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Performance amelioration of a Trombe wall by using Phase Change Material (PCM)

Miqdam Tariq Chaichan[1], Khalil Ibrahim Abaas[1]

Mechanical Eng. Dept., University of Technology, Baghdad, Iraq[1]

Abstract: The energy crises and environmental pollution are two main obstacles facing humanity nowadays. New techniques used as green building designs for sustainable architecture as a part of the efforts in confrontation of these circumstances. One of the sustainable architectural technologies is Trombe wall that employed for heating and ventilation.

In the recent article, the Trombe wall concept was studied by designing and fabricating a Trombe wall. The wall fabricated from simple, locally available and cheap materials. The wall tests conducted in Baghdad-Iraq wintertime (Dec-2014 and Jan-2015). The suitability of such wall for Iraqi houses examined. The results indicated that the designed wall is suitable for utilization in Iraq wintertime. PCM usage in such wall shows good results. Also, applying paraffin wax as PCM gave adequate storing media in addition to its availability and low prices.

Keywords: Trombe wall, phase change materials (PCM), Charging-discharging time, Paraffin wax.

I. INTRODUCTION

Trombe walls known as storage walls or solar heating walls (SHW) reduce a building's energy consumption up to 30% [1 & 2]. When we talk about buildings, we must mention that buildings cause about 33% of the world's total greenhouse-gas emissions [3]. Trombe wall uses clean, sustainable and green solar energy in the building ventilation, heating, and in some applications cooling of buildings.

Trombe walls absorbing solar radiations and store it to provide thermal comfort in buildings in various climatic regions [4]. A Trombe wall stores energy during daytime periods and supplies energy as hot air when a building's is cooled at night [5 & 6]. Researchers and designers put variable configurations of Trombe walls to use it at various climates.

A simple Trombe wall consists of a glass, and airspace separates the wall from the outdoor surrounding [7]. Trombe wall designed to use materials with high energy-storage capacity. Adobe, stone, concrete and bricks can be considered as an example of these elements. To increase the solar energy absorption rate, the external surface of the wall is colored in black [8]. Trombe wall usually positioned facing south to achieve optimal performance. Trombe wall absorbs diffused and direct solar rays during the day. The stored heat transfers to the interior by convection or conduction at night [9]. The air gap between the glass and the wall varies from 3 cm to 6cm [10]. The stored energy in the wall released gradually by radiation and convection. The heat transfer is used to increase building's occupants' comfort. Trombe walls can be designed into variable shapes. There is a commercial Trombe wall filled with gypsum board. The wall outer layer is masonry while the inner layer is a gypsum board; the wall supplied with an air gap between the layers. Khedari mentioned that well natural ventilation experienced with this type of Trombe walls [11]

Structural engineers considered thick massive wall as heavy walls and increased the building's load. This problem is solved by using a phase-change material [12]. Many researchers used a phase-change material (PCM) such as eutectic salts or salt hydrates to ameliorate wall efficiency. These materials are lighter than building materials and store more heat in a smaller volume [13 & 14]. Latent Heat Storage materials absorb and release heat when this storage material passes through a phase change from solid to liquid or vice-versa. The latent heat storage materials studied during the last four decades are usually hydrated salts, eutectics, Paraffins, and fatty acids [15]. Bourdeau conducted a numerical study about this issue; he concluded that a 3.5 cm phase-change material wall can replace and perform similarly as a 15 cm concrete wall [16]. Onishi carried out a CFD simulation on the thermal behavior of a room supplied with a PCM Trombe walls. Three phase-change materials were analyzed in this study. The study results indicated that the use of phase-change materials in Trombe walls is valuable for reducing energy consumption in buildings [17].

Iraq has long hours of sunshine and owns about more than 3000 radiance hour per year in Baghdad region. The solar intensity ranged between 416 W/m^2 to 833 W/m^2 in January and June, respectively. Iraq's winter extends for two months in middle and south governorates and it last for more than four months at North governorates [18]. Trombe wall usage in Iraq becomes urgent demand because of the severe conditions of Iraq environment after three great wars and two decades of aridity [19].

Many Iraq researchers performed valuable papers in this field. Khalifa conducted a computerized dynamic simulation for a Trombe wall facing south in Baghdad. The researchers used paraffin wax and hydrated salt as PCM encapsulated in copper capsules. They realized that a hydrated salt storage wall of an 8cm thick was more efficient than a concrete wall with a 20 cm thick [20].

Abaas built up a simple type solar heat storage Trombe wall and tested it at Baghdad winter. The study results show the used Trombe wall has an ability to assist the buildings heating systems at night in winter seasons [22]. Faris used a finite volume method to solve the problems of heat transfer, and a turbulent flow characteristic through a room has a Trombe wall. The study selected Baghdad city winter climatic conditions in January. The air gap thickness was changed (1, 2, 3, and 4cm) while the thickness of Trombe wall was maintained constant. The study concluded that the air velocity depends on the air gap thickness. Also, there is a temperature fluctuation in the room during the charging hours, where ventilation has to be used to reduce these fluctuations [23].
The motive of this research was to design and fabricate a simple solar storage wall (Trombe wall) that can be fixed facing south for winter days and remove in other seasons. In recent study, the intent was made to evaluate the concept of using PCM in a Trombe wall at Baghdad city winter days. The study determines the energy supplied to the Trombe wall, the charging time and the practical conditions of its performance.

II. EXPERIMENTAL SETUP

Simple Trombe wall was designed and manufactured as Fig. 1 represents. The central parts of the wall are:
The thermal storage wall: the wall used in this study consists of a wooden box with $1m^2$ (all sides and the back were 2 cm thickness). The box isolated from outside by glass wool (1cm thickness). Ten holes (1 cm dia. each) drilled on the lower place on the left side of the wall to enter cold air vent. Ten holes were drilled at the right upper side as a hot air exit.
The back plate: A dark black copper plate (3 mm thickness) fixed to the inside face of the walls. The plate was covered with aluminium foils to reflect the diffused solar rays to the pipes.
The PCM pipes: Nine lines of dark black aluminium pipes filled with paraffin wax used in this study. These pipes were tightening well to prevent its movements. The pipes diameter is 2.54cm, and its length is 1 m, and the pipe material thickness is 0.8mm. The pipes openings were closed tightly by a wooden stuffing.
The glass cover: The Trombe wall face covered with transparent glass (3mm thickness). Two wooden doors covered the glass face of the wall after sunset.
The air takes a long path through the passages between the pipes inside the wall. Near the upper holes, a small air fan (7 cm dia.) fixed, to draw the hot air out of the wall. Eleven thermocouples type K were used to measure temperatures; these thermocouples calibrated for the measured temperature range. Three placed inside three different pipes to measure the temperature variation of Paraffin wax. Three thermocouples fixed on three pipe's walls while the plate measured by means of three thermocouples fixed in three variable places. One thermocouple used to measure the inlet cold air temperature and another one for outlet hot air. The tests conducted in Baghdad city winter days.
The measuring tests accomplished during the last two weeks of December 2013, all January and the first two weeks of February days from 2014-2015.

Materials and Pipes Preparation

Paraffin wax consists of a mixture of mostly straight chain n-alkanes that release a large amount of latent heat. Paraffin wax is a heat of fusion storage material; it is available in a large temperature range. Paraffin characterized by its safe, non-corrosive, and fewer expensive specifications. It is a chemically inert and stable below 500°C; also, it has little volume variation when it melts. In the recent study, Iraqi paraffin wax was chosen; Table 1 lists its thermal properties of the used wax. This material selected due to cost consideration, where its price is 2$/kg in Iraq markets. Each pipe filled with 400 gram of wax, and the total wax mass was 7.2 kg. Fig. 2 shows a photo of the wax inside the pipes.
The equation that calculates the stored energy in the pipes during daytime hours (for every one hour) is:

$$Q_s = m_w C_w (T_{t+1} - T_t) \quad \text{………. (1)}$$

Where: Q_s = the storage energy inside wall pipes (kJ)
m_w = wax mass in wall pipes (kg)
C_w = wax specific heat (kJ/ kg. K)
$(T_{t+1} - T_t)$ = The increase in wax temperature for each hour of daylight (K).

The whole day stored energy calculated by the equation:

$$Q_{S.\,Total} = Q_{7\text{-}8} + Q_{8\text{-}9} + \dots + Q_{3\text{-}4} \quad \text{…… (2)}$$

For the drawn energy by the fan during its operation time calculated by the equation:

$$Q_u = \dot{m}_a\, c_p (T_{air\ out} - T_{air\ in}) \quad \text{.... (3)}$$

Where: Q_u = the drawn energy from wax pipes in the wall (kW).
$\dot{m}_a$ = drawn air quantity (kg/s).
c_p = air specific heat (kJ/kg.K).
$T_{air\ out}$ = the fan delivered outer air temperature (K).
$T_{air\ in}$ = the temperature of the air entering the wall (K).
The total drawn energy for one day was calculated by:

$$Q_{u\ total} = Q_{u\ 4.5\text{-}5.5} + Q_{u\ 5.5\text{-}6.5} + \dots \quad (4)$$

The amount of the delivered air can be calculated depending on fan diameter and air velocity and air density, as follow:

$$\dot{m}_a = A\, V_a\, \rho_a \quad \text{…….. (5)}$$

Where: A = the fan area (7 cm dia.) (m^2).
V_a = outlet air velocity (m/s).
ρ_a = air density (kg/ m^3).

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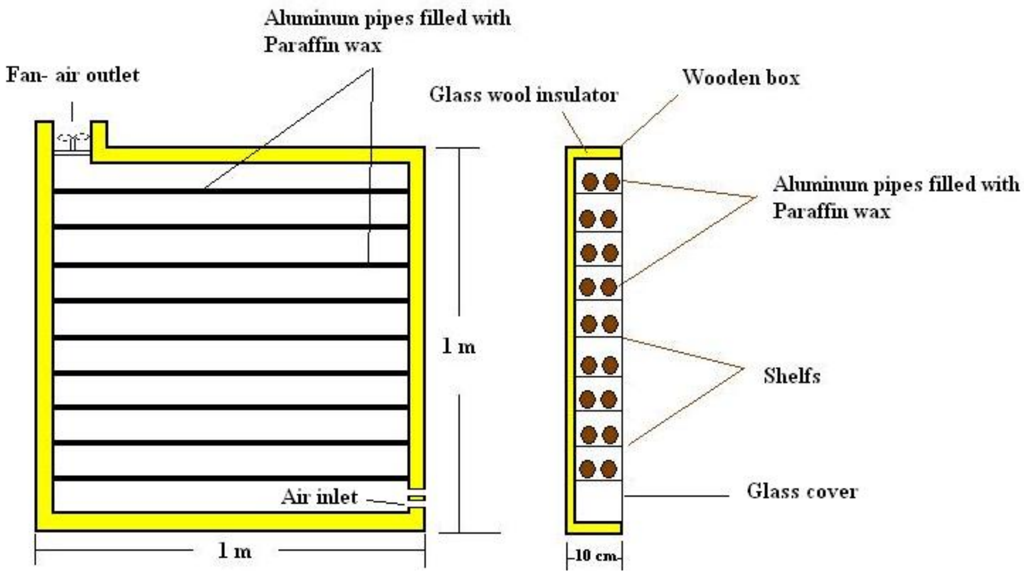

Fig. 1, Sketch diagram for the front and side views of the studied wall.

Fig. 2. A photo of the paraffin wax inside the pipes

TABLE 1
Thermo-Physical Properties for the Used Iraqi Paraffin Wax in the Present Study

Material Property	Range
Melting temperature (°C)	45
Latent heat of fusion (kJ/kg)	190
Solid-liquid density (kg/m^2)	930/830
Thermal conductivity (W/m °C)	0.21
Solid, specific heat (c_{ws}) (kJ/kg °C)	2.384
Liquid, specific heat (c_{wl}) (kJ/kg °C)	2.49

The Wall Cost

In this study, the design focused on using locally available and low-cost materials. Table 2 listed the used materials and its prices at the Iraq local markets.

TABLE 2
The Trombe Wall Used Material's Costs

The Material	Cost in US dollars
Glass cover	15 \$/m^2
Wooden cover	12 \$/m^2
The copper plate	15 \$/m^2
The aluminium sheet	3 \$/m^2
The pipes	1 \$/m
Iraqi paraffin wax	2 \$/kg
fan	20 \$

The total cost of the Trombe wall used in this study was 101.4 \$. This cheap wall instigates to more studies and better designs to achieve the optimum design that most suitable for utilization in Iraqi houses.

Experimental Procedure

The wall design idea depends on using the greenhouse effect. The solar radiation subjected to the wall passes through the glass cover toward the pipes. A part of the radiation diffuses and hits the aluminium reflector that returns it back to the pipes. The other diffused rays reflect by the glass and the heat inside the wall increases.

The preparation of the system for the first time involved filling the pipes with paraffin wax. The wax was heated to a high temperature of 70 °C to constrain it to melt. After the whole wax had melted; it was filled in the black colored pipes with similar weights and left to cool down. The cooling and wax solidification process started at room temperature. After the wax solidified and the pipes temperatures reduced to room temperature; the pipes opening were stuffed with wooden filling. The pipes then were heated to examine if there was a leakage from its ends. When the pipes are ready, it was fixed in the wall and covered with the glass cover. The wall was fixed vertically facing south. The readings took at the beginning of each hour starting from 8 AM of every test day. At sunset, the wall's glass face was covered with a wooden door to prevent heat outflow to surrounding. The fan operated, and the wall exit air temperatures were measured and recorded every one hour.

Two shiny days were chosen every week along the tested period, and the average of the recorded readings took in the calculations.

III. RESULTS AND DISCUSSIONS

Trombe wall characterized as a storage wall that stores solar energy at day time. Fig. 3 shows the average of the charging period of the used wall, starting from 8 AM till 4 PM, for December 2014. The curves indicate a similar trends, they all rose from 8 AM till 1 PM then they declined due to the solar irradiance reduction. The paraffin wax gained high temperatures depending on two main parts of the wall: the reflected wall in the behind that reflected all the distributed rays to the pipes. The second is the greenhouse effect that used to increase the temperature inside the wall. Also, the plate gained high temperature compared with air temperature, mainly from the wall inner temperature. The figure shows that high temperature as 59^{o}C was reached depending on Iraq high solar radiation intensity even in winter. At Baghdad region, the average shining hours at December are 8.7 hours. The maximum temperature is 17.6 ^{o}C, and the minimum temperature is 5.6^{o}C.

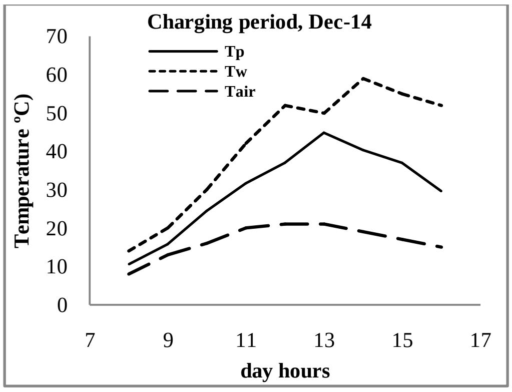

Fig. 3. Charging temperature distributions for the plate, wax and ambient air at Dec-2014

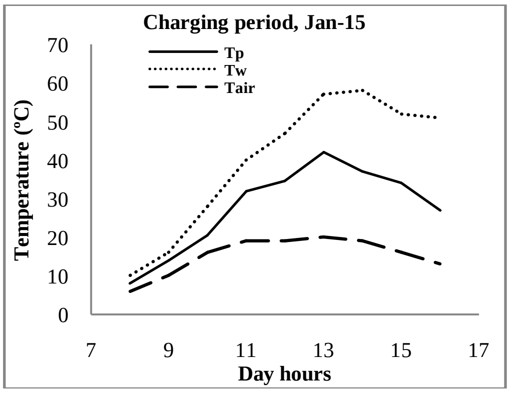

Fig. 4. Charging temperature distributions for the plate, wax and ambient air at Jan-2015

Fig. 4 represents the charging behavior on January 2015 for the tested Trombe wall in Baghdad wintertime weathers conditions. The wall behaved in the same former described trends for the same reasons.

Fig. 5 declares the discharging period for the used Trombe wall at December 2014. Discharge time started at 4 PM and lasted at 10 PM. Although of the limited size of the used wall but its discharge period lasted for eight hours that give an indication of the convenience of this wall for Iraqi winter weathers. Plate's temperature reduced at a high rate compared with the PCM pipes. The metal plate gains and losses heat quickly compared with the PCM pipes that pass through phase changing period causing lower heat losing rate. At the beginning of the discharge period, the outlet air temperature was high as 39^{o}C, which means a controlling method must be used for the air driving inside the conditioned room to prevent the discomfort conditions. At 10 PM, the discharge air outlet reached 22^{o}C that is good, but not sufficient for supplying the room comfort conditions.

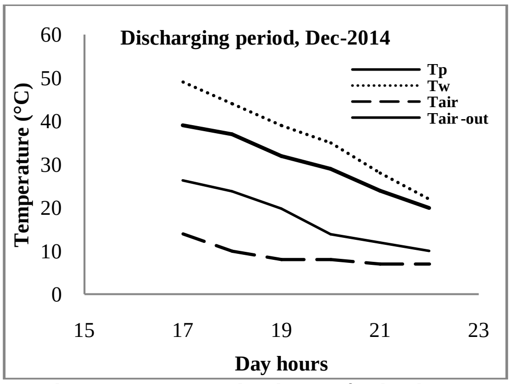

Fig. 5. Discharging temperature distributions for the plate, wax and the wall outlet air at Dec-2014

The same trends are shown for discharge period of the wall in January 2015, as Fig. 6 manifests. The descending rate in the curves is higher compared with Fig. 5 due to lower ambient air temperatures and less stored energy in the wall. The drop in air temperature has an influence on the working hours of the wall that reduced to five hours compared with six at December. Also, at 9 PM the outlet air temperature reached 20 ^{o}C, while this temperature was achieved at 10 PM at December.

Fig. 7 indicates a comparison between the temperatures of the plate temperature (Tp) and the wax temperature (Tw) at the charging period for the whole tested period (Dec-2014 and Jan-2015). The curves show approximately converging results for Tw and Tp with higher rates for Dec-2014 curves. The increments were 9 and 3.7 for Tp and Tw respectively. The temperatures increments caused by the differences in the solar intensity increments for the two months.

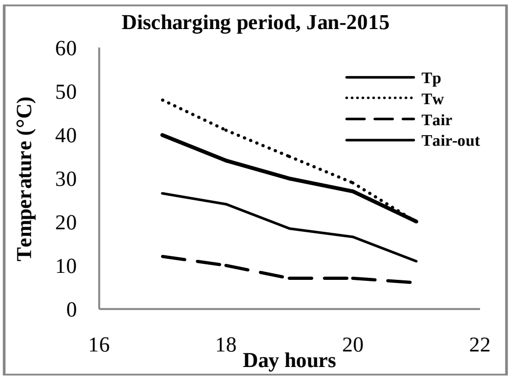

Fig. 6. Discharging temperature distributions for the plate, wax and the wall outlet air at Jan-2015

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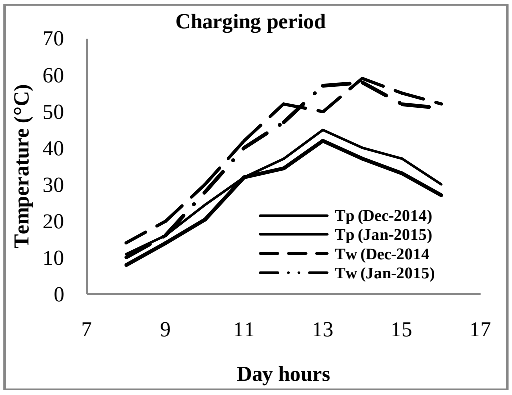

Fig. 7. A comparison between charging temperature distribution for the plate and wax for the tested period

The same comparison was made for the discharging period as Fig. 8 reveals. The Tw curves declined at a higher rate for Jan-2015compared with Dec-2014. The lower air temperatures at January explain the decline rate. The average reductions achieved were 3.7 and 20.2% for Tp and Tw respectively. A high part of the difference between the two months results revert to the working hours reductions in January compared with December.

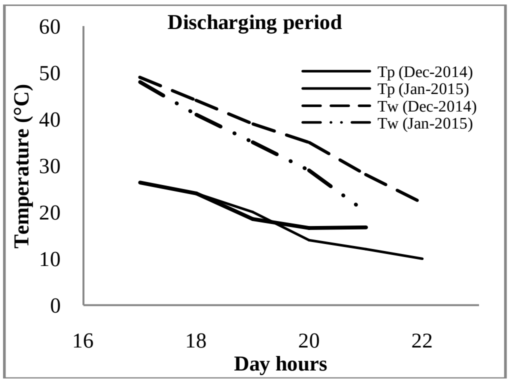

Fig. 8. A comparison between discharging temperature distribution for the plate and wax for the tested period

Fig. 9 presents a comparison between the outlet air temperatures for the tested period. The curves show higher supplied temperatures in December compared with January temperatures for all discharging hours range.

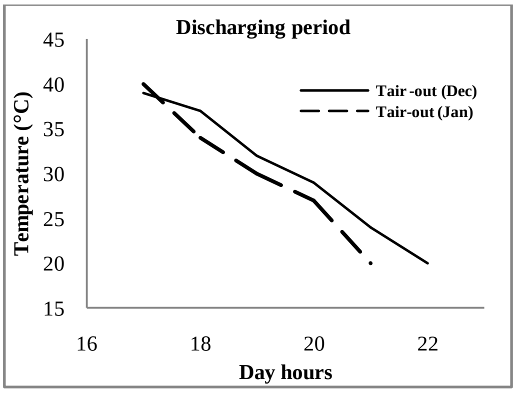

Fig. 9. A comparison between the outlet air temperature for the tested period

Also, a longer working range at December is achieved. The results of the outlet temperatures for the two months reveal the suitability of this wall for Iraq weathers.

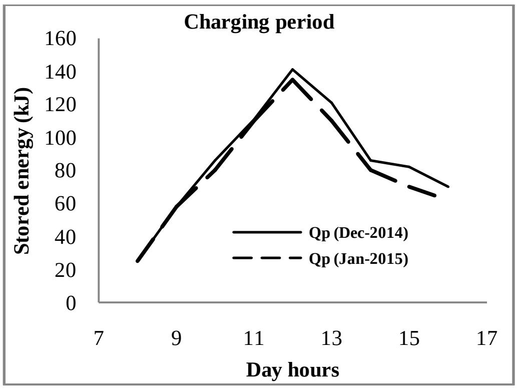

Fig. 10. Charging period stored energy for the plate in the Trombe wall for the tested months

Fig. 10 represents the charging period's stored energy for the plate in the Trombe wall for the tested months. At December that has higher solar intensity and longer shining hours the stored energy preceded that achieved in January with about 6.4%.

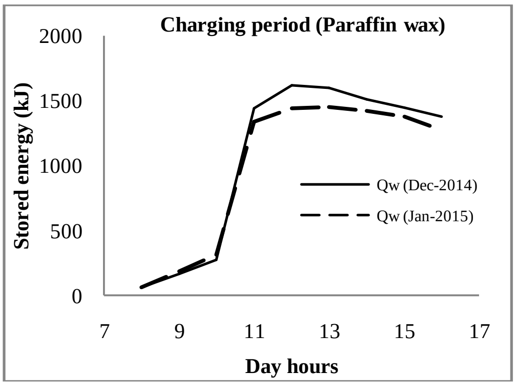

Fig. 11. Charging period stored energy for the paraffin wax in the Trombe wall for the tested months

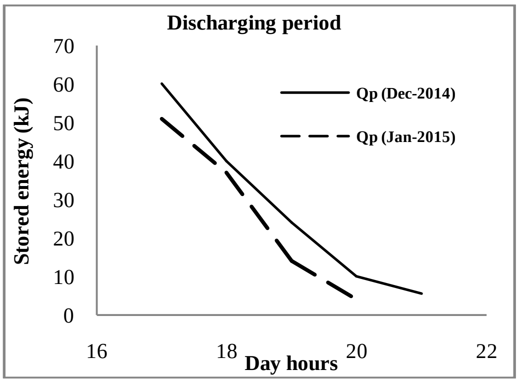

Fig. 13. Discharging period stored energy for the paraffin wax in the Trombe wall for the tested months

Fig. 11 explicates the charging period's stored energy for the paraffin wax in the examined Trombe wall for the tested months. The curves are converging with a little rise of December results due to the formerly mentioned reasons. The stored energy for December was higher with about 7.77% of the produced stored energy for January.

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For the period from 10 to 11 AM, the stored energy increased profoundly with converging values for the two months. This period is the phase change time where the wax turned from the solid phase to the liquid one.

Fig. 12 illustrates the discharge time of the stored energy for the plate. The decline rate for the stored energy is high due to the high heat transfer rate between the plate and air in addition to little stored energy during the charging period.

Fig. 13 shows the discharging time for the stored energy of the paraffin wax in the Trombe wall for the tested months. The reduction in the stored energy for January was 4.3% less than that for December. Also, there is a period from 6 to 7 PM the stored energy for the two months was almost identical. The most of this period is the phase change time for the paraffin wax when it entered solidification phase change period.

IV. CONCLUSION

In the recent research, a Trombe wall was designed and fabricated from simple, locally available and cheap materials. The wall tested in Baghdad-Iraq wintertime (Dec-2014 and Jan-2015). The study focused on the suitability of such wall for supplying hot air to rooms at wintertime using clean, available and green power that is solar energy. The results indicated that the designed wall is suitable for using in Iraq wintertime. Also, using paraffin wax as PCM gives proper storing media in addition to its availability and low prices.

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BIOGRAPHIES

Miqdam Tariq Chaichan received the B.S. in Mechanical Engineering from Baghdad University in 1982 and M.S. degrees in Power Generation from University of Technology in 1989. Since 1999, he tough in several universities and investigated in many fields likes fuel and combustion, ICE, alternative fuels, Solar and Sustainable Energy. He is now Assistant Professor in Mechanical Engineering Dept., University of Technology; Baghdad, Iraq.

Khalil Ibrahim Abaas received the B.S. and M.S. degrees in Mechanical Engineering from Mechanical Eng. Dept., UOT in 1981 and 2006, respectively. Since 1986, he taught in Mechanical Eng. Dept., UOT, Baghdad, Iraq, He investigated in Alternative and Sustainable Energy and power generation. He is now Lecturer in Mechanical Engineering Dept., University of Technology; Baghdad, Iraq.