Optimum Trombe wall thickness in the Mediterranean Tunisian context: An energetic and economic study

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Abstract
Trombe walls figure among many passive devices used in the Mediterranean climate to minimize heating demands in residential buildings. The thickness of this massive wall is a critical parameter that influences the effectiveness of the system. Insufficient wall thickness conducts to an important interior temperature fluctuation, and huge wall thickness will increase costs and thermal resistance. In this paper, the optimum thickness of four different construction materials (concrete, stone, adobe, and brick), which can be used in the Trombe wall, was determined using an energetic and economic analysis. The energetic results with TRNSYS software show that the best materials, which can contribute to a reduction by 50% in heating loads of a single room, are stone and concrete. For the economic analysis, the life cycle cost and the payback period were calculated for each construction material. The results show that the optimum thickness for stone and concrete are, respectively, 34 and 32 cm with a payback period of 2.85 and 2.65 years.

KEYWORDS
life cycle cost, optimum thickness, passive heating, TRNSYS, Trombe wall

1 | INTRODUCTION

Despite the regression of the global energy demand in 2020 by 4.5% due to the COVID-19 pandemic, the first statistical analysis in 2021, showed that energy consumption and emissions are expected to return to historical trends with 4.1%.

Fortunately, renewable energy, led by wind and solar energy, continued to grow significantly. Wind and solar capacity increased by 238 GW last year.

Making an energy demands classification by sector, it was found that the building sector represents 20%–40% of the world’s total energy consumption, in which 33%–55% is consumed by Heating, Ventilation, and Air Conditioning, to maintain the desired thermal performance and lead to an acceptable condition of comfort in buildings.

Tunisia is one of the developing countries which have a big problem with its energy balance. According to recent statistics, during the period 2010–2017, the Tunisian energy context was characterized by an important decrease in the energetic resources by 38% with an increase in the demands by 14%.

As a solution, the use of renewable energies figures is among the decisive alternative to preserve the energy security of the country knowing that Tunisia has more than 3200 h of sunshine per year.

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Facing this problem, many technologies and approaches are being used to reduce annual energy demand and achieve net-zero energy buildings.  

Trombe walls, also known as storage walls and solar heating walls, figure among the passive architectural heating systems which can reduce nearly 20%–30% of the total energy consumption in buildings if they are well-conceived.  

To optimize the energetic contribution of the Trombe wall system, several studies have been carried out on improving the performance of this system by acting on its various accessories and on the developing of new concepts which improve heat transfer or storage.  

The type of material used for Trombe wall construction is the most crucial part of this solar system. Indeed any material with high storage capacity can be used. However, the use of lightweight materials with high storage capacity or the use of phase change materials (PCM) reduces the size of the mass wall.  

Na Zhu et al. have shown with a numerical study that the Trombe wall associated with PCM could reduce indoor temperature fluctuations and improve thermal comfort all over the year compared with the classical Trombe wall.  

In this context, Zalewski et al. have studied the integration of PCM to improve storage capacity. An advantage of this composite solar wall is that the solar gains are released with a time shift by 2 h 40 min, and the change phase material can limit the losses to the outside and increase exchanges in the cavity.  

Another important parameter is the area. An economic work undertaken by Jaber and Ajib on a typical Jordanian house showed that the optimum ratio between the surface of the Trombe wall and the total surface of the south wall is 37%.  

These studies have concern also thermal insulation and the glazing effect.  

For example, Xiaoqiang Hong et al. have provided evidence for a new Trombe wall design with a Venetian blind. The operation of this type of wall can be in winter heating mode, summer sun shading mode, and transition season ventilating mode.  

A recent study by Bendong Yu et al. concluded that a thermal-catalytic-Trombe wall can be a good solution for space heating and air purification. They found that this system can provide a reduction of 28.3% in terms of the total thermal load and it can produce a total volume of clean air of 8328.7 m³/m².  

The water blind-Trombe wall system developed by Zhongting Hu et al. is another new Trombe wall design. This wall can offer the possibility of space heating, ventilation, and domestic hot water and it can reduce by 42.6% the overall thermal load yearly.  

Although there are many studies, the research in solar wall thickness remains limited. Generally, the optimal thickness of a Trombe wall depends on the material used, the latitude, and on the climate of the place where it will be installed.  

But on the first hand increasing the thickness will increase the thermal capacity of the storage wall and also its cost, on the other hand, insufficient wall thickness results in excessive interior temperature swings. Many research tried to calculate the optimal thickness that can be the solution to this equation. For example, Agrawal B et al. showed that in the Indian context with concrete, there is a lag of 120–150 min for heat delivery from outside to inside for each 10 cm and they proposed a 30–40 cm thick concrete Trombe wall for optimal results.  

However, this optimum thickness cannot be determined only by a thermal analysis but also by an economic study that takes into consideration many parameters such as material construction cost, energy cost, inflation, discount rates, and building lifetime.  

In this study, four different construction materials, which are concrete, stone, brick, and adobe were investigated energetically and economically to determine the optimum Trombe wall thickness.  

For the energetic study, TRNSYS simulation software was used to determine the annual heating loads of a simple test room in the Tunisian context.  

Concerning the economic investigation two main parameters were analyzed for each material; life cycle cost (LCC) and payback period.  

2.1 Functioning principle  

The Trombe wall consists of a massive wall generally made of stone, brick, or concrete, with high inertia and black color installed at a small distance from the glazing Figure 1. The Trombe wall can be considered as a high capacitance solar collector directly coupled to the room. The wall absorbs solar radiation and conducts part of the thermal energy to the building by natural convection through the solar chimney formed by the glazing on one side and the wall on the other. Solar heat absorbed by the outer surface of the wall is slowly conducted through the solid wall to the inner surface and then into the room through radiation and convection.  

The advantage of the wall’s significant thermal capacity is that it can store solar heat during the day and transfer it to the building space at night.  

In summer, generally, the Trombe wall is shaded and the two vents are closed. In this case, it becomes an external
vertical wall. However, some researchers have demonstrated that the Trombe wall can provide cross ventilation between the interior of the building and the external environment when the upper opening of the glazing allows the extraction of hot air from the lower opening of the Trombe wall.

### 2.2 Thermal analysis

The heat stored by the wall is transferred to the building by conduction, convection, and radiation.

The rate of the heat transferred by conduction through the wall is calculated from Fourier’s law:

$$ Q_{\text{cond}} = \frac{(T_{w,e} - T_{w,i})}{R_{cd}} = \frac{(T_{w,e} - T_{w,i})}{\frac{e}{\lambda R_{cd}}}, $$

where $T_{w,e}$ is the external wall temperature, $T_{w,i}$ is the internal wall temperature, $R_{cd}$ is the conduction resistance, $e$ is the Trombe wall thickness (m), and $\lambda$ is the thermal conductivity of the wall (W/mK).

Considering one-dimensional transient heat transfer with no heat generation and constant thermal properties, the heat conduction equation for each layer of the Trombe wall is written as follows:

$$ \frac{\partial^2 T_i}{\partial x_i^2} = \frac{1}{\alpha} \frac{\partial T_i}{\partial t} \quad \text{for} \quad 0 < x_i < e, \quad \text{and} \quad i = 1, 2, ..., N. $$

With $\alpha = \frac{\lambda}{\rho \cdot C_p}$ = thermal diffusivity (m$^2$/s).

The boundary conditions are:

$$ -\lambda \frac{\partial T_i}{\partial x_i} = h_i S (T_i - T_i(x_i = 0, t)) = Q_{cvi}, $$

$$ -\lambda \frac{\partial T_N}{\partial x_N} = h_o S (T_N(x_N = e, t) - T_o) = Q_{cv,o}, $$

with $h_i$ and $h_o$ as the convective heat transfer coefficients at inside and outside wall surfaces, respectively. Heat transfer coefficients for natural convection are directly related to the Nusselt number.

$$ Nu = \frac{h_i L}{\lambda} \rightarrow h_i = \frac{Nu \lambda}{L}. $$

The Rayleigh number based on the air gap spacing $L$ is defined as:

$$ Ra = \frac{g \beta (T_1 - T_2) L^3}{\alpha \nu}. $$

For vertical cavities, a correlation-based on Wright is used.

### FIGURE 1 Trombe wall functioning principle.
\[ Nu = 0.0673838 \times Ra^{1/3} \quad \text{if} \quad 5 \times 10^4 < Ra < 10^6, \]

(7)

And \[ Nu = 0.028154 \times Ra^{0.4134} \quad \text{if} \quad 10^4 < Ra < 5 \times 10^4. \]

(8)

And \[ Nu = 1 + 1.7596678 \times 10^{-10} \times Ra^{2.298} \quad \text{if} \quad Ra < 10^4. \]

(9)

The thermal resistance to the energy flux between the gap and the room when the mass flow rate of the air in the gap is finite is given by:

\[
R = \frac{A}{m C_p} \left[ \exp\left( -\frac{2h_A A}{m C_p} - 1 \right) - 1 \right] .
\]

(10)

where \( C_p \) is the specific heat of the air (J/kgK), \( h_c \) is the air gap heat transfer coefficient (W/m² K), and \( A \) is the Trombe wall area (m²).

The heat dissipated by radiation is calculated from the equation

\[
Q_{rd,w} = \int_0^H \int_0^L \frac{T_w^4 \left( T_{\text{room}} - T_{\text{room}}^4 \right)}{\frac{1}{\varepsilon_y} + \frac{1}{\varepsilon_w} - 1} \ dx \ dz .
\]

(11)

### 3 | ENERGETIC STUDY

#### 3.1 | Building prototype

To investigate the influence of the thickness of different construction materials, a 3 m² Trombe wall facing south was added to a typical single-zone building model Figure 2.

In this case, a simple clear 4 mm glazing was installed 10 cm above the Trombe wall, and to ensure the air circulation between the building and the Trombe wall, two vents of 0.25 m/0.15 m were added at the upper and the lower position of the solar wall.

The building has a total floor area of 16 m², the perimeter is 43.4 m and the ceiling height is 3 m.

The building is made of typical Tunisian construction materials. The vertical walls of this room are made of simple 12-holes bricks covered on both sides by a cement plaster layer.

The thermal conductance of this type of wall is equal to 1.9 W/m²K.

The horizontal roof is made of concrete with a total thickness of 0.3 m. To minimize thermal losses, the roof was isolated by a 5 cm thick polystyrene panel. Its thermal conductance is equal to 0.6 W/m²K. The floor has a total thickness of 0.25 m with a thermal conductance equal to 2.29 W/m²K.

A single glazed window facing south is used. It has an area of 2.4 m² with a solar transmission coefficient of 0.85 and a solar reflection coefficient of 0.075. The thermal conductance of this type of window is equal to 5.74 W/m²K.

The wooden door has an east orientation with a total area of 1.8 m² and a thermal conductance equal to 0.44 (W/m²K).

A little infiltration flow rate of 0.2 air change per hour is adopted here.

The heating thermostat setting is adjusted at 18°C for heating in winter and the relative humidity is set at 30%.

The climatic data (solar radiation, ambient temperature, relative humidity, etc.) is hourly data obtained from the TRNSYS library. The TRNSYS TMY file contains the data files for the typical meteorological year data sets based on the measured meteorological phenomena measured in the Tunis city (Lat 36.83°N, Long 10.23°E).

#### 3.2 | Numerical simulation

Yearly heating loads of this typical Tunisian building are estimated using TRNSYS software.

It consists of connecting components graphically in the Simulation Studio. Each component represents a part of the problem. There are some components that represent the meteorological data, Type 56 is the component that represents the building, Type 36 is the component that represents the Trombe wall, and to visualize the results an online plotter was added, Figure 3.

This program was validated by an experimental setup in previous work. The results obtained by experimental measurements and those obtained by simulation with the TRNSYS program were compared. and this comparison showed a good agreement.
A simplified simulation strategy flow diagram of the current study is shown in Figure 3.

### 3.3 Annual heating demands

In this section, the effect of four different Trombe walls made with various construction materials on the annual heating demands of the building prototype was investigated. These materials were concrete, stone, adobe, and ordinary brick.

The thermal properties of these construction materials are shown in Table 1.

![TRNSYS simulation diagram.](image)

**Table 1** Thermal properties of the construction material.

| Material | Thermal conductivity (W/mK) | Specific capacitance (J/kgK) | Density (kg/m³) |
|----------|-----------------------------|------------------------------|-----------------|
| Concrete | 1.701                        | 960                          | 2300            |
| Stone    | 1.360                        | 840                          | 2200            |
| Adobe    | 0.631                        | 900                          | 1500            |
| Brick    | 0.456                        | 940                          | 700             |

A simplified simulation strategy flow diagram of the current study is shown in Figure 3.

In this section, the effect of four different Trombe walls made with various construction materials on the annual heating demands of the building prototype was investigated. These materials were concrete, stone, adobe, and ordinary brick.

The thermal properties of these construction materials are shown in Table 1.

Figure 4 visualizes the heating demands of the selected building before and after the installation of the Trombe wall system with different thicknesses.

For technical considerations, the solar wall has a total thickness varying between 0.1 and 0.5 m.

It is important to note that all the results obtained in the case of a 0.00 m thick Trombe wall correspond to the case of the typical building without a Trombe wall system. This case highlights the importance of installing this kind of wall in Tunisian buildings.

As it can be noticed, the annual energy consumption in winter for the selected residential building without Trombe wall system is 811.8 kWh.

The results shown in this figure demonstrate that approximately a reduction of 50% in annual heating loads can be obtained using a 0.1 thick Trombe wall for all considered material construction.

The important reduction in annual heating demands was obtained in the case of high thermal inertia materials such as stone and concrete. The minimum total heating loads were 315 kWh for stone and 290 kWh for concrete.

For all considered material construction, the annual heating loads decrease while the wall thickness increases until a specific thickness beyond it an increase in heating demands was observed.

This optimal thickness is 0.2 and 0.25 m for brick and adobe and between 0.35 and 0.4 m for concrete and stone.

This is due to the increase of the conduction thermal resistance, which minimizes the conduction heat flux entering the room, and also to the high thermal capacity provided with high thermal inertia material.

### 4 Economic Analysis

#### 4.1 Trombe wall cost

The total Trombe wall cost is related essentially to the construction material, wall area, wall thickness, and the type of glass used to cover the wall.
According to the Tunisian real estate agency and for reasons of confidentiality, the average cost of the total Trombe wall is varying between 75 and 350 TND for each cubic meter of the wall. So after calculation, the total Trombe wall cost was obtained for each thickness of construction material Figure 5.

Based on this figure, it can be seen that with the increase of Trombe wall thickness the total cost of the system increases linearly, while the cost of energy consumption decreases until an ideal value, and then it increases.

In addition, the cheapest wall is the brick wall followed by the stone one, and the most expensive wall is the concrete wall.

### 4.2 LCC analysis

LCC analysis was used to evaluate the cost and benefit of high-performance building envelopes and for historic building types.

The optimum Trombe wall thickness could not be deduced only by a thermal analysis but also by an economic investigation taking into account many parameters.

In this study, the Trombe wall optimization is estimated using LCC criterion defined as follows:

\[
LCC = C_{TW} + CM_{TW} + C_{Aux_{Ene}} - C_{Sav_{Ene}}
\]

(12)
Where $C_{TW}$ is the Trombe wall cost, $CM_{TW}$ is the maintenance cost of the Trombe wall, $C.AuxEne$ is the auxiliary energy cost, and $C.SavEne$ is the cost of saved energy due to Trombe wall.

The estimation costs are calculated for a building lifetime assumed to be equal to 30 years.

Over this period, the effects of the inflation rate “$i$” for the energy cost and the market discount rate “$d$” for the value of money should be taken into account. 41

According to the central bank of Tunisia, and during the last years, an average of 6% for the inflation rate and 8% for the discount rate can be considered for the rest of the calculations.

An actual value of the cost of energy consumption during a building life-cycle of $N$ years has been obtained by multiplying the annual cost of energy by a present worth factor (PWF) defined as follows:

$$PWF = \sum_{u=1}^{N} \left( \frac{1 + i}{1 + d} \right)^u = \frac{1 + i}{d - i} \left[ 1 - \left( \frac{1 + i}{1 + d} \right)^N \right]. \quad (13)$$

The total cost $C_T$ includes the calculated energy consumption cost and the Trombe wall cost. It is written as follows:

$$C_T = PWF \times C_{ene} + C_{TW}. \quad (14)$$

The optimum Trombe wall thickness is the value that minimizes the total cost $C_T$ by taking into account all these parameters.

### 4.3 Payback period

To judge whether the use of a Trombe wall is desirable or not for investment positions, a payback period $b$ should be calculated. This parameter can identify the time required to recover the cost of the total investment, it is defined as the cost of the Trombe wall divided by the annual energy savings, and it can be deduced from the following expression:

$$b = \frac{C_{TW}}{A_{ene,sav}}. \quad (15)$$

### 4.4 Economic optimization

For all construction material considered, the LCC initially decreases while the thickness of the wall increase until a specific optimum thickness beyond it the LCC increases Figure 6.

In Table 2, the optimal thickness of each material was identified from Figure 6 and the payback period was calculated for each case.

It is clear that the minimum LCC is obtained for the heavy materials (concrete and stone) that have an important heat capacity.

The results also demonstrated that the optimal thickness in heavy materials is more important than in light materials. This thickness was 0.2 m in the case of brick material compared to 0.32 m for concrete.

According to the results, the payback period reaches 2.56 years for the concrete material and 0.67 years for the brick material. This is because brick material is much cheaper than concrete and stone, but
in terms of LCC, concrete is more efficient than brick regarding the important economy of energy that it can make.

5 | CONCLUSIONS

To minimize heating loads in buildings, the optimization of a passive heating system, which is the Trombe wall, is done.

This study aims to determine the optimum Trombe wall thickness in the Tunisian context using energetic and economic analysis.

Energy-saving, LCC analysis, and payback period were analyzed to determine the optimum Trombe wall thickness of four materials often used in Tunisia. A sensitivity analysis showed that economic parameters, such as material cost, energy cost, inflation and discount rates and building lifetime, and physical parameters of materials used in the construction of the massive wall have a noticeable effect on optimum Trombe wall system and energy savings.

The results showed that over a building lifetime of 30 years the concrete Trombe wall is the most economical wall with an optimum thickness of 0.32 m and a payback period of 2.56 years.

NOMENCLATURE

| Symbol | Definition |
|--------|------------|
| A      | Trombe wall area (m²) |
| b      | payback period (Year) |
| C_{Aux Ene} | auxiliary energy cost (TND) |
| C_{Sav Ene} | saved energy cost due to Trombe wall (TND) |
| C_{ene} | energy cost (TND) |
| CM TW | maintenance cost of the Trombe wall (TND) |
| C_p | specific heat of the wall (J/kg K) |
| C_{p,a} | Specific heat of air (J/kg K) |
| C_T | total cost (TND) |
| C_{TW} | Trombe wall cost (TND) |
| d | discount rate (%) |
| e | Trombe wall thickness (m) |
| g | gravitational acceleration (m/s²) |
| h_i | internal convective heat transfer coefficient (W/m² K) |
| h_o | external convective heat transfer coefficient (W/m² K) |
| i | inflation rate (%) |
| m | air mass flow rate in the gap (kg/s) |
| Nu | Nusselt number |
| PWF | present worth factor |
| Q_{cond} | conduction heat flux (W) |
| Q_{rd, w} | radiation heat flux (W) |
| Q_{cv} | ventilation heat flux (W) |
| R | thermal resistance between the air gap and the room (K/W) |
| Ra | Rayleigh number |
| R_{cd} | conduction resistance (K/W) |
| T | temperature (K) |
| t | time (s) |
| T_m | mean air temperature in the gap (K) |
| TND | Tunisian National Dinar |
| T_r | room temperature (K) |
| T_{w, e} | external Trombe wall temperature (K) |
| T_{w, i} | internal Trombe wall temperature (K) |
| α | thermal diffusivity (m²/s) |
| β | thermal expansion coefficient (K⁻¹) |
| λ | thermal conductivity (W/m K) |
| ν | kinematic viscosity (m²/s) |
| ρ | density (kg/m³) |

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