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The Impact of Width of the Air Gap Channel on the Mass Flow Rate, Rayleigh Number, and Efficiency of Passive Solar Heating System

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ABSTRACT

The mass flow rate and Rayleigh number has been investigated experimentally on the passive solar using Trombe wall consist of (industrial wax) used as phase change material (PCM). A test rig of a cubicle was made of PVC sandwich panel except the south wall, Trombe wall; covered with a clear glass of 6 mm thickness. The six experiments were carried out during the winter season in Kirkuk city with six different widths of the air gap channel (10, 15, 20, 25, 30, and 35) cm. The experimental resultts show that the mass flow rate proportional directly to a width of the channel and inversely with Rayleigh number. Moreover, the highest efficiency was obtained at a depth of 30 cm, where it was about 2.45 times the efficiency of 10 cm.

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تأثير عرض قناة الفجوة الهوائية على معدل التدفق الكتلي، رقم رايلي وكفاءة نظام التدفئة الشمسية السلبية

الخلاصة

تم دراسة معدل التدفق الكتلي ورقم رايلي تجريبيا على منظومة الطاقة الشمسية السلبية باستخدام جدار ترومب يحتوي على (شمع صناعي) ويستخدم كمواد متغيرة الطور (PCM). تم إنشاء مقصورة اختبار من الواح معزولة حراريا من مادة (PVC) باستثناء الجدار الجنوبي، حيث غطيت جدار ترومب من الخارج بطبقة من الزجاج الشفاف بسمك 6 ملم. أجريت ستة اختبارات خلال فصل الشتاء في مدينة كركوك بستة اعماق مختلفة لقناة الفجوة الهوائية (10، 15، 20، 25، 30، 35) سم. حيث اظهرت نتائج الاختبارات بأن معدل تدفق الكتلة يتناسب طرديا" مع عرض القناة وعكسًا مع رقم رايلي. علاوة على ذلك فان أعلى كفاءة التي حصلت عليها عند عمق 30 سم ، حيث كانت بحوالي 2.45 مرة من كفاءة 10 سم.

1. INTRODUCTION

Direct passive solar heating is a method used to take advantage of solar energy in heating processes during cold weather, and the Trombe wall is one of the types of this method. The basic idea of the Trombe was patented by Morse in 1881. It was named after architect Felix Trombe and architect Jacques Michel, who popularized this heating system in the early 1960s [1-3]. A Trombe wall is a massive thermal store, built from common building materials such as brick, concrete, and concrete. Phase change materials. The Trombe wall faces the south and is covered by a single or double glass layer. The exterior of the Trombe wall is painted dark to increase the absorption of sunlight passing through the glaze during the day. There are many theoretical and experimental studies conducted on the Trombe wall which include temperature distribution within the air gap, heating load analysis, and thermal efficiency ... etc. Free convection heat transfer was studied within a Trombe wall channel since 1980 [4-9], the optimum thickness and vent dimensions were measured in Trombe [10-13], where thermal simulation models of various wall materials from Trombe [14-20] were performed, and the thermal performance of the trombe wall was improved [21]. The CFD techniques has been introduced to study temperature distribution and velocity

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Nomenclatures

b	width of air gap, (m)
g	gravitational acceleration, (m/s^2)
h	distance between vents, (m)
H	height, (m)
l	distance between inner surface of storage wall and center of the Cubicle, (m).
L	length, (m)
Q	dimensionless volume flow rate
q_c	convection heat transfer, (W)
q_v	circulation heat transfer, (W)
T	temperature, (°C)
W	Width, (m)

Greek symbols

β	volumetric coefficient of expansion (1/k)
ν	kinematic viscosity, (m^2/s)
ρ	density, (kg/m^3)
θ	temperature dimensionless
$\dot{V}$	volumetric flow rate, (m^3/sec)
$\dot{m}$	mass flow rate, (kg/sec)

Non-dimensional terms

Gr	Grashof number
Pr	Prandtl number
Ra	Rayleigh number

Subscripts

a	ambient
c	convection
f	film
i	inner glass surface
inlet	inlet air to the air gap
o	outer surface of the storage wall
outlet	outlet air from the air gap
r	room
w	wall

profile within the passive solar buildings [22,24], effect of glazing type [25-28]. Abdul-Jabbar and Ehsan [29] presented a comparative study of the performance of some thermal storage walls such as concrete and hydrate salts ($CaCl_2\ 6H_2O$) and paraffin wax (N-eicosane) for different wall thicknesses under the weather conditions in Iraq. They have obtained that hydrate salt with a thickness of 8 cm wall is optimized to maintain thermal storage and comfortable temperature in the room with less fluctuations. Kamal and Mishra [30] simulated a Trombe wall for porous and non-porous construction using marble and quartz as porous materials and concrete and brick as non-porous materials. The simulation results showed that the thermal efficiency of a porous wall has been higher than a non-porous wall and quartz wall by 57.2%. Castel et al.[31] PCM were experimentally studied in two typical construction materials (traditional and alveolar brick) in the ordinary construction at real conditions. They have seen that PCM reduces the pick temperature to 1C and smooth daily fluctuation inside the zone. Moreover, power consumption has decreased by 15%. Pasupathy and Velraj [32] investigated the energy conservation between two typical rooms, one of them having a PCM panel on the roof and the other without PCM; they observed from the ceiling simulation, PCM gives more stability for inside room temperature than another type, although free-floating in ambient temperature. Hassan et al. [33] presented an experimental study of the thermal performance of PCM integrated into concrete blocks in two different arrange-ments and tested in the hot climate of UAE in extreme month. They are formed as insulation wall covered on both sides by two PCM wallboards and another consist of air cavity and FCM plan inside a pair of a concrete wall. Both types reduced the cooling load, the first type reducing 44% and the second type reduced 10.5% for duration test time of 24 h. Fortunato et al. [34] developed a mathematical model of thermal storage using PCM using the finite differential method applied in MATLAB to derive temperature within PCM and estimate the time required for complete solubility. The results obtained can be used as guidelines for further studies in thermal storage systems.

The present study aims to investigate experimentally the effect of air gap width on the air flow rate, Rayleigh number, and thermal efficiency of a Trombe wall consist-ing of wax capsules.

2. EXPERIMENTS METHODOLOGY

2.1. Description of Test Rig

Fig. 1 is shown a photographic of a test rig with dimensions of (*L* =1.5 m, *W*=1 m and *H* = 1.5 m), made of PVC sandwich insulation panel of 3 cm thick, The Trombe wall made of wood frame with dimension of (*W* = 94 cm, *H* = 144 cm and *Z* = 9.6 cm) consist of 99 cylindrical capsules of Paraffin wax with dimensions of 6 cm outside diameter, 9.6cm length and 0.5 cm wall thick, and they distributed as a matrix form of (11×9) in a line arrangement inside the wall. The both sides of the wall are covered with aluminum plate 2 mm thick and the exterior surface painted black, where the passive storage wall moving inside the air gap region uniformly by four slide guide. Fig. 2 shows the steps of constructing the Trombe wall starting from the configuration of phase change material capsules, and they are inserted into the wood frame, finally covering both sides of storage wall with aluminum plates, a 6 mm thick single glass is covering the air gap from the exterior and the cubicle has been completely sealed to prevent the infiltration with the surrounding.

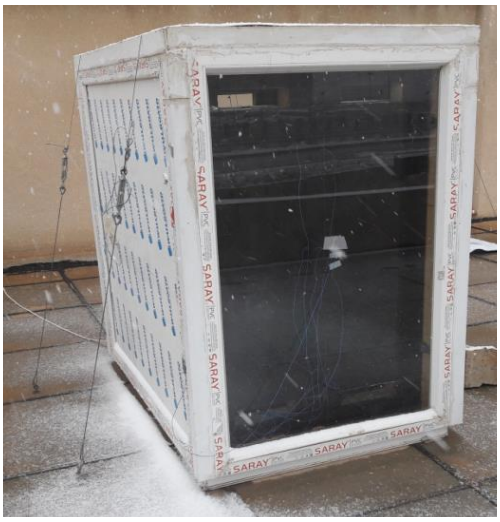

Fig. 1. Photographic of test rig.

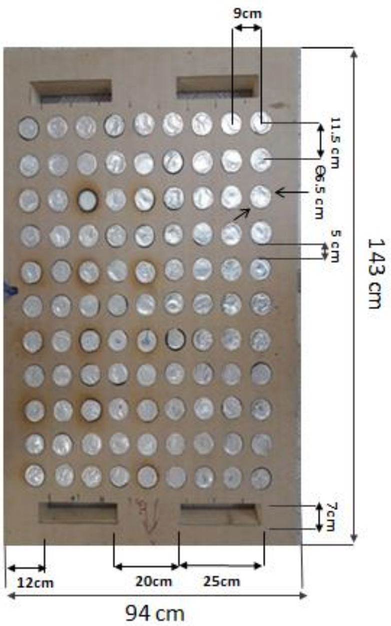

Fig. 2. Arrange and install of paraffin wax capsules inside the wood frame.

2.2. Operating principle

Trombe wall is a passive solar heating system which works based on the principle of the greenhouse that heat from the sun in the form of shorter wavelength and energy U.V radiation passes through a glass that covers the wall. The air in the gap between wall and glass panel is heated through conduction. Trombe walls usually have vents at both the top and bottom of the enclosure. As air is heated, it passes through top vent into the room, heating the room via convection and at the same time, the cold air is drawn into gap through bottom vents to be heated by the sun and rise up. This creates a cycle of warm air.

The Experiment Setup and measurement instruments, where a 32 channel temperature data logger temperatures type (Applent AT4532) with accuracy of (0.2%+1ºC) and resolution(0.1ºC) has been used for monitoring the temperature inside the cubicle and thermal storage wall during the period of the experiment for one month, where which started from 1st December 2016. A 32 thermocouple extension wires type K was used in the different location inside storage wall, air gap space and inside test room. The outside cubicle weather data have been recorded directly during experiment period by weather station type (Wireless weather station HP 2000) with accuracy (±1 ºC for temperature and ±5% for humidity).

3. DATA REDUCTION

Heat exchange between the inner surface of storage wall and inside the room may depend on the convection heat transfer coefficient and can be expressed in the form of Rayleigh number, calculated from the product of Grashof number and Prandtl number [34].

$$\mathrm{Ra} = \mathrm{Gr}\,\mathrm{Pr} \quad (1)$$

$$\mathrm{Gr} = \frac{g\beta\,\Delta T\, l^3}{\nu^2} \quad (2)$$

where

$$\Delta T = T_i - T_r \quad (3)$$

$$\beta = \frac{1}{\left(\frac{T_i + T_r}{2}\right) + 273} \quad (4)$$

In addition to convection heat transfer that which discussed above, there is another energy added to the cubicle through entering the air from inside cubicle to the air gap channel and circulating naturally due to change in air density by heating as shown in Fig. 3. The air volumetric flow rate through the air gap channel may be calculated based on the mathematical relation that obtained by Akbari and Borders [4].

$$\dot{V} = Q\,\nu\,Gr\,H \quad (5)$$

where

$$Q = 10^{[A + B\log L + C(\log L)^2]} \quad (6)$$

$$A = 0.0851\left[1 - \exp\left(-3.412(\theta_g - 0.4217)\right)\right]^2 - 0.92 \quad (7)$$

$$B = 0.1331 + 0.6563\exp(-8.521\theta_g) \quad (8)$$

$$C = -0.0619 + 0.0712exp(-6.762\theta_g) \quad (9)$$

$$\theta = \frac{T_{outlet} - T_{inlet}}{T_m - T_{inlet}} \quad (10)$$

where

$T_m = T_o$ if $T_o > T_g$ or $T_m = T_g$ if $T_g > T_o$

$$L = \frac{H}{Gr\,b} \quad (11)$$

Therefore the amount mass flow rate has been calculated from:

$$\dot{m} = \rho\dot{V} \quad (12)$$

where ρ, ν and Pr are evaluated at film temperature [33].

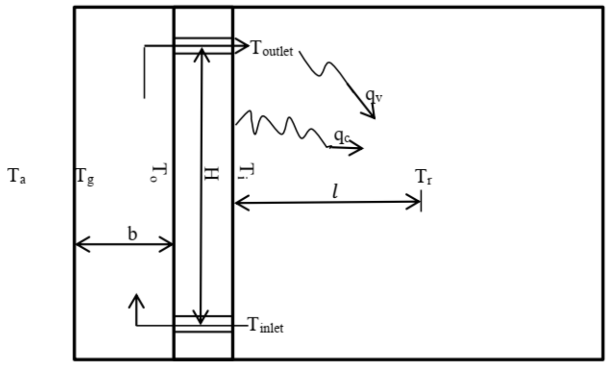

Fig. 3. Sketch of the cubicle with details of phase change material storage wall.

4. RESULTS AND DISCUSSION

4.1. Weather Data

The experiments that conducted on the test rig shown in the Fig. 1 under actual weather conditions of Kirkuk city. During December 2016 and Fig. 4 shows the results of ambient temperature, solar intensity, and the wind speed for the above duration.

4.2. Effect of the Air Gap on the Mass Flow Rate

Fig. 5 shows that the effect of the air on the mass flow rate. The measurements were performed at the air gap widths (10, 15, 20, 25, 30, and 35) cm to study mass flow rate. The results showed that mass flow increased with increases air gap width with respect to the temperature difference within the air gap, due to an increase in convection heat transfer. The maximum mass flow rate obtained at 35 cm width, the mass flow rate ranged (0.0058 to 0.014) kg/s.

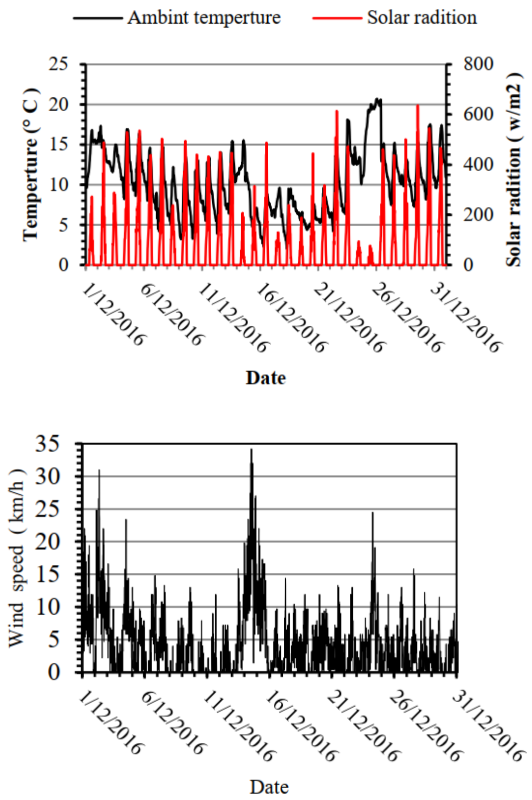

Fig. 4. The details of weather data during of the experiment period at December 2016.

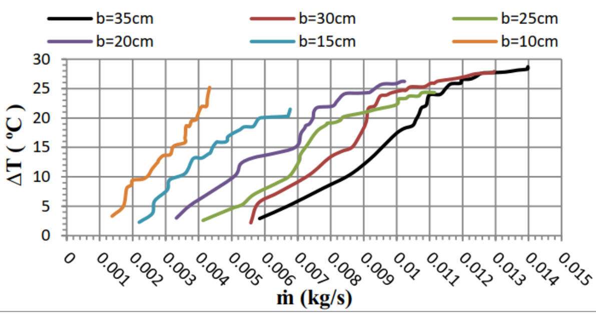

Fig. 5. Mass flow rate through the air gap channel according to the temperature difference for different width

Figs. 6(a)-(f) are shows that the variation of Rayleigh number inside test rigs during 24 hrs. with respect to the variation of the temperatures inside and outside the test rig for all experiment cases. The Ra number changes with time according to the environment condition as described in Figs. 6(a)-(f), it indicates the direction of heat transfer within the test rig. The Ra number was rapid rises during

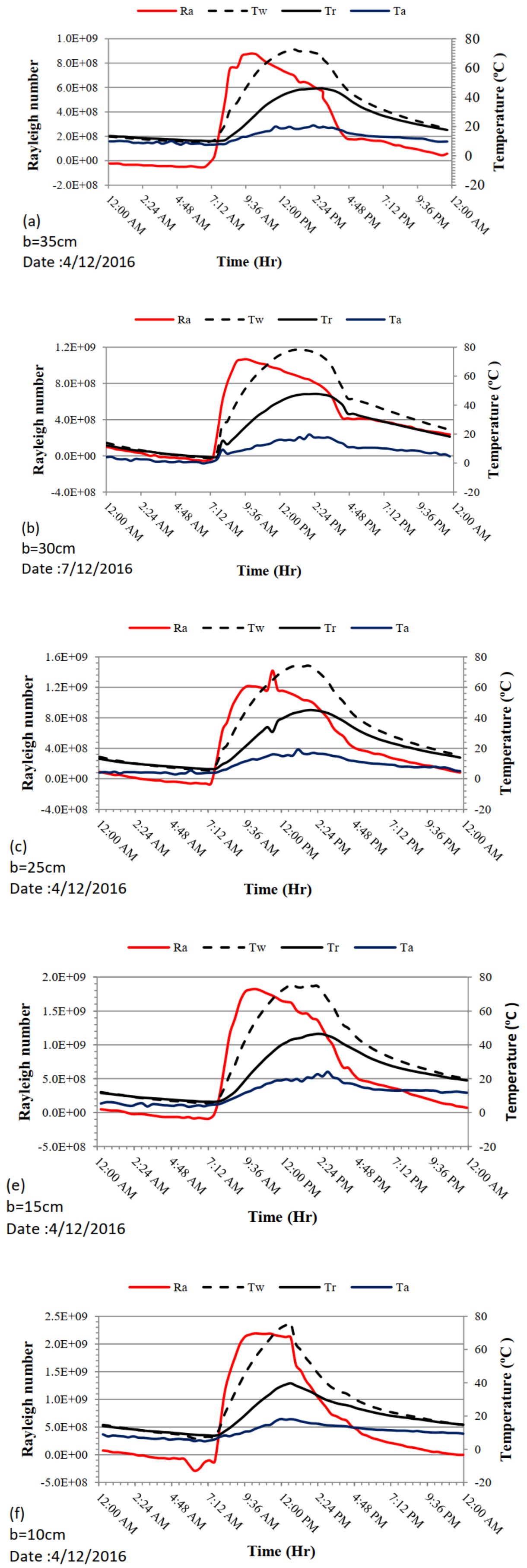

Fig. 6. Variation of Ra number and temperature change inside a test rig according to the ambient temperature for different width air gap channel during 24 hrs.

the sunrise when the Trombe wall absorbing energy from sun radiant. The previous figures show that the Ra decreased to the minimum values during sunset in all cases, this is due to reduce the temperature difference between (*Tw* and *Tr*). We observed from previous figures, the Ra number changes to the negative values after midnight when the (Tr) is greater than Tw and this indicates a reversal of heat transfer direction from inside test rig to the storage wall and this due to energy depletion from a Trombe wall

4.3. Thermal Efficiency

The efficiency of the Trombe wall depends on the quality in heat exchange between the Trombe wall and the air. Fig. 7 shows the efficiency of the Trombe wall for different air gap widths. The period of the experiment divided into two parts at the day to illustrate the relationship between the thermal efficiency and the solar intensity. The efficiency of the Trombe wall is at the minimum values until noon in all cases as shown in Fig. 7(a), because it needs to store energy to compensate for the amount of energy had been consumed at night. Fig. 7(b) shows that thermal efficiency increased in all cases even though the solar intensity has decreased. We remark a significant efficiency variation for the Trombe wall that due to a higher temperature level within the air gap. results showed that 30cm width of the air gap gives the best efficiencies among all cases ranged about 80% at the 100 W/m^2 solar intensity, as for the 10 cm width, the efficiency did not exceed 13% at its best.

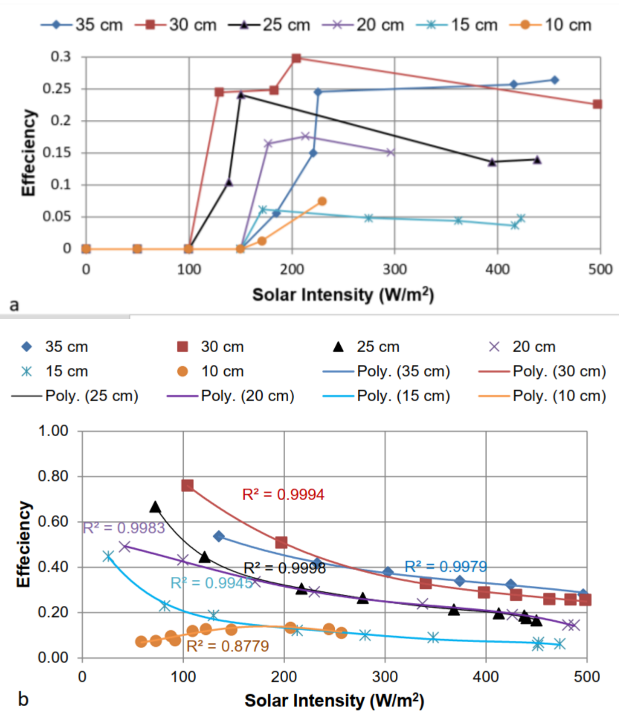

Fig. 7. The efficiency of the Trombe wall vs. solar intensity for different widths of the air gap. (a) before afternoon, and (b) after afternoon.

5. CONCLUSIONS

The data from this investigation yield some insights into the performance of Trombe wall, by varying the air gap depth from 10 to 35 cm in a test rig. The following are the main conclusions from this investigation:

1. The mass flow rate depends on the depth of the air gap and it is directly proportional to the width of the air gap depth. The maximum mass flow obtained at 35 cm and it was greater than the mass flow rate in the 10 cm width by 2.5 times
2. Ra number is inversely related to the width of the air gap, the maximum Ra number obtained at 10 cm, which was greater than a 35 cm Ra number by 1.2 times.
3. The effect of the air gap was clearly observed on the efficiency of the passive solar system. Where the maximum efficiency obtained at 30 cm, which was greater than the efficiency of about 2.45 time.

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