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ScienceDirect

Solar Energy 122 (2015) 820–833

SOLAR ENERGY

www.elsevier.com/locate/solener

Ventilated Trombe wall as a passive solar heating and cooling retrofitting approach; a low-tech design for off-grid settlements in semi-arid climates

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Received 22 May 2015; received in revised form 29 September 2015; accepted 6 October 2015
Available online 10 November 2015

Communicated by: Associate Editor Matheos Santamouris

Abstract

In the coming years, it is anticipated that if we continue with the same pace of energy consumption, communities will continue to face three major challenges; a mounting increase in energy demands, pollution, and global warming. On a local scale, Egypt is experiencing one of its most serious energy crises in decades. The energy consumed in indoor cooling and heating is the biggest portion of total energy consumption in residential buildings. This paper is an experimental simulation study for building retrofitting in off-grid settlements in semi-arid climates, using Trombe wall as a low-tech passive heating and cooling solution. In this study, we made developments to the conventional classic Trombe wall using occupant-centered design and living lab experimental methods. The thermal efficiency of the proposed Trombe wall design is simulated during winter and summer peaks. In the proposed design we used gray paint instead of typical black paint in addition to 15 cm reversible natural wool insulation and two 3 mm thick roll-up wool curtains. The new design reduced the heating load by 94% and reduced the cooling load by 73% compared to the base case with an annual energy savings of 53,631 kW h and a reduction in CO_2 emissions of 144,267 kg of CO_2. The living lab test proved that the proposed design of the Trombe wall is economically viable and the payback time is 7 months. It is recommended that the proposed design be monitored for a whole year to have an accurate assessment of its efficiency. A post occupancy evaluation is also needed to measure local residents' acceptance and perceived comfort after retrofitting.

Keywords: Trombe wall; Passive solar heating and cooling; Semi-arid climate; Energy consumption; Low-tech retrofitting; Occupant centered approach

1. Introduction

The world is experiencing one of its most serious energy crises in decades (IEA, 2014). By 2050, global temperatures are anticipated to continue to rise and greenhouse gas emissions are expected to be more than double if we carry on with our energy inefficient building methods (Hootman, 2013). Many countries have become more import reliant and gradually more effected by the problems associated with fuel poverty (Timilsina and Zilberman, 2014). Today's buildings consume more than 40% percent of the world's primary energy, which are responsible for 30% of greenhouse gas emissions (Heinberg and Lerch (red.), 2010). This is more energy than any other sector of the world's economy, including transportation and industry (IEA, 2013). Domestic heating and cooling alone consumes one

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http://dx.doi.org/10.1016/j.solener.2015.10.005
0038-092X/

fifth of total fossil fuel energy production worldwide (Lechner, 2009), meaning our homes add to many environmental problems like greenhouse gas emissions, which contributes to man-made global warming (Santamouris (red.), 2003). Accordingly, we pay a high environmental cost for our future.

Currently, Egypt unwisely produces about 94% of its electricity from fossil fuel sources (RCREEE, 2013a). Nevertheless, the government has recently begun making plans for investing in nuclear energy. The demand for thermal indoor comfort is increasing, which is consequently responsible for a higher demand for heating and cooling, which already accounts for 50% of energy consumption in Egypt (NREA, 2013; RCREEE, 2013b). This is due to the current inefficient housing stock. We indulge in our profligate lifestyles and are becoming less sustainable due to the government policy of providing subsidized electricity. Because of the recent mounting local energy crisis and electricity power cuts, energy conservation has slowly started to become a main concern. Energy efficiency has now gained a prominent role at the political level with the formulation of a quantitative target to save 20% of today's consumption by 2020 (NREA, 2013). However, the government's existing measures are mainly focused on new buildings, often ignoring the existing buildings that represent the largest share of the building stock, appeal to the majority of the consumers, and remain the least efficient. This conundrum tasks independent researchers to work on alternative retrofitting solutions that incorporate solar passive heating and cooling strategies in a country, which, according to RCREEE, has high potential in solar energy (RCREEE, 2013b).

In this study, the ventilated Trombe wall was simulated and experimented as a retrofitting low-tech, passive heating and cooling solution. Our proposed Trombe wall is considered a design development for the existing classic Trombe wall type found in discourse. The main objective of this study is to increase the building efficiency in achieving indoor thermal comfort while reducing the current energy load for heating and cooling. This will consequently reduce CO_2 emission during building operations. The simulation showed a higher percentage of efficiency in achieving indoor thermal comfort compared to recent studies, and the living lap experiment proved the ventilated Trombe wall be cost effective for Egyptian standards. In addition, there was an added contribution in applying an occupant-centered retrofitting approach in a living lab environment for remote off-grid settlements.

1.1. Trombe wall usage in passive solar heating and cooling

Unlike conventional heating and cooling strategies, passive solar and natural air conditioning methods achieve comfort through a knowledge of local climate and vernacular design (Anderson and Wells, 1981), showing us how to utilize natural elements to provide the amenities we need without negatively impacting the earth (Chiras, 2002). Earlier, Kreider and Kreith discussed how solar passive strategies can be economical for building thermal control (Kreider and Kreith, 1982), while Koch-Nielsen added later, that it is even more economical in hot climatic zones where both air conditioning for cooling and heating is required (Koch-Nielsen, 2002). Thorpe affirmed that, if suitable passive solar solutions are incorporated in existing buildings, building energy demands can drastically be reduced (Thorpe, 2011).

A Trombe wall is a system that makes use of indirect solar gain (Kachadorian, 2006). It is a thermal mass wall normally made from stone, brick, or adobe, painted in black, and placed behind south facing glazing (Saadatian et al., 2012). The immense thermal mass serves as heat storage from solar energy which is transferred to the interior of the building for winter heating or to evoke air movement for summer cooling (Gan, 1998). It stores daytime solar gain and releases it back at night when residents most benefit from the heat (Kachadorian, 2006). There are various Trombe wall systems from classic to composite ones, and their efficiency is discussed and compared in several works of research (Agrawal, 1989; Nahar et al., 2003). The Trombe wall is mainly used in cold and mild climates (Haggard et al. (red), 2009); however, for a long time there have been numerous studies on the Trombe wall for passive solar heating for arid climates (Tasdemiroglu et al., 1983; Boukhris et al., 2009), as well as several robust studies on reducing the drawback of the Trombe wall in summer for hot climates (Ghrab-Morcos et al., 1993; Soussi et al., 2013).

1.2. Previous studies

A considerable number of scholars have investigated glazed ventilated and non-ventilated Trombe walls by studying its steady state performance (Hami et al., 2012), modeling techniques (Bojić et al., 2014), thermal efficiency (Burek and Habeb, 2007), and in-situ performance (Rabani et al., 2015). Some strategies have been adopted to enhance the efficiency of Trombe walls in summertime, improving natural ventilation (Stazi et al., 2012a), the provision of shade (Chen et al., 2006) and proper insulation (Stazi et al., 2012b). Several researchers discussed that the main consideration in guaranteeing a successful retrofit using passive solar Trombe wall systems is to properly design the suitable size, position, and orientation of its components (Athienitis and Santamouris, 2002). It has been discussed thoroughly and proved that wall thermal storage, thermal insulation, black paint thermal properties, size of air vents, and glazing type are the main components that have significant effects on the efficiency of ventilated Trombe walls (Saadatian et al., 2012).

The Trombe wall has many advantages. A study on life cycle costs shows major advantages in applying Trombe walls as a cost efficient solution for indoor thermal comfort in winter time, while reducing annual CO_2 emissions by approximately 455 kg CO_2 (Jaber and Ajib, 2011).