Thermal and Economic Feasibility of Trombe Wall Utilization in a Model Building

Raheleh Nowzari

Submitted to the
Institute of the Graduate Studies and Research
in partial fulfillment of the requirements for the Degree of

Master of Science
in
Mechanical Engineering

Eastern Mediterranean University
February 2009, Gazimağusa
North Cyprus

Approval of the Institute of Graduate Studies and Research

Prof. Dr. Elvan YILMAZ
Director (a)

I certify that this thesis satisfies the requirements as a thesis for the degree of Master of Science in Mechanical Engineering.

Assoc. Prof. Dr. Fuat Egelioglu
Chair, Department of Mechanical Engineering

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Master of Science in Mechanical Engineering.

Assoc. Prof. Dr. Ugur Atikol
Supervisor

Examining Committee

1. Prof. Dr. Ibrahim Sezai ______________________________
2. Assoc. Prof. Dr. Ugur Atikol ______________________________
3. Assoc. Prof. Dr. Fuat Egelioglu ______________________________

ABSTRACT

The duration of solar radiation during the day time plays an important role in the performance of thermal storage walls (i.e. Trombe walls). Cyprus weather conditions are believed to be ideal for the application of Trombe wall for heating purposes in buildings, but to the present knowledge no such application is presently available.

The objective of this study is to investigate the temperature behavior of a building integrated with a thermal storage wall and a window for direct solar gain for supplying heat in winter. This is achieved by modeling and simulation with the TRNSYS (Transient System Simulation) program. A hypothetical two story building with a total floor area of 120 m^2 has been modeled with the program. A Trombe wall is used on the south façade of the ground floor. Additionally a direct gain window of area 6.5 m^2 is placed on the south façade of the First floor. The hourly indoor temperature variations on the ground floor are compared with that of the First floor. It is assumed that the model building is located in Cyprus and Larnaca climatic conditions are used for simulation.

The results of the simulation show that approximately 95% of the total heating demand of the $60m^2$-zone can be met by a vented Trombe wall of area $15m^2$. It is verified that thermally insulating the building with 5cm-thick extruded polystyrene improves the thermal comfort by approximately 17%. It is observed that with a Trombe wall of area $15m^2$, the room air temperature can be easily maintained in the range between 19 and 21.5 °C, whereas the temperature on the First floor fluctuates between 17.3 and 20.5 °C during the coldest days of winter while the outside temperature ranges between 4 and 14°C.

The Life Cycle Cost (LCC) analysis indicates that constructing a 15m^2 Thermal storage wall in Cyprus is economically feasible compared to installing a 3-kW gas heater, as the saving-to-investment ratio is found to be 2.3.

ÖZET

Günlük güneş radyasyon (güneşlenme) müddetinin, ısıl depolama duvarı, Trombe-duvarı'nın performansını önemli ölçüde etkilediği bilinmektedir. Kıbrıs'ın hava koşullarının Trombe-duvarı'nın ısıtma amaçlı kullanılması için ideal olduğuna inanılmasına rağmen böyle bir uygulamamın yapıldığına hiç tanık olunmadı.

Bu çalışmanın amacı, bir Trombe-duvarı ve doğrudan enerji kazanımı olan bir pencere ile donatılmış bir binanın Kış mevsimine ait sıcaklık davranışlarını incelemektir. Bu amaca erişmek için TRNSYS (*Transient System Simulation* – Geçici Sistem Simulasyonu) yazılımı, toplam 120 m^2 döşeme alanı bulunan varsayılı bir binayı modellemek için kullanılmıştır. Binanın zemin katında, güney cephesine bakan bir Trombe duvarı ile birinci katında, güneye açılan doğrudan güneş enerjisi kazanımı sağlayabilen bir pencere kullanılmıştır. Binanın Kıbrıs'ta konuşlandırıldığı varsayılmış ve Larnaka hava koşulları dikkate alınmıştır.

Simulasyon sonuçları, 60 m^2'lik zemin kat bölgesi ısıtma talebinin %95'inin 15 m^2'lik Trombe-duvarı ile karşılanabileceğini göstermektedir. Bina'nın 5 cm kalınlığında ekstrüde polistren levha ile yalıtılması halinde, ısı konforunun yaklaşık %17 daha iyi olacağı da doğrulanmıştır. 15 m^2'lik ısıtma alanına sahip Trombe-duvarı ile oda sıcaklıkları en soğuk günlerde dahi 19 ile 21.5°C arasında kolaylıkla korunabildiği gözlemlenmiştir. Öte yandan birinci katta sıcaklık 17.3 ile 20.5°C arasında değişim göstermiştir.

Yaşam döngüsü maliyet analizleri, 15 m^2'lik bir ısıl duvarın, 3-kW'lık bacalı bir gaz sobası ile kıyaslandığında, ekonomik olurluğunun bulunduğunu göstermektedir. Bu hesaplarda Tasarrufun Yatırıma Oranı (TYO) 2.3 olarak hesaplanmıştır.

ACKNOWLEDGMENT

In the first place I would like to record my gratitude to my supervisor Assoc. Prof. Dr. Ugur ATIKOL for his supervision, advice, and guidance from the very early stage of this research. Above all and the most needed, he provided me unflinching encouragement and support in various ways.

Many thanks go in particular to Prof. Dr. Ibrahim SEZAI and Assoc. Prof. Dr. Fuat EGELIOGLU for the valuable advice in science discussion and using their precious time to read this thesis and give critical comments about it.

My parents deserve special mention for their inseparable support and prayers. My Mother, Effat, is the one who sincerely raised me with her benevolent and gentle love. Thanks Majid, Leila and Mohammad Reza for being supportive and caring siblings.

To My Sister

Dr. Haniyeh NOWZARI

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

$\bar{v}$	Average air velocity in gap
g	Acceleration of gravity, (m/s^2)
h	Wall height
T	Temperature, (ºC)
T_m	Mean air temperature in the gap
C_1	Vent pressure loss coefficient
C_2	Gap pressure loss coefficient
A_g	Total cross sectional area of the gap
A_v	Total outlet area of the vent
T_a	Ambient air temperature
T_R	Room air temperature
K_a	Air thermal conductivity
L	Gap between wall and first glazing
Gr	Grashof number
Pr	Prandtl number
Re	Reynold's number
h_c	Gap air heat transfer coefficient
w	Wall width
R	Thermal resistance of air flow to energy transfer
A	Area, (m^2)
$\dot{m}$	Mass flow rate of air in the gap
C_{pa}	Specific heat of air

$\dot{Q}_v$	Rate of energy flow by ventilation of gap air
$\bar{\rho}$	Average air density in gap
A_F	Floor area
$\dot{m}_{\inf.}$	Mass flow rate of infiltration air
η	Efficiency
$\dot{m}_{v,k,i}$	Mass flow rate of ventilation air of ventilation type k
C_p	Specific heat
U	Overall heat transfer coefficient, (W/m^{2}K)

Subscripts:

GF	Ground Floor
FF	First Floor
TW	Trombe Wall
F	Floor
IS	Inner Surface
OS	Outer Surface
SW	South Wall
S	South
A	Ambient
w	wall

CHAPTER 1

INTRODUCTION

The lack of energy resources (oil, coal, etc.) has led to an unreasonable rise in the cost of energy. As a result of worldwide crisis, the utilization of energy has become an essential issue and therefore, energy conservation in the sense of fuel saving has become of great importance.

Cyprus has no natural oil resources so; the required fuel has to be imported for its energy demands. As the price of fuel is increasing frequently in the international market, the investigation for an alternative energy source is essential. Also a large number of the buildings in Cyprus are not energy efficient.

Solar energy is one of the renewable sources of energy which is widely available in Cyprus.

The reduction of the building energy requirement for room air heating, cooling, lighting, etc. to a minimum is an important step toward energy conservation in Cyprus. This can be achieved by utilizing passive solar features (direct gain, thermal storage wall, etc.) in the buildings. The basic rule in design of passive solar buildings is to size, orient and locate the building components in order to acquire the maximum advantages of the climate for comfort conditioning of the building.

Cyprus has an ideal climate for taking advantage of thermal storage wall because of its long duration of solar radiation and large daily temperature fluctuations in winter. The mean diurnal variations in ambient temperature of Cyprus are around 8 ºC in winter and 14 ºC in summer (Kalogirou S.A., 2002). But such an application has not been used in Cyprus up to present.

The objective of this study is to investigate the temperature behavior of a model building integrated with a vented Trombe wall and a direct solar gain window of area 6.5 m^2. The Life Cycle Cost analysis is performed in order to examine the economic feasibility of using Trombe wall in buildings compared to installing a 3-kW gas heater. The organization of the thesis is as follow:

In Chapter 2, different studies around the world on passive solar strategies are introduced.

In Chapter 3, different passive solar heating strategies are introduced. Detailed explanations about thermal storage wall and direct gain heating systems are given because these two systems are used in the simulation of the hypothetical building.

In Chapter 4, the TRNSYS software program and its components are introduced and the characteristics of the hypothetical building and Trombe wall are defined. The mathematical description related to the Trombe wall and the building components are illustrated in this chapter as well. Finally, the simulation strategy with TRNSYS is explained.

In Chapter 5, the simulation results are presented and analyzed also, the economic analysis is performed in this chapter. In Chapter 6 general conclusions are derived by analyzing the results.

CHAPTER 2

LITERATURE REVIEW

Passive solar buildings have been the subject of several experiments and papers. In this chapter the literature on passive solar heating systems will be discussed.

Kalogirou S.A. et al. has studied the effects on the heating and cooling load, resulting from the use of building thermal mass in Cyprus, by modeling and simulation with the TRNSYS (Transient System Simulation) program. A typical four-zone building with an insulated roof and a Trombe wall on the south wall of one of the zones has been considered. The results of the simulation show that there is approximately 47% reduction in heating load requirement of the zone, while at the same time a slight increase of the zone-cooling load is demonstrated. According to this research the optimum overhang size is in the range of 1 to 1.5 m and the most efficient value of wall thickness is found to be 25 cm. It is found that the Effect of air gap size between the glazing and thermal storage wall is trivial and also insulation of roof is a must for better comfort conditions. 7.5% reduction in cooling load of building is obtained whenever ventilation is used during summertime (Kalogirou S.A., 2002).

The thermal performance of two passive solar systems, a classical Trombe wall and a composite Trombe-Michel wall, has been studied by Jibao Shen et al. A classical Trombe wall is a massive wall which is installed at a small distance from a glazing. The composite Trombe-Michel wall is similar to the classical Trombe wall; it consists of an insulating wall at the back of the massive wall which decreases heat loss during the cold periods. The models were created with finite difference method (FDM) and with TRNSYS software for comparison of the results. The composite wall model developed with FDM was validated by experimentation; also a new TRNSYS model (a Type) had been created for the composite solar wall. The simulation results of both classical and composite Trombe wall, with TRNSYS software and with FDM were compared. The inside surface temperatures of the classical and composite Thermal storage walls obtained by FDM and TRNSYS program are shown in Figure 2.1. It was found that the composite wall has better energetic performances than classical wall in cold and/or cloudy weather (Shen J. et al, 2007).

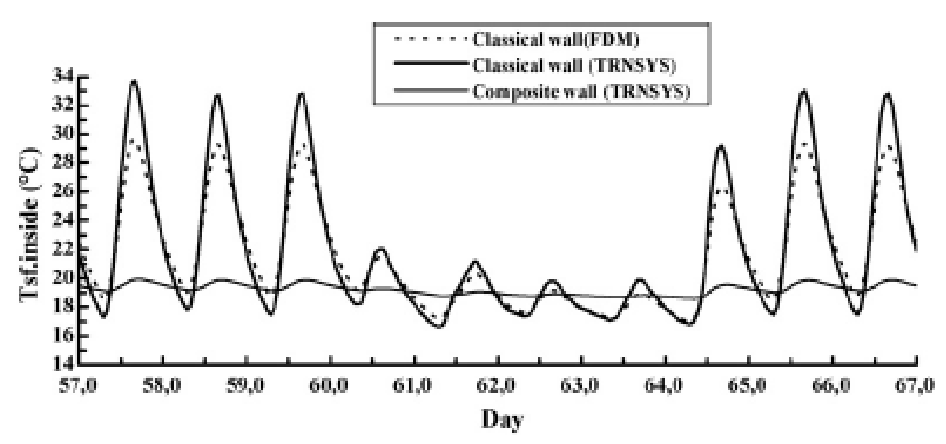


Figure2.1 Inside surface temperature of the classical and composite Trombe wall ($T_{sf\ inside}$) (Shen J., 2007).

More than 100 passive solar buildings have been constructed in the high altitude region of the Indian State of Himachal Pradesh under the Passive Solar Building Program. The thermal performance of a passive solar bank building at Shimla has been evaluated by S.S. Chandel and R.K. Aggarwal (2008). This Solar bank consists of a heat-collecting wall (Trombe wall), a roof-top solar air heater with an electric heating backup, sunspaces and double-glazed windows. The relaxing living conditions were obtained as the results of using these solar passive features in the building. The study has shown that low cost solar heating systems with backup heaters are the most effective replacement to the high cost central electric/gas/wood-fired heating- systems. Also by using the passive solar heating systems in buildings, there would be a great reduction in installation and maintenance cost of heating systems. It is found that the heat losses in the building is reduced by about 35% and the electricity needed for the building space heating become less with the use of solar passive features (Chandel S.S. et al., 2008).

An experimental approach to the thermal response of passive systems has been done by Huseyin Onbasioglu and A. Nilufer Egrican (2002) in Turkey. A full scale model of a passive heating system, a single zone with a thermal wall (the thermal wall of the zone is similar to the Trombe wall but it has a very slight thermal storage capacity) has been constructed. Two more spaces were added to the test cell: the control room on the east side and the west room. By means of concurrent temperature, velocity and flux measurements, the thermal performance of the passive solar heating system has been investigated. The temperature and velocity have been measured with the sensors inserted on the glazing and at the vents of the Trombe wall. The results have shown two extreme situations; one was the maximum heat transfer to the test room and the other was the beginning of the heat loss to environment by means of reverse circulation (night time cooling). In order to prevent reverse circulation, the vents should have been covered during the night time. Also it has been found that any change in solar intensity could cause fluctuation in the temperature of the thermal wall (Onbasioglu H., 2002). The Test facility which was constructed at the Istanbul Technical University Campus is shown in Figure 2.2.

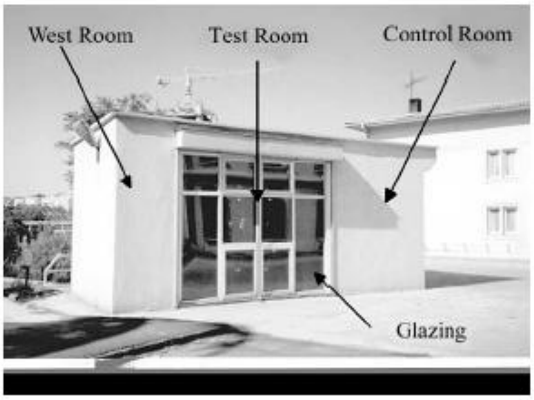


Figure2.2 The Test facility at the Istanbul Technical University Campus (Onbasioglu H., 2002).

A simple analytical model of the Trombe wall has been designed by R.J. Duffin and Greg Knowles (1985). With this model the various parameters affecting the wall performance like, the thickness of the wall can be analyzed. Also for improving the efficiency of the Trombe wall, different design criteria have been examined and prior methods have been compared with this work (Duffin R., 1985).

Energy conservation is important for both existing and new buildings. An approach for renovation of an existing building south facade with unvented Trombe wall has been developed by Zerrin Yilmaz and Arch Basak Kundakci (2008) in Istanbul, Turkey. With the application of FDM for calculations, under unsteady-state heat transfer conditions, the existing and the renovated buildings thermal performances have been compared. Different wall materials have been examined besides glass cover. The hourly variations of Trombe wall interior surface temperature have been applied to compare the thermal performance of the building with the existing facade with that of the renovated facade. The results have shown that, application of a Trombe wall to the facade of an existing building, plays a great role in energy conservation, but changing the wall material of the building does not influence the room temperature and the inner surface temperature of the Trombe wall a lot (Yilmaz Z., 2008).

Theoretical and experimental investigations of heat transfer in a Trombe wall have been done by W. Smolec and A. Thomas (1993). An extended two-dimensional model has been used to calculate the heat transfer in a Trombe wall and the experimental confirmation has been described.

The experimental studies have been carried out by Smolec et al. (1993) on a Trombe wall (after the necessary improvements) which was located in an old building (around 70 years old), at the Experimental Solar Energy Station of the Polish Academy of Science in Kozy. Copper-constantan thermocouples have been used to measure the temperature distributions inside the wall, also the inlet and outlet air temperature of the vents has been measured. A hot wire anemometer has been used to measure the air velocity in the outlet vent. In theoretical analysis, the height of the wall has been divided into four equal sections, the temperature distribution inside all surfaces and the internal and external surface temperature of the Trombe wall has been computed. Also the temperature of the air inside the channel has been calculated. The measured temperatures have been compared with the computed ones and it was found that there is a good agreement between them. For convection heat transfer in the Trombe wall a new semi-empirical expression has been recommended (Smolec W., 1993).

An experimental study on passive solar systems thermal performance has been done by I. Blasco Lucas et al. (2000) in San Juan, Argentina. In this work, the thermal performance of three passive solar systems (Massive/Trombe wall, Direct gain and Sunspace) has been examined, also the thermal performance of two traditional useful systems for different situations and climate seasons have been considered. The variables that have been measured with sensors from several points of the physical models are solar irradiance, outdoor temperature and indoor temperature. It has been found that all passive solar systems present solar gains throughout the year. The Trombe wall and the Sunspace have represented the best results because they have shown great solar donation in winter and small gain in summer (Blasco Lucas I., 2000).

Five different passive solar heating strategies have been constructed during the 2002-2003 heating season in Muncie, Indiana (Figure 2.3). Those five passive solar systems were Direct gain, Trombe wall, Water-wall, Sunspace and Roofpond. They were made of wooden frame and all had the same thermal insulation properties. The thermal performance and comfort conditions of the mentioned solar systems have been examined by Fernandez-Gonzalez A. (2007). The results of the study have shown that the thermal storage capacity of Trombe wall test-cell is lower than Direct gain test-cell but the diurnal variation in its indoor operative temperature is much lower than Direct gain test-cell. Also it has been found that the Direct gain strategy has the largest diurnal variations of temperature and Roofpond strategy has the smallest one (Fernandez- Gonzalez A., 2007).

Figure2.3 South view of the five passive solar test-cells (from the left): Direct Gain (DG), Trombe-wall (TW), Water-wall (WW), Sunspace (SS), and Roofpond (RP). (Fernandez- Gonzalez A., 2007).

Fourteen test rooms have been built at Los Alamos National Laboratory between 1977 and 1982 (Balcomb J., 1992). Each of the seven test structures contains two single zone rooms facing to the south (Figure 2.4). The insulation partitions have been used to separate the rooms. In order to minimize the effect of the mass of the test-cell, 2.5 cm extruded polystyrene foam insulation has been used in the interior side of each room. Also an American Society for Testing and Materials (ASTM) type nozzle has been used to measure the flow rate periodically. Incandescent light bulbs were added to the test rooms as auxiliary heaters. In one year (between 1980 and 1981), Los Alamos test rooms included water wall, Trombe wall, direct gain, phase change wall, sunspace and heat pipe collectors. Also During 1981-82, an unvented Trombe wall was built in a test-cell. The Los Alamos experiment was done to determine the productivity of the passive solar heating strategies. Also, obtained data from the tests were used to confirm the simulation programs.

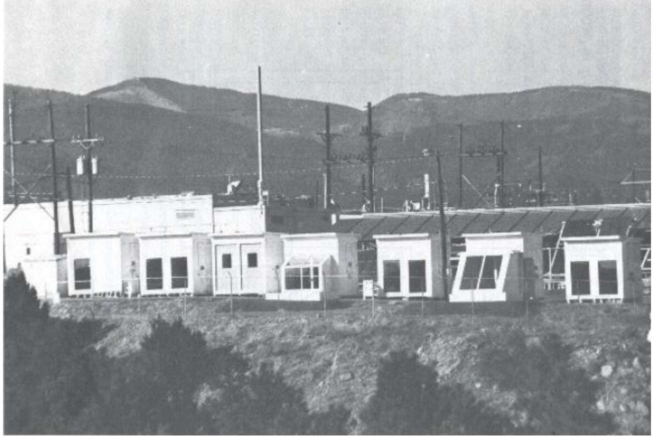


Figure2.4 Test cells at Los Alamos (Balcomb J., 1992)

A comprehensive Passive Solar program called PASSYS has managed test cells across eleven European countries from 1986-1993. During the program, the thermal performance of the standard building components and passive solar building components has been examined. A vented Trombe wall also has been constructed in Lyngby, Denmark (PASSYS, 1994).

An investigation on retrofitting an existing building with different passive solar heating systems like vented/unvented Trombe wall, direct gain and black painted wall has been done by Arvind Chel et al. (2008) in India. In the study the energy conservation, reduction in emissions (e.g. CO_2) and economics have been considered. The building under investigation was used to store honey and the required room air temperature for storing honey was in the range of 18-27 ºC. TRNSYS program has been used to estimate the thermal performance of the building including passive solar heating systems. Also some experiments have been directed for recording the air temperature of building. The TRNSYS simulation results have shown that the suitable air temperature of the honey storage building can be easily maintained by using a Trombe wall on the south side of the building. It has been found that, with a vented Trombe wall, the room air temperature would be in the range of 19-23.3 ºC. The error analysis has shown a good agreement between the result of the simulation with TRNSYS and the obtained data from the experiment (Chel A., 2008).

In present work, an investigation was carried out in order to evaluate the feasibility of the passive solar heating systems especially thermal storage wall in Cyprus. The diurnal temperature variations in Cyprus are ideal for the application of Trombe walls, but no such application is presently available. The objective of this study is to examine the possible benefits resulting from such an application. To do this, the temperature behavior of a hypothetical building integrated with a direct solar gain window and a Trombe wall is analyzed by using TRNSYS software. The typical model house is a two story building which is assumed to be located in Larnaca. The Trombe wall is placed on the south facade of the ground floor and the window for direct solar gain is located on the south façade of the first floor. Optimization studies have been performed in order to find out the proper width and thichness of the Trombe wall for the climatic conditions of Cyprus.

CHAPTER 3

PASSIVE SOLAR HEATING STRATEGIES

3.1 Historical Review

The consumption of world fossil fuel is a pulse action of a relatively short duration in the long history of human existence. The rapid increase in energy usage in the past 50 to 100 years can not continue indefinitely as the earth’s finite supply exhausts. It takes people only 300 or 400 years to use traditional energy resources like fossil fuels, while it took millions of years for the earth to fertilize and to store those resources in convenient forms.

To meet our demands for the immediate future and for generations to come and because of the rapid depletion of fossil-fuel resources on a worldwide basis, an urgent search for alternative energy sources is necessitated.

Nuclear fusion and solar energy stand out as the brightest long-range promises toward meeting the continually increasing demand for energy. Because of recent progress in controlled fusion reactions, one cannot expect this source of energy to modify the world energy picture before the turn of the next century. As solar energy conversion is concerned, the source is inexhaustible, the process is pollution-free, and the technology is established (Hsieh, J. S, 1986).

Interest in solar energy has occurred in waves. In response to low energy prices, the great enthusiasm of the early 1960s died out completely by the end of the decade.

Interest exploded again in reaction to the oil embargo of 1972 and lasted until about 1981. Another revival interest in energy conservation and renewable sources of energy was experienced in 1990s as a result of environmental concerns, worries about social sustainability and national energy vulnerability (Balcomb, J. 1992).

Solar energy is abundant and inexhaustible also, it is thinly distributed over a wide area so the only difficulty related to this source of energy is how to tap and store it economically to promote widespread usage.

3.2 Passive vs. Active Solar Heating Systems

There are two principle categories of solar heating systems: namely passive and active.

A complete active solar system includes energy storage devices, solar collectors, and pumps or fans for transferring energy to the storage or to the load. Either liquid or air is used as the collector fluid in active solar systems (see Figure 3.1). Space cooling, space heating or the hot water production can be the load.

Technically it is possible to construct an active solar system to supply the total design load for heating and cooling, but from the economical point of view such a system would not be cheap and may be oversized for most of the year. So economic analysis should be used to determine the optimum size of a solar system and its ability to meet the load.

For water and/or space heating, active solar systems have been combined with heat pumps. Heat pump supplies auxiliary energy when the solar source is not available. A solar system in parallel with a heat pump make the most proper and economical arrangement in residential heating but a heat pump which is placed in series with the solar storage tank, supplies higher water temperature and it is an advantage to the domestic systems.

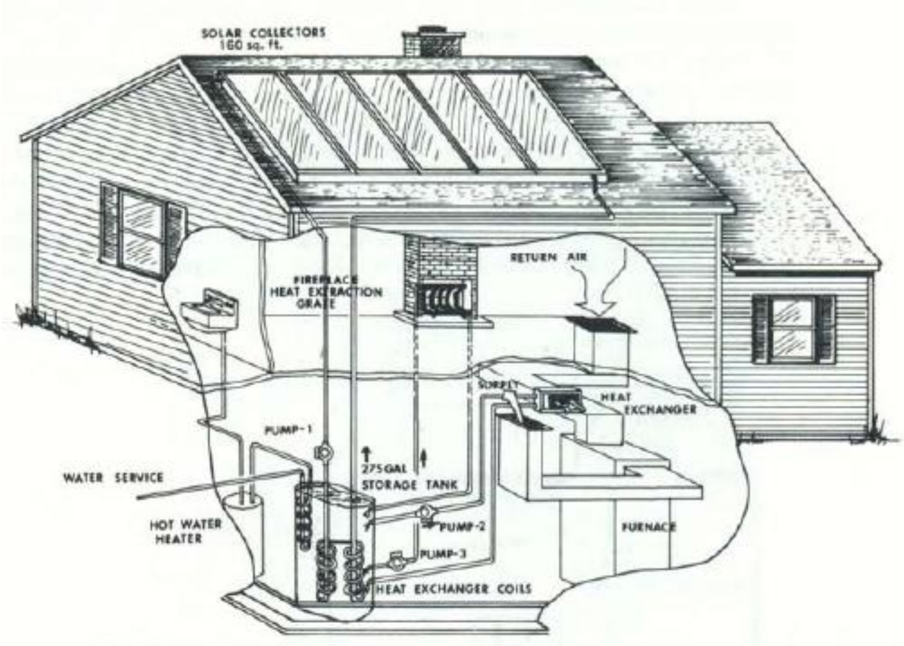


Figure3.1 Solar space and hot water heating system (Hsieh, J. S., 1986).

Passive energy is more sustainable than active energy systems because passive systems use far fewer natural resources to build and maintain. They have little to no operating costs, often have low maintenance costs, and emit no greenhouse gases in operation. Passive systems are designed so that they can take natural energy from the sun to heat a building and use specific design principles to cool a building. Passive energy systems are also cheaper than active systems because they are less susceptible to malfunction since they rely completely upon nature, rather than using mechanical equipment to produce energy (www.eslarp.uiuc.edu).

3.3 Passive Solar Heating Strategies

There are historical and archaeological examples of the use of passive solar techniques by Native Americans (Figure 3.2). Before the 1970s, very few buildings were consciously designed to make use of passive solar energy. For instance, in the 1930s some direct-gain buildings were constructed in the Midwest, and in 1946 at the Massachusetts Institute of Technology, a group of engineers experienced with passive solar test rooms (Balcomb, J., 1992).

Figure3.2 Thousands of years ago, the Anasazi Indians in Colorado incorporated passive solar design in their cliff dwellings (www.nrel.gov).

Passive systems incorporate solar collection, storage and distribution into the architectural design of the building and make minimal or no use of fans to deliver the collected energy to the structure (Kalogirou, S., 2002). Radiation, conduction and natural convection are the means of heat transfer in a passive solar building.

The sun tends to warm the building by day and the building losses heat at night that is why every building is passive. The interior heat transfer and the position and movement of sun are predictable, so it is possible to design buildings in a way that maximizes the benefits of this movement.

Site selection, building orientation, material specification and window configuration of a passive heating system should be an integral part of the architectural planning process.

Occupants are required in many passive solar buildings to take an active role in rising and lowering thermal shades, and operating vents to promote or to reduce convection, in order to maintain the required thermal comfort. These daily adjustments familiarize occupants with the thermal behavior of their building and operating it efficiently. Efficient passive heating operation is achieved without occupant intervention because of the recent developments in construction materials such as low-E glazing and selective surfaces.

The four most important elements affecting the thermal performance of a passive solar building are (Moore F., 1993):

- The size of the solar aperture (window, greenhouse, skylight, etc.),
- The amount of energy conservation achieved as a result of envelope insulation and infiltration control,
- The amount and placement of the thermal storage mass (to reduce excessive temperature swings and reduce overheating),
- The weather (insolation and air temperature).

Glass acts as very efficient solar collector because it is highly transparent to short wavelength solar radiations but quite opaque to the long ones, as a result, the transmitted solar energy strikes interior surfaces and warms them. This is called greenhouse effect. The best aperture for collecting the maximum solar heat is a south-facing one titled at an angle normal to the winter sun. The size of the aperture also is important; the larger one is not necessarily better; if it is too large it can cause overheating or a wasteful venting of collected solar heat. From the economical point of view it is too expensive to construct a large aperture. Also the heat loss at night can increase due to a large aperture.

Insulation and sealing are the most important means of energy conservation in passive solar buildings. Reducing the conductive heat lost and infiltration through the building envelope increase the efficiency of the passive solar heating and so less energy is required to heat the building.

Thermal storage is another important element in passive solar heating systems that absorbs stores and later releases the heat to the interior. The components like masonry walls, concrete floors, water container, etc, act as thermal storage in passive solar buildings. During a sunny day, the thermal mass absorbs the excess solar heat entering the building and at night, the thermal mass releases the heat to keep the building warm. This process prevents overheating as well. With a larger thermal mass, less temperature swing occurs during a daily cycle, thus greater level of thermal comfort can be achieved and less auxiliary heat is needed.

All three components of a passive solar building (i.e. solar aperture, conservation and thermal mass) reduce heating cost and all increase the construction cost of the building, so in order to get benefit, the construction cost of each should be weighed against the energy cost savings that they produce (Moore F.,1993).

Two climate variables which affect the passive solar heating performance are ambient dry-bulb temperature and insolation. Wind speed also affects the building heat loss. The impact of humidity on building heating performance is negligible. Some of the passive solar heating strategies are mentioned in Table 3.1. In the present study, direct gain and thermal storage wall are considered.

Table 3.1 Passive Solar Heating Strategies

Strategy	Explanation
Direct Gain	Sunlight is admitted to the space (by south facing glass) and virtually all of it is converted to thermal energy.
Indirect Gain Thermal Storage Wall	Thermal storage material is placed between the room and glazing (sun), to store heat during the day and to radiate it to the interior space at night.
Sunspace	A south facing "greenhouse space" is constructed in front of a thermal storage wall exposed to the direct rays of the sun.
Indirect Gain Water Wall	Water wall is same as thermal storage wall, but thermal storage materials are replaced with water.
Heating Cycle-Roof pond	It uses water encased in ultraviolet ray inhibiting plastic beds underlined with a dark color, which are placed on a roof. They collect and store heat during the day. At night roof ponds are covered and stored heat is radiated into the space below.

3.4 Direct Solar Gain

The direct gain passive solar building has south-facing windows that admit the sunlight directly into the living space, where it strikes the interior massive structure and is converted to thermal energy (see Figure 3.3). The solar gains serve either to meet part of the current heating needs of the building or to be stored in the thermal mass to meet heating needs that will arise later. The structural masses help adjust the excessive temperature within the building.

Most direct gain buildings include:

- Large south facing windows,
- Thermal mass,
- Overhang and
- Night insulation

The large windows are used to admit the sunlight. Insulation of the exterior parts of the building is desirable to prevent releasing of heat from the interior thermal mass to the outdoor environment; also the floor area should be insulated to isolate the interior of the building from the earth. Overhang is needed above the south glass to shade it in summertime. Night insulation reduces the heat losses through the glass during the night. Some of the heat from the massive surfaces (concrete floor and masonry walls) is immediately released back into the room by convection and radiation while the rest releases slowly to the room at night and keeps the room warm. Thermal mass is of a great importance in the effective operation of direct gain system.

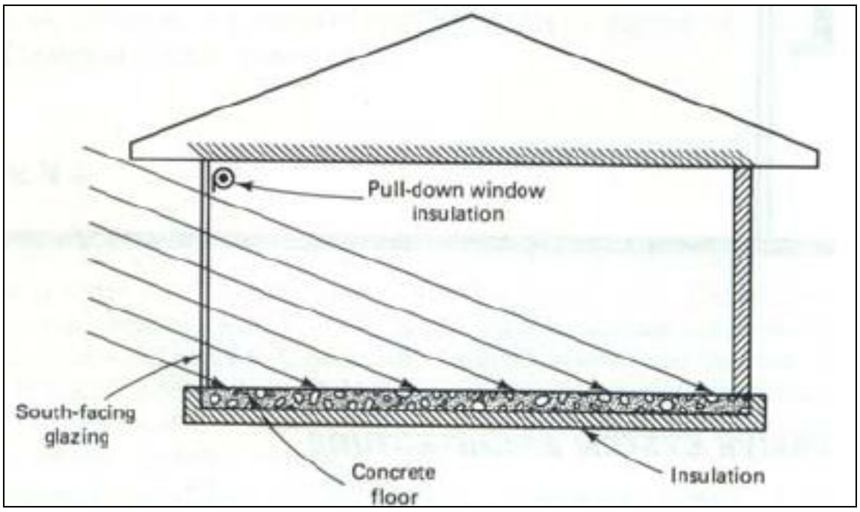


Figure3.3 Direct gain passive heating system (Hsieh, J. S., 1986).

Direct gain systems have advantages and disadvantages. They provide daylight in the building and view to the south. In comparison with non solar buildings, the incremental cost is low especially if the massive materials like adobe in the southwest and concrete floor in the southeast have been used in the construction of the building.

There would be some limitations, for selecting the materials and the construction methods in direct gain building because of their requirements for distributing thermal mass. The use of decorating floor and wall coverings is limited in such buildings; for example carpets and large rugs act as insulating covers and prevent heat to be stored in the floor slab and cause overheating.

Direct gain buildings with no intentional thermal mass are called suntempered buildings. In general, without sufficient thermal mass, If the south facing glazing area exceeds 15 percent of the heated floor area, the suntempered building experience overheating (Moore F., 1993). These buildings are often built for sale by well-meaning builders without the added expense of thermal mass.

3.4.1 Direct Gain Design Guidelines

The following guidelines apply to design direct gain systems (Balcomb et al., 1984):

- Generally speaking, in direct gain spaces only floors should be dark in color, light-colored walls and ceilings are desirable in order to reflect sunlight around the space and thus distribute the sunlight as much as possible before being absorbed.
- Concrete or brick is recommended as flooring material.
- For south facing glazing area, recommended limits are 7% of floor area for low mass buildings and 13% of floor area for high mass buildings.
- The insulation should be located outside of the thermal mass. This serves to reduce the loss of stored heat from the thermal mass to the exterior, while encouraging the free transfer of heat between the mass and interior.

3.5 Thermal Storage Wall

A thermal storage wall consists of the wall itself and the glazing over the outer surface. The large mass of the wall is usually constructed of solid masonry (Trombe wall) or water-filled containers (water wall).

3.5.1 History of Trombe wall

The Trombe wall is also known as a solar wall, thermal storage wall, collector storage wall, or simply storage wall. E. L. Morse was the first to describe the Trombe wall concept in a 1881 patent (Morse, E.L., 1881). The idea was popularized again in 1972 by the French inventor Felix Trombe and the architect Jacques Michel (Trombe, F., 1972).

In recent years the National Renewable Energy Laboratory (NREL) has designed some of the most publicized Trombe walls; two buildings with Trombe wall in Colorado (the Solar Energy Research Facility and the NREL Visitor Center) and one at Zion National Park, Utah (the Zion Visitor Center). The Grand Canyon House in Arizona and the Van Geet residence in Colorado are the other two well-known residential buildings with Trombe walls (www.nrel.gov).

3.5.2 Principles

Trombe wall is the most attractive indirect-gain passive heating design. It is a thick south facing (in the northern hemisphere) wall located directly behind a glazing (single or double) installed a few inches in front of the wall with an air gap between the glass and the outer face of the wall as shown in Figure 3.4. The wall is made of the masonry material (concrete, brick, adobe or stone) that absorbs a lot of heat and usually is dark in color on the glazing side to absorb insolation. The thicker the masonry, the smaller the temperature swings in the living space and the longer the delay in conducting the heat through the wall (Moore F., 1993). The Trombe wall can be vented or unvented. Vents are placed at the bottom and top of the wall to allow some of the zone air to circulate through the Trombe air gap. The Trombe wall is a clever device for collecting and storing heat from the sun during the day and releasing heat into a building space during the night. Heat is conveyed to the indoor space by conduction through the wall and natural convection in the air gap fed by vents. By selecting the optimum thickness for the Trombe wall, the maximum heating effect is postponed to an evening time when the greatest heating is needed.

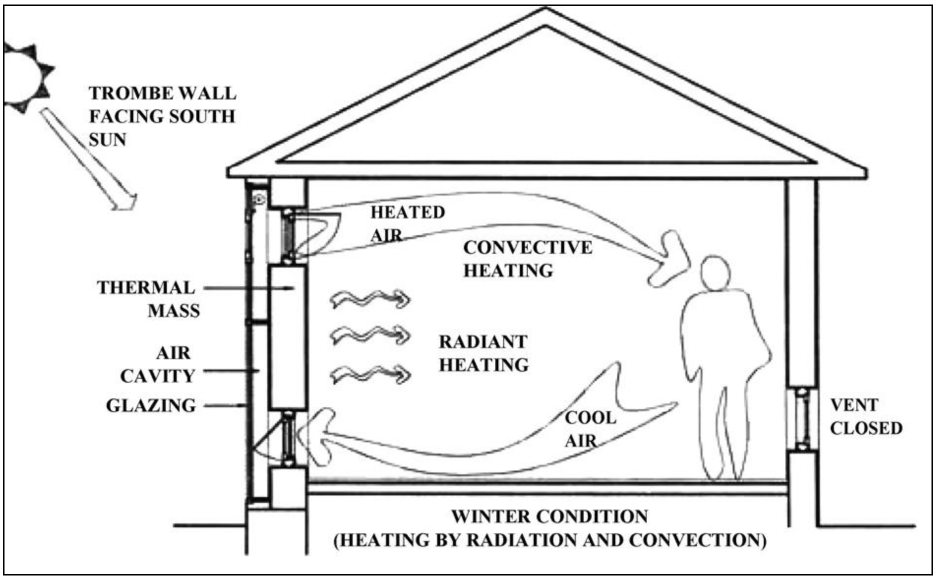


Figure3.4 Vented Trombe wall diagram (Chel, A. et al., 2008)

3.5.3 Thermocirculation air vents

Although the thermal stability is one of the advantages of unvented Trombe walls but they are slow, they require a long time to warm up the room after a night without sunlight. The interior temperature of the building is increased with the addition of vent openings at the top and bottom of the masonry wall. This allows the warmed air to circulate between the air gap and the room and being replaced by the coolest air in the room by natural convention (Moore F., 1993).

The problem comes up after the sunset, the outer wall surface temperature and the temperature of the air in the gap drop below the room temperature, the cool air in the gap becomes more dense and flows into the room through the lower vent and the warm air near ceiling being drawn into the top vent, this is called reverse thermocirculation and it causes an undesirable cooling process in the room at night. There are some methods to prevent reverse thermocirculation through the vents. They are manually operated dampers or a lightweight film which is top-hinged over the room side of the top vent and is the most widely used vent control (Moore F., 1993). Dampers are not recommended because without a sensitive indicator, it is impossible to know the air flow direction, so it is difficult for occupants to determine the proper time for opening and closing the dampers. During the summer the vents should be closed permanently in order to prevent overheating. A Trombe wall with and without vents has been simulated in nine U.S climates (Balcomb, J., 1992).

An alternative to the vented Trombe wall is direct gain/unvented Trombe wall combination. In such a system, unvented Trombe wall is used for nighttime heating and direct gain is used for daytime heating performance.

One of the substantial sources of heat loss in all types of Trombe walls is wall to glass radiant transfer. In order to reduce the radiant transfer from the wall to the glass (environment), a selective surface or a normal black surface can be applied. Two characteristics are important for the wall's outer surface: the solar absorptance and the longwave emittance. Black foil is optically selective because it has high solar absorptivity and low emissivity.

3.5.4 Thermal storage wall Advantages and Disadvantages

In comparison with other passive systems, Trombe walls perform well. The thermal mass provides a buffer between the occupants and the temperature variations of the solar absorber. The heat is transferred through the thermal storage mass slowly by conduction, due to this; temperatures are both delayed and moderated. This allows the delay of delivery of solar heat to the interior in a reliable and predictable manner. The building trades are familiar with the masonry and concrete construction; also the masonry walls serve structural functions and are typically used to support part of the roof.

Generally, it is not necessary to use night insulation in Trombe wall systems because the masonry wall separates the air inside the room from the glazing effectively.

One of the difficulties is related to the cleaning of the Trombe wall. The space between the glazing and the Trombe wall is too narrow to provide access for maintenance; therefore glazing must be removed for cleaning and repainting of the absorber surface (Moore, F.). One solution to this problem is to use the sliding doors in system. Also instead of using night insulation that is difficult to install, activate and maintain, it is recommended to put a selective surface on the thermal storage wall to increase the performance.

3.5.5 Trombe Wall Design Guidelines

The following guidelines apply to design thermal storage wall systems (Balcomb et al., 1984):

- The optimum glazing orientation for thermal storage walls is due to south: however, the effect of wall orientation is relatively small for small derivations about due south.
- Vents usage depends on whether the building needs more daytime heat than is provided by direct gain. If so, then vents may be appropriate. Vents combine with direct gain in driving building temperature swings. There is a small increase in annual heating performance of the thermal storage wall due to vents.
- In unvented Trombe systems, the space between the glass and masonry wall is not critical (1 inch is adequate). In vented Trombe systems, the necessity for unrestricted airflow requires that the minimum clearance be at least 6 inches.

- Trombe wall optimum thickness varies between 10 and 16 in. depending on masonry materials and whether vents are used. For buildings occupied only during the day, a thinner wall provides relatively quicker warm-up.
- A selective surface on the outside face of a thermal storage wall can be used to improve performance. It has the advantage of not requiring manual operation. If a selective surface is used, vents should not be installed since dust accumulation may impair its selective optical qualities by increasing its emittance and decreasing its absorptance.
- Thermal storage walls are very sensitive to the solar absorptance (i.e. color darkness) of the wall surface. As the absorptance decreases, performance falls off very rapidly; therefore it is better to use a black absorber surface on the wall outer surface.

3.5.6 Water Wall System

Water wall is a thermal storage wall system consisting of water-filled containers located behind a south facing glazing (in the north hemisphere). The heat is transferred through the water wall as a result of convective circulation of water within the container. Water is constantly being mixed, as a result, the temperatures of both sides (i.e. solar side and room side) of the wall become almost same also, the room temperature swings are greatly reduced in comparison with direct gain system. Water is a very effective heat-storage medium because of its high specific heat and low cost but its containerization is a considerable problem. The advantage of using water in a thermal storage wall is the ability to achieve high values of thermal storage capacity within a smaller volume.

3.6 Sunspace

A sunspace (which is much like a greenhouse) combines the features of direct and indirect-gain passive heating systems. It is built on the south side (in the north hemisphere) of a building. As sunlight passes through glass or other glazing, it warms the sunspace; the interior of the building is heated indirectly by the heat conducted inward through the masonry wall (see Figure 3.5). Proper ventilation through the openings in the masonry wall allows the heat to circulate into the building and provides additional heating. Sunspaces are the most-often-retrofitted of all passive systems because of their attractive sunlit living space and also their ability to deliver heat to the adjacent living space. But the construction cost of the sunspace is comparatively high.

There are two different ideas about the shape of the sunspace glazing. Some designers prefer to use only vertical glazing although they know there would be a slight reduction in the heating performance of the system (about 15 to 25 percent, depending on climate) (Moore, F.), others prefer to use some or all sloped glazing to get more solar gain. But it is difficult to construct and shade a sloped glazing.

Although night insulation curtains or shutters would help the performance of the system but they are almost never used in sunspaces. The reason is that they are inconvenient to install and operate, especially on sloped glazing; also the sunspace air temperature goes beyond the limits of the comfort zone frequently. The optimum thickness for a masonry wall in sunspace system is 12 in., although 8 in. performs nearly as well (Balcomb J., 1984). Vents to the outside are essential in order to prevent overheating in summer.

If a sunspace is used as a greenhouse, then the surfaces in dark corners should be made light in color to improve plant photosynthesis (Moore F.).

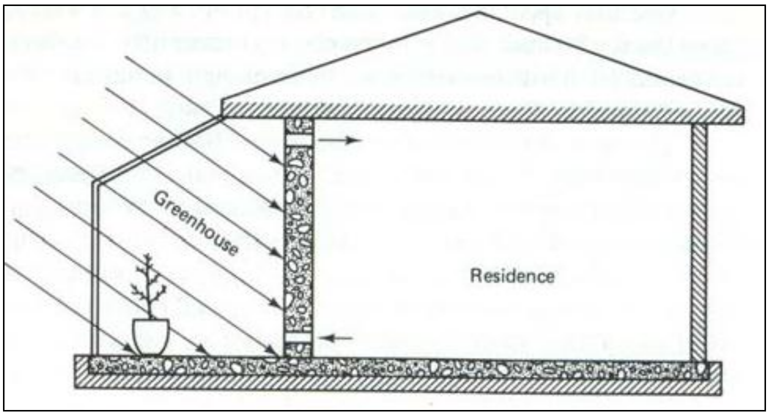


Figure 3.5 Sunspace passive heating system (Hsieh, J. S., 1986)

CHAPTER 4

MATHEMATICAL MODELING WITH TRNSYS

Most of the passive solar designs were done with intuition or rule-of-thumb and without any analysis when the passive solar movement began in the 70s. A complex whole building energy analysis can be performed in a much more rapid and inexpensive way with the advanced computer programs nowadays. The computer simulation programs allow a researcher or designer to vary physical parameters and optimize designs. The TRNSYS (Transient System Simulation) program is one recent building energy simulation tool capable of such an analysis.

The present work is concerned with the performance of two passive strategies; direct solar gain through a window and thermal storage wall (i.e., Trombe wall). TRNSYS program is used for the simulation.

4.1 TRNSYS simulation program

TRNSYS is a complete and extensible simulation environment for the transient simulation of systems, including multi-zone buildings. This software is developed in 1974 by the University of Wisconsin-Madison, USA and has been continually upgraded since then. The modular structure of the program is one of the key factors in TRNSYS’ success over the last 30 years. The Engineers and researchers around the world have used the program 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 (wind, solar, photovoltaic, hydrogen systems), etc (Klein S.A. et al., 2007).

In this software basic code is written in FORTRAN-77 language. All users and third-party developers are allowed to add custom component models, using all common programming languages (C, C++, PASCAL, FORTRAN, etc.). The other advantage of TRNSYS is that it can be easily interfaced to many other applications (e.g. Microsoft Excel, Matlab, etc.) through interactive calls during the simulation.

TRNSYS applications include (Klein, S.A. et al., 2007):

- Solar systems (solar thermal collectors, etc.)
- Low energy buildings and HVAC systems with advanced design features (natural ventilation, slab heating/cooling, double facade, etc.)
- Renewable energy systems
- Cogeneration, fuel cells

The program contains many subroutines that model subsystem components. Most of the components of the thermal energy systems like weather data or other time-forcing functions have been added to the TRNSYS library.

TRNSYS consists of a suite of programs:

- The SIMULATION STUDIO,
- the SIMULATION ENGINE (TRNDll.dll) and its executable (TRNExe.exe),
- the Building input data visual interface (TRNBuild.exe), and
- the Editor used to create stand-alone redistributable programs known as TRNSED applications (TRNEdit.exe).

A TRNSYS project is typically setup by connecting components graphically in the Simulation Studio. Each Type or component is described by a mathematical model in the TRNSYS simulation engine and has a set of matching PROFORMA's in the Simulation Studio. The Proforma has a black-box description of a component, inputs, outputs, parameters, etc. TRNSYS components are often referred to as TYPES. The TYPE number of a component relates the component to a FORTRAN subroutine, which models that component. The multi-zone building model is known as TYPE 56. The Simulation Studio generates a text input file for the TRNSYS simulation engine. That input file is referred to as the DECK FILE (Klein S.A. et al., 2007).

The program gives a report of material properties of the components, building geometry, orientation, solar gain, internal gain, and HVAC control strategies. The calculations are usually carried out on an hourly basis, using a full year of weather data.

4.1.1 TRNSYS SIMULATION STUDIO

The simulation studio (known as IISiBat) is the main interface in the program. A new project can be created by drag-and-dropping components to the workspace, connecting them together and setting the global simulation parameters. The project information are saved in a Trnsys Project File (*.tpf). As the simulation has been run, the Studio creates a text file that contains all the information on the simulation (input file).

There is an output manager in the Studio that allows the user to control which variables are integrated, printed or plotted. Also there is an error manager that allows the user to study in detail what happened during the simulation.

Generating a skeleton for new components (using the FORTRAN Wizard), view and edit the components Proformas and view output files, can be done in the simulation studio.

4.1.2 BUILDING VISUAL INTERFACE

The tool used to enter input data for multi-zone buildings is *TRNBuild* (known as Prebid). It allows the user to specify all the building structure details, in addition to everything that is needed to simulate the thermal behavior of the building, like windows optical properties, heating and cooling schedules, etc. All the information required to simulate the building is created by TRNBuild in a building description file (*.bui).

4.2 The Hypothetical Building Characteristics

In order to analyze the thermal performance of the Passive solar heating strategies (Trombe wall and Direct-gain heating systems) with TRNSYS program, a hypothetical house has to be defined. As it is mentioned before, the TYPE 56 component and TRNBuild program have been used to generate the model building in the TRNSYS program. TRNBuild reads in and processes the file having extension **.**BUI containing the building description and generates two files that will be used by the TYPE 56 during a TRNSYS simulation.

To simulate the thermal behavior of the building, TYPE 56 requires a great deal of building data (geometrical data, wall construction data, etc.) and other data (i.e. radiation, ambient temperature, humidity, etc.) which influence the building heating. Other components have to be connected to TYPE 56 in order to prepare the necessary information for the simulation. The simulation strategy is explained in section 4.4.

In this study, the hypothetical house is a two storey building which is assumed to be located in Larnaca airport, Cyprus (Latitude: 34^{o} $88^{'}$ N, Longitude: 33^{o} 63’ E). The building has a total floor area of 120m^2 and it faced true south. The Trombe wall is located on the south facade of the ground floor (GF). Each wall of the building (except the south wall of the ground floor) has a double glazing window on it. A three dimensional view of the model building is shown in Figure 4.1.

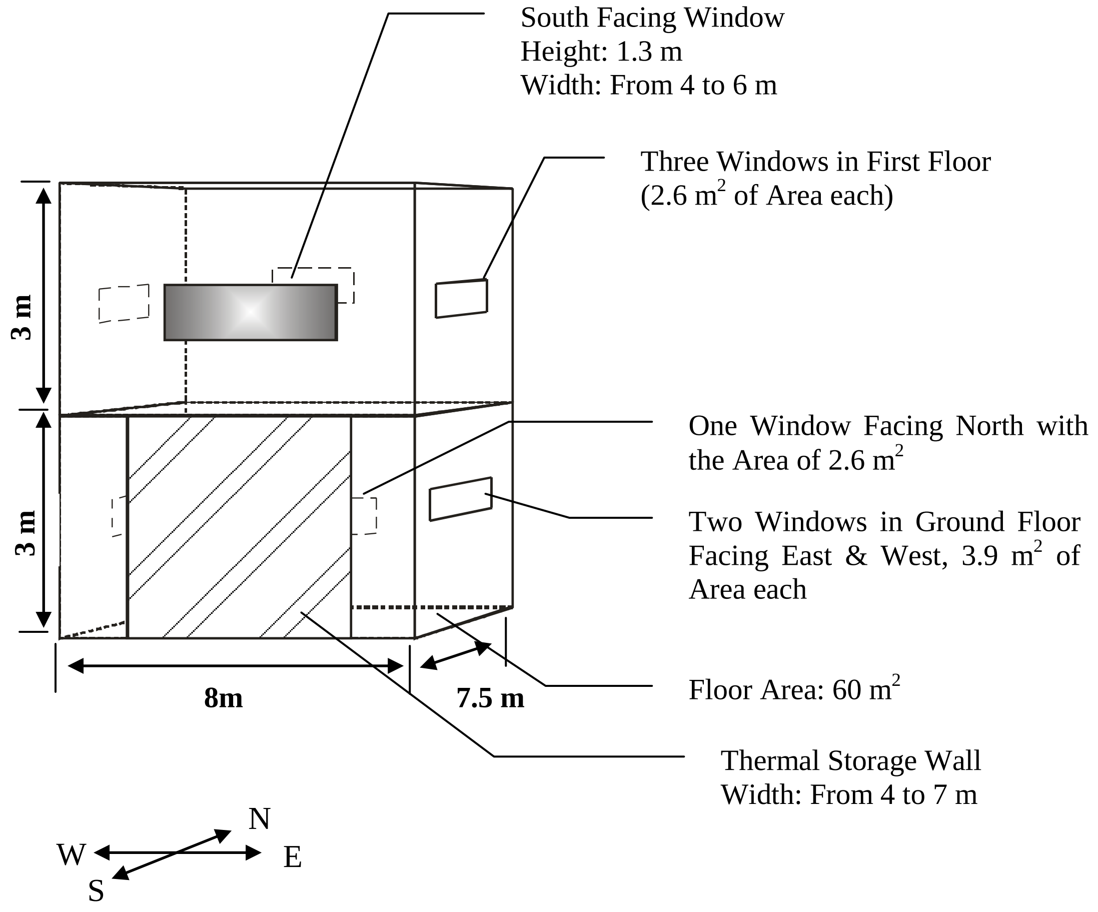


Figure 4.1 The Hypothetical two storey building with open space on both floors

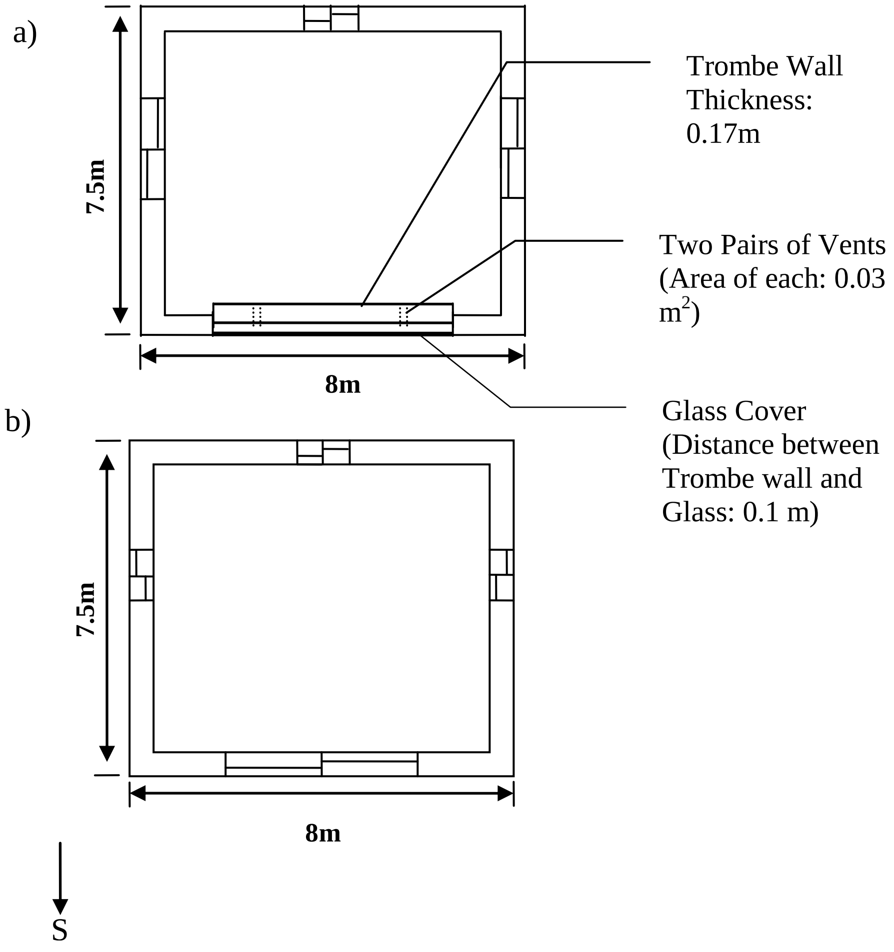


Figure 4.2 Plan view of the Hypothetical house: a) Ground Floor, b) First Floor

It is assumed that an overhang is placed on top of the Trombe wall in order to prevent overheating during summertime but it is not shown in the figures.

The construction materials and the dimensions which are used in the TRNBuild are presented in detail for each floor (Ground floor and first floor) and for the Trombe wall in Tables 4.1- 4.4.

4.2.1 Ground Floor Characteristics

Table 4.1 Ground floor construction

Ground floor characteristics (Area = 60 m^2) Length × Width × Height = 8m × 7.5m × 3m			
Sort	**Area (m^2)**	**Construction Materials (inner layer to outer layer)**	**Thickness (cm)**
North wall	24	Common Plaster Brick Common Plaster Extruded Polystyrene	2 20 3 5
East wall	22.5	Common Plaster Brick Common Plaster Extruded Polystyrene	2 20 3 5
West wall	22.5	Common Plaster Brick Common Plaster Extruded Polystyrene	2 20 3 5
South wall	24	This wall includes Trombe wall* (Trombe wall is made of Heavy reinforced concrete)	Trombe wall thickness: 17
Floor	60	Floor (Tile) Stone Silence Concrete Insulation	0.5 6 4 20 5
Ceiling	60	Concrete Sandstone Tiling	16 3

* Trombe wall characteristics will be explained in section 4.2.3.

The total heat transfer coefficient (U-value) has been calculated automatically by the program for each wall. The U-value of all External walls (North, East and West walls) is around 0.423 W/m^2.K and that of the Trombe wall is around 4.044 W/m^2.K. The U-values of floor and Ceiling are 0.412 W/m^2.K and 3.687 W/m^2.K, respectively. The convective heat transfer coefficient (h) on the inner surfaces of the building has been calculated internally in the program.

4.2.2 First Floor Characteristics

The construction materials and their dimensions on the First floor are given in Table 4.2. The floor area of the First floor is 60 m^2 and its height is 3m. The total heat transfer coefficient (U-value) of the walls and the convective heat transfer coefficients have been calculated internally by the program.

Table 4.2 First Floor construction

First floor characteristics (Area = 60 m^2) Length × Width × Height = 8m × 7.5m × 3m			
Sort	**Area (m^2)**	**Construction Material (inner layer to outer layer)**	**Thickness (cm)**
North wall	24	Common Plaster Brick Common Plaster Extruded Polystyrene	2 20 3 5
East wall	22.5	Common Plaster Brick Common Plaster Extruded Polystyrene	2 20 3 5
West wall	22.5	Common Plaster Brick Common Plaster Extruded Polystyrene	2 20 3 5
South wall	24	Common Plaster Brick Common Plaster Extruded Polystyrene	2 20 3 5
Floor	60	Sandstone Tiling Concrete	3 16
Roof	60	Common Plaster Concrete Extruded Polystyrene	2 15 5

As it is mentioned before, each wall of the building has a double glazing window on it. Different window types have been defined in the library of the program (w4-lib.dat). In the present study a double glazing window with the ID number of 1002 is selected from the window library in TRNSYS. TRNBuild displays the U-value (describing window losses) and the g-value (i.e. solar heat gain coefficient) of the selected window for user information. The Solar Heat Gain Coefficient (SHGC) is the fraction of incident solar radiation admitted through a window and it is expressed as a number between 0 and 1. For the window with ID number 1002 the U-value is 2.83 W/m^{2}K and the g-value is 0.755. The characteristics of the windows are shown in Table 4.3.

Table 4.3 The characteristics of the windows

Ground Floor			
North wall	1 Double Glazing window	Area = 2.6 m^2	U-value = 2.83 W/m^{2}K
East wall	1 Double Glazing window	Area = 3.9 m^2	„
West wall	1 Double Glazing window	Area = 3.9 m^2	„
First Floor			
North wall	1 Double Glazing window	Area = 2.6 m^2	U-value = 2.83 W/m^{2}K
East wall	1 Double Glazing window	Area = 2.6 m^2	„
West wall	1 Double Glazing window	Area = 2.6 m^2	„
South wall	1 Double Glazing window	Area = 6.5 m^2	„

4.2.3 Trombe Wall Characteristics

The thermal storage wall characteristics have been selected carefully in order to maximize the thermal efficiency of the system. In TRNBuild, the Trombe wall has been defined as a heavy reinforced concrete wall with 0.17 m thickness, which is located on the south facade of the ground floor. Two pair of vents are placed at the top and bottom of the Trombe wall in order to allow air circulation between the room and the gap. The thermal storage wall properties are shown in Table 4.4.

Table 4.4 Trombe wall characteristics

Thermal Storage Wall Characteristics	
Height	3 m
Width	4 - 7 m (variable)
Thickness	0.17 m
Conductivity	1.28 W/m.K
Specific Capacitance (The product of the wall density and wall specific heat)	2112 kJ/m^3.K
Wall Solar Absorptance	0.75 (see Table A.1 in Appendix A)
Number of glazing in front of Trombe wall	single, with 0.004 m thickness
Space between wall and glazing (gap size)	0.1 m
Extinction *	0.016
Refractive Index	1.526 (Hsieh, J. S., 1986)
Vent Area	0.03 m^2
Distance between vents	2.5 m
Inlet air flow rate	100 kg/hr.

* Extinction: the product of the extinction coefficient (K) and the glazing thickness (KL product). The extinction coefficient for a White Glass (< 0.01% Fe_2O_3) is around 0.04 cm^{-1} (Hsieh, J. S., 1986).

4.3 Mathematical Description

4.3.1 Mathematical Description of the Trombe wall

Depending on the selected control strategy, air in the gap can be exchanged with either the room air or the environment, or the flow of air through the gap may be stopped. The flow of air may be driven by a fan or by thermosiphoning. This method of moving air is not easily quantified, and the resulting model incorporates several assumptions. Analytical studies of the thermosiphoning air have been limited to the case of laminar flow and have neglected pressure losses in the inlet and outlet vents. The only published measurements of thermosiphon mass flow rates are those of Trombe et al. (Trombe, F. et al., 1977). These measurements indicate that most of the pressure losses are due to expansion, contraction and change of direction of flow, all associated with the inlet and outlet vents (Klein, S.A. et al., 2007).

The thermal circuit used to model the performance of the Trombe wall is shown in Figure 4.3.

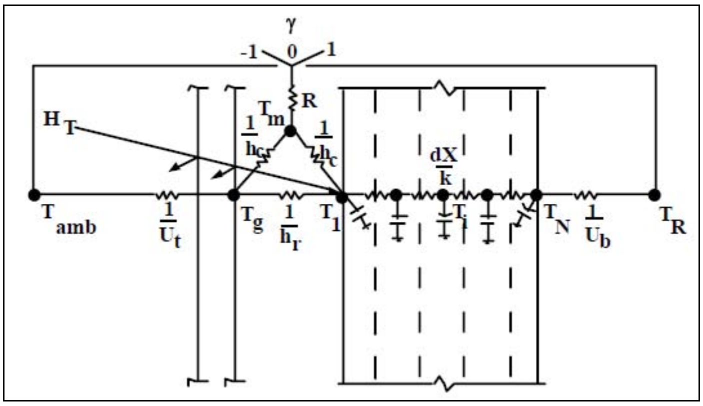


Figure 4.3 Thermal Storage Wall Thermal Circuit Diagram (Klein, S.A. et al., 2007)

The Bernoulli's equation has been applied to the entire air flow system to determine the thermosiphon mass flow of air in this model. For simplicity, it is assumed that the temperature and density of the air in the gap varies linearly with height. The mean air velocity in the gap is obtained from the solution of Bernoulli's equation (Klein, S.A. et al., 2007).

$$\bar{v} = \sqrt{\frac{2gh}{\left(C_1\left(\frac{A_g}{A_v}\right)^2 + C_2\right)} \cdot \frac{(T_m - T_s)}{|T_m|}} \qquad \text{(Eq. 4.1)}$$

where T_s is either T_a (Ambient air temperature) or T_R (Room temperature), depending on whether air is exchanged with the environment or the room, T_m is the mean air temperature in the gap, C_1 is vent pressure loss coefficient, C_2 is gap pressure loss coefficient, A_g is cross sectional area of the gap and A_v is the total outlet area of the vent. The term $(C_1 (A_g/A_v)^2 + C_2)$ represents the pressure losses of the system. The ratio $(A_g/A_v)^2$ accounts for the difference between the air velocity in the vents and the air velocity in the gap.

The thermal resistance (R) to energy flow between the room and the gap when the mass flow rate of air ($\dot{m}$) is finite is given by (Klein, S.A. et al., 2007)

$$R = \frac{A\left[\left(\frac{\dot{m}C_{Pa}}{2h_c A}\right)\left(\exp\left(-\frac{2h_c A}{\dot{m}C_{Pa}}\right) - 1\right) - 1\right]}{\dot{m}C_{Pa}\left(\exp\left(-\frac{2h_c A}{\dot{m}C_{Pa}}\right) - 1\right)} \qquad \text{(Eq. 4.2)}$$

where C_{pa} is the specific heat of air, h_c is the convective heat transfer coefficient, and A is the area.

The control function, γ determines whether mass flow rate of air is allowed and to what sink the air is exchanged. In the program, $\gamma = 1$ shows that the air in the gap exchange with the room air (vented Trombe wall), γ = -1 shows that the air in the gap exchange with the environment and γ = 0 shows that there is no air flow in the gap (unvented Trombe wall).

If γ = 1 and $\dot{m}$ = Input (i.e. the amount of the mass flow rate of air should be entered to the program by user), the rate of energy flow by ventilation of gap air is calculated by (Klein, S.A. et al., 2007):

$$\dot{Q}_v = 2\dot{m}C_{Pa}\left(T_m - T_R\right) \tag{Eq. 4.3}$$

And if γ = -1 and $\dot{m}$ = Input

$$\dot{Q}_v = 2\dot{m}C_{Pa}\left(T_m - T_a\right) \tag{Eq. 4.4}$$

For the calculation of the mass flow rate of air internally in the program, the following equation is used

$$\dot{m} = \overline{v}\overline{\rho}A_g \tag{Eq. 4.5}$$

where $\overline{\rho}$ is the average air density in gap.

The value of hc, the heat transfer coefficient between the gap air and the wall and glazing, depends on whether or not there is air flow through the gap. For no flow rate ($\dot{m}$ = 0), h_c is given as (Randall, K. et al., 1979)

$$h_c = \frac{k_a}{L}\left(0.01711\left(Gr.\Pr\right)^{0.29}\right) \tag{Eq. 4.6}$$

For ($\dot{m} \neq 0$) and Re > 2000 (Kays, W.M., 1966)

$$h_c = \frac{k_a}{L}\left(0.0158\,\mathrm{Re}^{0.8}\right) \tag{Eq. 4.7}$$

For ($\dot{m} \neq 0$) and Re $\leq$ 2000 (Mercer, W.E., 1967)

$$h_c = \frac{k_a}{L}\left[4.9 + \frac{0.0606\left(x^*\right)^{-1.2}}{1 + 0.0856\left(x^*\right)^{-0.7}}\right] \qquad \text{(Eq. 4.8)}$$

Where

$$x^* = \frac{h}{\mathrm{Re}.\mathrm{Pr}.\frac{2A_g}{1+w}}$$

The radiation heat transfer coefficient, h_r is determined by (Shen, J. et al., 2007)

$$h_r = \sigma F_e\left(T_g^{\ 2} + T_{TW}^{\ 2}\right)\left(T_g + T_{TW}\right) \qquad \text{(Eq. 4.9)}$$

Where

$$F_e = 1\big/\left(\left(1/\varepsilon_g\right) + \left(1/\varepsilon_{TW}\right) - 1\right)$$

where F_e is the emission factor between the inside surface of the glazing and the outside surface of the Trombe wall, T_g is the temperature of the glazing, T_{TW} is the temperature of the outer surface of the Trombe wall, ε_g is the emissivity of the glazing, ε_{TW} is the emissivity of the outer surface of the Trombe wall and σ is the Stefan-Boltzmann constant.

4.3.2 Mathematical Description of the Building

The model building in TYPE 56 is a non-geometrical balance model with one air node per zone, representing the thermal capacity of the zone air volume and capacities which are closely connected with the air node (for example furniture). The heat balance on the zone air node is shown in Figure 4.4.

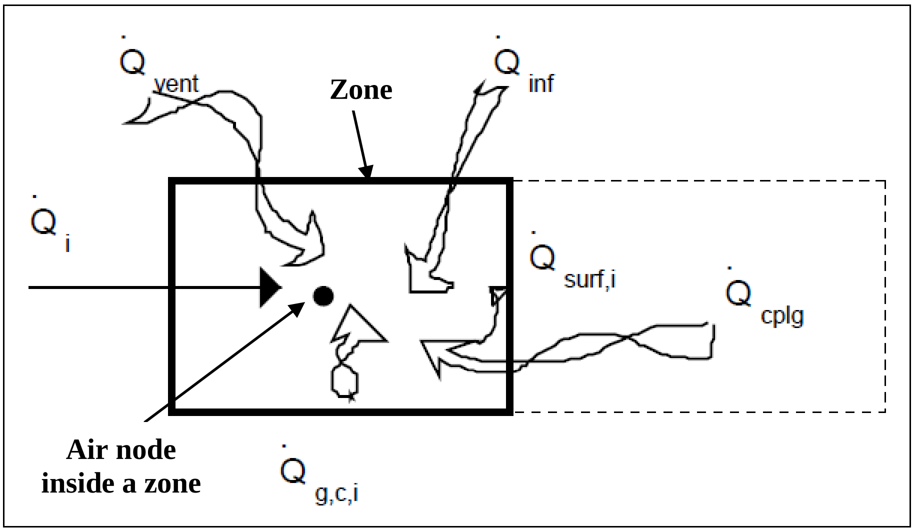


Figure 4.4 Heat balance on the zone air node (TRNSYS manual, 2007).

The convective heat flux ($\dot{Q}_i$) to the air node inside a zone is calculated by

$$\dot{Q}_i = \dot{Q}_{surf,i} + \dot{Q}_{\inf,i} + \dot{Q}_{vent} + \dot{Q}_{g,c,i} + \dot{Q}_{cp\lg,i} \qquad \text{(Eq. 4.10)}$$

Where

$\dot{Q}_{surf,i}$ is the convective heat flow from all inside surfaces and is given by

$$\dot{Q}_{surf,i} = U_{w,i} \cdot A_{w,i} \cdot \left(T_{wall,i} - T_i\right) \qquad \text{(Eq. 4.11)}$$

$\dot{Q}_{\inf,i}$ is the infiltration gains (air flow from outside only), given by

$$\dot{Q}_{\inf,i} = \dot{m}_{\inf,i}.C_p.\left(T_a - T_i\right) \qquad \text{(Eq. 4.12)}$$

$\dot{Q}_{vent,i}$ is the ventilation gains and k shows the ventilation type. $\dot{Q}_{vent,i}$ is given by

$$\dot{Q}_{vent,i} = \sum_k \dot{m}_{v,k,i}.C_p.\left(T_{ventilation,i} - T_i\right) \qquad \text{(Eq. 4.13)}$$

$\dot{Q}_{g,c,i}$ is the internal convective gains (by people, equipment, illumination, radiators, etc.)

$\dot{Q}_{cp\lg,i}$ is the gain due to (convective) air flow from zone i or boundary condition, given by

$$\dot{Q}_{cp\lg,i} = \sum^{adj.zones} \sum^{surfacessitoj} \dot{m}_{cp\lg,s} C_p \left(T_j - T_i\right) + \ldots + \sum^{knownbound} \dot{m}_{cp\lg,s} C_p \left(T_{b,s} - T_i\right)$$

(Eq. 4.14)

Where $\dot{m}_{cp\lg,s}$ is the mass flow rate of air entering zone i across walls or windows. For each wall or window separating zones of floating temperature or each wall having a known boundary condition, it is possible to specify a convective coupling. The mass flow rate is the product of the zone air volume, air density, and air change rate. Infiltration occurs always from outdoor conditions, while ventilation occurs from a specified (possibly variable) temperature (Klein, S.A. et al., 2007).

The sky temperature (T_{sky}) is computed using the following equation

$$T_{sky} = E_{sky}^{1/4}\left(T_a + 273.13\right) - 273.13 \qquad \text{(Eq. 4.15)}$$

where E_{sky} is the emissivity of the sky in the presence of clouds and T_a is the ambient air temperature(Klein, S.A. et al., 2007).

The rate of change of internal energy for any free floating zone is equal to the net heat gain or

$$C_i \frac{d}{dt} T_i = \dot{Q}_i \qquad \text{(Eq. 4.16)}$$

Where Ci is the thermal capacitance of zone i ($C_i = V_i \cdot \rho \cdot C_p$ with V_i = zone volume). The net heat gain, $\dot{Q}_i$, is a function of zone i temperature (T_i) and the temperatures of all other zones adjacent to zone i.

To simplify the solution of the set of equations $\dot{Q}_i$ is considered constant during any time-step, evaluated at average values of the zone temperatures. In this case, the solution to the differential equation for final temperature for a given time interval is

$$T_{i,\tau} = T_{i,\tau-\Delta t} + \frac{\bar{\dot{Q}}_i}{C_i} \cdot \Delta t \qquad \text{(Eq. 4.17)}$$

Where

Δt = the simulation time-step

$T_{i,\tau-\Delta t}$ = the zone temperature at the beginning of the time-step.

The temperature variation is linear, such that the average is:

$$\bar{T}_i = \frac{T_{i,\tau} + T_{i,\tau-\Delta t}}{2} \qquad \text{(Eq. 4.18)}$$

The final temperature for each zone i is obtained by the following equation

$$T_{i,\tau} = 2\bar{T}_i - T_{i,\tau-\Delta t} \qquad \text{(Eq. 4.19)}$$

4.4 Simulation Strategy

Nowadays computer simulation programs are powerful tools for evaluating the performance of HVAC systems. In the present study the TRNSYS program is used for deriving the results. The TRNSYS library includes many of the components which are currently found in thermal energy systems.

In order to simulate a system, the desired components (TYPEs) have to be selected from the Direct Access Tool in Simulation Studio. The program has the capability of interconnecting system components in any desired manner. Once all the required TYPEs have been placed in Simulation Studio, an information flow diagram for the system needs to be constructed to facilitate identification of the flow of information between the components. To do this; components have been connected using the LINK tool.

Each TYPE is presented as a box, which requires a number of parameters and inputs to produce outputs. A given output of a component may be used as an input to another component (s).

For creating the project in the Simulation Studio, it should be decided what factors will be of interest and which components have to be used in the simulation. In the present study, a hypothetical passive solar building (with Trombe wall) which is assumed to be located in Cyprus is simulated. The following components are used in the simulation Studio:

Table 4.5 Components (Types) which are used in the simulation Studio

Component (TYPE)	**Description**
Type 109-TMY2	Weather data reader and processor
Type 56	Multi-Zone Building
Type 36	Thermal Storage Wall
Type 2	ON/OFF Controller
Type 33	Psychrometrics
Type69	Sky Temperature
Type 65	Online plotter
Type 25	Printer

The descriptions of components are as follows:

4.4.1 Type 109-TMY2 (Weather data reader and processor)

This component serves the main purpose of reading weather data at regular time intervals from a data file, converting it to a desired system of units and processing the solar radiation data to obtain tilted surface radiation and angle of incidence for an arbitrary number of surfaces. In this mode, Type 109 reads a weather data file in the standard TMY2 (Typical Meteorological Year) format. The TMY2 format is used by the National Solar Radiation Data Base (USA).

In the present study, Larnaca climatic conditions are used for simulation. In the World Meteorological Organization (WMO) the identification number of Larnaca is 176090. The weather data are given on hourly basis.

4.4.2 Type 56 (Multi-Zone Building)

This component models the thermal behaviour of a building. The building description is read by this component from a set of external files having the extensions *.bui, *.bld, and *.trn. The files can be generated based on user supplied information by running the preprocessor program called TRNBuild. In fact the hypothetical building has to be defined in the TRNBuild. The characteristics of the walls and windows (i.e. materials, dimensions, orientations, etc.) and all the information related to the building have to be defined in TRNBuild. The characteristic of the hypothetical building was explained previously in section 4.2. Type 56 has to be connected to the Type 109 by a link to get the necessary weather data information for the simulation.

4.4.3 Type 36 (Thermal Storage Wall)

This component defines the Trombe wall and its characteristics in the simulation. Type 36 is connected directly to Type 56, in other word; Type 36 will be considered as the south wall of the defined model building in TRNBuild. The especial thermal storage wall characteristics like the wall height, thickness, etc have to be specified in this component. The solar radiation data, ambient air temperature and other climatic information have been entered to the Type 36 via a link from Type 109.

4.4.4 Type 2 (ON/OFF Controller)

The on/off controller generates a control function which can have a value of 1 or 0. A high limit cut-out is included with this controller, the control function will be set to zero if the high limit condition is exceeded. This controller is used to close the vents of the thermal storage wall when the inside air temperature of the building exceeds the high limit cut-out (around 20 °C), in that case the vented Trombe wall becomes an unvented one. Closing the vents prevents the reverse thermo circulation at night.

4.4.5 Type 33 (Psychrometrics)

It calls the TRNSYS Psychrometrics routine, returning the following corresponding moist air properties: dry bulb temperature, dew point temperature, relative humidity, etc.

4.4.6 Type 69 (Sky temperature)

This component determines a fictive sky temperature which is used to calculate the long-wave radiation exchange between an external surface and the atmosphere.

4.4.7 Type 65 (Online plotter)

The online graphics component is used to display the selected system variables (the user desired outputs) while the simulation is progressing. This component provides valuable variable information and allows users to immediately see if the system is not performing as desired. The selected variables will be displayed in a separate plot window on the screen.

4.4.8 Type 25 (Printer)

The printer component is used to write the selected system variables (the user desired outputs) at specified intervals of time in a file. In the present work, the simulation time step is hourly base. The simulation has been performed for the winter time (13th and 14th of January) to investigate the heating performance of the Trombe wall. The cooling performance of the system has not been considered in this study.

A simplified simulation strategy flow diagram of the current study is shown in Figure 4.5.

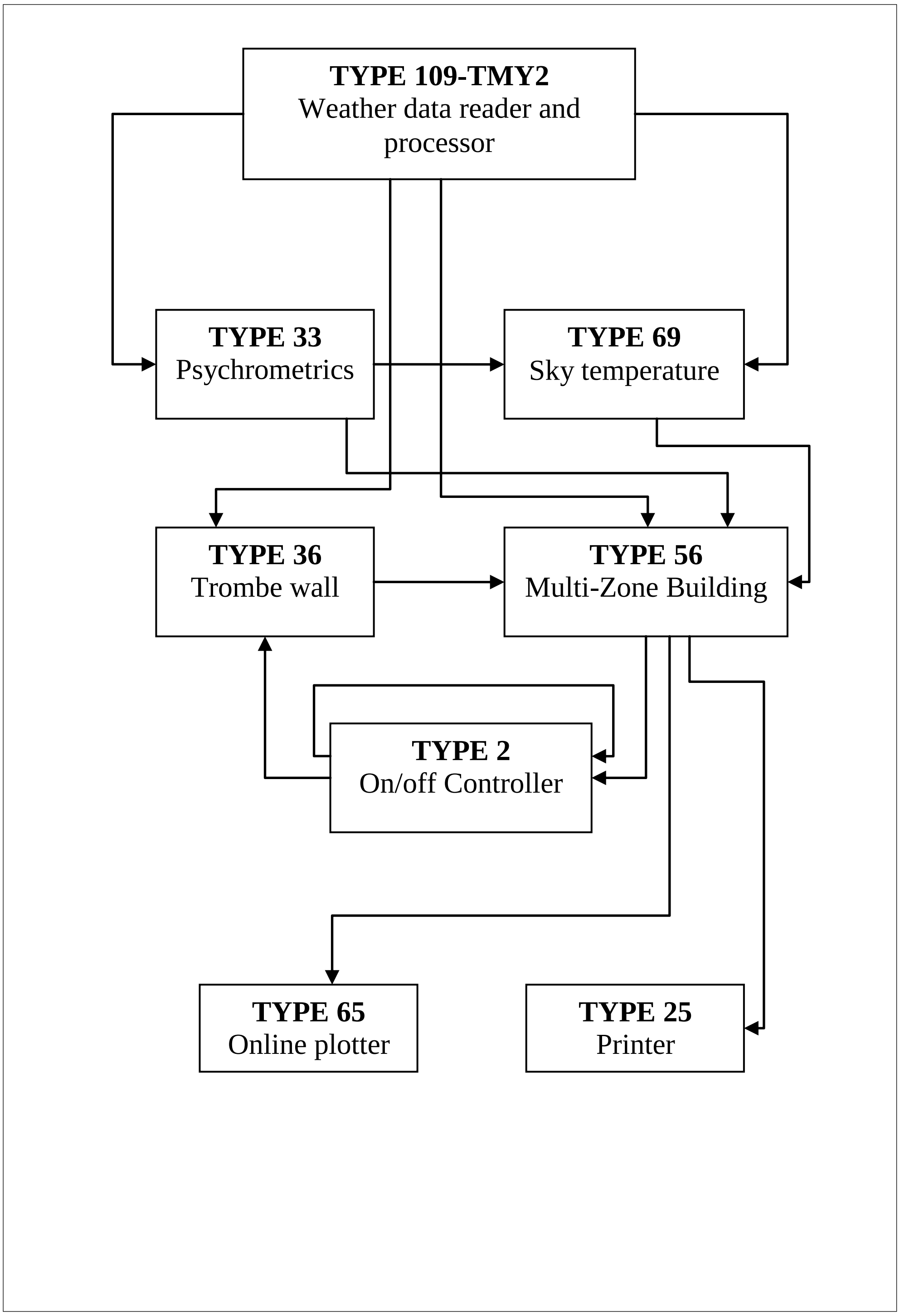


Figure 4.5 Passive Solar Building Simulation Strategy with TRNSYS

4.5 Validation of the TRNSYS Simulation Set-up

In order to verify the validity of the set-up of components used, the TRNSYS program is run by simulating the conditions of an experimental work. The mentioned experimental study has been done by H. Onbasioglu and N. Egrican in Istanbul Technical University in Turkey (Onbasioglu, H., Egrican, N., 2002). Onbasioglu et al. studied a full scale room having dimensions 3.3 × 3.3 × 3 m^3. A double glazing cover is located 0.2 m in front of the south wall (thermal wall) of the room. The thermal wall is made of 0.16 m Brick and has a very slight thermal storage capacity. The temperature of the inner space has been measured by sensors. In the present work the mentioned experimental study is simulated with TRNSYS program (Figure 4.6). It can be seen that the results obtained from the TRNSYS are in a good agreement with the experimental results of Onbasioglu et al. (2002).

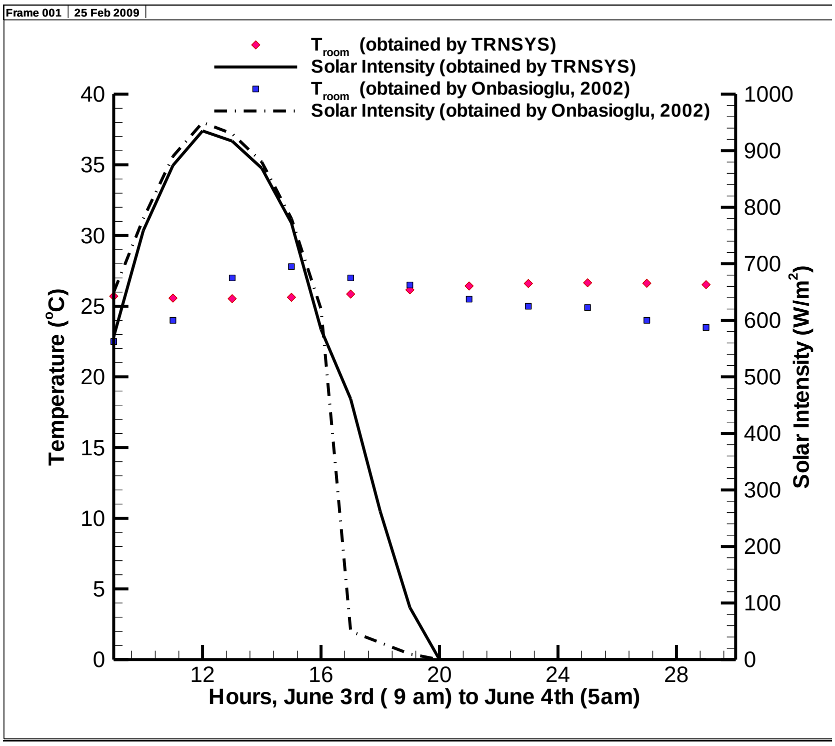


Figure 4.6 Comparison of TRNSYS simulation results (the test cell inside air temperature and solar intensity) with the experimental results obtained by Onbasioglu H. (2002).

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Simulation Results

In this chapter, the simulation results obtained by TRNSYS program for the hypothetical building integrated with a thermal storage wall are presented. The model building and Trombe wall characteristics were adjusted to obtain the most optimum results. The aim is to investigate the thermal performance of the Trombe wall system in Cyprus weather conditions and to decide whether the conventional heating systems can be replaced by this type of passive heating strategy or not. The simulations have been accomplished for January because it is one of the coldest months of the year. (Most of the results are obtained for 13th and 14th of January).

For simplicity some symbols are used on the Figures Like, T_{GF}: Air Temperature of the Ground Floor, T_{FF}: Air Temperature of the First Floor, TW: Trombe Wall, A_F: Floor Area of the building, and A_{SW}: South Wall Area.

The thermal storage wall characteristics have been explained previously in chapter 4. It is assumed that the height of the Trombe wall is 3 m. According to the study which has been done by Kalogirou S. et al. in Cyprus (Kalogirou, S. et al., 2002), the optimum thickness of the Trombe wall is in the range of 0.15 to 0.25 m, and because it is difficult to make a concrete wall with the thickness of 0.15 m, it is decided to use 0.17 m as the thickness of the Trombe wall in the present study.

The hourly ambient air temperature (T_a) of the Larnaca airport in Cyprus (the hypothetical location of the model building) and the solar intensity rate on January 13th and 14th are shown in Figure 5.1. The temperature variations of the inner and outer surfaces of the vented Trombe wall (A_{TW}: 15 m^2) and also, the temperature variations of the single glass cover which is placed in front of the Trombe wall, in January 13th and 14th are shown in Figure 5.2. It is known from the literature (Kalogirou, S. et al., 2002) that the optimum gap size is equal to 0.1 m. It can be observed from the Figure that the wall outer surface temperature (T_{OS}) is higher than the wall inner surface temperature (T_{IS}). The outer surface temperature of the Trombe wall ranges between 26°C and 42°C while the inner wall surface temperature varies between 24°C and 32°C. The range of the inner surface temperature shows the stability of indoor air temperature.

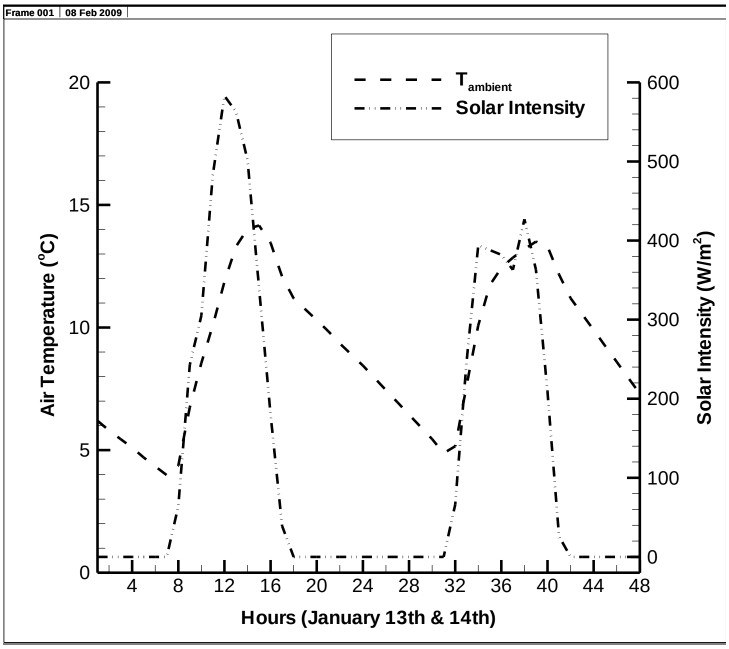


Figure 5.1 Solar intensity and ambient air temperature variations on January 13th & 14th

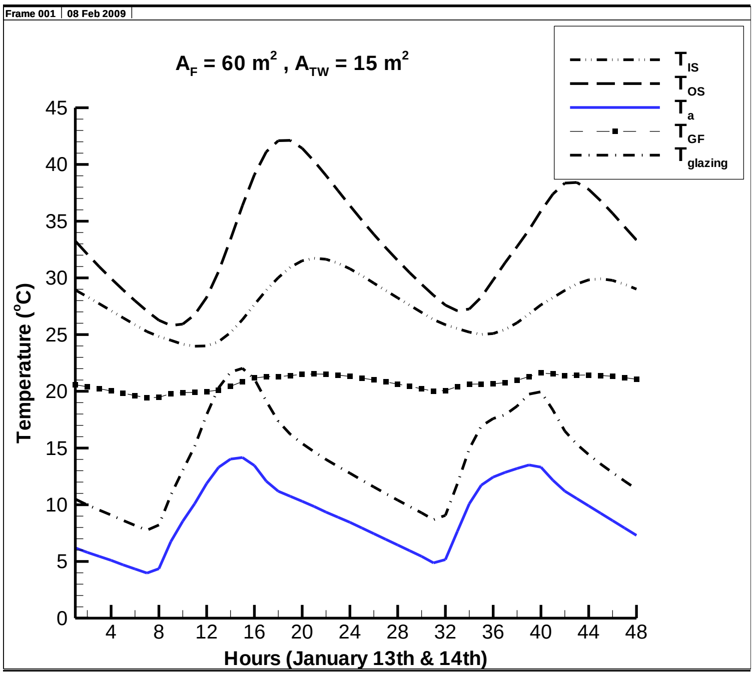


Figure 5.2 The hourly temperature variations of the Inner (T_{IS}) & outer (T_{SO}) Trombe wall surfaces (A_{TW}: 15m^2), Glazing and Ground floor on January 13th and 14th.

In order to find the optimum area of the Trombe wall, different width sizes are examined. Figures 5.3 - 5.6 show the indoor air temperature of the building for different sizes of Trombe walls (Areas of which range from 12 - 21 m^2). As can be seen in the Figures, the highest temperature on the ground floor (23.30 °C) and the highest temperature on the first floor (21.26 °C) have been obtained from the building which uses a Trombe wall of area 21 m^2. Also a Trombe wall of area 15 m^2 provides sufficient heating to the rooms (indoor temperature of the ground floor (T_{GF}) ranges between 19 °C and 21.5 °C and the indoor temperature of the first floor (T_{FF}) ranges between 17.3°C and 20.5°C). The obtained results show that the appropriate Trombe wall area for such a building is in the range of 15 m^2 to 21 m^2 and this is a parameter that may be decided on economic merits. According to the economic analysis which has been explained in Chapter 5, the construction cost of a

Trombe wall of area 15 m^2 in Cyprus, is economically feasible compare to the cost of using a gas heater.

It is found that, the solar radiation directly influences the air temperature on the First floor. In the morning, as the sun rises and the solar radiation comes in effect, the ambient air temperature and the air temperature on the first floor increase simultaneously. By sunset, the temperatures fall down. This is because of the direct solar energy gain through windows. However, the daily temperature profile of the ground floor is different. During the day the Trombe wall stores the heat and after a while, it gives the heat back to the room, so the room will be heated even after sunset. This process can be seen in the Figures 5.3 - 5.6. The air temperature fluctuations of the ground floor (the zone which is included Thermal storage wall) are very small (approximately 2°C) during a day. This is the advantage of using Trombe wall as the heating system in the buildings. The indoor air temperatures of the ground and first floors for different sizes of Trombe walls are shown in Figures 5.7 and 5.8.

A vented Trombe wall is the subject of the present work. It is known from the literature that unvented Trombe walls require a long time to warm up in the morning after a night without sunlight. Addition of air vents at the top and bottom parts of the thermal wall allows air warmed between the glazing and wall absorber surface to rise by natural convection, flowing into the room through the top vent openings. The result is a quicker warm-up in the morning (Moore, F., 1993). It is also found in the literature that the vents improve the overall performance of the Trombe wall by about 10-20% in severe climates, but they are not a significant advantage in mild, sunny climates (Balcomb, J., 1992). The hourly indoor temperatures of the ground floor for different sizes of Trombe walls are shown in Figure 5.7. It can be observed that in the morning the room (ground floor) temperature increases at a reasonable rate before it reaches the daily maximum, also it can be seen that the room temperature only changes by approximately 3°C throughout the day.

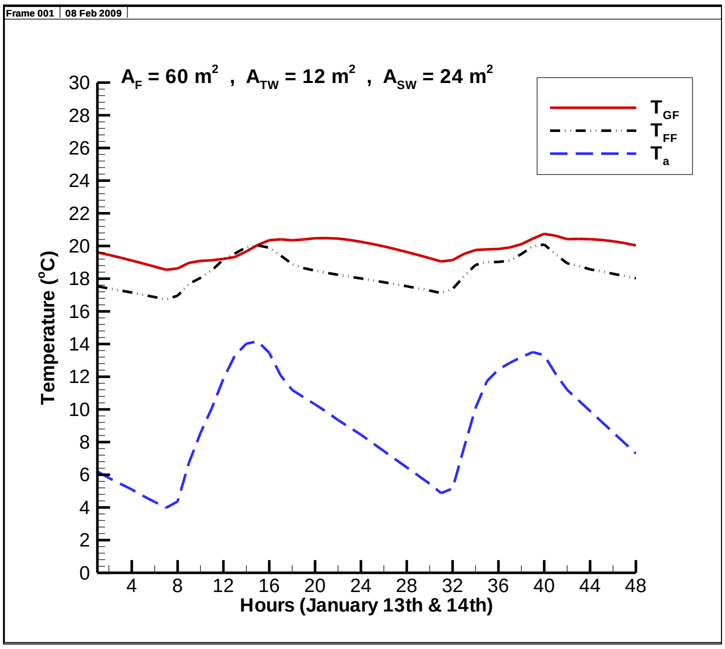


Figure 5.3 The hourly indoor temperature variations on the Ground floor and First floor, and variations of the ambient air temperature on January 13^{th} & 14^{th} (A_{TW}: 12 $m^{2)}$

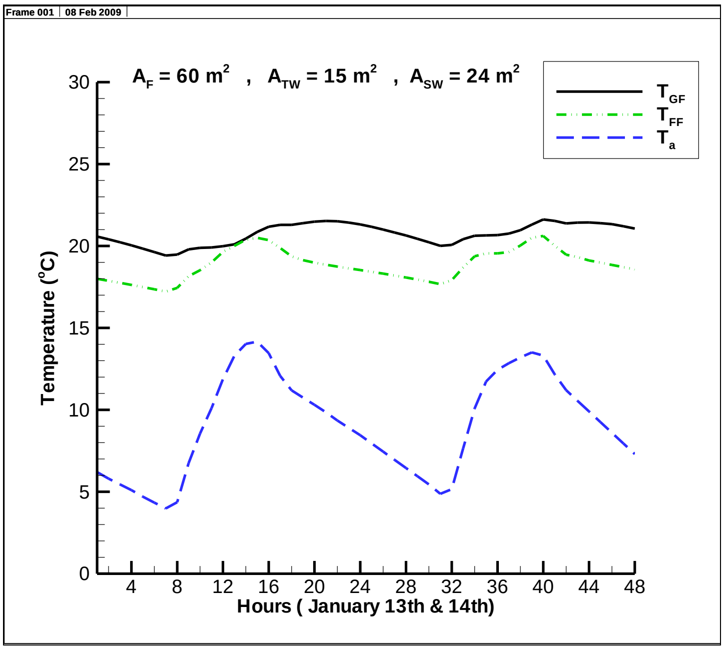


Figure 5.4 The hourly indoor temperature variations on the Ground floor and First floor, and variations of the ambient air temperature on January 13^{th} & 14^{th} (A_{TW}: 15 m^2)

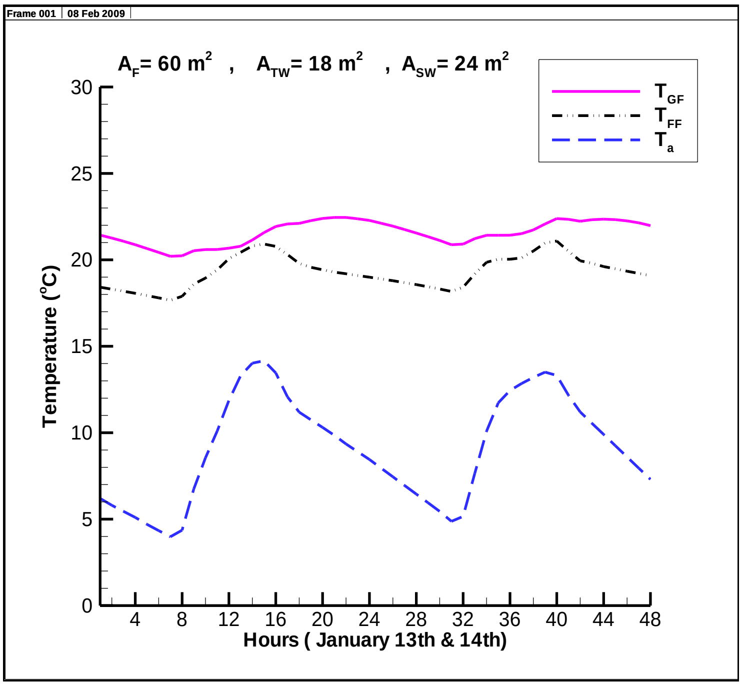


Figure 5.5 The hourly indoor temperature variations on the Ground floor and First floor, and variations of the ambient air temperature on January 13th & 14th (A_{TW}: 18 m^2)

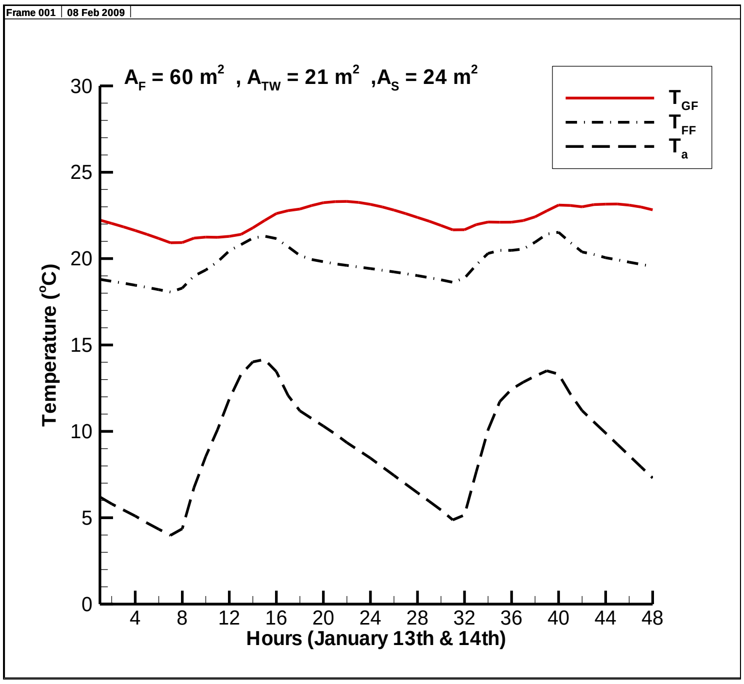


Figure 5.6 The hourly indoor temperature variations on the Ground floor and First floor, and variations of the ambient air temperature on January 13th & 14th (A_{TW}: 21 m^2)

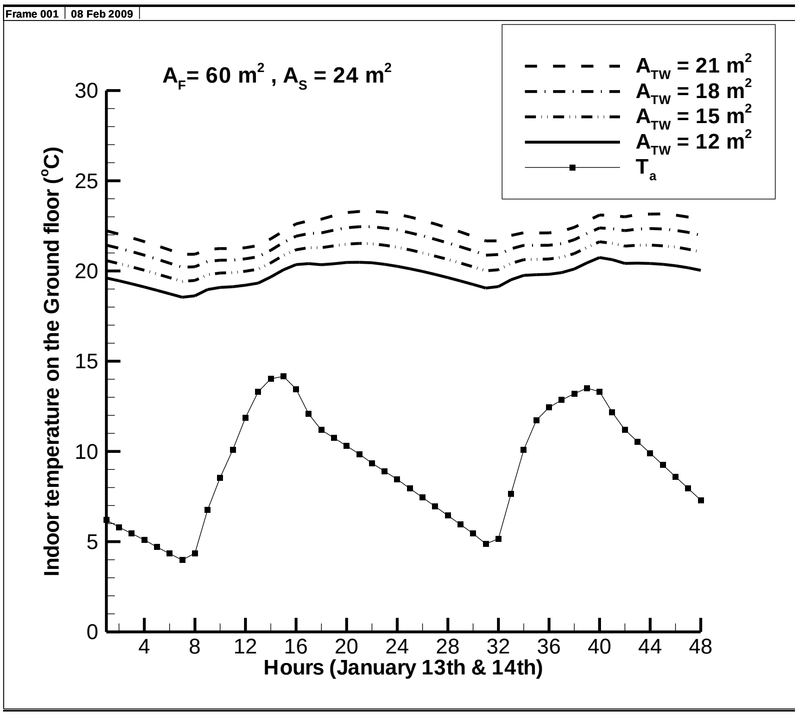


Figure 5.7 Indoor temperature variations on the Ground floor for different sizes of Trombe walls on January 13th & 14th .

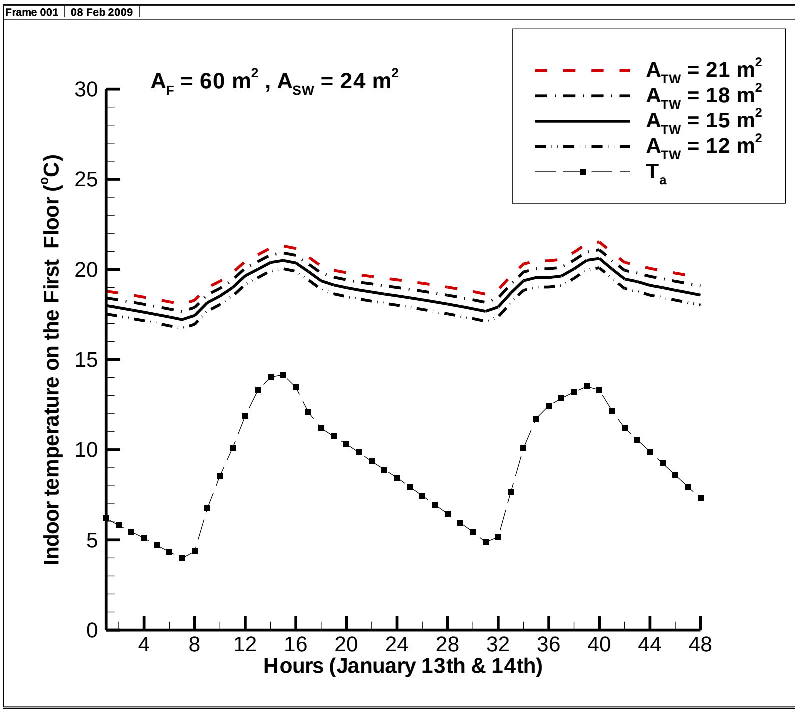


Figure 5.8 The Indoor temperature variations on the First floor for different sizes of Trombe walls on January 13th & 14th

In the present study the building walls are assumed to be built with normal bricks covered with 5cm extruded polystyrene as thermal insulation material on the exterior surfaces. The effect of having no thermal insulation on the thermal performance of the building is investigated for reference. The simulation results of the building integrated with a Trombe wall of area 15m^2 and with thermal insulation on each wall of the building and on the roof, and the one without insulation are shown in Figure 5.9. It is found that the indoor air temperature of the building without thermal insulation is less than that of the building with insulation during a day. The obtained results, concerning the insulated building, show that the temperature of the ground floor ranges between 19°C and 21°C and the temperature of the first floor varies between 17°C and 20°C approximately during a day. But in the case of the building without thermal insulation, the temperature variations are significant. The temperature of the ground floor ranges between 16°C and 18°C and that of the first floor varies between 10°C and 16.5°C approximately during a day. It has been shown by Kalogirou, S. et al. (2002) that the thermal Insulation can reduce the required heating load of a building by about 47%.

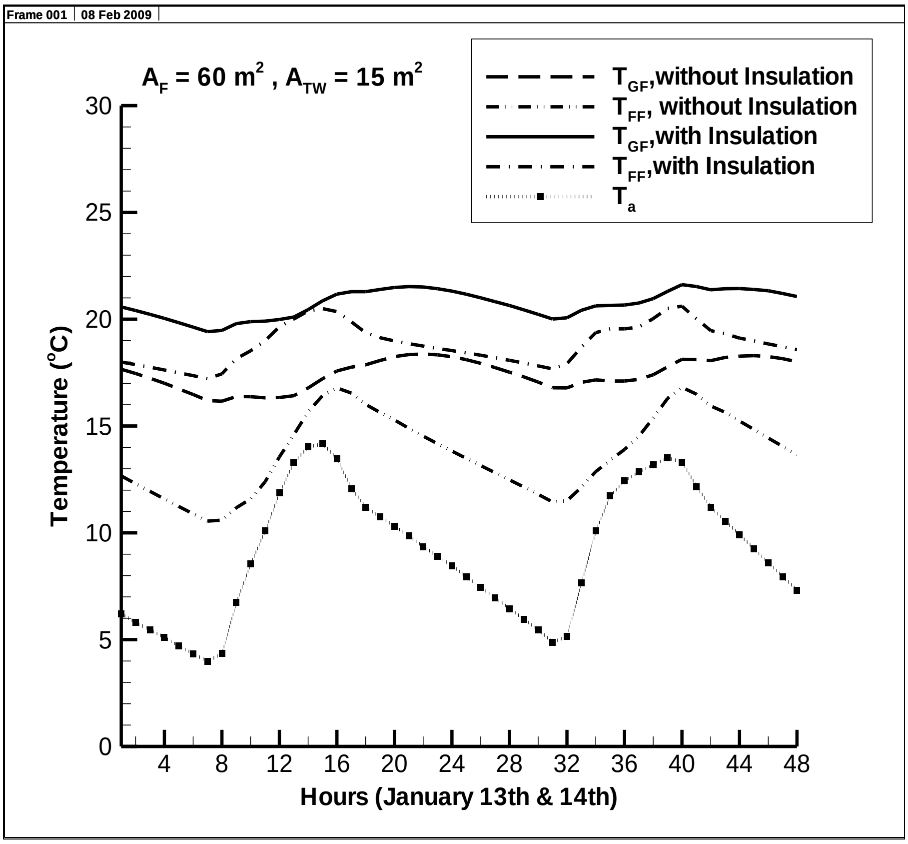


Figure 5.9 Indoor temperature variations on the Building with thermal insulation and the one without insulation on January 13th & 14th

As it is mentioned before in chapter 4, the hypothetical building has a floor area (A_F) of 60 m^2 at each floor level. But in order to examine the thermal performance of the Trombe wall of area 15 m^2 in larger houses, the size of the building floor area has been changed and two different sizes (75 and 90 m^2) of floor areas have been selected for the simulation. At the building with floor area of 75 m^2 the temperature on the ground floor ranges between 19ºC and 20.5ºC and at the building of area 90 m^2 the temperature of the ground floor varies between 18.5ºC and 20ºC approximately (Figure 5.10). It is observed that the thermal wall of area 15 m^2 has a satisfactory thermal behavior in both sizes of buildings.

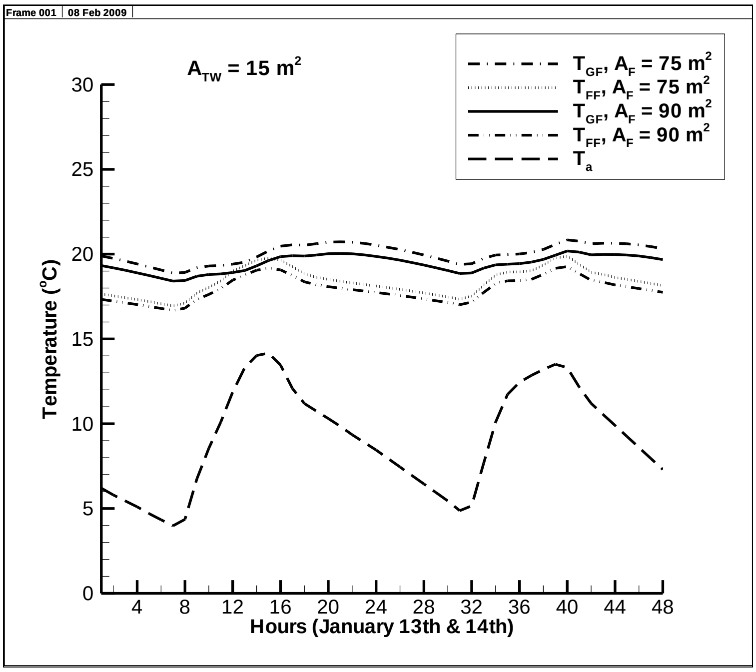


Figure 5.10 Indoor temperature of the building for two different floor areas (A_F), on January 13th and 14th (A_{TW}: 15m^2)

The hourly temperature variations of the model house integrated with a vented Trombe wall of area 15m^2 during January, February and March are shown in Figure 5.11. It can be seen that the desired room temperature can be provided by the Trombe wall. The desired room temperature in winter time is around 20ºC in Cyprus.

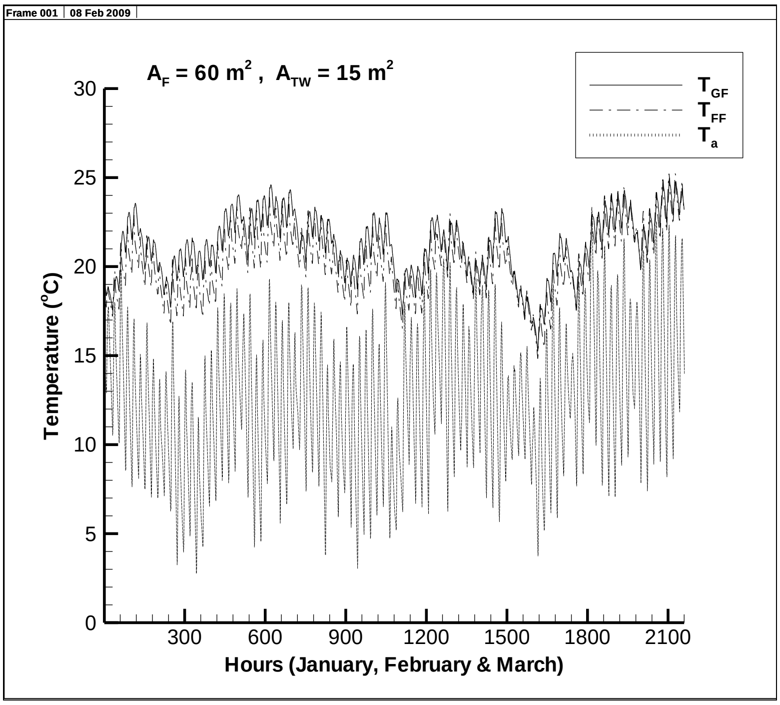


Figure 5.11 Hourly indoor temperatures on the building and the variations of ambient air temperature in January, February and March.

The area of the largest window of the building (which is located on the south wall of the First floor) has been changed in the program in order to consider the changes in indoor temperature of the first floor (Figure 5.12). The window area ranges from 5.2 to 7.8 m^2. The simulation results show that the size of window has a small influence on the zone temperature.

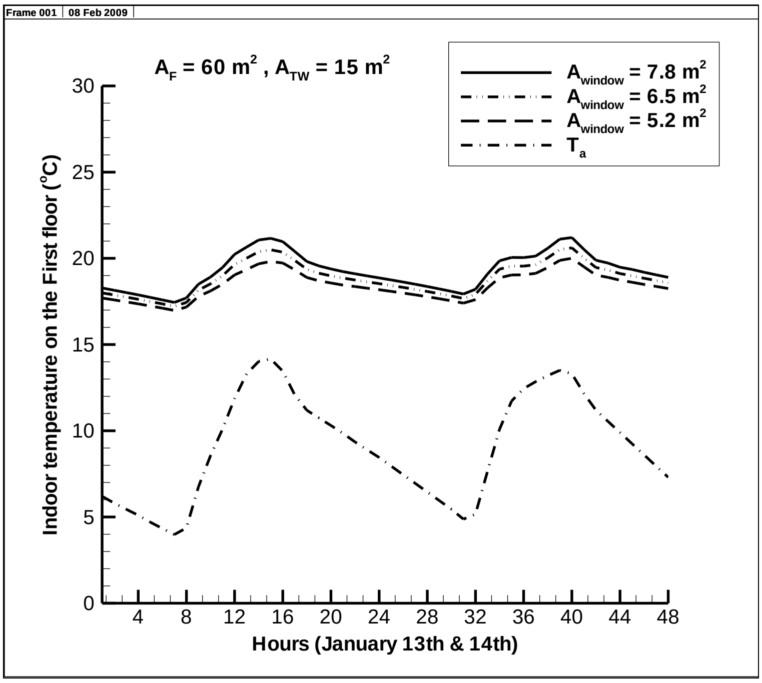


Figure 5.12 Variations of indoor temperature due to different sizes of window on January 13th and 14th (A_{TW}: 15 m^2)

The rate of heat demand of the ground floor and the rate of energy in which the Trombe wall of area 15m^2 can produce in a year are shown in Figure 5.13. It can be seen that sometimes the rate of energy which is provided by Trombe is more than the heating demand of the zone. The extra heat can be removed from the building easily by ventilation.

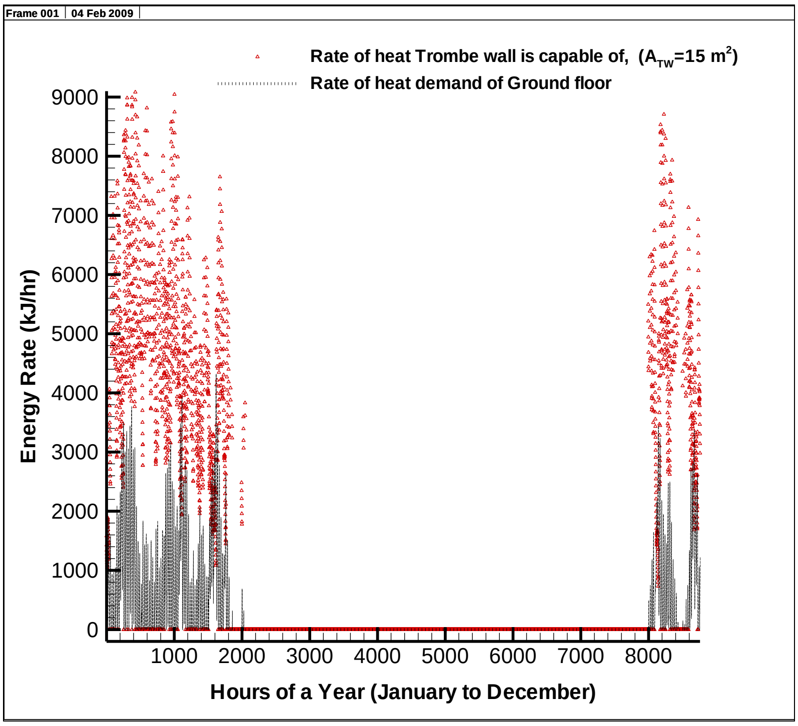


Figure 5.13 The rate of energy transferred to the Ground floor by Trombe wall (A=15 m^2) and the rate of heat demand of the Ground floor during a year.

5.2 Economic Feasibility Analysis

The economic feasibility of using thermal storage wall as the heating system of the buildings in Cyprus is considered in this chapter.

One of the conventional air heating systems in Cyprus is Gas Heater. According to the Turkish Design Guide (Turkish Chamber of Mechanical Engineers, 1995), the average room air design temperature in winter is approximately 20 ºC. For the model building (without Trombe wall) which has a floor area of 60 m^2 and 5 cm of thermal insulation material (polystyrene foam) on the walls and on its roof, a 3 kW gas heater is needed to raise the air temperature of the building (ground floor) up to 20 ºC. In Cyprus the cost of a 3 kW gas heater is around 300 Turkish Lira ($187, assume $1 = TL 1.6). Gas heater uses L.P.G. (Liquid Petroleum Gas) to produce heat and the price of one kilogram of L.P.G. is 2 TL and the lower Heating Value of L.P.G. is 45627 (kJ/kg) (The State Institute of Statistics, 1992). The efficiency (η) of a gas heater is nearly 85%. It should be noticed that a gas heater needs maintenance every year which costs 100 TL per year.

The heating demand (Q_{HEAT}) of the ground floor is estimated by assuming there is a normal wall instead of Trombe wall on the south façade of the ground floor. For a comfortable environment, a temperature of 20 ºC is assumed for the room. The heating demand is estimated by calculating the heat losses through the envelope of the building by assuming the room temperature at 20 ºC. The following equation is used for calculating the heat loss of each building component associated with the envelope of the building during a year.

$$Q_{LOSS} = \sum_{j=1}^{8760} U\,A\,(T_i - (T_a)_j) \qquad \text{(Eq. 5.1)}$$

$$Q_{HEAT} = \sum^{n} Q_{LOSS}$$

Where n is the number of components such as external walls, windows, ceiling and floor. U is the Overall heat transfer coefficient through the building envelope components, A is the area of each component, T_i is the inside temperature of the room and T_a is the ambient air temperature at each hour of a day. The heating demand (Q_{HEAT}) of the ground floor (without Trombe wall) is found to be 2095131.2 kJ per year.

C_{LPG} is the cost of L.P.G. per kilojoule and is calculated by the following formula,

$$C_{LPG} = \frac{\text{Cost of L.P.G. per kg}}{\text{Heating Value of L.P.G.}} \qquad \text{(Eq. 5.2)}$$

$$= \frac{2\ (\text{TL/kg})}{45627\ (\text{kJ/kg})} = 4.38 \times 10^{-5}\ (\text{TL/kJ})$$

The annual energy cost of using Gas Heater (C_{GH}) is

$$C_{GH} = \frac{C_{LPG} \times Q_{HEAT}}{\eta} \qquad \text{(Eq. 5.3)}$$

$$= \frac{4.38 \times 10^{-5}\ (\text{TL/kJ}) \times 2095131.2\ \ (\text{kJ/year})}{0.85} = 107.9\ \text{TL/year}$$

The economic analysis is performed for the model building integrated with a Trombe wall as well. In the analysis a Trombe wall of area 15 m^2 and thickness of 0.17 m is considered. The construction cost of a concrete wall of thickness 0.17 m is around 34 TL/m^2. The cost of single glass cover is nearly 153 TL/m^2 (Atikol, U., 2008). The total construction cost of the Trombe wall is approximately 190 TL/m^2 in Cyprus. So a Trombe wall of area 15 m^2 costs 2850 TL in Cyprus. The total amount of supplied heat (Q_{TW}) by the thermal storage wall of area 15 m^2 is 1986722.2 kJ per year (see Figure 5.14). For the building integrated with Trombe wall, the annual savings are approximately 103 TL/year (see Eq. 5.4).

$$\text{Annual Savings} = \frac{Q_{TW} \times C_{LPG}}{\eta} \qquad \text{(Eq. 5.4)}$$

$$\text{Annual Savings} = \frac{1986722.2\ (\text{kJ/year}) \times 4.38 \times 10^{-5}\ (\text{TL/kJ})}{0.85}$$

$$= 103\ \text{TL/year}$$

A small program is written in EXCEL software program to verify the economic feasibility of using thermal storage wall in a 60m^2-room (ground floor) for the heating purpose. For the building integrated with Trombe wall, The total initial investment would be approximately 2950 TL, which includes the construction cost of a Trombe wall of area 15 m^2 and the cost of a portable gas heater (as an auxiliary heater). Additionally, 15 TL is needed for the maintenance of the portable gas heater each year. For an ordinary building (i.e. the room Without Trombe wall), a gas heater is used for the heating purpose. The cost of a 3 kW gas heater is 300 TL. Instead of Trombe wall, a normal wall should be placed on the south side of the room. The construction cost of an external wall (which is made of normal Brick and covered by 5 cm of polystyrene), is 1320 TL. Also a double glazing window (a window of area 4 m^2) is placed on the south wall which costs 680 TL. In addition, 100 TL is needed each year for the maintenance of gas heater. The discount rate is approximately 18% in Cyprus and the cost analysis is done for 15 years. The detailed information of the cost analysis is given in Appendix B.

The Life Cycle Cost (LCC) analysis shows that the Life Cycle Net Savings is 300 TL and the Savings-to-Investment Ratio is 2.3. The Simple Payback period is found to be around 6 years (see Eq. 5.5 - 5.7). Hence, in present case it is more economically feasible option to use a Trombe wall for winter heating application in Cyprus. In the equations PV stands for present value.

$$\text{Life Cycle Net Savings} = \sum \text{PV Annual Savings} - \sum \text{PV Life Cycle Investments}$$

$$= 524 – 224 = 300 \text{ TL} \qquad \text{(Eq. 5.5)}$$

$$\text{Savings-to-Investment Ratio} = \sum \text{PV Annual Savings} / \sum \text{PV Life Cycle Investments}$$

$$= 524 / 224 = 2.3 \qquad \text{(Eq. 5.6)}$$

$$\text{Simple Payback Period} = \text{Initial Investments} / \text{Annual Savings}$$

$$= 650 / 103 = 6 \text{ years} \qquad \text{(Eq. 5.7)}$$

Summer shading is to be provided with an overhang extending 1.2 m from the wall. This should prevent overheating during summer as Kalogirou S.A. et al. (Kalogirou, S., et al., 2002) stated in their investigation. A motorized Rolling shutter would cost 1750 € (~3500 TL) in Cyprus. The project would not be feasible if such an expensive device is used.

It is found that the total heating demand of the 60m^2-zone is around 2095131.2 kJ per year. The total amount of heat in which a Trombe wall of area 15m^2 can supply is nearly 1986722.2 kJ per year. It is found that approximately 95% of the total heat load of the zone can be met by the proposed thermal storage wall (see Figure 5.14).

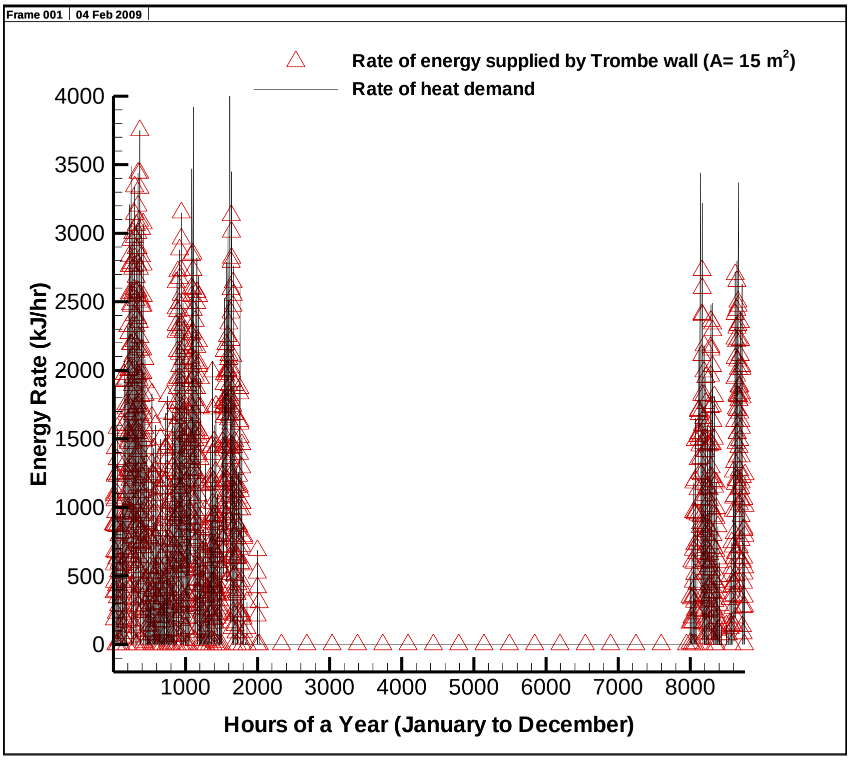


Figure 5.14 Rate of heat demand of the building (Ground floor) and Rate of energy supplied by Trombe wall (A_{TW} = 15 m^2) during a year.

CHAPTER 6

CONCLUSION

The aim of this work was to investigate the temperature behavior of a hypothetical building integrated with the Trombe wall in Cyprus. The hourly simulations are performed for the two coldest days of winter (January 13^{th} and 14^{th}).

It is observed that the outer surface temperature of the Trombe wall and the temperature of the glazing are highly responsive to changes in solar intensity rate since they are directly exposed to solar radiation. But the inner wall surface is not directly exposed to solar radiation as a result it is not sensitive to changes in solar intensity rate. The maximum temperature of the outer surface of wall is found to be approximately 40°C which is high enough for transferring sufficient heat to maintain the room temperature in the region of 20°C.

Comparison of the hourly temperature profile of the ground floor with that of the first floor shows that the Trombe wall has an advantage of creating a less fluctuating temperature compared to direct gain window in the building. With a Trombe wall of area 15 m^2 the indoor temperature of the ground floor ranges between 19 °C and 21.5 °C and the indoor temperature of the first floor ranges between 17.3°C and 20.5°C. In the morning, as the solar radiation comes in effect the indoor temperature of the first floor increases and by sunset it falls down. But the indoor temperature of the ground floor increases even after sunset (until mid-night), so the zone remains warm at night. It is assumed that the Trombe wall is made of concrete because it has high density and specific heat capacity values; therefore its thermal storage capacity is also high and this helps conveying the heat into the building at a slow rate in the night time.

The effect of having no thermal insulation on the temperature behavior of the building is examined. The simulation results of the building (included a Trombe wall of area 15m^2) with thermal insulation show that the temperature of the ground floor ranges between 19°C and 21°C and the temperature of the first floor varies between 17°C and 20°C approximately during a day but in the building without thermal insulation the temperature of the ground floor ranges between 16°C and 18°C and that of the first floor varies between 10°C and 16.5°C approximately in a day.

By enlarging or reducing the area of the largest window of the building (which is located on the south wall of the first floor), by approximately 1.3 m^2, the indoor temperature of the first floor does not change much (temperature variations are less than 1°C) and it shows that the size of window has small influence on the room temperature.

The total heating demand of the zone (Ground floor) is equal to 2095131.2 kJ per year. It is found that about 95% of total heating demand of the 60m^2- zone can be met by a Trombe wall of area 15 m^2. A portable gas heater is assumed to be used as an auxiliary heater when the total heating demand can not be met by the Trombe wall.

The obtained results from the Life Cycle Cost analysis show that constructing a Trombe wall of area 15m^2 in Cyprus is economically feasible compared to installing a 3-kW gas heater. The Savings-to-Investment Ratio is found to be 2.3 and the simple payback period is around 6 years.

It is concluded that the conventional heating systems in buildings can be replaced by Thermal storage wall due to the fact that this type of passive solar heating strategy shows a good thermal performance in the climatic conditions of Cyprus. Precaution should be taken to shade these walls properly during the summer season. It is also advised to facilitate air ventilation through the wall-glass gap to cool the wall during the summer.

REFERENCES

Atikol, U., Assefi, H., Azizian, M. R., Gharebaghi, M.(2008). Effect of demand-side management on the feasibility of high-performance windows. The 3rd IASME/WSEAS International Conference on energy and environment (EE ’08), Cambridge, UK.

Balcomb, J. (1992). Passive Solar Buildings. *The MIT press, Cambridge, Massachusetts, London, England*.

Balcomb, J., Jones, R., McFarland, R., Wary, W. (1984). Passive solar heating analysis: A design manual. *Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers*.

Blasco Lucas, I., Hoese, L., Pontoriero, D. (2000). Experimental study of passive systems thermal performance, *Renewable Energy* Vol. 19 pp. 39-45.

Chel, A., Nayak, J.K., Kaushil, G. (2008). Energy conservation in honey storage building using Trombe wall, *Energy and Building* Vol. 40 pp. 1643-1650.

Chandel, S.S., Aggarwal R.K. (2008). Performance evaluation of a passive solar building in Western Himalayas, *Renewable Energy*.

Duffin, R.J., Knowles, G. (1985). A simple design method for the Trombe wall, *Solar Energy* Vol.34, No.1, pp. 69-72.

Fernandez-Gonzalez, A. (2007). Analysis of the thermal performance and comfort conditions produced by five different passive solar heating strategies in the United States Midwest, *Solar Energy* Vol. 81 pp. 581-593.

Hsieh, J. S. (1986). Solar Energy Engineering, *Prentice-Hall, Englewood Cliff.*

Kalogirou, S., Florides, G., Tassou, S. (2002). Energy analysis of buildings employing thermal mass in Cyprus, *Renewable Energy* Vol. 27 pp. 353-368.

Klein, S.A., Beckman, W.A., Mitchell, J.W., Duffie, J.A., Duffie, N.A., Freeman, T.L., et al.(2007). *TRNSYS manual*, University of Wisconsin-Madison.

Kays, W.M.(1966). Convective heat and mass transfer, *McGraw-Hill book Co*. p.180.

Moore, F.(1993). Environmental control systems, Heating Cooling lighting. *McGraw Hill.*

Morse, E. L. (1881). Warming and Ventilating Apartments by Sun's Rays, *U. S. Patent,246, 626*.

Mercer, W.E., Pearce, W.M., Hitchcock, J.E.(1967). Laminar forced convection in the entrance region between parallel flat plates, *Journal of heat transfer,* Vol. 89, pp. 251-257.

Onbasioglu, H., Egrican, N. (2002). Experimental approach to the thermal response of passive systems, *Energy Conversion & Management* Vol. 43 pp. 2053-2065.

PASSYS. (1994) .The PASSYS Project: PASSYS Test Components Descriptions. European Commission, Directorate-General XII for Science, Research and Development.

Randall, K.R., Mitchell, J.W., El-Wakil, M.M.(1979). Natural convection heat transfer characteristics of flat-plate enclosures, *Journal of heat transfer*, Vol. 101, pp. 120-125.

Shen, J., Lassue, S., Zalewski, L., Huang, D. (2007). Numerical study on thermal behavior of classical or composite Trombe solar walls, Energy *and Buildings* Vol. 39 pp. 962-974.

Smolec, W., Thomas, A. (1993). Theoretical and experimental investigations of the heat transfer in a Trombe wall , *Energy convers*. Mgmt Vol. 34, pp. 385-400.

Seem, J.E. (1987). Modeling of Heat in Buildings, Ph. D. thesis, *Solar Energy Laboratory, University of Wisconsin Madison*.

Trombe, F.(1972). *U. S. Patent 3,832,992*.

Trombe, F., Robert, J.F., Cabanot, M., Sesolis, B. (1977). Concrete Walls to collect and hold heat, *Solar Age*, Vol. 2, No. 8, pp. 13-19.

Turkish Chamber of Mechanical Engineers, Design Guide for Central Heating. (1995). 11th Edition, ISBN-975-395-153-1, Turkey.

The State Institute of Statistics.(1992).Energy consumption in the manufacturing industry (large scale). Ankara: Prime Ministry of Republic of Turkey, 1997 [in Turkish].

http://www.eslarp.uiuc.edu/arch/ARCH371-F99/groups/k/solar.html. The East ST. Louis Action Research Project website. University of Illinois.

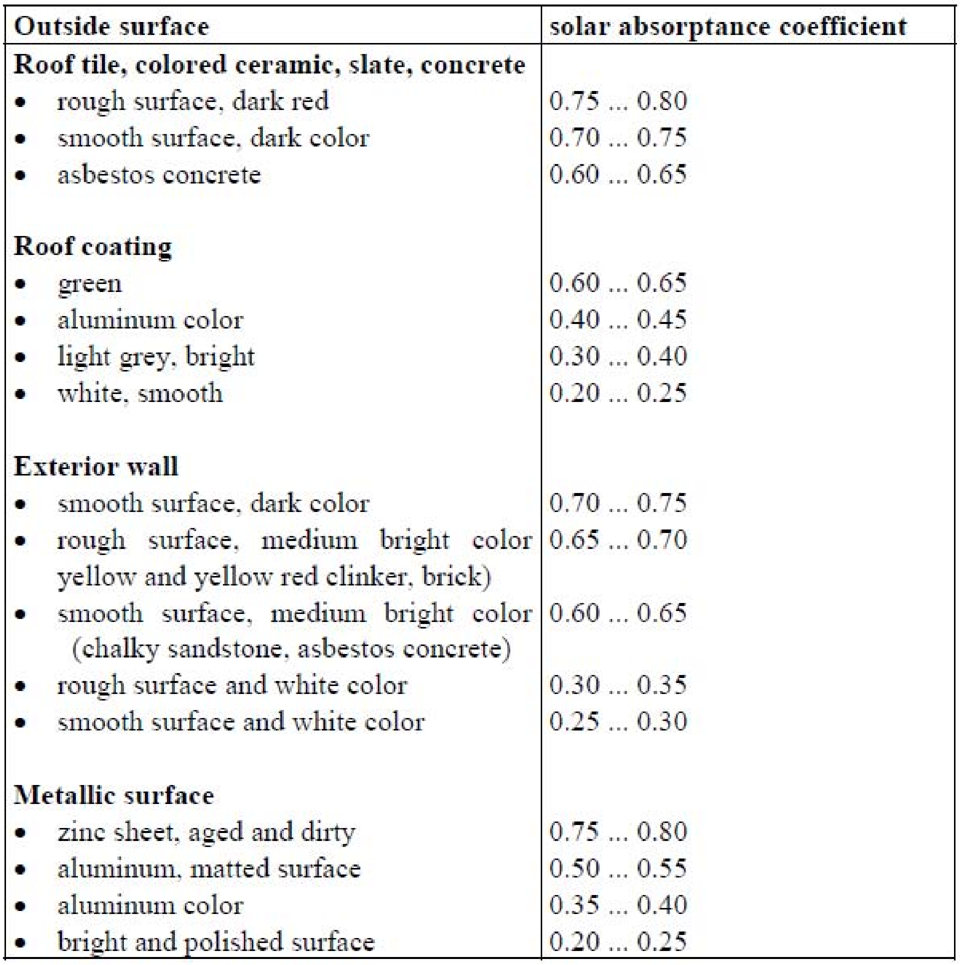
http://www.nrel.gov/learning/re_passive_solar.html.NREL (National Renewable Energy Laboratory) website.

Yilmaz, Z., Kundakci, A.B.(2008).An approach for energy conscious renovation of residential buildings in Istanbul by Trombe wall system, *Building and Environment,* Vol.43 pp. 508-517.

APPENDICES

APPENDIX A

Table A.1 Solar absorptance coefficients for different surfaces (TRNSYS manual, 2007)



Outside surface	**solar absorptance coefficient**
Roof tile, colored ceramic, slate, concrete	
• rough surface, dark red	0.75 ... 0.80
• smooth surface, dark color	0.70 ... 0.75
• asbestos concrete	0.60 ... 0.65
Roof coating	
• green	0.60 ... 0.65
• aluminum color	0.40 ... 0.45
• light grey, bright	0.30 ... 0.40
• white, smooth	0.20 ... 0.25
Exterior wall	
• smooth surface, dark color	0.70 ... 0.75
• rough surface, medium bright color yellow and yellow red clinker, brick)	0.65 ... 0.70
• smooth surface, medium bright color (chalky sandstone, asbestos concrete)	0.60 ... 0.65
• rough surface and white color	0.30 ... 0.35
• smooth surface and white color	0.25 ... 0.30
Metallic surface	
• zinc sheet, aged and dirty	0.75 ... 0.80
• aluminum, matted surface	0.50 ... 0.55
• aluminum color	0.35 ... 0.40
• bright and polished surface	0.20 ... 0.25

APPENDIX B

Appendix B

Life Cycle Cost Analysis of a Trombe wall and a 3-kW gas heater

TABLE 1

Life Cycle Investment Schedule

Year	Trombe wall	Gas heater	Net Amount
0	2,950 TL	2,300 TL	650 TL
1	15 TL	100 TL	-85 TL
2	15 TL	100 TL	-85 TL
3	15 TL	100 TL	-85 TL
4	15 TL	100 TL	-85 TL
5	15 TL	100 TL	-85 TL
6	15 TL	100 TL	-85 TL
7	15 TL	100 TL	-85 TL
8	15 TL	100 TL	-85 TL
9	15 TL	100 TL	-85 TL
10	15 TL	100 TL	-85 TL
11	15 TL	100 TL	-85 TL
12	15 TL	100 TL	-85 TL
13	15 TL	100 TL	-85 TL
14	15 TL	100 TL	-85 TL
15	15 TL	100 TL	-85 TL
16			0 TL
17			0 TL
18			0 TL
19			0 TL

Table 1: Life Cycle Investment Schedule

- In Year 0, Trombe wall: sum of initial investments of Trombe wall & a portable gas heater.
- In Year 0, Gas heater: sum of initial costs of a 3-kW gas heater & a normal wall & a double glazing window.
- In Year 1-15: schedule of future costs (the annual operation & maintenance) for the portable gas hetaer and the 3-kW gas heater.

The net amount for each year is the difference between Trombe wall costs and gas heater costs for each year.

TABLE 2

Annual Savings	103 TL
Discount Rate	18%
Analysis period (years)	15
Residual value	0 TL

Table 2: Given Data:

- net annual savings (the sum of regular annual savings & expenses).
- discount rate.
- the number of years for the analysis.
- sum of residual value of ECM equipment at end of 10 yr service life.

Life Cycle Cost Analysis Calculations

TABLE 3: Savings Calculations

Formula: PV Annual Savings = Annual Savings / (1 + Discount Rate)^{year}

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Annual Savings	0 TL	103 TL	103 TL	103 TL	103 TL	103 TL	103 TL	103 TL	103 TL	103 TL	103 TL	103 TL	103 TL	103 TL	103 TL	103 TL
PV Annual Savings	0 TL	87 TL	74 TL	63 TL	53 TL	45 TL	38 TL	32 TL	27 TL	23 TL	20 TL	17 TL	14 TL	12 TL	10 TL	9 TL
Σ PV Annual Savings	524 TL															

TABLE 4: Investments

Formula: PV Life Cycle Investment = Life Cycle Investment / (1 + Discount Rate)^{year}

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Residual
Net Life Cyle Investments	650 TL	-85 TL	-85 TL	-85 TL	-85 TL	-85 TL	-85 TL	-85 TL	-85 TL	-85 TL	-85 TL	-85 TL	-85 TL	-85 TL	-85 TL	0 TL
PV Life Cycle Investments	650 TL	-72 TL	-61 TL	-52 TL	-44 TL	-37 TL	-31 TL	-27 TL	-23 TL	-19 TL	-16 TL	-14 TL	-12 TL	-10 TL	-8 TL	0 TL
Σ PV Life Cycle Investments	224 TL															

Formula: Annual Savings - Net Life Cyle Investments

Net Cash Flows	650 TL	188 TL	188 TL	188 TL	188 TL	188 TL	188 TL	188 TL	188 TL	188 TL	188 TL	188 TL	188 TL	188 TL	188 TL	103 TL

(for IRR calculation)

Output

TABLE 5: Results

	OUTPUTS
Net Present Value (NPV)	**300 TL**
Savings-to-Investment Ratio	**2.3**
Internal Rate of Return (IRR)	**28%**
Simple Payback (years)	**6.3**

<u>Formulas:</u>

Life Cycle Net Savings = Σ PV Annual Savings - Σ PV Life Cycle Investments

Savings-to-Investment Ratio = Σ PV Annual Savings / Σ PV Life Cycle Investments

Internal rate of return = Discount rate, where SIR = 1.0, or NPV = 0

Simple payback = Initial investment / annual savings