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Computer Simulation of Trombe Wall for Porous and Non-Porous Strutcures

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ABSTRACT

Computer simulation of porous Trombe wall has been carried out for providing comfortable thermal environment. During sunshine hours excess heat is stored within the porous absorber and there is stratification in the porous layer. For two different porous materials viz. marble and quartzite, explicit expressions for heat flux and thermal efficiency of the porous system have been developed. The experimental results have been validated with numerical computations using the developed model. It has been observed that Trombe wall contributes 20% to 30% of the total heating of the buildings depending upon type of material. The average thermal efficiency of the wall has been found to be 29.09% for brick wall, 37.27% for concrete wall, 45.35% for marble wall and 57.2% for quartzite wall respectively.. The results from presented mathematical model would help the designers of passive solar systems to use this model for selecting optimal constructive parameters of the non-porous Trombe wall.

Keywords: *Thermal Performance Passive Systems; Porous Walls; Non Porous Walls; Trombe Walls*.

1.0 Introduction

Energy from the Sun can be collected and utilized in many different ways which may be grouped into three basic categories such as direct thermal applications, solar thermal-electric applications and fuel from biomass. All of these technologies exist and have been well demonstrated. The recent rapid escalations in the costs of fossil fuels and increasing awareness regarding environmental pollution issues and the finite size of fossil resources have changed the scenario. Therefore, alternate energy sources have to be developed for supplementing and eventually replacing fossil resources. The other potential application of solar energy in providing comfortable thermal environment in the living space is based on passive heating and cooling concepts. For providing a non-fluctuating temperature in a living room, a massive wall is usually introduced between the glazing and the room. Usually this massive wall, known as Trombe wall, is made of either concrete or consists of water drums stacked over one another as shown in Fig.1 The concept of a Trombe wall with and without vents is used for providing comfortable environment in the living space [1,2]. It is, however, necessary to provide ventilation to let the fresh air flow for diluting the effects of moisture, dust and gases. The energy required for heating this ventilating air could be sizable and hence the idea of a „Trombe wall‟ which is provided with circular pipes for the flow of air [3, 4]. This idea of ventilated Trombe wall is more useful in dairies and farms, where animals are confined to remove the odour, moisture, dust and gases produced by the animals in the confinement. The building must be ventilated continuously with fresh air for diluting these unhealthy products. In hot climatic conditions, the hot air may be used for heating the gravel for domestic purposes. This idea offers an application of solar passive systems like that of a storage wall provided with a network of circular pipes through which ambient air flows either by natural convection or forced convection mode. The natural convection heat transfer plays an important role in a significant group of constructive solutions of passive structures utilized in buildings [5-7]. The thermal performance of two passive cooling systems under hot and humid climate condition has been experimentally investigated by Chungloo and Limmeechokchai [8-10].

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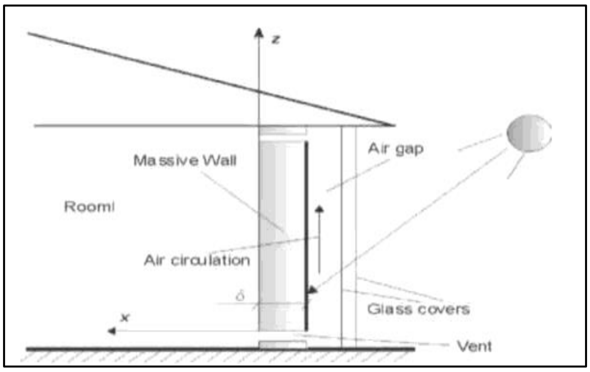
The experimental results were obtained from a test cell and a controlled cell with identical walls but different roof configurations. The applications of the two systems in hot and humid climate are found to sustain the room temperature of the test cell to be lower than the ambient temperature by 2.0-6.2oC and lower than the room temperature of the controlled cell by 1.4-3.0oC.

Various techniques have been developed and used to enhance the thermal storage effect of a Trombe wall, such as installing an absorber plate in the air gap and using a black surface on the heat storage wall. Insulated layers are installed outside the Trombe wall for reducing heat loss at night in a cold climate. But the heat storage capacity of the wall also reduces significantly by using outside insulated layer. A shading device is installed in the air gap in order to improve heat accumulation of the Trombe wall at day time and reduce its heat loss at night time [7]. In winter, the shading device can be opened at day time to allow the black massive wall to absorb solar heat directly and shut down at night to minimize heat loss of the wall. In summer, the shading device can be closed at day time to decrease the direct heat gain from solar radiation and prevent overheating. Chandel and Aggarwal [5] have carried out experimental studies on passive solar building and concluded that high cost conventional heating systems can be replaced by using solar heating with backup heaters. The present paper mainly deals with the study of few basic concepts utilized in the architecture of the building to maintain thermally comfortable environment without using any passive means of energy.

Fig 1: Schematic Diagram of Trombe Wall' System [1]



2.0 Literature Review

Akbarzadeh et al. [1] have made experimental flow visualization studies which provide a deeper insight into the fundamental flow mechanisms. The air velocity and temperature measurements have been used to explore the natural convection heat transfer processes involved in the thermo-circulation flow. The effects of the wall parameters such as wall-glazing distance and vent size on the thermal performance of the wall have been considered.

They have correlated adequate experimental results by using expressions derived for natural convection processes occurring between vertical parallel plates, i.e. the vertical heated wall surface and the cooler vertical glazing panel. This type of fundamental heat transfer information is important as the overall performance of Trombe wall systems can be adequately modeled using the large range of simulation techniques presently available for thermal network analysis.

The change in thermo circulation performance over the range of wall-glazing distance tested was not significant. Bansal and Thomas [2] have presented a steady state method for sizing four indirect gain passive solar heating systems, viz. mass wall system, water wall system, Trombe wall system and solarium.

This method is developed for use by architects and builders who can quickly check if passive heating is feasible at a particular location by calculating the area of the passive building element. Blasco et al. [3] have studied the thermal performance of three passive systems viz. Trombe wall, direct gain and sunspace and two conventional constructive systems viz. with / without low energy measures for various situations (with / without night / day protection and ventilation) and climatic seasons (winter, summer, spring and autumn) and measured variables are solar intensity, outdoor temperature and indoor temperature taken from different points of the physical models.

Chandel and Aggarwal [5] have evaluated the thermal performance of a passive solar bank building in Shimla (H.P.), India which incorporates a heat-collecting wall and a roof-top solar air heater with an electric heating backup, sunspaces and double-glazed windows..

Chel et al. [6] have investigated energy conservation, mitigation of $C0_2$ emissions and economics of retrofitting for a honey storage building with Trombe wall, located at Gwalior (India), for winter heating application. TRNSYS building simulation software was used to estimate the passive heating potential of Trombe wall for a honey storage building. Chen et al. [7] have conducted experiments on the thermal performance of an advanced Trombe wall with shading in the air gap of a passive solar house in Dalian.

They investigated the thermal performance in terms of temperatures, heat fluxes and their acquisition in a Trombe wall with shading effects. Chen and Liu [9] have studied heat transfer and flow in two types of solar composite walls with porous absorber. In order to analyze the performance of the flow and temperature field in the solar composite wall, an 'unsteady' numerical simulation model has been developed. Gan [11] has studied Trombe walls for passive cooling of buildings in summer using use CFD technique to simulate a Trombe wall for summer ventilation with solar heat gains and conduction heat transfer. The effect of parameters such as the channel width and height, heat gains and wall insulation that influence the performance of a Trombe wall has been investigated. It would also be desirable to increase heat exchanges within the channel using a fan as proposed by Boutin and Gosselin.

Jaber and Ajib [12] have studied thermal, environmental and economic impacts of Trombe wall system for a residential building in Mediterranean region. They concluded that Trombe wall system does not reduce the maximum load. On the other hand, it reduced the annual heating energy consumption. Properly sized roof overhangs shade the Trombe wall during summer when the sun is high in the sky. Koyunbaba et al. [13] have made an attempt to validate the simulation model with experimental results of a prototype building integrated photo voltaic (BIPV) Trombe wall built in Izmir, Turkey.

A transient energy analysis for determining the performance of a BIPV Trombe wall integrated to the facade of a room has been carried out. The mass flow rates for natural ventilation were calculated in the range of 0.013 kg/s for irradiance of 638.6 W/m^2 to 0.035 kg/s for irradiance of 750.88 W/m^2 for a typical day of February. The results showed that the heat stored in the wall during the day is transferred into the room during night time when there is no radiation. As the mass flow rate of air circulating in the air duct increases after the vents are opened, the thermal energy transferred to the wall from the room increases and it stabilizes above a given flow rate value.

Koyunbaba and Yilmaz [14] have compared the thermal performances of single glass, double glass and a Si semi-transparent photo voltaic (PV) module integrated on the Trombe wall facade of a model test room built in Izmir, Turkey. A transient energy analysis for determining the thermal performance of the integrated Trombe wall has been carried out. Nayak et al. [15] have developed a mathematical model based on Fourier series solution for solving the heat conduction equation. The periodic approach leads to closed form solutions which are readily amenable to numerical computations on the computer.

They have analyzed and compared the thermal performance of three typical passive heating systems viz. [16-17] Trombe wall with (forced) or without (natural) air circulation, water wall and solarium for two cases, viz. (i) when the glazing is left uncovered throughout and (ii) when the glazing is covered with an insulation during off sunshine hours.

Ram and Garg [18] have presented a periodic analysis of the behavior of a ventilated south-facing Trombe wall / roof consisting of pipes, laid in a solid block.

One surface of the block is exposed to the sun and the other surface is in direct contact with a room maintained at a constant temperature. Raman et al. [19] have described the development of a solar passive system which can provide thermal comfort throughout the year in composite climates. In the first phase, a passive model (passive model 1) comprising of two sets of solar chimneys was developed and monitored for its performance for one complete calendar year.

The additional cost of providing passive components and wall insulation was estimated to be about 20% of the cost of a conventional room. The passive system described in this paper seems to have good potential keeping in view the increasing costs of electricity and deteriorating power situation. Shen et al. [20] have studied the thermal performances of passive solar systems, viz. a classical Trombe wall and a composite Trombe-Michel wall. The mathematical models were developed with the finite difference method (FDM) and with TRNSYS software. The results of simulation with FDM and with TRNSYS have been compared.

The model for the composite wall developed with FDM was validated by experimentation. Smolec and Thomas [22] have developed a numerical code based on PASOLE in order to compare theoretical temperature distributions in a Trombe wall with experimental data. Sodha et al. [23] have used periodic analysis to evaluate the thermal flux entering an air-conditioned space for passive heating through the transwall.

The thermal performance of the system has been evaluated in terms of the heat flux entering the air-conditioned space which is assumed to be maintained at 20°C. The time-dependent thermal performance of the transwall can be predicted in order to understand its importance from a thermal load leveling viewpoint. Upadhya et al. [24] have presented a transient analysis of a transwall for an air-conditioned room.

They have incorporated the effects of the wall design and climatic parameters on optimizing the water-wall thickness outside and inside the trap material while keeping the total thickness of the water column constant. Zalewski et al. [25] have presented the results of a comparative study of four different types of solar walls. These results have been obtained using a numerical simulation model. An extensive experimental study has been conducted on a composite solar wall in order to validate the model.

The model is then used to study the energy efficiency of solar walls in different locations and under different climatic conditions. Then the thermal performance of these walls during the summer period has been analyzed. These walls improve thermal efficiency for collecting solar energy and manage comfortable environments particularly in the summer to avoid overheating. The results of this study are fundamental in helping architects to decide the best suited configuration for each type of building. Zalewski et al. [26] have presented the results of an experimental study of a small-scale Trombe composite solar wall incorporating a phase change material (PCM). The phase change material, in the form of a brick-shaped package, was inserted into the wall. Because of the diverse position of the bricks, each brick reacts differently to solar radiation and heat transfers in the ventilated channel. Dragicevic and Lambic [27] have presented numerical analysis of efficiency of the modified Trombe wall system with forced convection. The analyzed system consists of a double glass glazing and a massive wall with opening and a central channel in it. A fan is provided at the bottom vent of the wall in order to increase the efficiency.

The modified Trombe wall is more advanced as compared with simple Trombe wall with a relatively low thermal resistance which is considered as a reference in experimental analysis. The numerical results have shown that thermal efficiency of modified Trombe solar wall increases with the increase in both solar radiation intensity and air velocity in the entrance duct. The thermal efficiency of solar wall also increases with increasing air velocity in the entrance duct at constant solar radiation.

Further, thermal efficiency of the system decreases with the rise in air inlet temperature in the entrance duct. The results have been compared with their experimental values and have been found to be in good agreement.. Ruiz-Pardo et al. [28] have reviewed the calculation methods for the evaluation and design of energy and thermal performance of buildings presented by the European and International Standard UNE-EN ISO 13790. These methods have a varied range of details for calculating the energy utilization of passive heating and cooling in different building zones as well as for calculating the heat transfer and solar heat gains of special elements such as ventilated Trombe walls. Fares [29] has studied the effects of changing Trombe wall components on the thermal load in the building. The parameters selected to study the effects are the wall type (thermal mass), thermal mass thickness, ratio of Trombe wall area to total wall area and the layer count of glass coat, viz. one layer, two layers or three layers. The thermal load, solar gain and auxiliary energy have been calculated considering the changes in these parameters.

This research aims to attain and maintain the internal thermal comfort level using the passive solar heating system by considering changes in Trombe wall components. This leads to an optimal selection of Trombe wall components in order to reduce as much as possible the heating load in winter and the cooling load in summer. An important result is that an energy saving of 83% has been obtained when using such a Trombe wall. Stritih and Novak [30] conducted a numerical and an experimental study on a wall consisting of a transparent insulation material covering a solar collector made of black paraffin. An air channel behind the solar collector was used to supply the pre-heated air for the ventilation of the house. Their numerical analysis has shown that the optimum wall thickness was 50 mm and the melting point of paraffin was a few degrees above room temperature. Khalifa and Abbas [31] created a dynamic simulation computer model of a south-facing thermal storage wall. They examined two types of PCMs viz. the hydrated salt $CaCl_2.6H_20$ and paraffin wax encapsulated in copper capsules with length to diameter ratio of 0.76.

They concluded that a 0.08 m thick thermal storage wall made from the hydrated salt gave better thermal performance than a 0.20 m thick concrete wall and the 0.05 m thick wall made from paraffin wax. Fernndez-Gonzlez [33] has presented a summary of the thermal performance of five different passive solar test-cells (Direct Gain, Trombe wall, Water wall, Sunspace and Roofpond) and a control test-cell during the 2002-2003 heating season in Muncie, Indiana.

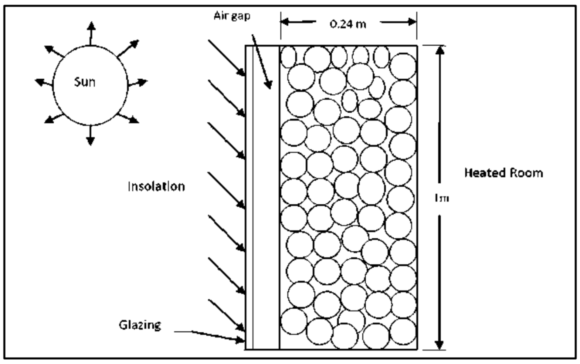
The thermal storage wall had an area of 4.4 m^2 and included four vents each with an area of 0.1 m^2. He concluded that the Trombe wall produced an extremely stable indoor environment with a low variation in the operating temperature. Bhandari and Bansal [34] have used the concept of solar heat gain factor for calculating the net energy gain of passive heating elements and other components of a building due to incident solar radiation. Mishra & Kamal [35] carried out thermal analysis of Trombe wall for non porous structure out for providing comfortable environment conditions.

Explicit expressions for heat flux and thermal efficiency of the non porous system using different thermal energy storage materials have been been used for numerical computations in order to developed. The following data given in Table 1 have validate the experimental results.

Table: 1. Physical and Thermal Properties of Thermal Energy Storage Materials (Mishra & Kama! [35])

Sr. No.	Material	Thermal Conductivity k_m (W/m-K)	Density ρ (kg/m^3)	Specific Heat c_p (J/kg-K)
1	Brick	0.69	1600	840
2	Concrete	1.5	2243	837
3	Marble	2.7	2650	840
4	Quartzite	5.17	2635	732

Fig: 2. Schematic Diagram of a Porous Wall



Numerical computations have been carried out using the developed model which validates the experimental results. The thermal stratification in Trombe walls for non-porous structures is analyzed and it was observed that thermal energy storage wall made of quartzite gives better performance than other types of walls. This model is also useful for predicting thermal performance of other passive heating and cooling systems. Numerical simulation has been used to analyze the thermal performance of heat transfer and air flow in porous Trombe wall. For two different porous materials viz. marble and quartzite, explicit expressions for heat flux and thermal efficiency of the porous system have been developed. The experimental results have been validated with numerical computations using the developed model. Kamal and Mishra[36] carried out computer simulation of porous Trombe wall for providing comfortable thermal environment. During sunshine hours excess heat is stored within the porous absorber and there is stratification in the porous layer.

The porous absorber works as a thermal insulator when no sunshine as shown in Fig.2.
A study of thermal stratification in the porous and non-porous Trombe walls has not been carried in the literature so far.

The literature further reveals that there has been a limited application of a numerical approximation technique such as finite element method for analyzing the solar thermal walls. Only finite difference method has been used to a certain extent by a few authors so far in their analysis.

The performances of Trombe walls and Trans walls have been analyzed using an approximate numerical solution procedure based on finite element analysis for the different cases of these two types of walls.

3.0 Results and Discussions

Fig. 3 shows the variation of specific heat of porous absorber with porosity for four different materials such as brick, concrete, marble and quartzite. As porosity of porous absorber increases, specific heat of porous absorber is also increasing. The specific heat of quartzite is much lower than that of brick, concrete and marble.

The density and thermal conductivity of porous absorber using brick, concrete, marble and quartzite decrease when porosity is increasing as shown in Figs.4 and 5 respectively.

Fig: 3. Variation of Specific Heat with Porosity for Different Materials

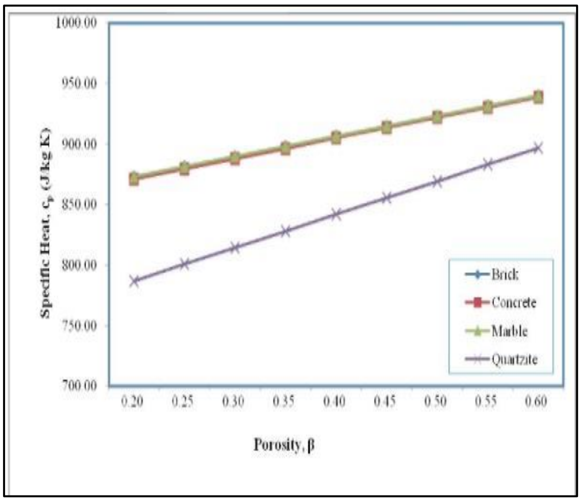
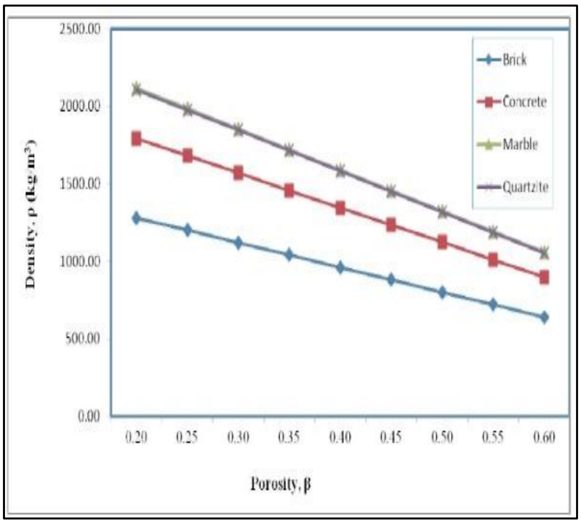


Fig: 4. Variation of Density with Porosity for Different Materials



Fia: 5. Variation of Thermal Conductivity with Porositv for Different Materials

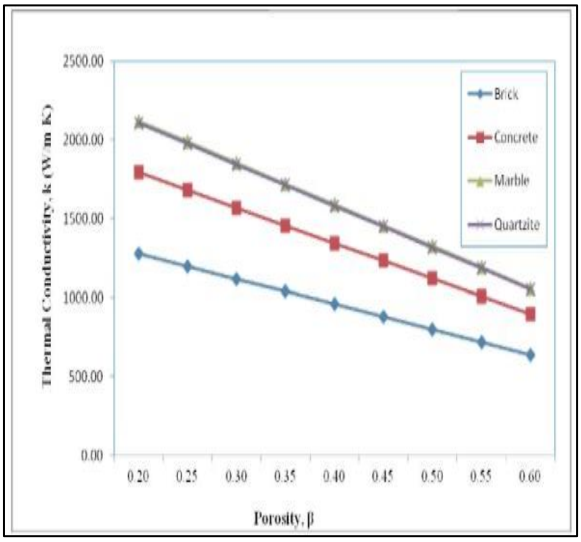


Fig. 6 shows the variation of fluid (air) temperature for different mass flow rates of air and ambient temperature with time of the day. It was observed that as mass flow rate of air increases, the fluid outlet temperature of porous collector decreases. Similarly Fig. 7 shows the variation of volumetric heat transfer coefficient with particle diameter of marble for different mass flow rates of air.

It was observed that as mass flow rate of air increases, the volumetric heat transfer coefficient also increases for a given particle diameter.

Fig: 6. Variation of Fluid (Air) Temperature for Different Mass Flow Rates of Air and Ambient Temperature with Time of the Day

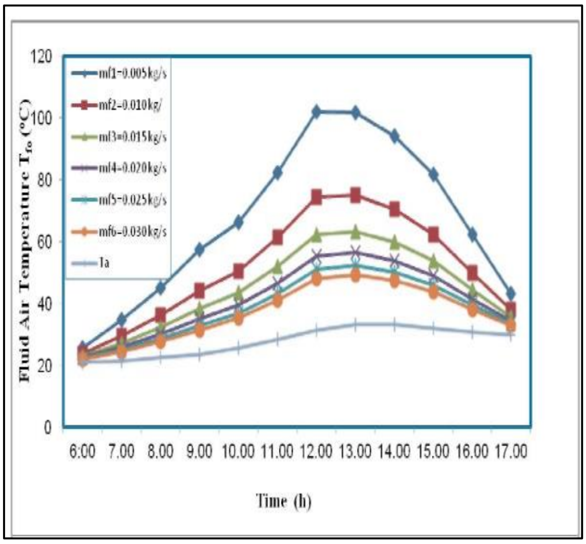


Fig: 7. Variation of Volumetric Heat Transfer Coefficient with Particle Diameter for Different Mass Flow Rates of Air

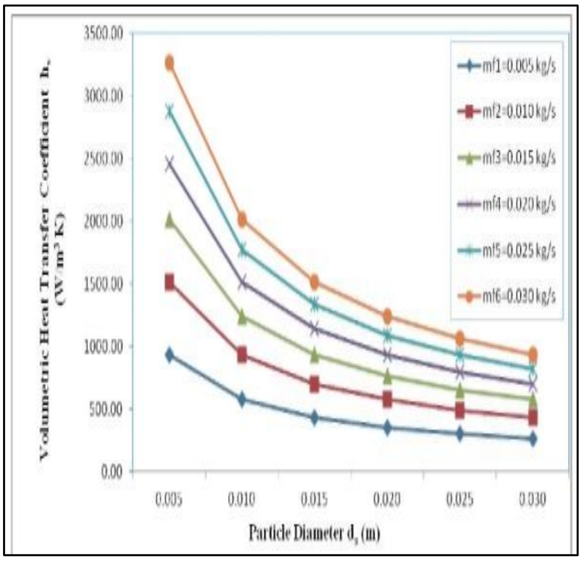


Fig: 8. Variation of Volumetric Heat Transfer Coefficient with Mass Flow Rate of Air for Different Particle Diameters

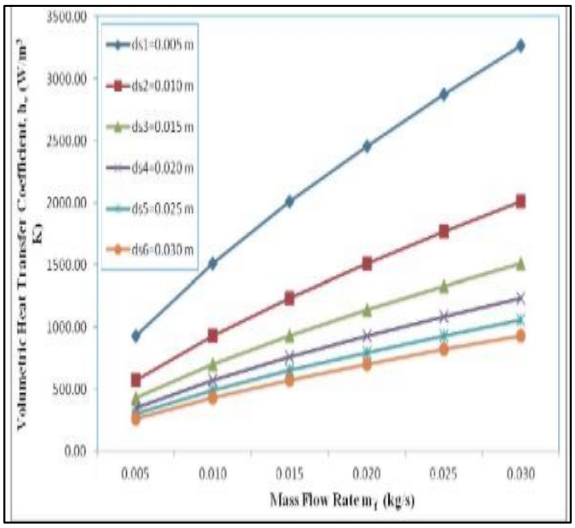


Fig. 8 shows the variation of volumetric heat transfer coefficient with mass flow rate of air for different particle diameters of porous marble. It was observed that as particle size increases, the volumetric heat transfer coefficient decreases for a given mass flow rate of air.

The variations of volumetric heat transfer coefficient and surface heat transfer coefficient for a surface heat transfer coefficient increases with increasing particle diameter for a given mass flow rate of air.

Fig. 10 shows the variations of volumetric heat transfer coefficient and surface heat transfer coefficient with particle diameter for different porosities and a given mass flow rate of air (0.010 given mass flow rate of air (0.010 kg/sec) and different porosities for different particle diameters of porous marble are shown in Fig. 9. It was observed that volumetric heat transfer coefficient decreases and kg/sec) for porous quartzite walls.

It was observed that for a given mass flow rate of air, volumetric heat transfer coefficient is decreasing with increasing particle size while surface heat transfer coefficient first increases, reaching an optimum value before decreasing.

Fig: 9. Variations of Volumetric Heat Transfer Coefficient and Surface Heat Transfer Coefficient with Particle Diameter for Different Porosities and a Given Mass Flow Rate of Air for Porous Marble Walls

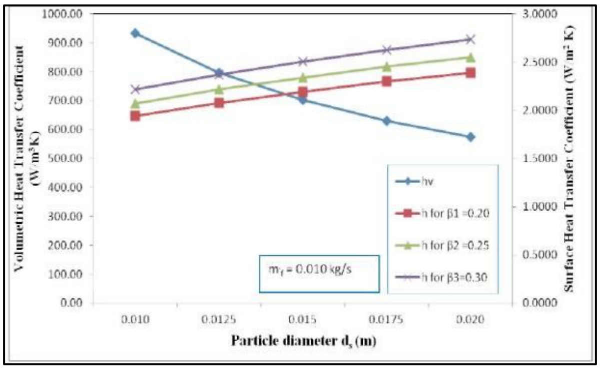


Fig: 10. Variations of Volumetric Heat Transfer Coefficient and Surface Heat Transfer Coefficient with Particle Diameter for Different Porosities and a Given Mass Flow Rate of Air for Porous Quartzite Walls

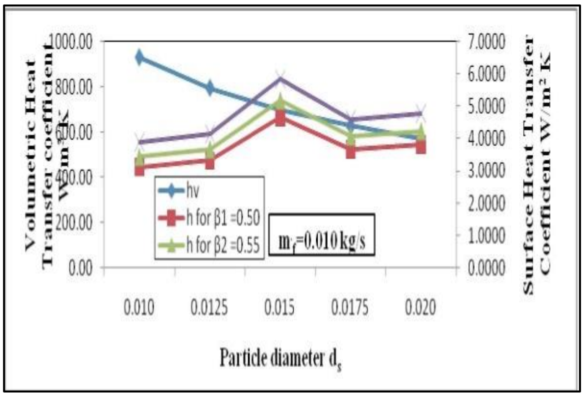
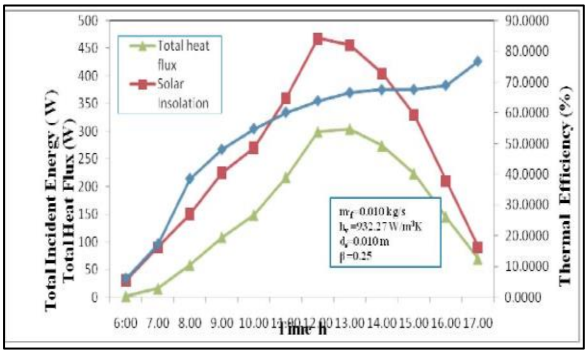
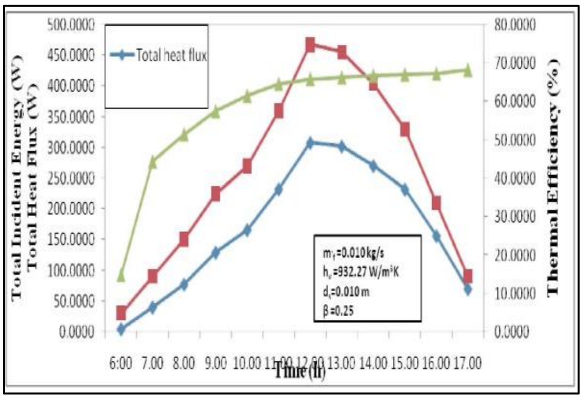


Fig: 11. Variations of Total Incident Energy, Total Heat Flux and Thermal Efficiency for Porous Marble Wall with Time of the Day at x=0.24 m



Figs. 11-13 show the variations of total incident porous Trombe walls made of the same materials. The energy, total heat flux and thermal efficiency of average thermal efficiencies of porous Trombe walls marble and quartzite walls with varying time. It was made of marble and quartzite have been found to be observed that marble and quartzite porous absorbers 52.56% and 57.94% respectively, improve the thermal performance as compared to non

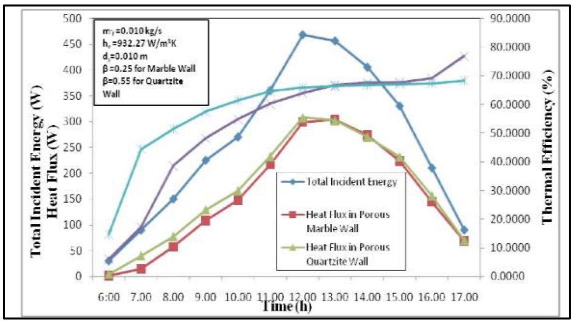
Fig: 12. Variations of Total Incident Energy, Total Heat Flux and Thermal Efficiency for Porous Quartzite Wall with Time of the Day at x=0.24 m



Figures 14, 15, 16 and 17 show the temperature stratification in the Trombe walls made of brick, concrete, marble and quartzite as thermal energy storage materials. It is observed that marble and quartzite showed the maximum temperature rise than brick and concrete. Figures 18, 19, 20 and 21 show hourly variations of heat flux with wall thickness across brick, concrete, marble and quartzite walls respectively.

It is observed that marble and quartzite give more thermal energy storage than brick and concrete which can be utilized during off-sunshine hours Figures 14, 15, 16 and 17 shows the temperature stratification in the Trombe walls made of brick, concrete, marble and quartzite as thermal energy storage materials. It is observed that marble and quartzite showed the maximum temperature rise than brick and concrete. Figures 18, 19, 20 and 21 show hourly variations of heat flux with wall thickness across brick, concrete, marble and quartzite walls respectively. It is observed that marble and quartzite give more thermal energy storage than brick and concrete which can be utilized during off-sunshine hours

Fig: 13. Comparison Between the Variations of Total Incident Energy, Heat Fluxes and Thermal Efficiencies of Marble and Quartzite Walls with Time of the Day at X=0.24 M



From the techno-economic point of view, the locally available materials such as brick and concrete give lesser thermal energy storage. For a typical value of = 0.36 , i.e. at the inside surface of the wall, the hourly variations of sol-air temperature and temperatures in Trombe walls made of different thermal energy storage materials viz. brick, concrete, marble and quartzite [Table 1] are shown in Fig. 12 and hourly variations of solar insolation and heat fluxes in the Trombe walls are shown in Fig. 13. Figure 14 shows hourly variation of thermal efficiency for different thermal energy storage materials. It is observed that the average thermal efficiency of quartzite is maximum viz. 57.2% as compared with other materials. The thermal efficiency of marble and quartzite walls increases after 15:00 hrs due to energy storage in these walls which provides the heating effect inside the room during off-sunshine hours.

Fig: 14. Variation of Temperature Across Wall Thickness for Brick Wall

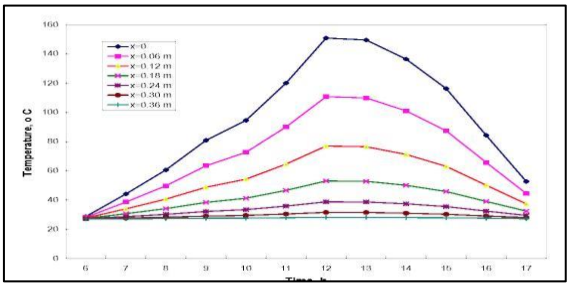


Fig: 15. Variation of Temperature across Wall Thickness for Concrete Wall

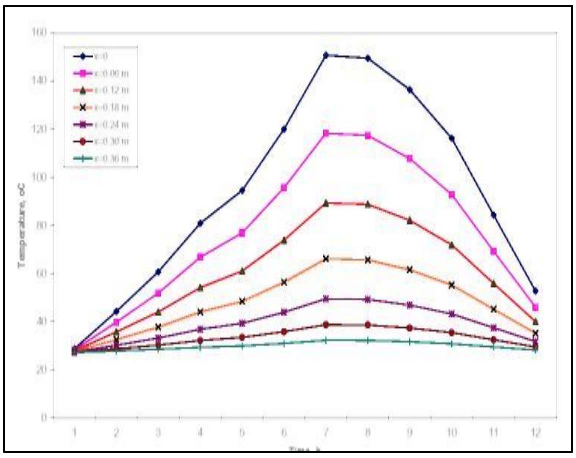


Fig: 16. Variation of Temperature Across Wall Thickness for Marble Wall

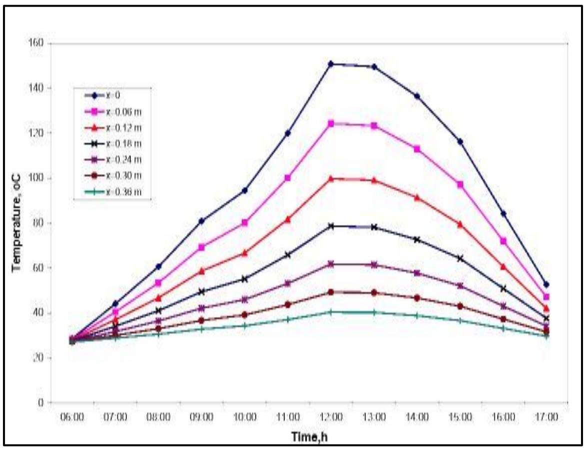


Fig: 17. Variation of Temperature Across Wall Thickness for Quartzite Wall

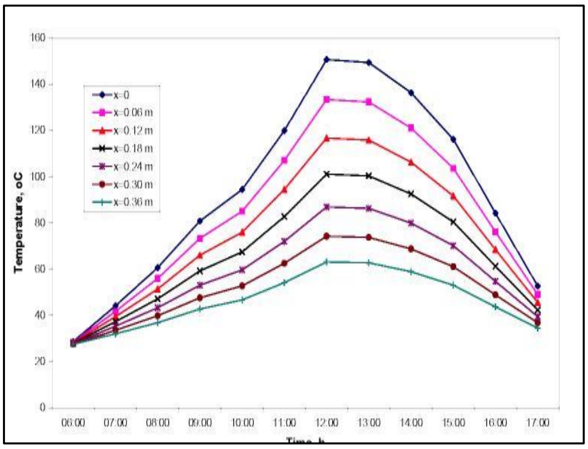


Fig: 18. Variation of Heat Flux with Wall Thickness across Brick Wall

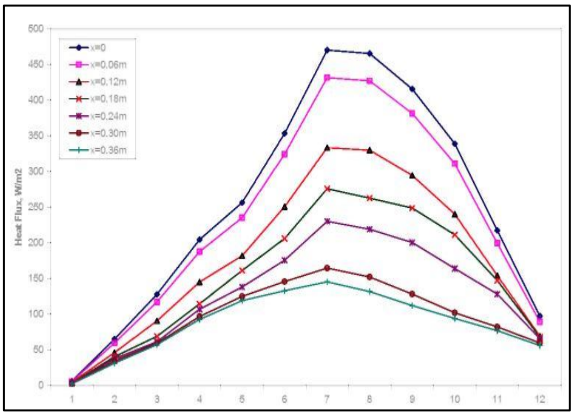


Fig. 19 Variation of Heat Flux with Wall Thickness across Concrete Wall

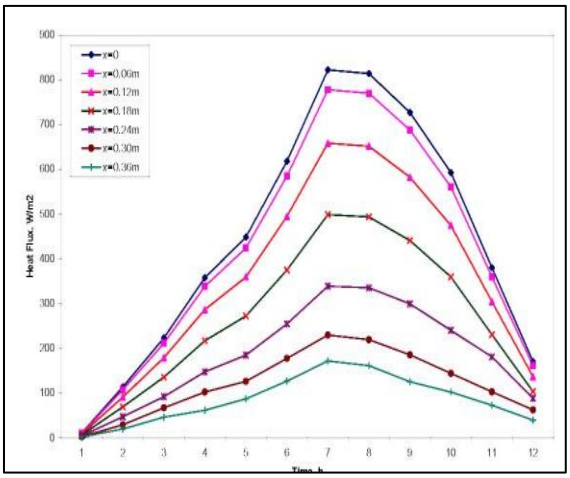


Fig: 20. Variation of Heat Flux with Wall Thickness across Marble Wall

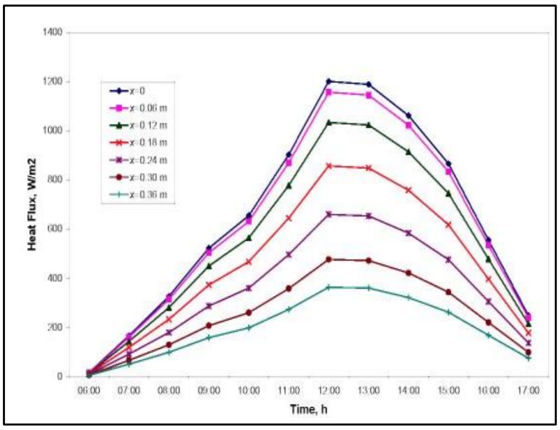


Fig: 21. Variation of Heat Flux with Wall Thickness Across Quartzite Wall

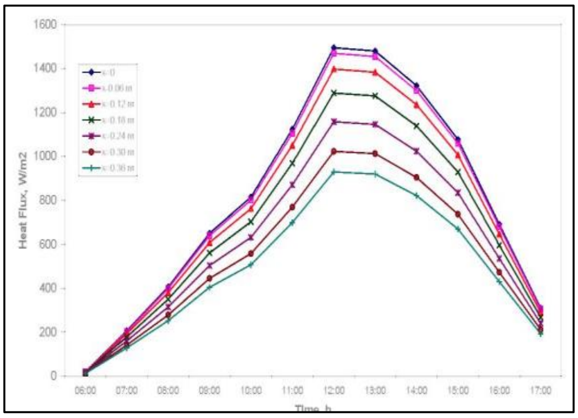


Fig: 22. Variation of Sol-air Temperature and Temperatures in Brick, Concrete, Marble and Quartzite Walls at x=0.36 m with Time of the Day

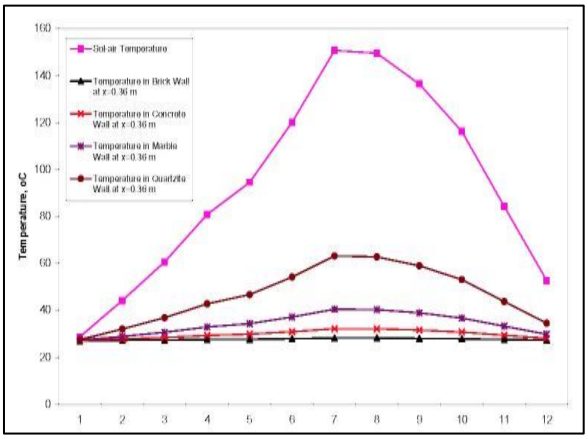


Fig: 23. Variation of Heat Fluxes in Brick, Concrete, Marble and Quartzite Walls at x=0.36 m and Solar Insolation with Time of the Day

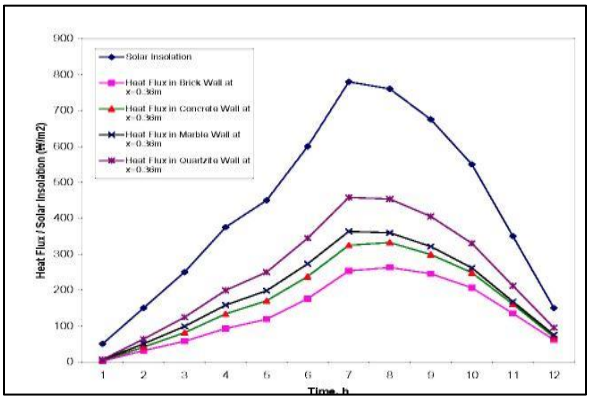
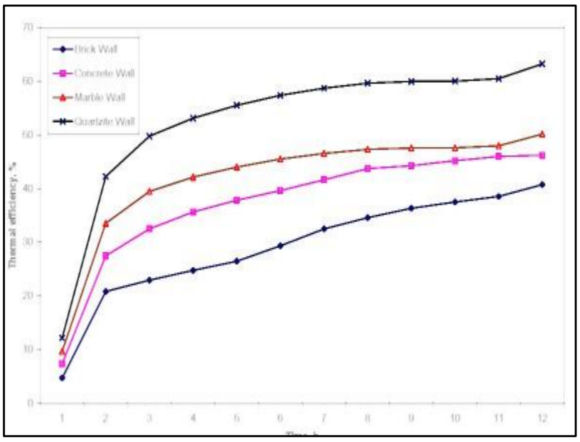


Fig: 24. Variation of Thermal Efficiency with Time of the Day for Different Wall Materials



4.0 Conclusions and Recommendations

It has been observed that Trombe wall contributes 20% to 30% of the total heating of the buildings depending upon type of material. The average thermal efficiency of the wall has been found to be 29.09% for brick wall, 37.27% for concrete wall, 45.35% for marble wall and 57.2% for quartzite wall respectively.. The results from presented mathematical model would help the designers of passive solar systems to use this model for selecting optimal constructive parameters of the non-porous Trombe wall.

A thermal model has been developed to study the effects of the porous absorber on heat transfer and air flow in porous Trombe wall for two types of absorbers viz. marble and quartzite. The average thermal efficiencies of porous Trombe walls made marble and quartzite have been found to be 52.56% and 57.94% respectively. The performance of passive heating or cooling systems is significantly influenced by the additional heating load in winter season and cooling load in summer season.

Hence the porous Trombe wall can be designed by considering the annual net heating effect of the wall. The occurrence of overheating and inefficient use of solar energy can be avoided by considering the effects of particle size and porosity of the porous absorber on the air temperature in the heated room. The optimal constructive parameters of the porous structures can be selected by the designers of passive solar systems using the results from the presented mathematical model

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