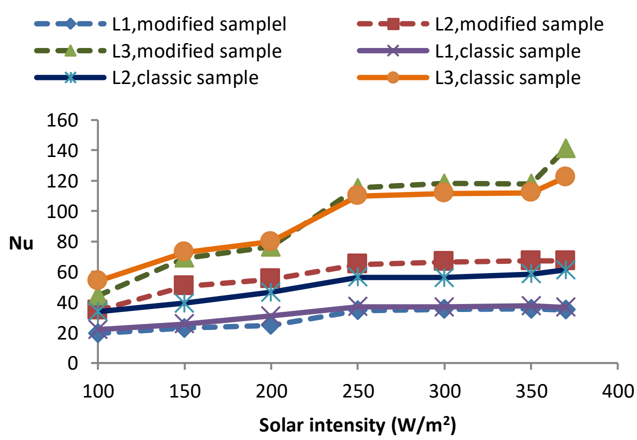

Fig 4:- Evaluation of average Nusselt number along the air channel during 7 and 8/1/2018 at certain solar

C. *Thermal efficiency*

The thermal efficiency of a Trombe wall system plays an important role in measuring its performance. Therefore, the relationship between solar intensity and average thermal efficiency was drawn for January 7th and 8th, 2018. Based on Fig.5, it can be seen that the samples had similar ascending and descending patterns. The value started to decrease until

200 W/m^2 and then it increased back. It is obvious from Fig.5 that the absorbent surface had a significant effect on the thermal efficiency of the Trombe Wall system since the classic sample gave a higher thermal efficiency than the modified sample along various solar intensity ranges. The thermal efficiency difference between the two samples was initially 6% at 100 W/m^2 then it started to decrease until it reached 2.7% at 370W/m^2. The difference between the thermodynamic efficiencies of the two samples was due to the low thermal heat resistance of the modified sample compared to the classic sample, as a result of the copper chips layer. Therefore, it may allow much heat transfer via conduction through the massive wall than the classic sample. This phenomenon led to reduced temperature distribution on the absorbent surface and increased test room temperature.

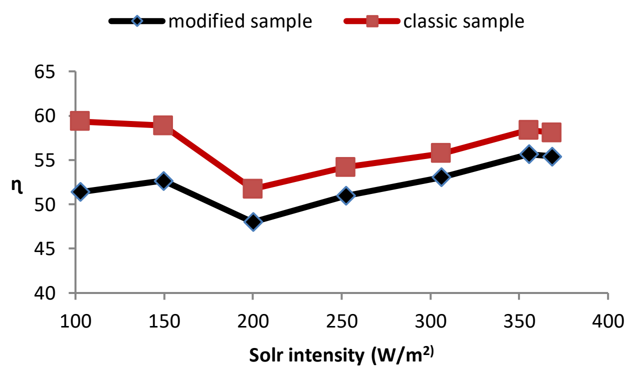

Fig 5:- Evaluation of average thermal efficiency during 7 and 8/1/2018 at certain solar intensity.

V. CONCLUSION

From the comparative results obtained from the Trombe wall system samples, it can be observed that the absorbent surface type had a significant effect on the Nusselt number and the least effect on thermal efficiency. The results showed that the Nusselt number average increased directly with increasing solar intensity and height level along the air channel. The Nusselt number rate of the modified sample was about 10% higher than that of the classic sample. L3 gave the highest Nusselt number rate along the air channel, i.e., higher than L1 and L2 (around 228% and 133%, respectively) in the modified sample and (192% and 88%, respectively) in the classic sample. The thermal efficiency of the modified sample was approximately 5% less than that of the classic sample.

- *Nomenclatures*

b=Channel depth (cm)
g= Gravitational acceleration (9.81 m/s^2)
H= Height of massive wall (cm)
H_v=Height of vent (cm)
h=Height of test rig (cm)
I_t=Solar intensity (W/m^2)
L1, L2 and L3=Levels of height along the channel (32, 64 and 96 cm)
l=Length of test rig (cm)
P=Absolute pressure (10^5 Pa)
R_A= Specific gas constant (287.05 J/kg.K)
T=Temperature (°C)
T=Thickness of massive wall (cm)
W=Width of massive wall (cm)
W_v=Width of vent (cm)
w=Width of test room (cm)

- *Greek symbols*

β=Coefficient of expansion coefficient (K^{-1})
η=Efficiency
μ=Dynamic viscosity (N.s/m^2)
ϑ=Kinematic viscosity (m^2/s)
ρ=Density (kg/m^3)

- *Non-dimensional terms*

Gr=Grashof number
Nu= Nusselt number
$\overline{\text{Nu}}$=Average Nusselt number
Pr=Prandtl number
Ra=Rayleigh number

- *Subscripts*

a=Ambient
f=Film
$g_{1,\,2\text{ and }3}$=Internal glass surface
go=External glass surface
low=Lower vent
up=Upper vent
r=Room
$w_{1,\,2\text{ and }3}$=Wall

REFERENCES

[1]. P. E. Okpani and M. N. Nnabuchi, "Determination of Hourly Temperature Variation in the Elements of a Poultry Brooder Pen Heated by Trombe Wall .," Pacific J. Sci. Technol., vol. 10, no. 2, pp. 905–918, 2009.
[2]. T. G. Özbalta and S. Kartal, "Heat gain through Trombe wall using solar energy in a cold region of Turkey," Sci. Res. Essays, vol. 5, no. 18, pp. 2768–2778, 2010.
[3]. R. J. Williams, "Passive Solar Heating": An arbor Science 1983.
[4]. J. D. Balcomb, "Passive Solar Buildings," p. 554, 1992.
[5]. T. R. B. H. Akbari, "Free convective laminar flow within the trombe wall channel," 1978.
[6]. R. C. K. T. R. Borgers, H. Akbari, "Free Convective Turbulent Flow Within The Trombe Wall Channel," 1979.
[7]. R. Ben, "Natural convection and conduction wall systems in Trombe," vol. 34, no. 415, pp. 1237–1248, 1991.
[8]. A. Yakhot and M. Arad, "Numerical Investigation of Laminar Mixed Convection in Trombe Wall Channel," Int. J. Numer. Methods Fluids, vol. 950, no. February 1997, pp. 935–950, 1999.
[9]. A. Briga-Sá, A. Martins, J. Boaventura-Cunha, J. C. Lanzinha, and A. Paiva, "Energy performance of Trombe walls: Adaptation of ISO 13790:2008(E) to

the Portuguese reality," Energy Build., vol. 74, pp. 111–119, 2014.

[10]. A.M.Hussein, "A theoretical study of laminar free convection through porous Trombe wall with passive solar energy," Al-Taqani Journal Vol.21, no. 1,pp.140-150, 2008.

[11]. M. Rabani and V. Kalantar, "Numerical investigation of the heating performance of normal and new designed Trombe wall," Heat Mass Transf. und Stoffuebertragung, vol. 52, no. 6, pp. 1139–1151, 2016.

[12]. S. A. M. Burek and A. Habeb, "Airflow and thermal efficiency characteristics in solar chimneys and Trombe Walls," Energy Build., vol. 39, no. 2, pp. 128–135, 2007.

[13]. E. F. A. and S. A.Azat, "the impact of a width of the air gap channel on the mass flow rate,Rayleigh number, and efficiency of the passive solar heating system," Tikrit J. Eng. Sci., vol. 25, pp. 60–68, 2018.

[14]. J. Holman, Heat Transfer, Mc Graw Hill, p. 758, 2010.

[15]. J. C. Dixon, The Shock Absorber Handbook: Second Edition. 2007.

[16]. J. D. Balcomb, "Passive Solar Buildings," p. 554, 1992.