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Trombe wall size-determination based on economic and thermal comfort viability

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ABSTRACT

The present work attempts to develop an approach for Trombe wall (TW) sizing through an integrative appraisal of energy consumption, economics and thermal comfort. There are many studies in the literature regarding TW sizing and its energy and economic viability. Nevertheless, they lack the separate energy and economics life cycle cost assessments of the TW based on the cases of building being new or existing. Besides, they leave out thermal comfort aspect and insulation status of the buildings. The current study is an effort to fill those gaps.

The approach is tested in a case study, a hypothetical building's living room that is incorporated with a TW. A simple parametric study has been carried out by varying the TW area from 6.0 m^2 to 16.2 m^2 to perform energy and economic assessments. The results revealed that for thermally insulated new building where the room is only occupied in winter the construction of a TW is economically viable. If the building is not thermally insulated, the construction of a TW is only feasible if its area is greater than 9 m^2. It is observed that the economic viability of the TW becomes better as its area increases. If the room is used in summer as well, there will be an extra cooling load due to the existence of the TW and economic feasibility is only achieved if there is insulation in the building. In uninsulated existing buildings, the construction of a TW is not economically feasible. The cumulative distribution frequency of various comfort parameters such as room temperature, relative humidity and CO_2 concentration levels are also plotted for each feasible TW area for determining the best personal comfort level.

1. Introduction

Trombe walls (TW) are devices used to store solar energy thermally during daylight hours and emit it as heat, particularly at times when the sun is not available. It is a passive solar heating strategy that employs a heavy i.e. high density and specific heat capacity, masonry or concrete dark painted wall with a glass cover on its outer surface.

Glass cover that is highly permeable to solar portion of the electromagnetic radiation spectrum transmits the shortwave radiation. The transmitted radiation impinges to the outer surface of the dark painted TW where it is absorbed and stored as thermal energy. Accordingly, time dependent temperature gradients occur in the TW. On the opposite side of the wall (facing to the space, which is to be heated) energy dissipation arises via convection and radiation. The glass placed on the outer surface generates greenhouse effect, which increases the temperature of the air existing between the TW and the glass cover and prevents loss of heat via long wave radiation to the sky from outer surface of the wall. Various designs of TW are possible, such as vented TW for introducing heated air (between the wall and glass) to the space that is to be heat via natural convection (Duffie and Beckman, 2013).

Although in many studies TW performances are found to be favorable, they have not found wide acceptance among the architects and homeowners. One of the main reasons is their appearance and the other is the doubts about their economic viability. Thus, this study is an effort to develop an approach for revealing the conditions and features of economically feasible TWs by taking into consideration both annual energy consumption and thermal comfort.

TWs are studied extensively from various aspects such as mathematical modelling, CFD modelling and simulations, real life applications and monitoring etc.

CFD simulations of a 200 mm thick concrete TW were carried out under Belgrade weather conditions by Bajc et al. (2015) with ANSYS FLUENT software. The authors evaluated the temperature profiles of the neighboring space to the TW. They concluded that the wall has positive impact for increasing the space temperature during winter, though it generates additional loads for summers. Shen et al. (2007) developed models for classical and composite TWs by employing finite difference method. The authors compared the results of their models;

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heat fluxes and wall temperatures with results obtained from the simulations of TRNSYS Type 36 module (module for modelling and simulating TWs with TRNSYS). The results for developed model was accurate and the composite wall performed better than classical wall in terms of energy for cold weather. Kalogirou et al. (2002) also employed TRNSYS Type 36 module for analyzing the energy performance of a TW that was applied to a 196 m^2 building in Cyprus. They revealed that TW significantly reduces the heating energy demand however, it generates additional cooling requirement. Stazi et al. (2012) on the other hand did an experimental study to reveal the behavior of TW during summer for the Mediterranean climate. The authors found out that with roller shutters, temperature of the TW and heat gains to the space reduced by 1.4 °C and 0.5 MJ/m^2 respectively.

Although many research exist on TWs from various aspects it is apparent that there is lack of studies regarding the economical appraisal of them particularly reckoning the feasibility and comfort. The most prominent recent studies in the literature about this matter is presented here.

Chel et al. (2008) for instance investigated the energy conservation, CO_2 mitigation and economical potential for retrofitting a honey storage building with TW. In their work, it has been found that retrofitting the honey storage building with TW will have payback time of seven moths making it an economically viable application. Jaber and Ajib (2011) differently studied the thermal and economical optimization of TW for a residential building in Jordan. The authors revealed that if the 37% of the south wall's area is occupied by TW optimum energy saving and life cycle cost is achieved. Bojić et al. (2014) on the other hand did optimization study of TW by considering the wall thickness for a house located in Lyon, France. The authors employed Energy Plus for energy simulations and Genopt for the optimization. Their results revealed that the optimum thickness of the clay-brick TW is 0.35 m with eight years of payback time if electricity is used to cover the heating demand. In another study, the economic feasibility of a 0.15 m-thick TW was investigated for a newly built specific house project (Atikol et al., 2013). The authors evaluated the economic feasibility of TW for a 46 m^2-living room challenging the traditional heat pump system of $COP = 3.0$. They found that the TW would be feasible for the house design considered.

The optimization and feasibility studies of TWs given above are only focusing on the economical aspect and fall shortage of investigating the possibility of exceeding the thermal comfort levels. Moreover, these studies do not differentiate between the new buildings and existing buildings or buildings with thermal insulation and those without thermal insulation. These alternative cases surely possess different results as far as the economic feasibility assessment is concerned. The present study is different from the previously published research in these aspects, aiming at proposing an economic feasibility approach that also takes into account of the thermal comfort. The approach has been applied to a case study virtual building that is in Cyprus.

2. Comfort-based economic feasibility approach

One of the most critical points in feasibility decision making is the evaluation of the project economics. In the present work, it is aimed to appraise the economic value of constructing a TW made out of reinforced concrete by comparing its performance with the use of a standard split unit air conditioner-heat pump. This is done by considering the time value of investments and savings of both systems during the life cycle of the project. The economic parameters that can be used to make economic decisions are net present value (*NPV*), savings-to-investment ratio (*SIR*), internal rate of return (*IRR*) and simple payback period (*PP*). These can be expressed mathematically as follows:

$$NPV = \sum_{1}^{n} AS_{PV} - \sum_{1}^{n} LCI_{PV}, \tag{1}$$

$$SIR = \frac{\sum_1^n AS_{PV}}{\sum_1^n LCI_{PV}}, \tag{2}$$

$$IRR = \text{Discount rate}, \quad \text{where} \quad SIR = 1, \quad \text{or} \quad NPV = 0, \tag{3}$$

$$PP = \frac{\text{Initial Investment}}{\text{Annual Savings}}. \tag{4}$$

where, AS_{PV} is the present value annual savings, LCI_{PV} is the present value life cycle investments and n is the number of years taken for economic lifetime of the project. This is a well-known method and was used in other studies before (Agboola et al., 2015; Atikol et al., 2013). *PP* is only meaningful if it returns periods less than one year because the value of money is likely to change significantly over longer periods of time.

For any application, if *SIR* is greater than 1, that application can be accepted to be economically viable. Therefore, in the present study *SIR* is used as an indicator for feasibility.

In the estimation of the investment required for a TW, it is necessary to take into account the cost of the reinforced concrete wall and the aluminum or PVC window in front of it. It goes without saying that in newly built houses the net investment is found by taking into account the avoided cost of the standard wall that would be otherwise built instead of the TW, such that:

$$I_{New} = C_{TW} - C_{SW}. \tag{5}$$

where I_{New} is investment required to build a TW in a newly built house, C_{TW} is the cost of building a TW, C_{SW} is the avoided cost of standard wall. C_{SW} can be higher in thermally insulated houses, resulting in lower I_{New}. In retrofit projects, the demolition of the existing standard wall, where the TW is to be built, has a cost as well, which has to be added on the cost of TW, such that:

$$I_{Ret} = C_{TW} + C_{DW}. \tag{6}$$

where I_{Ret} is investment required to replace an outer wall with a new TW and C_{DW} is the cost of knocking down the outer wall in question.

For the estimation of energy costs, there are two scenarios. In the first scenario, the occupied zone under investigation is only used in winter, whereas in summer the occupants use another living space in the northern part of the house. In this case, the energy cost of cooling is not taken into consideration. In the second scenario, the room is also occupied in summer and hence the air conditioner is used in the cooling mode. The TW increases the cooling load in spaces they are built even if it is shaded by an overhang (Kalogirou et al., 2002); therefore this may affect its economic feasibility.

Achieving economic feasibility does not always provide satisfaction to consumers. Likewise, in this project it is required to check the possibility of overheating (especially during the heating season), level of relative humidity and adequacy of ventilation rate for indoor air quality (IAQ). Failing to achieve required levels might lead to uneasiness of the occupants of the room. Therefore, the indoor temperature, relative humidity and IAQ must be checked throughout the simulation period for each TW size under investigation. The procedure of comfort-based feasibility approach is simplified in Fig. 1. The auxiliary system in Fig. 1 is a standard split unit air conditioner-heat pump that conditions the room if necessary (when the heat supplied by the TW is not enough to attain desired air temperature). It is also essential to clarify the meaning of comfort that is in the layout of the approach in Fig. 1, as the state of physical ease that can be quantified by employing thermal, environmental and personal factors. Precisely, air temperature, relative humidity, ventilation rate, IAQ etc. are among these factors.

3. Energy simulations

In this study, a residential hypothetical building's living room is the setting for TW application. Thus, occupants of this building are customarily in during nighttime hours and absent during daytime hours