FEASIBILITY STUDY OF TROMBE WALL SYSTEM IN MIDDLE EAST AND EUROPE

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1. Introduction

Trombe wall system was first developed by American named Edward Morse in 1881 (Morse1881) and recently revived by the French inventor Felix Trombe (Duffie and Beckman, 2006). Trombe wall is made of a material that absorbs a lot of heat, such as concrete or masonry coated with a dark (Duffie and Beckman, 2006); it will be placed behind South facing glass to increase the thermal mass to receive high amounts of solar gain. The heat absorbed from the sun is conducted slowly through the storage mass to the inner surface. The air heated by convection rises and passes into the heated space. During the period of no sunlight, heat stored in the thermal mass wall is radiated and convected into space to be heated. Energy can be transferred to the room by air circulating through the gap between wall and glazing through openings at the top and bottom of the wall. Circulation can be natural convection controlled by dampers on the vent openings or by forced circulation by fans (Duffie and Beckman, 2006). Trombe wall system is shown in Figure (1).

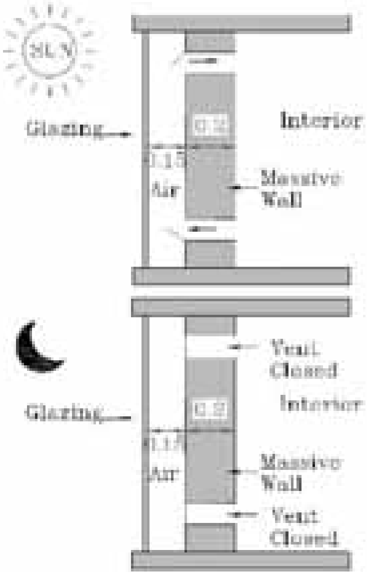

Fig. 1: Trombe Wall System

Many theoretical and experimental studies have shown that indoor comfort is improved as well as reduction in annul heating energy due to well-designed Trombe walls (Jie et al., 2007; Zbalta and Kartal, 2010; Smolec and Thomas, 1991; Fernndez-Gonzlez, 2007; Shen et al., 2007; Torcellini and Pless, 2004; Chel et al., 2008; Jaber and Ajib, 2011).

In this work thermal, thermal performance of Trombe wall system is hourly simulated by TRNSYS software in two climate zones; Amman (Mediterranean climate) and Berlin (cold climate). Moreover, optimum size of this system will be determined by Life Cycle Cost (LCC) criterion. This will lead to develop an approach for designing the most economic residential building in Middle East and Europe.

2. Thermal Optimization

Trombe wall is among the important passive solar heating systems, which has been investigated in this work. A masonry wall of 0.2 m thickness, coated with a dark, heat absorbing material and covered by a single layer of glass, placed from about 0.15 m away from the masonry wall is selected, as shown in Figure (1). The detailed parameters of Trombe wall are listed in Table (1).

Tab. 1: Trombe Wall Parameters

Orientation	South
Trombe wall area ratio (a)	0 - 52
Windows shading coefficient	0.9
Wall height (m)	3
Wall thickness (m)	0.2
Wall thermal conductivity ($W^{-1}m°C$)	1.75
Wall specific heat X density ($kJ^{-1}m°C$)	1932
Wall solar absorbance	0.9
Glazing emittance	0.9
Window R-value ($m^{-2}°C^{-1}$ W)	0.333
Space between wall and Glazing (m)	0.15
Number of glazing	1

A solid storage wall can be considered as a set of nodes connected together by a thermal network, each with a temperature and capacitance. The network used in TRNSYS (2006) is shown in Figure (2). The wall is shown divided into N nodes across it thickness (Duffie and Beckman, 2006).

The thermosyphon mass flow of air in this model has been determined by applying Bernoulli's equation to the entire air flow system. For simplicity, it is assumed that the density and temperature of the air in the gap varies linearly with height. The average air velocity through the gap is (Duffie and Beckman, 2006);

$$\bar{V} = \left[\frac{2gh}{C_1\left(\frac{A_s}{A_v}\right)^2 + C_2}\,\frac{T_m - T_r}{T_m}\right] \qquad \text{(eq.1)}$$

where; C_1 and C_2 have been determined by Utzinger (1979) to be 8.0 and 2.0, respectively, h the wall height (m), T_m the mean air temperature in the gap (°C), g the acceleration of gravity (m^2), T_r the room air temperature (°C).

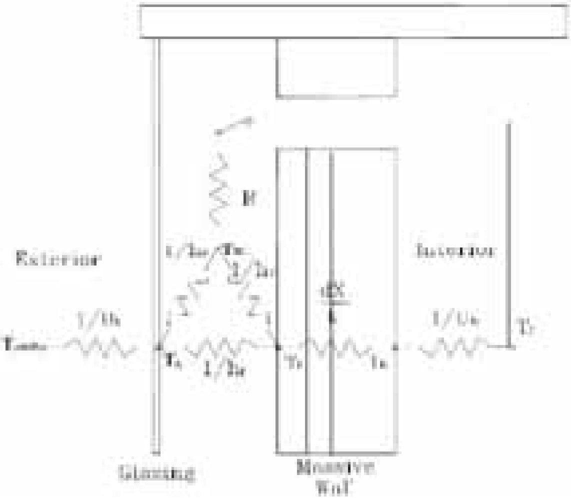

Fig. 2: Thermal Schema of Trombe Wall

The thermal resistance (R) to energy flow between the gap and the room when mass flow rate of air in the gap is finite is given by Solar Energy Laboratory (2006);

$$R = \frac{A\left[\left(\frac{\dot{m}C_p}{2h_cA}\right)\left(exp\left(-\frac{2h_cA}{\dot{m}C_p}\right)-1\right)-1\right]}{\dot{m}C_p\left(exp\left(-\frac{2h_cA}{\dot{m}C_p}\right)-1\right)} \qquad \text{(eq.2)}$$

where; $\dot{m}$ is the mass flow rate of air in the gap (kg/s), C_p the specific heat of air ($kJ.kg^{-1}$ $°C^{-1}$), h_c the gap air heat transfer coefficient $kJ.m^{-2}$. $°C^{-1}$), A the Trombe wall area (m^2).

TRNSYS Software, simulation program tool, will be used for estimating the performance of Trombe wall system. TRNSYS Simulation software is an acronym for a TRaNsient SYstem Simulation program. TRNSYS is a complete and extensible simulation environment for the transient simulation of systems, including multi-zone buildings. It is to validate new energy concepts, from simple domestic hot water systems to the design and simulation of buildings and their equipment, including control strategies, occupant behavior, alternative energy systems such as wind, solar, photovoltaic and hydrogen systems (Solar Energy Laboratory, 2006). The calculations are influenced by climatic factors such as outdoor temperature, solar radiation and the relative humidity. Properties for the indoor climate of the building can be calculated based on these simulated results.

The annual heating load as well as annual energy gain conducted through the wall and convected by air flow into the heated space is calculated. The change in energy storage in the wall is negligible over a one month period. The energy that enters the space may go, in part, to meet the building load. The calculation procedure assumes that the heat from the wall offsets the heating load whenever the building temperature is below the maximum temperature limit. Whenever the building temperature exceeds this maximum value, the excess energy is dumped. Practically, this is done by installing roller shutters insulation curtains between glass and masonry wall layer.

A residential building is selected in this study, as shown in Figure (2). The building is a rectangular shape with floor area of about 154 m^2, perimeter is 43.4 m and ceiling height is 3 m. This building is well insulated and ventilated according to ASHRAE Standard 62.2 (ASHRAE, 2004).. With proper thermal insulation added to walls and ceiling a good reduction of the cooling demand has been achieved. Heating thermostat setting (indoor set point temperature) is adjusted at 20°C dry bulb temperature and 30% relative humidity (ASHRAE, 2008).

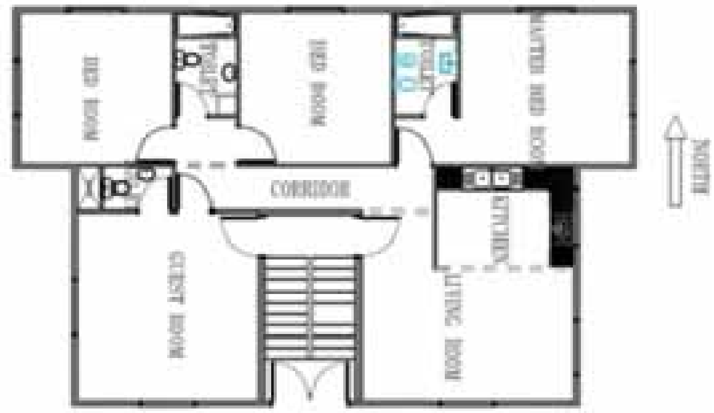

Fig. 2: Residential Building Model

The hourly climatic data are obtained from INSEL library (Doppelintegeral, 2009). Then the hourly cooling load for selected locations is calculated by TRNSYS software. The annual energy consumption in winter season for the selected residential building, before adding the Trombe wall system, is 2,352 kWh and 8,326 kWh for Amman and Berlin respectively. The maximum load is 3.78 kW in Amman and 4.59 kW in Berlin.

The effect of Trombe wall ratio (a), the percentage of Trombe wall to the total South wall, on building heating is presented in Figure (3).

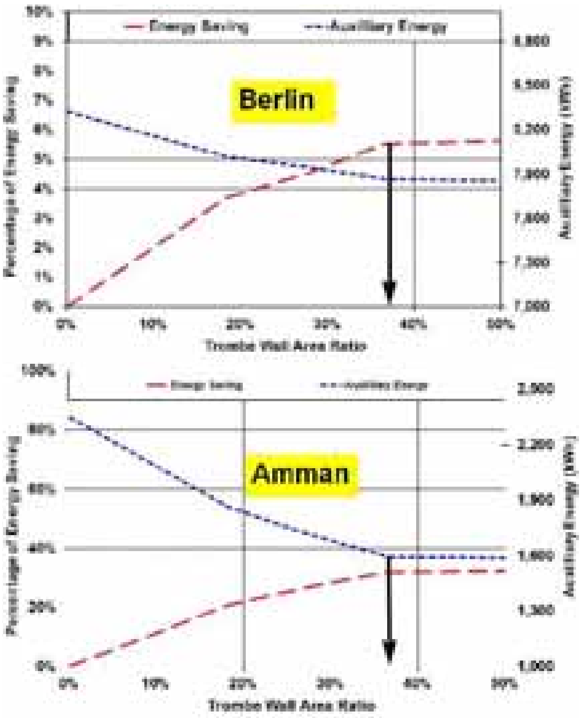

Fig. 3: Annual Auxiliary Energy due to Trombe Wall

Figure (3) shows that Trombe wall system has a considerable benefit in cold climate (Berlin) and Mediterranean climate (Amman). The calculated benefits are due to both reduction in auxiliary energy system size and reduction in fuel consumption.

By increasing Trombe wall area ratio by increment of 18%, about 22.3% and 3.7% of heating auxiliary energy will be saved annually in Amman and Berlin, respectively. Moreover, by increasing Trombe wall area ratio by increment of 37%, about 32.1% and 5.5% of heating auxiliary energy will be saved annually in Amman and Berlin.

Furthermore, the ability of Trombe wall in covering the total annual heating load after ratio of 37% is becoming negligible. That's mean the technical optimum Trombe wall area ratio is 37% in Amman and Berlin.

3. Economic Optimization

An optimization of indirect EAC is estimated using economic figures from local markets for each location using Life Cycle Cost (LCC) criterion. The objective function which will be optimized is LCC function which equal to (Arora, 2004);

LCC = (auxiliary system cost + maintenance cost for auxiliary system - auxiliary system salvage cost) + (basic material cost + EAC cost) + (annual auxiliary energy cost - annual cost of saved energy + running cost) (eq.3)

The economic analysis of employing Trombe wall is presented in Figure (4).

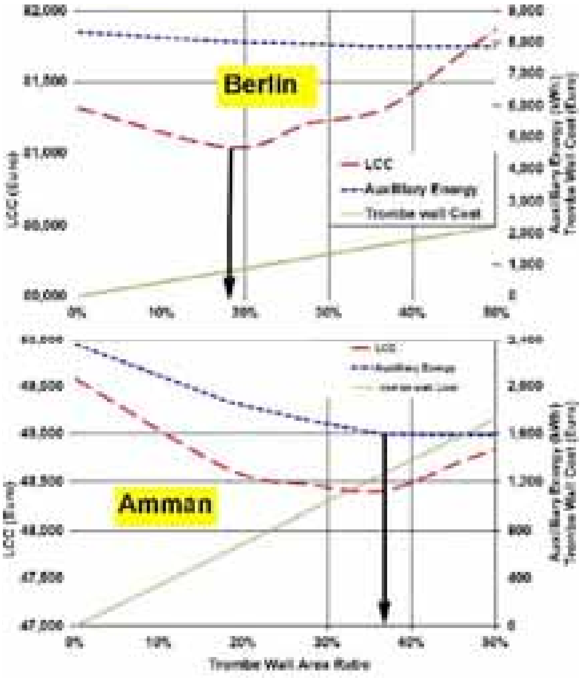

Fig. 4: Trombe Wall System Economic Analysis

The above Figure shows Trombe wall cost, auxiliary energy needed after installing Trombe wall and Life Cycle Cost (LCC) of the building as a function of Trombe wall area ratio for Amman and Berlin climate zones.

The results show that LCC of the conventional heating system and fuel consumption over 30 years, before installing Trombe wall system, is about 49,259 Euro. Moreover, the economic optimum point is occurred at Trombe wall ratio of 37% with extra investment of 1,260 Euro. Furthermore, about 1,169 Euro can be saved over the life cycle of the building. The optimum area ratio has reduced LCC by 2.4%. On the other hand, CO_2 emissions will reduce of about 445 kg.

The optimum Trombe wall area ratio from thermal and economical point of view is 18% in Berlin. This need initial cost of 810 Euro. The annual energy saving is 3.7% will be achieved. LCC has been annually reduced by 0.3%. On the other hand, CO_2 emissions will reduce of about 181 kg.

4. Conclusion

It is concluded from this research that Trombe wall system doesn't reduce the maximum load. On the other side it is reduced the annual heating energy consumption. That's because Trombe wall system depends on the availability of solar radiation; when there is high solar radiation a less heating demand is required and vice versa.

Literature was shown that Trombe wall should be insulated for summer cooling in order to prevent undesirable overheating of room air due to convection and radiation heat transfer from the wall (Gan, 1998). Properly sized roof overhangs shade the Trombe wall during summer when the sun is high in the sky. Shading Trombe wall can prevent the wall from getting hot during the time of the year when the heat is not needed (Torcellini and Pless, 2004; Ellis, 2003).

In this research, it is recommended to use roller shutters to prevent solar radiation from entering the building and insulation curtains between glass and masonry wall layer to avoid heat transfer to the building during summer. Moreover, the foundation area should be insulated in the usual way with rigid insulation board to reduce heat loss from the solar wall to the foundation.

5. References

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