TROMBE-MICHEL WALL DESIGN & CALCULATION METHODS,

D.Fidaros[1]*, C. Baxevanou[2], A. Karagiannis[2], A. Tsangrassoulis[1]

[1]Department of Architecture Engineering, University of Thessaly, 38221, Volos, Greece

[2]School of Science and Technology, Hellenic Open University, 26335, Patras, Greece

(dfeid@uth.gr)

ABSTRACT

Trombe Wall is a SAH (Solar Air Heating) system that can combine passive heating and ventilated cooling during the yearly period, a factor extremely significant in Mediterranean climate conditions. The scope of the present work is to summarize guidelines for Trombe design according to international literature and to present the state of the art of the available computational tools for the assessment of its energy performance. The design guidelines according to the literature review concerns mainly the Trombe wall orientation, the wall area, the storage wall thickness, the ventilation slots, the cover glass properties and the air gap width. As far it concerns, the computational tools, a variety of models are presented beginning from analytical models with steady state and/or unsteady analytical calculations, monthly quasi steady models, BES (Building Energy Simulations) and CFD (Computational Fluid Dynamics) models, steady and transient, 2D and 3D geometries. As it concerns the design beyond the general guidelines available in international literature related with the design of SAH systems, there is a need for the development of quasi steady explicit models, which should be (a) easily used by the engineers and designers and (b) well-calibrated for various SAHs configurations and operations. Appertaining to the computational tools there is still a lot of space for research for various operations of a Trombe wall (with and without ventilation, insulation and supplementary storage material - eg pcm - and natural or forced air circulation for heating and/or cooling). These models could be used for design optimization and for energy performance assessments. Also, analytical and CFD models could be used along with experimental results for the tuning of quasi steady and BES models. Finally, CFD studies can be used for the assessment of the performance of individual sections of SAH systems aiming at the improvement of their performance.

KEYWORDS

Computational tools, Design guidelines, Solar Air Heating, Trombe wall

1. INTRODUCTION

Solar walls, also known as Trombe-Michel walls, are parts of building envelope that are designed to absorb solar radiation and store heat and at same time reducing the building's energy requirements. If a solar wall is properly installed it can be an important architectural feature that can reduces energy demand by up to 30% [1]. It transfers heat to a depth equal to one and a half times its height and according to [2] can reduce the final energy consumption for heating up to 47%.

Trombe walls are divided into: a) ventilated and non-ventilated [3], b) with natural or forced circulation [2,4], c) with and without insulation

[5,6], d) only for winter operation or/and for summer operation as a solar chimney.

There is an extensive literature on the design and operation as well as the energy performance assessment of Trombe walls. An important part of the literature concerns measurements in pilot constructions with important conclusions which are difficult to be generalized. Furthermore, for the optimization of the design as well as the calculation of the energy efficiency, it is often suggested non user friendly software and/or specialized commercial tools non trivial to an unfamiliar average designer. Even ISO 13790 [7] is essentially limited to the description of Trombe-Michel wall operation only to mechanical ventilation. This is one of the factors that precludes the widespread application of such a useful passive heating system.

In the present work an attempt is made to present on the one hand the basic general guidelines for the design of a Trombe wall and on the other hand, the state of the art of the available computational tools for the assessment of its energy performance, covering all the range from quasi-steady, analytical, BES (Building Energy Simulations) and CFD (Computational Fluid Dynamics) models.

2. METHODOLOGY

The literature review is organized in two basic sections. The first concerns the computational tools and the second section concerns design guidelines.

A wide range of computational tools is presented beginning from quasi-steady models (implicit and explicit) with monthly or seasonal time step, to analytical models steady state or unsteady with a small time step, to BES tools commercially available or research type until Computational Fluid Dynamics (CFD) models 2D and 3D, steady- state or unsteady. The presented computational tools are designed for the description and simulation of the whole structure operation of the passive element, or for the simulation of transport phenomena in the room which is equipped with the Trombe wall and finally for the simulation of transport phenomena of discrete sections of the passive system.

In the section 2 of the results, design guidelines according to the literature review are presented concerning mainly the Trombe wall orientation, the wall area, the storage wall thickness, the ventilation slots, the cover glass properties and the air gap width.

3. RESULTS AND DISCUSSION

3.1 Computational models

In this section is described the category of the software tools as they distinguished below in Quasi-steady models, the analytic solutions, the BES models and CFD simulations.

3.1.1 Quasi-steady models

The operation of a Trombe wall is a dynamic operation with the transport phenomena involved depending on the ever-changing external conditions and heat storage. This is therefore a difficult dynamic problem. In ISO-13790 [7] an analytical quasi-steady model is suggested for the calculation of a Trombe wall energy performance. In the 2004 version of the international standard (UNE-EN ISO 13790:2004) the calculation of the Trombe wall had to be done as an iterative process, because the effective solar area had to be known in order to calculate the solar gains of the air layer. The 2007 version uses the total area of the Trombe wall to calculate those gains, so, according to the equations of the 2007 version, iteration is not required and the suggested model can be considered explicit. This means that it can be solved by a spreadsheet. The important feature of the ISO model is that the quasi- steady model describes only the case of forced ventilated Trombe wall, where the air flow through the air gap is known. In paper [8], a revision of the ISO suggested model is presented and some corrections are suggested. This assessment pinpoints the existence of some errors in the equations provided in EN ISO 13790 [7] under steady state conditions and suggest some modifications. Nevertheless, it is still holds only for known air flow rates.

3.1.2 Analytical models

In fact, it has long been attempted to determine the performance of the solar passive elements function with an analytical tool that would allow the design of efficient devices. In [9] an analytical model is developed for calculating the energy efficiency of a Trombe wall with a monthly step using an equivalent electrical circuit and a series of simplistic assumptions. In this concept a number of analytical models have been suggested. Models that describe the operation of a solar chimney [10,11] or models that describe the operation of Trombe wall [12]. All these models are implicit and require some kind of iteration technique to solve the suggested system of equations. But unlike the quasi-steady models in the system of equations, the air flow in the gap is also calculated. Their most important feature is the assumption of the inside flow type in the gap. The type of flow (laminar or turbulent) and the numbers Ra and Re respectively determine the relationships that will be used to calculate the heat transfer coefficients. Therefore, each model corresponds to specific family of geometries (range of air gap width) and external climatic conditions.

Those analytical models cannot be used directly by engineers in the early stage of the design, since they require programming. Those models are often embodied in BES models either they are used for the calculation of the heat transfer coefficients and air flow rates, which are required by the explicit quasi-steady models.

3.1.3 BES models

BES (Building Energy Simulation) tools have been widely used to simulate the operation of Trombe walls located in relation with area where are installed. In work [13] the energy efficiency of a Trombe wall in the same building in different orientations and different cities in Portugal with Design Builder [14] and EnergyPlus [15] is calculated.

In [16] the performance of a Trombe wall is studied by simulating its operation with TRNSYS with hourly step as well as by LCA analysis. They conclude that based on the annual energy efficiency the Trombe wall should cover 37% of the surface of a wall. However, based on the life cycle analysis, it should cover 2.4%. The study concerns th city of the Amman, Jordan. In the same work the development of an interesting analytical model is examined.

Paper [17] studies a classical and a complex Trombe-Michel Trombe wall with TRNSYS and an in-house finite difference method experimentally validated. They prove that the used computational methods are effective and the Trombe composite wall appears better energy efficiency in cold and cloudy weather.

In [18] they measure the performance of a Trombe wall in a real building and at the same time, they calculate the performance with EnergyPlus. EnergyPlus does not have ready-made components for Trombe walls however it can be used to build related simulations. Its effectiveness for non- ventilated wall has been tested by Ellis in 2003 [19].

3.1.4 CFD models

As expected, CFD techniques have also been used to study the transfer henomena that develop on Trombe walls either in areas that relate exclusively to the wall area or in computational domains that extend throughout the room.

Thus the studies start from 2D geometries using finite volume method [20] or finite element methods [10], considering laminar or turbulent flows [21].

However, there exist studies in 3D geometries with the method of finite volumes. In paper [22] a CFD study is performed by simulating radiation with a DO model of a room in Belgrade equipped with a Trombe wall for typical days of a typical meteorological year. In the work [23] a solar chimney system with earth tubes is studied. The CFD model is certified with a corresponding experimental device. A similar study of a solar chimney is made in [24].

3.1.5 Models for discrete parts of a Trombe wall

The solar wall is practically a system for producing hot air from solar energy, ie a solar air heater (SAH). Its principle of operation is the same as that of a solar thermal collector, so its study can be based on corresponding studies of SAH systems used either for space heating or for Domestic Hot water (DHW) production. From a large number of studies for solar panels can be collected and examined information to increase efficiency focusing on increasing heat transfer with proper treatment of the absorption surface (roughness, fins, etc.) [25]. The work [26] examines the amplification of heat transfer using blades, rods or curved surfaces on the collection surface. The work [27] also examines the use of fins, the use of multiple air paths and the use of wires perpendicular to the air path in order to increase turbulence and consequently the convection coefficient as well as the heat exchange surface. The use of other matrix materials for heat storage is also considered in the work [28]. Finally, interesting analytical models can be drawn from work on more general SAHs and adapted to the characteristics of a Trombe wall [29]

3.2 Design guidelines

According to [30] the optimal orientation of a Trombe wall is ± 30 ° from the South.

The optimal Trombe wall surface to the total wall surface fraction is 37%. Above this percentage the energy benefit is negligible [16]. The height of the wall should be greater than 1 m so that it can be used as a solar chimney [31].

The optimal thickness of the storage wall depends on latitude, climatic conditions and heat losses [32]. The thickness of the storage wall is a key factor influencing the effectiveness of the Trombe wall. Concrete for example can delay heat transfer inside the building interior from 120 to 150 min for every 10 cm of thickness, while for a wall with thickness 20 cm heat will require several hours to reach the room interior [33]. The relationship between thickness and performance also depends on the type of solar wall. In a non-ventilated storage wall thickness increase can lead to reduction of heating gains, while in a typical ventilated Trombe wall will lead to increase of solar gains [34]. As a rule of thumb, the thickness of the storage wall ranges from 15 to 40 cm. Insufficient thickness leads to significant fluctuations in indoor temperature, but an increase in thickness leads to an increase in cost. Finally a very thick wall significantly delays the transfer of heat inside, which can cause thermal discomfort to the occupants [35].

Trombe wall performance also depends on the combination of material and color of the storage wall. The type of materials is the most important factor for the operation of the wall as it determines both he conductivity and the thermal capacity [21,36]. A concrete wall can reduce the mass required for heat storage by 90% compared to a paraffin panel and increase the efficiency by 20% [37]. Increasing the weight increases the heat storage capacity, however it also increases the static loads.

As far it concerns the ventilation slots, a larger number of openings with smaller dimensions is preferable to a large opening [34]. It is suggested to cover a 1-2% of the storage wall surface so not to reduce its thermal capacity [38]. Increasing of the area of supply slots in combination with increasing the thickness of the air gap between the glazing and the wall leads to better ventilation [39]. The optimal ratio of the slots' opening and the height of the wall is 3/20 when the width of the gap is greater than 0.1 m [40]. Finally as far it concerns the optimum ventilation control strategy it is suggested to open the slots 2- 3 h after the sunrise and to close them 1 h before the sunset [41].

A very important feature concerning the Trombe wall design is the type of cover glazing. In the case of a single glazing that could maximize the solar gains during the day the use of night insulation would be necessary to reduce heat loss [42]. For mild climates with significant sunshine such as the case of Greece, double glazing is recommended. Double glazing has better energy performance in summer to achieve passive ventilation [39].

Another suggestion is to replace the side walls of the Trombe wall with glazing. This can lead to an increase of 16% of the incident radiation as it can utilize the radiation both at sunrise and at sunset. This increase in incident radiation can lead to an increase in internal temperature of 3 to 6°C with negligible additional losses [43].

Another important proposal, which leads to an increase in construction costs, is the use of electrochromic materials in the glazing. These are transparent in the spectrum of solar (visible) radiation when the temperature is low and heating is required and opaque in both the visible and infrared spectrum of radiation when the temperature is high [44].

Finally important role has the width of the air gap between the cover and the storage wall. According to [40] the optimal width of the gap is the 1/10 of the height. Thus, the optimal width is between 0.2 and 0.3 m [40]. In others, however, the width of the gap must be limited to 2 to 5 cm in order to create a small space for air [13].

4. CONCLUSIONS

What could really help an engineer in the early stages of designing a passive solar system such as the Trombe wall would be the existence of a quasi-steady explicit model with a set of equations that could be solved sequentially on a spread sheet. Such a model currently exists only for mechanically ventilated Trombe wall, since the explicit quasi-steady models requires the knowledge of air flow through the air gap. Furthermore, the simplistic assumptions they contain may affect the results, especially if the geometry or climatic conditions under consideration are quite different from those for which they have been produced.

Analytical models do not have this limitation since they calculate the air flow. Nevertheless, they are implicit methods that require programming effort for the simultaneous solving of the equations' set. Besides, it should be kept in mind that each analytical model corresponds to specific limits of geometry and external climatic conditions, since the calculation of heat transfer depends on the type of flow in the air gap.

The BES models require specialized handling and data and they suffer from the ame appropriateness problems as the analytical models.

CFD models, either they concern the whole SAH either part of it require specialized programming qualifications or commercial resources. However, they can be used along with measurements for the validation of analytical and BES models and/or for the calculation of heat transfer coefficients used in quasi-steady models.

Another issue that could be considered is that the design guidelines should be used with care as they concern specific climatic conditions or they are derived by simulations with definite datasets.

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