# A calculation model for Trombe walls and its use as a passive cooling technique

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## ABSTRACT

A low energy technique for heat removal from the interior of a building under summer conditions is the employ of natural ventilation. There are several ways to promote this ventilation. The use of Trombe walls to obtain this objective is studied in the present work, with the aid of a combined mathematical-differences finites model. This is a transient model developed to take into account the thermal inertia of the wall and that can be easily applicable to a particular Trombe wall to estimate its behaviour. Additionally, the influence on heat balance done by different elements of the wall, and its properties was studied in a parametric work. This was done for different climates in Spain, and the results were analyzed with a new variable defined as DDD (degree-days difference). As a result of this parametric study, some guidelines of design were established in function of the climate conditions.

## 1. INTRODUCTION

The interest in passive solar heating has been increased in the last years, mainly for economic and environmental reasons. One of the most studied elements for this purpose is the Trombe wall. Its use can be an effective alternative on the reduction of the energy consumption in zones where heating is much more important than the refrigeration.

Nevertheless, in summer, the non wished effect of excessive heat gain can be presented through this element. This situation could be critic in those climates where summer is hot. In consequence, the Trombe wall utility must be carefully evaluated.

To increase the possibility of use of Trombe walls in hot climates, this element can be operated in different modes in order to minimize conduction heat gains through the storage wall and to maximize heat removal from the interior by the ventilation. Figure 1 shows the three modes of operation considered.

Mode (a) is useful to accumulate heat in the thermal mass of the storage wall if there is radiation falling. Mode (b) is used to remove energy from the storage wall in order to reduce the undesirable effect of heat conduction to the interior. Mode (c) uses the storage energy or the solar radiation falling to produce air ventilation. This mode is supposed to be working only if the exterior temperature is lower than interior.

## 2. MODEL DESCRIPTION

The air temperature and air velocity in the channel were calculated in a simplified mathematical model. Heat transfer through storage wall was calculated with a differences
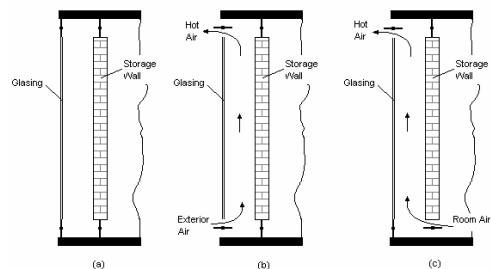


Figure 1: Diagram of operating modes for a Trombe wall in summer (a) closed, (b) exterior to exterior flow, (c) interior to exterior flow.

finites model.

## 2.1 Air Temperature

The air temperature in the layer, when this is in movement was calculated from Ec. 1. The schema of the model is showed in Figure 2.

$$Ta = Tp - \frac{v_A \cdot e}{V \cdot H}(Tout - Tin)$$

(1)

where:

$$Tp = \frac{Tg_L + Tw_L}{2}$$

(2)

$$V = \frac{h_c}{Cp \cdot \rho}$$

(3)

$$T_{out} = Tp - (Tp - Tin)\exp\left(-\frac{V}{e \cdot v_A} \cdot H\right)$$

(4)

$\rho$: average density of the air in the layer.
$Cp$: air specific heat capacity.
$h_c$: average convective heat transfer coefficient in the layer, Ec.(5).

$$h_c = \frac{Nu \cdot k}{e}$$

(5)

$k$: Thermal conductivity of air.
Nu: Nusselt number. Ec.(6) (Sparrow and Azevedo, 1985).

$$Nu = \left\{ \left(\frac{12}{(e/H)Ra}\right)^2 + \left(\frac{1}{0.619((e/H)Ra)^{1/4}}\right)^2 \right\}^{-1/2}$$

(6)

$Ra$: Rayleigh number.

## 2.2 Air Velocity

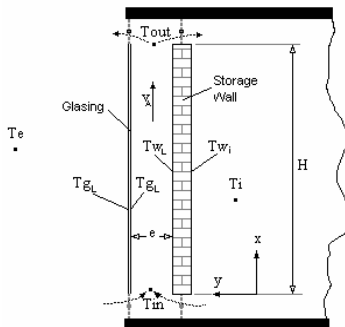The pressure difference, taking into account that

Figure 2: Schematic model.

the air temperature is not uniform in the vertical direction can be calculated with Ec.(7):

$$\Delta P = \frac{g \cdot M \cdot P_{atm}}{Ru}\left[\frac{H}{Ti} - \frac{H}{Tp} - \frac{e \cdot v_A}{V \cdot Tp}[\ln(Tout) - \ln(Tin)]\right]$$

(7)

where:
$\Delta P$: Pressure difference or stack pressure,
$M$: Molar weight of the air,
$P_{atm}$: Local atmospheric pressure,
$Ru$: Universal gas constant.

The air velocity is calculated from Ec.(8):

$$v_A = \left[\frac{2 \cdot \Delta P}{\rho \cdot \left(C_1\left(\frac{Ae}{Ain}\right)^2 + f\frac{H}{e} + C_2\left(\frac{Ae}{Aout}\right)^2\right)}\right]^{1/2}$$

(8)

where:
$C_1$: Pressure loss coefficient at the inlet of the channel.
$f$: friction factor for the channel.
$C_2$: Pressure loss coefficient at the outlet of the channel.
Ae: transversal area of the channel.
Ain: inlet area.
Aout: outlet area.

For this work it has been assumed rectangular inlet and outlet, and in consequence $C_1=1.5$, $C_2=1.0$, $f=0.056$ (Chen et al., 2003).

## 2.3 Heat transfer in the channel

The heat transfer in the channel was calculated in a simplified model based on the electro-thermal equivalent system shown in Figure 3.

In the electrical system, knows values are: all heat transfer coefficients, all material properties, outdoor temperatures, incident solar radiation, and superficial temperature of the storage wall.
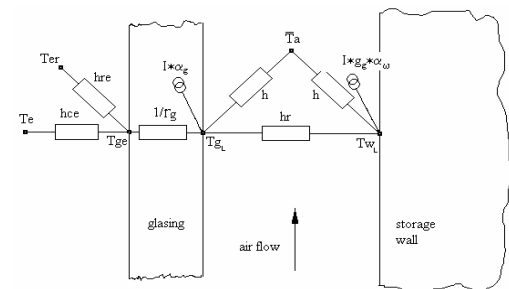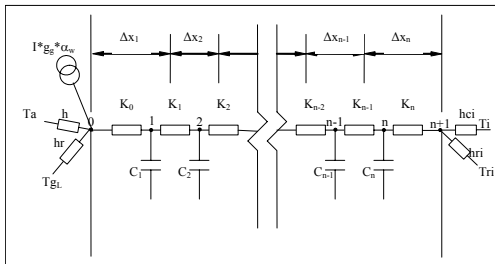
Figure 3: Electrical equivalent system.

Figure 4: Electrical equivalent representation of the storage wall model.

## 2.4 Heat transfer in the storage wall, and determination of superficial temperatures.

The model used in an electrical equivalent representation a sequence of conductances and capacitances as is shown in Figure 4.

On precedent paragraphs, isolated solutions were shown. To couple the whole system, an iterative process is necessary.

## 3. MODEL VALIDATION

The model was validated with the numerical model presented for Guohui Gan (Gan, 1998), who found a good agreement with experimental results.

The following figures (Figs. 5, 6 and 7) show the comparison between these two models for different parameters.

From the presented figures it is clear that good agreement between two models is achieved for most cases. Principal difference is on air flow rate for wall heights over 3m.

## 4. BEHAVIOUR OF TROMBE WALL UNDER SUMMER CONDITIONS

Climates selected for simulation were mainly of cities near to the Mediterranean Sea and for the months of June, July and August. Indoor air temperature and equivalent radiant indoor temperature were assumed to be invariables during the time simulated with a value of 25ºC.

Climatic data were simplified in two steps. The first step was to calculate two factors: the monthly degree-days over 25ºC and under 25ºC. The second step was to calculate the difference between the previous factors. By means of this simplification the climate is characterized in only one variable, defined as "DDD" (degree-
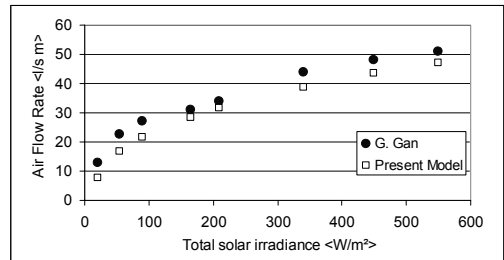


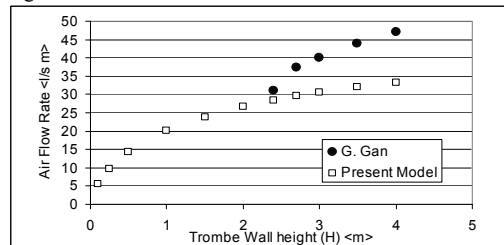Figure 5: Effect of solar irradiance on air flow rate.
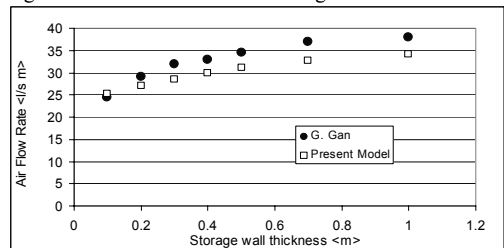


Figure 6: Effect of Trombe wall height on air flow rate.



Figure 7: Effect of storage wall thickness on air flow rate.

day difference) in Ec.9

$$DDD = (DD \text{ over } 25ºC)-(DD \text{ under } 25ºC) \quad (9)$$

Two kinds of climates were defined: "mild" and "hot". First ones are those with DDD<-100 ºC and second ones are those with DDD > 0 ºC.

The basic data of the Trombe wall model were: H=3m, e=0.1m, C1=1.5, f=0.056, C2=1.0, simple glassing, storage wall thickness=0.31 m, storage wall absortance=0.8.

## 4.1 Operation Mode Influence

As it was said in the introduction, simulations include three operation modes (Fig. 1). Also, three combinations of operation modes were performed.

- Combination (A). While there is solar radiation falling (direct, or diffuse), the Trombe wall will be operating in mode (a). In any other case will be operating in mode (c).

- Combination (B). While there is solar radiation falling (direct, or diffuse), the Trombe wall will be operating in mode (b). In any other case will be operating in mode (c).
- Combination (C). If there is solar radiation falling (direct, or diffuse), and the time is under 13 hour, the Trombe wall will be operating in mode (b). If the time is equal or over 13 hour, and there is solar radiation falling, the Trombe wall will be operating in mode (a). In any other case will be operating in mode (c).

In Figure 8, the heat gains through the storage wall are shown for several climates. It is seen that the heat increases when the difference of degree days enlarges. It is seen also, that combination (A) allows the highest heat gains while in combination (B) the heat gains are the lowest. But the difference between tree lines is close and they are approximately parallels.

Heat gain removal by the air is shown in Figure 9 for the tree operations combinations. It is seen that combination (A) is the most favorable to heat removal by air ventilation, but its advantage is reduced for hot climates. Combination (B) has a poor effect on heat

removal, and it is maintained approximately constant for all the climates considered. The combination (C) is located between (A) and (B), but it is close to combination (B).

The heat balance of the heat gains and heat removal is shown in Figure 10. As seen from the figure, is the combination (A) the most favorable for mild climates in summer, but for hot climates, combinations (A) and (B) are similar, being the combination (C) the worst, but with a short difference.

For a very different wall (thinner wall and higher U-value), as the shown in Figure 11, the heat balance has approximately the same tendency, but for hot climates combination (C) shows and intermediate behaviour between combinations (A) and (B), being combination (B) the best for the hottest climates.

### 4.2 Glassing Influence

Two glassing types were considered, simple and double. Figure 12, shows the heat balance for the Trombe Wall with simple and double glassing for two operation modes. It is seen that double glassing improves the Trombe wall behaviour for all the climates considered, but its advantage is higher for mild climates.

### 4.3 Insulation Influence and Wall thickness

Inner insulation for the storage wall was considered.

Figure 13 shows the heat gains through the storage wall for several climates. It is seen that for hot climates the advantageous of using insulation is greater than for mild climates.

In Figure 14, the air heat remove is shown. It is seen that there is not big difference between them.

Heat balance is shown in Figure 15. It is seen that for 4cm of thickness insulation an important
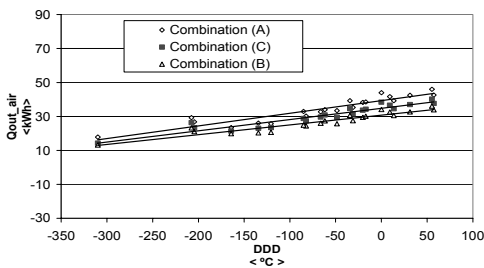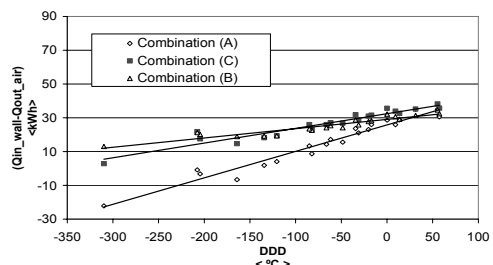


Figure 8: Operation mode influence on heat gains through the storage wall.
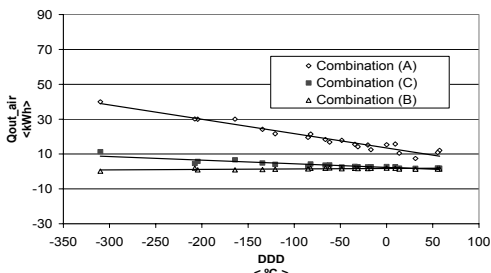


Figure 9: Operation mode influence on heat removal by the air ventilation.



Figure 10: Operation mode influence on heat balance (gains-heat removal).
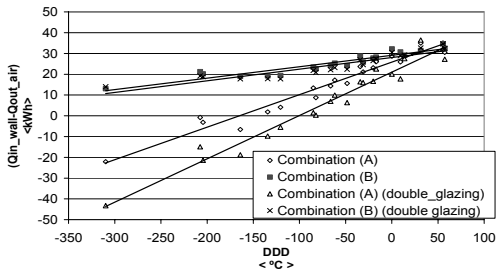
Figure 12: Influence of simple and double glassing on monthly heat balance (gains-heat removal).
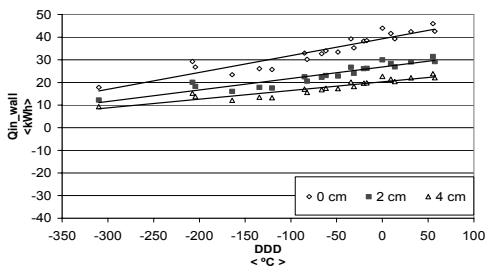


Figure 13: Inner insulation influence on heat gains through the storage wall.
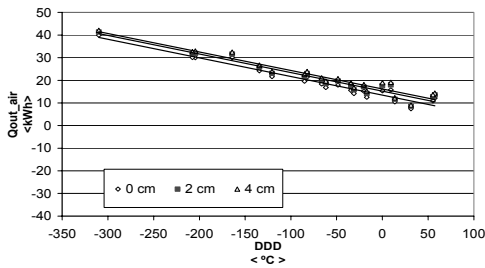


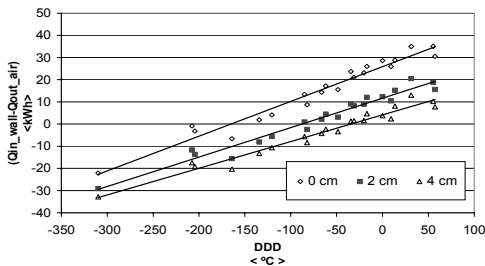Figure 14: Inner insulation influence on heat removal by the air ventilation.



Figure 15: Inner insulation influence on heat balance (gains-heat removal).

proportion of points are located under zero.

## 5. CONCLUSIONS

Combinations of operation modes of a Trombe wall affect its thermal behaviour. This effect is more relevant on climates with mild summer. The most convenient combination for these mild climates is the combination (A). It seems to be valid for a wide range of thermal inertia and heat conductance of the storage wall.

For hot climates, the combinations of operation modes are not as relevant as for mild climates, but the thermal mass and thermal resistance of the storage wall, could be a decisive variable to define the best combination of operation modes. Combination (A) can be more favourable if the thermal inertia and thermal resistance of the wall are higher than for a wall whit low value of thermal mass and resistance. For this last case, a combination (B) could be more adequate.

Double glassing improves Trombe wall behaviour, but its benefit is short in hot climates.

Inner insulation shows a strong benefit on Trombe wall behaviour. It is motivated by the fact that conduction heat gains are strongly diminished.

For a Trombe wall under summer conditions and constant indoor temperature, the conduction heat gains and air heat remove, are approximately linear with DDD (degree-days difference), defined in Ec. (9).

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