Explicit Model for Solar Air Heaters Performance Assessment for Winter and Summer Operation

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Abstract: - Towards zero energy consumption buildings, designers need an easy tool to assess in the first stage of the design the performance of passive heating and/or cooling elements like the Trombe wall. In the present work a quasi-steady explicit model is developed for the operation of naturally ventilated Trombe wall for heating and for cooling (operation as solar chimney), based on ISO 13790. For the heating period, three configurations were considered: a) Without thermal mass for heat storage, b) With thermal mass wall and, c) With remote heat storage system of phase change materials. For the cooling period the (b) configuration was considered. The developed model is consisted by a set of equations that can be solved sequentially (no need for software and/or programming) and can be in the early stage of building design to maximize the yearly utilizable heat gains. The heat storage wall can increase the utilization of thermal gains from 15% to 46%. The use of phase change materials can increase these thermal gains up to 77%. The successful summer operation depends on the external climatic conditions and requires management of operation with an automation system when the thermal solar gains overweight the ventilation losses.

Key-Words: - Passive solar systems, heat storage, quasi-steady explicit model, Trombe wall, solar chimney, solar heating, passive buildings

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1 Introduction

Towards zero-energy homes, among other things, passive systems solutions are being considered, whether they are new buildings or renovations of existing buildings [1]. In addition, for the design of new buildings, their energy efficiency, and therefore the integration of passive systems in the shell, should be taken into account from the initial stages of their design [2]. Solar Air Heater is a quite simple low maintenance device capable to increase fresh air temperature and thus, it can be used in several applications requiring low to moderate increase in temperatures such as space heating, drying, etc. A fairly common such system is the Trombe wall which is a high thermal capacity, solar radiation absorbing wall, with transparent insulation and an air-gap between the wall and the transparent element. The Trombe wall can be used as a passive heating system during the winter months while during the summer it can offer cooling by operating as a solar chimney.

In its winter operation the wall stores heat and supplies it to the adjoining room either by conductivity through the wall or by convection through ventilation slots. During the summer operation as solar chimney, a slot opens at the top of the glazing, while the upper slot, which connects the gap with the interior of the room, remains closed. In this way the hot air inside the air gap rises with thermal buoyancy and exits the gap to the outside environment through the glazing open slot. Vacuum is created in the space of the gap, as a result of which air enters from inside the room. In order for the device to operate as a solar chimney, it is necessary to have an opening on the north side of the room. Thus, due to the vacuum that is now created inside the room, air is forced to enter it from the north opening, resulting in the ventilation of the space.

The operation of a Trombe wall is a dynamic phenomenon with the transport effects involved depending on the ever-changing external conditions and heat storage. This is therefore a difficult dynamic problem. Nevertheless, in order for such a system to be integrated into the design of a building, the design engineer must have at his disposal a user-friendly computing tool for an initial assessment of its operation in the early stages of design.

Numerous software tools have been developed by many researchers for the simulation of a Trombe wall operation (EES, T*SOL, TRANSOL) [3,4,5]. The existing analytical models suffer from two shortcomings: The first is that even in the case of a monthly time step require iterations and thus some kind of programming effort, the second is that they require the knowledge of data like heat transfer coefficients and dynamic parameters for which the standards give some much-generalized values.

Some of these analytical models are embodied in BES (Building Energy Simulation) models, like Design Builder [6] which is used along with the EnergyPlus [7] to calculate the energy performance of buildings with Trombe wall in Portugal [8]. In fact, the most widely used BES models are the EnergyPlus [9, 10] and the TRNSYS [11, 12]. Yet they require the purchase and learning of software, so they are no adequate for early-stage design.

The next alternative is the use of CFD, which can be used either for the simulation of the operation of a whole Trombe wall along with the served room [9, 10, 13], either for the study of operation and design of discrete parts of a Trombe wall [14]. The use of CFD requires special knowledge, software, and computational time and is not adequate for early-stage designing, neither can be used by all the designers.

The last choice is the use of a quasi-steady model. ISO 13790 [15] and the corrections suggested by [16] are subject of the following limitations: (i) Holds only for mechanically ventilated Trombe walls (requires the knowledge of airflow through the air gap) and (ii) Does not account for the available thermal mass. Since this model concerns the operation of forced ventilated wall it cannot be directly applied for naturally ventilated one. It should be noted that the ISO 52016 [17], which replaced the ISO 13790, does not address the Trombe wall. In addition, the majority of these models relate to the winter use of the Trombe wall and not the possibility of using it as a solar chimney for cooling.

It is obvious that from the above models only the quasi-steady could be developed into explicit models that can be easily used in the initial design phase of a building.

In the present paper, user-friendly, simplified and explicit (they do not require iteration procedure for the resolve of the model's equation system, which can be solved sequentially) quasi-steady models are developed for winter and summer operation of a Trombe wall, based on the concept supported by ISO 13790:2009, for the prediction of the performance of various glazed SAHs. For the winter operation the addressed configurations will be: a) Opaque element with transparent insulation without thermal mass for heat storage, b) Trombe-Michel configuration with the appropriate mass thermal storage wall and, c) Opaque element with transparent and heat storage system away from the opening for day–night operation. For the summer operation the first configuration will be considered.

The heat transfer through radiation and convection and the heat storage will be described for steady-state conditions and the dynamic phenomena will be taken into account according to the instructions of the ISO 13790. The values for the air flow will be calculated according to the analytical energy balance model [18], for the case without thermal storage mass, and according to analytical model for the cases with [19] thermal storage mass. Those models will provide an easy tool for engineers in order to assess the energy savings from those passive systems at the first stage of the design without the use of special software for the simulation of annual behavior.

2 Quasi-steady models

2.1 Quasi-steady model for heating period

A quasi-steady model for the calculation of heat provided from a Trombe wall in a monthly period was developed according to ISO 13790 and the revision of Ruiz-Pardo et al. (2010) [16], adopting a number of simplification assumptions regarding the calculation of convective and radiative heat transfer coefficients.

The total energy contribution of the Trombe wall during a month, QTCC [kWh/mo] is calculated from the relationship,

$$Q_{TCC} = \eta_{H,gn} Q_{H,gn} - Q_{H,ht} \tag{1}$$

Where, $\eta_{H,gn}$, the dimensionless gain utilization factor for heating, depended on the whole building (building inertia) where the Trombe wall is installed. At the moment it will be considered 1 meaning that there is the adoption of an ideal situation where all the solar heat gains are utilized. $Q_{H,gn}$ [kWh/mo] is the total sum of solar gains from Trombe wall, and $Q_{H,nt}$ [kWh/mo] is the total sum of heat losses from Trombe wall.

$$Q_{H,ht} = Q_{tr} + Q_{ve} \tag{2}$$

In the above relationship, Q_{tr} [kWh/mo] is the total heat transfer by transmission, and Q_{ve} [kWh/mo] is the total heat transfer by ventilation. During Winter

Q_{ve} is zero since there is no external air entering the room through Trombe wall.

$$Q_{tr} = \left(H_{tr,adj}(\theta_{int,set} - \theta_e)t\right)/1000 \quad (3)$$

Where, $H_{tr,adj}$ [W/K] is the overall heat transfer coefficient by transmission of the Trombe wall, $\theta_{int,set}$ is the set-point temperature of the building, which will be considered 20 ºC, θ_e [4] is the temperature of the external environment and t is total period of the examined month [18].

$$H_{tr,adj} = H_o + \Delta H \quad (4)$$

Where, H_o [W/K] is the heat transfer coefficient of the non-ventilated wall, ΔH [W/K] is an additional heat transfer coefficient due to Trombe wall operation.

$$H_o = H_D + H_g + H_U + H_A \quad (5)$$

Where, H_D [W/K] is the direct heat transfer coefficient by transmission to the external environment, H_g [W/K] is the steady-state heat transfer coefficient by transmission to the ground, which is considered zero since Trombe wall is not adjacent to the ground, H_U [W/K] is the transmission heat transfer coefficient by transmission through unconditioned spaces which is also considered zero because there is no present unconditioned space and H_A [W/K] is the heat transfer coefficient by transmission to adjacent buildings which is considered zero as well because adjacent buildings are not considered.

$$H_D = b_{tr,x}\left[\sum_i A_i U_i + \sum_k l_k \psi_k + \sum_j x_j\right] \quad (6)$$

Where, $b_{tr,x}$ [-] is the adjustment factor which takes the value 1 because Trombe wall is adjacent to the external air, A_i [m²] is the area of element *i* of the building envelope, U_i [W/m²K] is the thermal transmittance of element i of the building envelope, l_k [m] is the length of linear thermal bridge k, ψ_k [W/mK] is the linear thermal transmittance of thermal bridge k, x_j [W/K] is the point thermal transmittance of point thermal bridge j. Since the analysis concerns only the Trombe wall the thermal bridges, both linear and point are ignored. This way the direct heat transfer coefficient calculation is reduced to

$$H_D = A_{sw} U_o \quad (7)$$

Where, A_{sw} [m²] is the Trombe wall area and U_o [W/m²K] the thermal transmittance of the whole wall Trombe structure.

$$\Delta H = \rho C_p \dot{V} \frac{U_o^2}{U_i^2} \kappa \delta \quad (8)$$

Where, ρ [kg/m³] is the air density, C_P [J/KgK] is the air specific heat capacity, $\dot{V}$ [m³/s] is the air flow rate through the gap between the Trombe wall glass and the thermal storage wall, $1/U_i$ [W/m²K] is the internal thermal resistance, κ [-] is a non-dimensional parameter related to the air layer temperature and, δ [-] is the ratio of the accumulated internal–external temperature difference when the ventilation is on, to its value over the whole calculation period.

$$U_o = \frac{1}{1/U_i + 1/U_e} \quad (9)$$

Where, $1/U_e$ [W/m²K] is the external thermal resistance.

$$U_i = \frac{1}{R_i + \left(R_c/2\right)} \quad (10)$$

Where, R_i [m²K/W] is the thermal resistance from the air layer to the internal environment and R_c [m²K/W] is the thermal resistance of the air in the air gap, which is calculated from the following relationship.

$$R_c = \frac{1}{h_r + \left(h_c/2\right)} \quad (11)$$

Where h_r [W/m²K] is the radiant heat transfer coefficient inside the air gap and, h_c [W/m²K] is the convection heat transfer coefficient inside the air gap which is taken equal to 10 for simplification for vertical internal flow [18].

$$h_r = \frac{\frac{1}{\varepsilon_{g,i}} + \frac{1}{\varepsilon_w} - 1}{\sigma\left(T_{ee}^2 + T_{ei}^2\right)\left(T_{ee} + T_{ei}\right)} \quad (12)$$

Where, $\varepsilon_{g,i}$ [-] is the glass air gap surface emissivity of the air gap surface, ε_w [-] is the wall air gap surface emissivity, σ is the Stefan Boltzmann constant equal to $5.67\mathrm{x}10^{-8}$. T_{ee} [K] is the glass air gap surface temperature and T_{ei} [K] is the wall air gap surface temperature. For simplicity and only for the calculation of radiant heat transfer are considered 15 ºC and 45 ºC correspondingly.

$$R_i = \frac{1}{h_i} + R_{ei} \quad (13)$$

Where, h_i [W/m²K] is the convective heat transfer coefficient to the internal room, taken equal to 10 (ISO 6946:2007) [20] and R_{ei} [m²K/W] is the thermal resistance through the storage wall which is calculated according to the wall layers.

$$R_{ei} = \sum_i \frac{d_i}{\lambda_i} \quad (14)$$

Where, d_i [m] is the width of the layer i and λ_i [W/mK] is the thermal conductivity of the layer i.

$$U_e = \frac{1}{R_e + \left(R_c/2\right)} \quad (15)$$

Where, R_e [m²K/W] is the thermal resistance from the air layer to the external environment

$$R_e = \frac{1}{h_e} + R_{ee} \quad (16)$$

Where, h_e [W/m²K] is the convective heat transfer coefficient to the external environment, taken equal to 25 for simplification for external vertical flow (ISO 6946:2007) and R_{ee} [m²K/W] is the thermal resistance through the glass cover calculated from

$$R_{ee} = \sum_i \frac{d_i}{\lambda_i} + R_\delta \quad (17)$$

Where, R_δ [m²K/W] is the thermal resistance of air between the glasses which can be taken from ISO 6946:2007 depending from the glass configuration.

$$\kappa = 1 - exp\left(-\frac{ZA_{sw}}{\rho C_p \dot{V}}\right) \quad (18)$$

Where, Z [W/m²K] is a parameter with which is taken into account the temperature evolution of the air along the air gap.

$$Z = \frac{1}{R_{VR} + \frac{1}{U_i + U_e}} \quad (19)$$

Where, R_{VR} [m²K/W] is the star equivalent resistance in the air layer calculated from the relationship

$$R_{VR} = \frac{h_r}{h_c(2h_r + h_c)} \quad (20)$$

$$\delta = \begin{cases} 0.08ln(\gamma_{al}) + 0.2 & \gamma_{al} > 0.7 \\ 0.3\gamma_{al} + 0.03(0.0003^{\gamma_{al}} - 1) & \gamma_{al} < 0.7 \end{cases}$$
(21)

Where, γ_{al} [-] is the gains/losses ratio of the air layer calculated from the following relationship

$$\gamma_{al} = \frac{Q_{gn,sw}}{Q_{ht,al}} \quad (22)$$

Where, $Q_{gn,sw}$ [kWh] is the solar heat gains of the air layer during the examined month and $Q_{ht,al}$ [kWh] heat losses of the air layer during examined month.

$$Q_{gn,sw} = I_w F_w g_{gl} A_{sw} \quad (23)$$

Where, I_w [kWh/m²] is the total monthly solar energy incident on Trombe wall, F_W [-] is the correction factor for non-scattering glazing, g_{gl} [-] is the total solar energy cover transmittance

$$Q_{ht,al} = \left(U_e A_{sw}\left(\theta_{int,set} - \theta_e\right)t\right)/1000 \quad (24)$$

$$Q_{H,gn} = Q_{int} + Q_{sol} \quad (25)$$

Where, Q_{int} [kWh/mo] is the heat gains from internal heat sources which is taken zero since only the operation of the Trombe wall is considered and Q_{sol} [kWh/mo] is the solar heat gains which is calculated from the following relationship

$$Q_{sol} = \left[\Phi_{sol}t + \left[\textstyle\sum_l\left(1 - b_{rt,l}\right)\Phi_{sol,l}\right]t\right]/1000 \quad (26)$$

Where, Φ_{sol} [W] is the time-average heat flow rate from Trombe wall, $b_{rt,l}$ [-] is the adjustment factor for the adjacent unconditioned space, Φ_{sol},l [W] is the time-average heat flow rate from solar heat source *l* in the adjacent unconditioned space which is taken equal to zero since only the Trombe wall is considered and t is the total period of daylight during the examined month [h].

$$\Phi_{sol} = F_{sh} A_{sol} I_{sol} - F_r \Phi_r \quad (27)$$

Where, F_{sh} [-], is the shading reduction factor for external obstacles, A_{sol} [m²] is the effective collecting area of Trombe wall surface, I_{sol} [W/m²] is the mean solar irradiation over the examined month per square meter of collecting Trombe wall surface, with a given orientation and tilt angle, Fr [-] is form factor between the building element and the sky which is taken 0.5 and Φ_r [W/m²] is the extra heat flow due to thermal radiation to the sky from the Trombe wall.

Given the above and expressing solar gains as a function of the total monthly radiation incident to the wall, I_w [kWh], the solar heat gains can be calculated from the following relationship

$$Q_{sol} = F_{sh} A_{sol} I_w - F_r \Phi_r t/1000 \quad (28)$$

$$\Phi_r = R_{se} U_c A_{sw} h_{re} \Delta\theta_{er} \quad (29)$$

Where, R_{se} [m²K/W] is the external surface heat resistance of the glass of the Trombe wall, A_{sw} [m²] is Trombe wall surface, U_c [W/m²K] is the thermal transmittance of the cover system of the Trombe wall, h_{re} [W/m²K] is the external radiative heat transfer coefficient from the external surface of the Trombe wall cover to the external environment, and $\Delta\theta_{er}$ [K] is the average difference between the external cover surface temperature and the apparent sky temperature which is taken only for the Φ_r calculation equal to 10 K for simplicity according to ISO 13790: 2008.

$$R_{se} = \frac{1}{h_e} \quad (30)$$

$$U_c = \frac{1}{R_c + R_{ee} + R_{se}} \quad (31)$$

The radiant heat transfer coefficient is calculated from a simplified relationship

$$h_{re} = 5\varepsilon_{ge} \quad (32)$$

Where ε_{ge} [-] is the cover external surface emissivity

$$A_{sol} = A_{sw} a F_s F_F F_W g_{gl}\left[U_o(R_e + R_c) + R_i \frac{U_o^2}{U_i U_e}\frac{\rho C_p \dot{V}}{A_{sw}}\kappa\right] \quad (33)$$

Where, α [-] is the wall absorption coefficient, F_S [-] is the shading reduction factor and F_F [-] is the frame reduction factor.

This way and with the adopted assumptions an explicit system of equations which can be resolved sequentially in a spread sheet was created, providing that the flow rate in the gap is known. The concept is to provide the flow rate as monthly average and as function of basic geometry characteristics of the Trombe wall using an energy balance model developed in [18] for the cases without thermal storage and in [19] for the cases with thermal storage. These models resolve simultaneously an implicit equation system with an hourly step for indicative days of each examined month.

2.2 Modifications of basic quasi-steady model

As it was stated at the beginning of paragraph 2.1 a basic assumption is that the gain utilization factor is considered unit which means that the model describes an ideal situation where all the Trombe wall solar gains are utilized as a whole. We know that in practice this does not happen. So, the above-developed model describes an ideal operation with which we can calculate the maximum limit of the Trombe wall performance. In practice, the wall Trombe performance depends on the available heat capacity of the conditioned room plus the passive element's heat capacity. The influence of available heat capacity is modeled through the calculation of the gain utilization factor $n_{H,gn}$. According to the [15] $n_{H,gn}$ is calculated from the following relationship, depending on heat balance ration γ_H.

$$\gamma_H > 0, \neq 1 \quad n_{H,gn} = \frac{1-\gamma_H^{a_H}}{1-\gamma_H^{a_H+1}}$$
$$\gamma_H = 1 \quad n_{H,gn} = \frac{\alpha_H}{\alpha_H+1} \qquad (34)$$
$$\gamma_H < 0 \quad n_{H,gn} = \frac{1}{\gamma_H}$$

$$\gamma_H = \frac{Q_{H,gn}}{Q_{H,nt}} \qquad (35)$$

Where, $Q_{H,gn}$ [kWh] is the total heat transfer by transmission and ventilation of the examined building zone, $Q_{H,nt}$ [kWh] total heat gains, and α_H a numerical parameter depending on the time constant.

$$\alpha_H = \alpha_{H,0} + \frac{\tau}{\tau_{H,0}} \qquad (36)$$

Where, $\alpha_{H,0}$, a dimensionless reference numerical parameter, equal to 1 for monthly calculation method, $\tau_{H,0}$, a reference time constant equal to 15 [h] for monthly method.

$$\tau = \frac{C_m/3600}{H_{tr,adj}+H_{ve,adj}} \qquad (37)$$

Where, C_m, [J/K] the internal heat capacity of the building zone, $H_{tr,adj}$, [W/K] the overall heat transfer coefficient by transmission and $H_{ve,adj}$ [W/K] the overall heat transfer coefficient by ventilation.

Since we want to study the Trombe wall performance in the modified models we will consider only the passive elements heat capacity.

a) Opaque element with transparent insulation without thermal mass for heat storage, C_m=0 and α_H =1
b) Trombe-Michel configuration with the appropriate mass thermal storage wall Cm = the storage wall heat capacity
c) Opaque element with transparent and heat storage system away from the opening for day–night operation. Cm = storage wall heat capacity + remote storage system heat capacity. In the case in which the remote storage system is a phase change material (pcm) it can be taken into account only the latent heat of the pcm.

2.3 Quasi-steady model for cooling period

The total energy contribution of the Trombe wall for the summer operation during a month, Q_{TCC} [kWh/mo], is calculated from the relationship

$$Q_{TCC}=\eta_{C,ls}Q_{C,ht}-Q_{C,gn} \qquad (38)$$

Where, $\eta_{C,gn}$, the dimensionless gain utilization factor for cooling, depended on the whole building inertia, considered as 1 eg all the heat losses offered by the Trombe wall are utilized. $Q_{C,ht}$ [kWh/mo] are the heat losses due to the Trombe wall operation and $Q_{C,gn}$ [kWh/mo] are the heat gains from the Trombe wall operation.

$$Q_{C,ht}=Q_{tr}+Q_{ve} \qquad (39)$$

In the above relationship Q_{tr} [kWh/mo] is the total heat transfer by transmission, which is calculated using the equations (1) – (24) and Q_{ve} [kWh/mo] is the total heat transfer due to ventilation offered by Trombe wall which is calculated with the following relationship

$$Q_{ve} = H_{ve}\left(\theta_{int,set} - \theta_e\right)t \Big/ 1000 \qquad (40)$$

Where, H_{ve} [W/K] the heat transfer coefficient due to ventilation through the Trombe wall

$$H_{ve} = \rho Cp\dot{V} \qquad (41)$$

The heat gains are calculated again using the equations (25) – (33). The required flowrate is taken by the energy balance model developed by authors in [18] with a small modification. The modification concerns the temperature at which the air enters the air gap which is considered equal to the external environment temperature.

3 Study case

The developed models were used for the calculation of a Trombe wall performance of an experimental chamber well insulated without available internal heat capacity. The chamber has a length 3 m, width 2.8, and height 2.8 m and it is constructed by polyurethane panels of 9 cm. Its south wall is covered by a Trombe wall height 2.1 m (distance between the ventilation holes) and a width 2.6 m. The ventilation slots are 7 apertures for the entrance of air from the room to the air gap (low apertures) and 7 apertures for the entrance of air from the air gap to the room (upper apertures) of 12.4 cm diameter. The air gap between the cover and the Trombe wall is 10 cm. The cover is made of a double 4-15-5 solar glass. For case (b) the storage wall is considered to have a thickness of 10 cm and it is constructed from bricks. For case (c) an organic pcm is considered (Dutil et al. 2010) [21] with latent heat 190 kJ/kg in with volume 0.05x0.5x2.8 m sited in the north wall of the chamber. For the case of summer operation, as solar chimney, the upper ventilation slots are considered closed while the upper section of the transparent cover is open to the environment. Additionally, an open window in the north wall allows external air enters to the room.

In Figure 1 a cross-section of the examined geometry without pcm (cases a and b) is given while in Figure 2 the cross-section with pcm is presented (case c). In Figure 3 the cross-section of the solar chimney operation is presented.

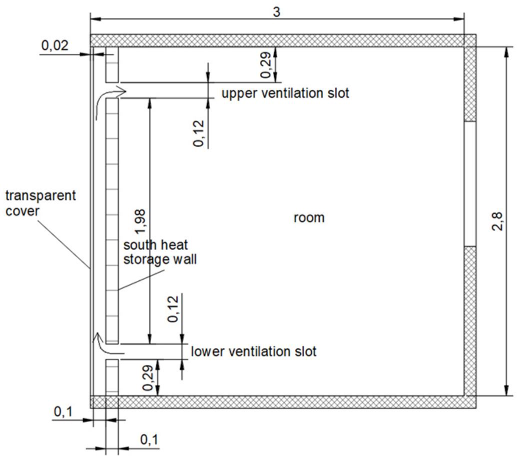

Figure 1 Cross-section of examined chamber without pcm (cases a and b)

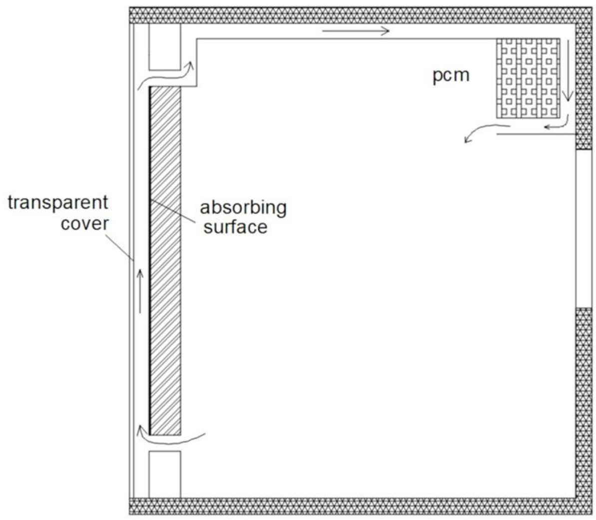

Figure 2 Cross-section with the pcm (case c)

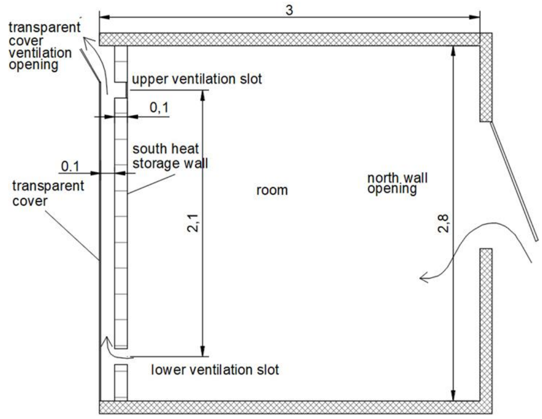

Figure 3. Cross-section for the solar chimney operation

The chamber is considered sited in Central Greece (latitude 39.39° and longitude 27.75°) with ground reflectance equal to 0.2. For the winter (October – April) operation the design temperature is 20 °C, while for the summer operation (May – September) the design temperature is considered 26 °C. In Table 1 the considered climatic conditions are presented.

Table 1. Considered climatic conditions

Month	Average Day Temperature, θ_e [C]	Total monthly radiation on horizontal, $H_{m,tot}$ [kWh/m^{2}mo]	Diffusive monthly radiation on horizontal, $H_{m,d}$ [kWh/m^{2}mo]
October	18.4	98.8	38.5
November	13.5	63.1	24.8
December	9.4	51.5	20.5
January	8	61.3	23.9
February	9.1	74.3	30.9
Mars	11.3	112.5	49.1
April	15.7	149.2	65.1
May	20.9	189.7	82.1
June	25.9	212.7	86.1
July	28.2	217.4	85.7
August	27.7	195.1	73.5
September	23.7	146.8	54.7

In Table 2 the optical and thermophysical properties of the considered materials are presented.

Table 2. Optical and Thermophysical properties

Property	Value	Property	Value
Air specific heat capacity, Cp [J/kgK]	1006	Glass air gap surface emissivity, ε_{gi} [-]	0.1
Air density, ρ [kg/m^3]	1.225	Storage wall absorption coefficient, α	0.97
Wall air gap	0.97	Cover external surface	0.8

surface emissivity, ε_w [-]		emissivity, ε_{ge} [-]	
Storage wall Specific heat capacity, C_{pw} [J/kgK]	1000	Bricks thermal conductivity $\lambda_{w,b}$ [W/mK]	0.64
Thermal resistance through the glass cover, R_{ee} [m^{2}K/W]	0.53	Total solar energy cover transmittance, g_{gl} [-]	0.6

In Figure 4 the monthly average flow rate though the air gap calculated according to [18] for case (a) and according to [19] for the cases (b) and (c) are presented. The existence of thermal storage mass reduces the mass flow rate by 10%.

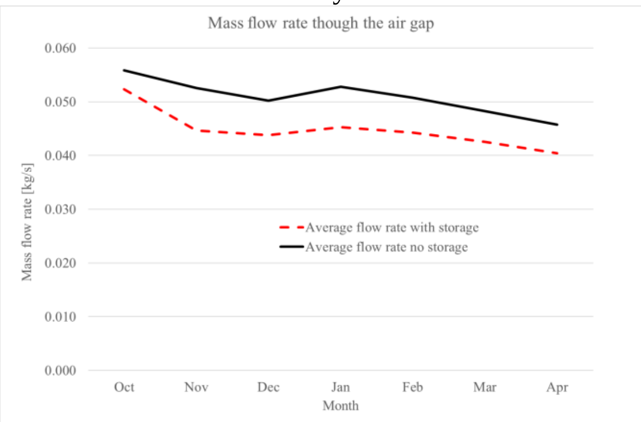

Figure 4. Mass flow rate through the air gap

In Figure 5 the monthly average flow rate through the air-gap according to [19] for the summer operation is presented.

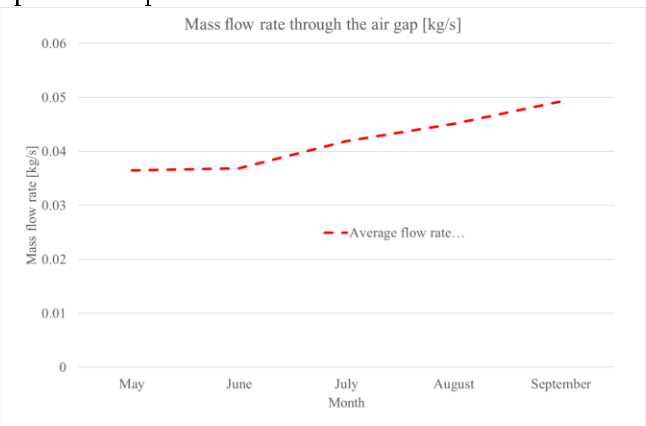

Figure 5. Mass flow rate through the air gap

3 Results and discussion

3.1 Results and discussion for the heating period

In the following Figure 6 the heating gains from the examined Trombe wall are given for the ideal operation, in which all solar gains can be exploited, for both cases with and without existence of thermal storage mass. It comes out that the influence of thermal storage mass is insignificant. The ideal heat gains follow the available solar radiation and the external air temperature.

In Figure 7 the utilizable heating gains for the three examined configurations are presented. It is obvious that during relative hot months although the Trombe wall gains are important their contribution to the energy balance is small. While during the winter months this contribution increases as the available heat storage capacity increases. The contribution of the Trombe wall without thermal storage is almost independent of the external climatic conditions and limited to low values around the whole year. The use of storage wall can increase the utilization of Trombe wall gains from 15% in October to 46% during the winter months. Even more important is the improvement achieved during the winter months with the usage of pcm that can increase the storage wall gain even up to 77%. Of course, if the examined wall served a bigger room with more important heat losses, then the utilization would be higher even during the autumn months.

In Figure 8 the percentage covered by Trombe wall heat losses is presented. Utilization of thermal mass always adds a 10% increase in the percentage of heat loss covered by the Trombe wall. However, the use of phase change materials provides coverage of more than 50% all year round and increases the coverage of heat loss during the winter months by more than 20% compared to the Trombe wall of 10 cm and by 30% compared to the solar thermal system without thermal mass.

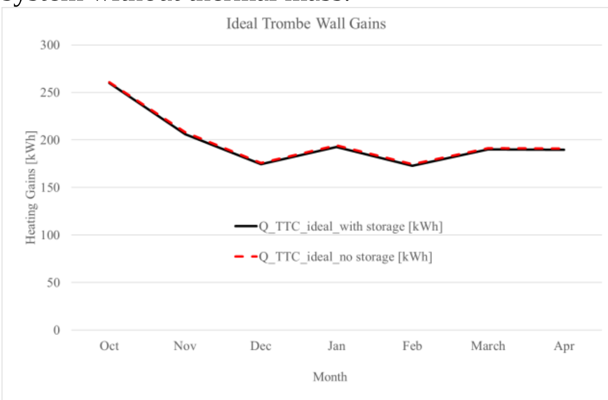

Figure 6. Trombe wall ideal heat gains

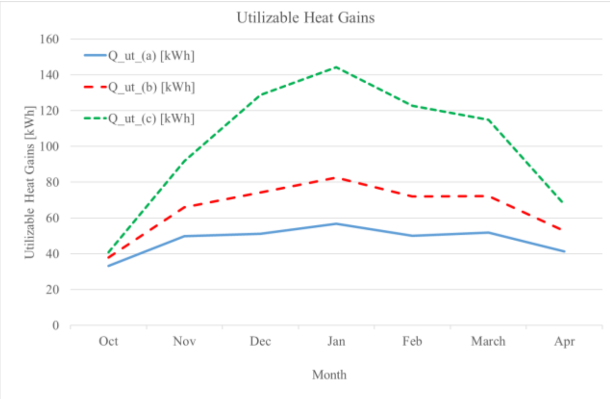

Figure 7. Trombe wall utilizable heat gains

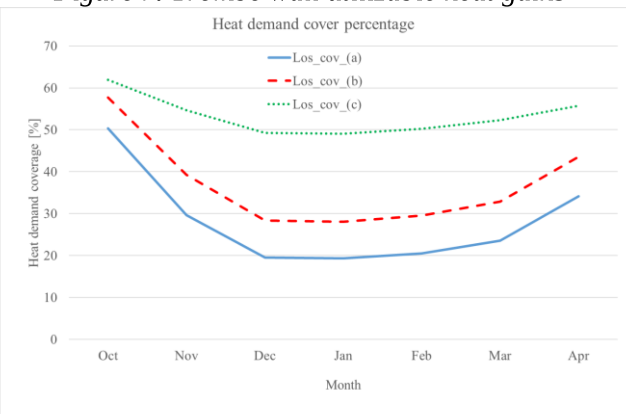

Figure 8. Heat losses cover percentage

3.2 Results and discussion for the cooling period

In Figure 9 are presented: a) the solar gains from Trombe wall, QC,gn [kWh/mo], which correspond to the cooling loads attributed to the operation of the wall, and b) the heat losses (through the shell and ventilation) due to wall operation as a solar chimney, which corresponds to the wall contribution to the cooling for the examined summer months.

Figure 9. Cooling loads and cooling contribution from Trombe wall

Figure 9 shows that in July and August, in addition to the solar gains through the Trombe wall, which are added to the cooling loads of the serviced building, and the 'losses' through the Trombe wall, which should contribute to cooling, are negative. This is because the outside temperature is higher than the design temperature of the room. Therefore, during these months, the Trombe wall cannot serve the space as a solar chimney and should be out of order and fully shaded.

Figure 10 gives the total energy contribution of the Trombe wall for the summer operation during a month, Q_{TCC} [kWh/mo], during the examined months.

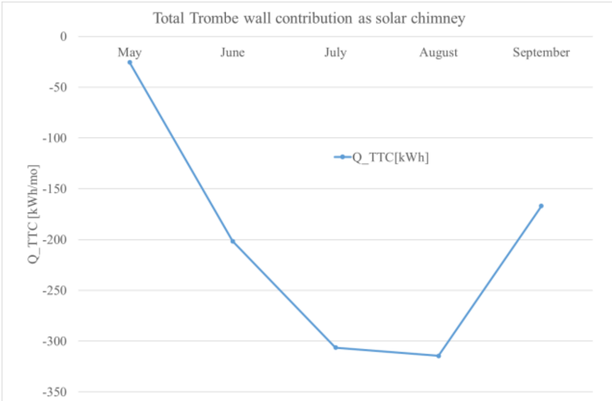

Figure 10. Total energy contribution from the Trombe wall, Q_{TTC} [kWh/mo]

From the Figure 10 it comes out that the total Trombe wall contribution as passive cooling element is never positive in any of the examined months. This means that the increase in cooling loads in the room, due to the operation of the Trombe wall, is always greater than the cooling due to ventilation. From Figure 9, however, it appears that a contribution to the coverage of cooling loads also exists in the months of May, June and September. This means that during these months some hours of the day the Trombe wall can contribute to the cooling of the building but other hours as well as overall, solar gains outweigh the cooling loads making the operation throughout the month negative. Therefore, during these months, the Trombe wall could only work with some automatic control system. Another modification could be to add insulation to the wall so that the temperature of the wall surface in contact with the room remains relatively low.

The model was then applied to the same Trombe wall in three other Greek cities with lower temperatures and available solar radiation (Thessaloniki, Ioannina and Kastoria) but keeping the air mass flow in the air gap equal to that calculated for the location describe in study case (case0), since is not expected to differ significantly. In the following Table 3, the climatic conditions in the examined alternative locations are given.

Table 3. Climatic conditions in the three examined locations

Month	Average Day Temperature, θ_e [C]	Total monthly radiation on horizontal, $H_{m,tot}$ [kWh/m^{2}mo]	Diffusive monthly radiation on horizontal, $H_{m,d}$ [kWh/m^{2}mo]
Thessaloniki			
May	21.1	179.1	82
June	25.9	198.6	86.6
July	28.2	209.5	86.1
August	27.7	184.7	73.1
September	23.5	136.7	53.6
Ioannina			
May	19.2	178.3	81.8
June	23.7	202.1	86.2
July	26.7	212	85.8
August	26.5	190.3	73.4
September	22.1	136.5	54.1
Kastoria			
May	18	173.6	81.7
June	23.1	201.8	86.6
July	25.7	206.3	86
August	25.1	185.5	73.2
September	20.9	138.5	53.7

Figure 11 shows a comparison of the heating gains from the Trombe wall, $Q_{C,gn}$ [kWh/ mo], during the examined months, which correspond to the contribution of the wall to the cooling loads. The comparison shows very small differences with a slight reduction of the burden during the months of May and September, while during the summer months the behaviors are almost identical.

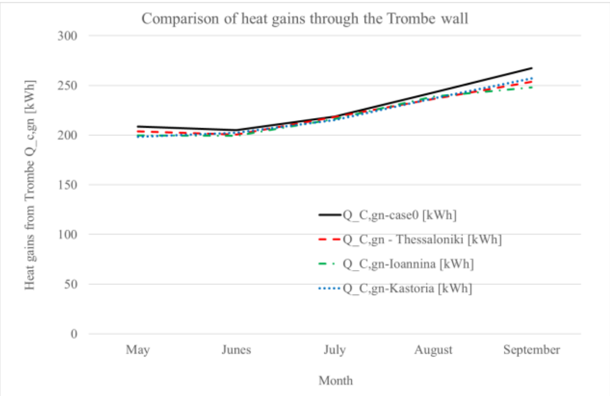

Figure 11. Heat gains from the Trombe in the examined locations

Figure 12 comparatively shows the losses (shell and ventilation) from the Trombe wall corresponding to the cooling contribution, $Q_{C,ht}$ [kWh/mo] for the summer months under consideration. Losses appear to be more affected by both radiation and temperature compared to the gains. Thessaloniki with temperatures and solar radiation very close to the climatic elements of case0 presents losses almost identical to case0. However, as the temperatures decrease, the contribution to cooling increases (Ioannina), while in Kastoria the contribution remains positive even during the months of July and August.

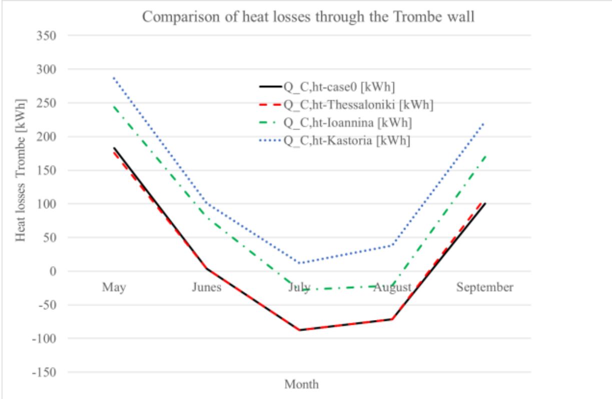

Figure 12. Heat losses through Trombe wall in the examined locations

Finally, Figure 13 gives the total contribution of the Trombe wall to cooling loads coverage during its summer operation, Q_{TCC} [kWh/mo]. In the final performance of the Trombe wall, Thessaloniki is almost identical to case0 with small differences in September, but Ioannina and Kastoria are clearly different. In these cities in May the total contribution of Trombe is positive throughout the month without the need for any automation.

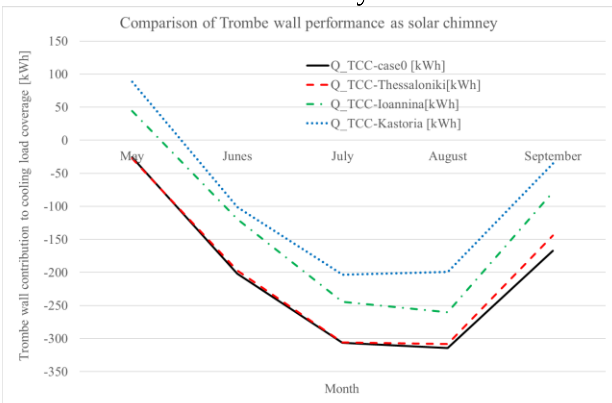

Figure 13. Comparison of Trombe wall performance as solar chimney in examined locations

4 Conclusion

The existence of thermal storage mass increase importantly the utilizable heat gains, from 15% in October to 46% during the winter months, and the coverage of heat demand. Even more important is the improvement achieved during the winter months with the usage of phase change materials that can increase the storage wall gain even up to 77%. In the examined case it comes out that during the relatively hot months, despite the fact that a significant percentage of the thermal losses is covered, a large percentage of the Trombe wall heat gains remain unexploited. This means that the wall in question is oversized for the room it serves.

When the examined Trombe wall operates as a solar chimney, in the examined location of Central Greece, it cannot contribute positively to the coverage of the cooling loads in any of the examined months. This is because even in May, June and September, ventilation cooling is not enough to exceed the cooling loads added to the room by the high temperatures that develop on the wall surface that is in contact with the room. However, this does not happen throughout the day. During these months it will have to operate with some automation system which will close the ventilation slots and automatically shade the Trombe wall at periods during which the thermal solar gains through it outweigh the losses (mainly through ventilation). In addition, some insulation could be added to the storage wall to maintain low surface temperatures of the room facing surface. Of course, this would differentiate the wall performance during the winter. Finally in July and August the wall should be fully shaded and the ventilation openings closed as the outside temperature is higher than the design temperature and so ventilation cannot contribute to the reduction of cooling loads.
However, if the same Trombe wall is placed in areas with lower solar radiation and mainly with lower outdoor temperature, then it is possible to have a positive contribution to the cooling of the space even without automation in May (Ioannina and Kastoria), while in Kastoria can operate with automation even during the purely summer months June - August.
The above conclusions emerged from an explicit model, whose equations can be solved sequentially on a spreadsheet, without any programming, provided that some estimate of the air supply within the gap can be made. Thus, it can be used at the first phase of design for the initial sizing according to the heat and cooling demands of the conditioned building zone. Since the proposed model can quantify the contribution of the Trombe wall, it can be used for a thechno-economical assessment of the Trombe wall design.

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Contribution of individual authors to the creation of a scientific article (ghostwriting policy)

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Dimitrios .K. Fidaros: Conceptualization, Methodology, Software, Writing - Review & Editing, Project administration, Funding acquisition
Aris Tsangrassoulis: Conceptualization, Writing - Review & Editing, Supervision

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