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The effect of building envelope insulation on cooling energy consumption in summer

Zhaosong Fang[a,b,c], Nan Li[a,b,c,*], Baizhan Li[a,b,c], Guozhi Luo[d], Yanqi Huang[a,b,c]

[a] Key Laboratory of the Three Gorges Reservoir Region's Eco-Environment (Ministry of Education), Chongqing University, Chongqing 400042, PR China
[b] The National Center for International Research of Low-carbon and Green Buildings, Chongqing 400042, PR China
[c] The Faculty of Urban Construction and Environmental Engineering, Chongqing University, Chongqing 400042, PR China
[d] China Southwest Architectural Design & Research Institute Corp., Ltd., Chengdu 610000, PR China

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ABSTRACT

Building energy consumption has increased in China with the rapid urban development and population growth of recent years. Based on the hot climate in Chongqing, two types of experimental chambers were constructed to investigate the effects of external wall insulation on energy consumption and the indoor thermal environment. An 'energy efficient' chamber was constructed using a thermal insulation system for the external wall, and a 'basic' chamber was constructed according to the general design for residential buildings of the 1980s and 1990s. Analysis of the experimental data for power consumption and the thermal environment of the two chambers showed that the indoor thermal environment of the energy efficient chamber was less affected by the outdoor environment and could be maintained at more comfortable conditions with less energy consumption than the basic chamber. The energy consumption of the energy efficient chamber was lower than that of the basic chamber, offering a savings of up to 23.5% in air conditioning energy consumption during the summer-time test period. Therefore, the results of this study demonstrate that use of an external wall insulation system can improve building energy efficiency.

1. Introduction

With economic development, energy consumption and environmental impact have become concerns around the world. According to a previous study, more than 50% of materials taken from nature are used to build different types of buildings and their ancillary facilities [1]. At the same time, the operational processes of buildings consume nearly 50% of the world's energy [1]. In China by the end of 2020, the residential housing construction area is estimated to reach 68.6 billion m^2. Over this same time, the building energy consumption ratio within the total national energy consumption will rapidly increase by more than 33% [2]. Therefore, improving the energy efficiency of buildings and reducing building energy consumption are urgent problems for the construction industry. According to the composition of building energy consumption, the thermal performance of the building envelope is the main factor affecting energy consumption [3]. Thus, walls that contain external thermal insulation can not only create a more comfortable indoor thermal environment [4,5] but also reduce the energy consumption of the heating or air conditioning system [6,7].

Since the 1970s, researchers in Western countries have been studying energy efficiency, and many advances have been realized. Kossecka and Kosny (2002) [8] examined the theoretical performance of six configurations of insulation placement in heavy walls in Program DOE2.1E. The energy consumption of a ranch house in six climatic regions of the United States was simulated. They concluded that walls with exterior insulation perform best, leading to the energy requirements for heating and cooling. By contrast, the model with only interior insulation performed the worst. Niccolo et al. (2009) [9] analyzed the influence of the thermal inertia of external walls on the energy performance of well-insulated buildings. Their results showed that the wall system with the highest energy performance had a proper combination of dynamic thermal transmittance and thermal admittance values. Zbynek and Marek (2010) [10] analyzed the heat transfer through hollow bricks in the vertical direction by means of

* Corresponding author at: Faculty of Urban Construction and Environmental Engineering, Chongqing University, Chongqing 400045, PR China.
Tel./fax: +86 023 65123453.
E-mail address: nanlicqu@126.com (N. Li).

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computational fluid dynamics (CFD) simulations. The results showed that the natural upward convection disappeared only for very high and narrow cavities. Wilhelm et al. (2012) [11] investigated the use of wall insulation in residential villas in Dubai and found that proper insulation of the exterior wall can result in an energy savings of 30%. Masoso and Grobler (2008) [12] also found that annual cooling load decreases with increasing interior temperature and becomes negative when the interior set-point temperature increases beyond a set value (25.72 °C). Surapog et al. (2012) [13] concluded that insulation can generally help improve the thermal performance of walls based on the results of both experimental and simulation studies on the comparative energy and economic performance of walls used to enclose air-conditioned spaces. Most of the previous research focused only on the effects on energy performance of the insulated walls, whereas few focused on the conditions of the indoor environment.

Comparing China with the Western countries, research in China has advanced rapidly in this decade, especially concerning building energy efficiency in the hot summer and cold winter zone. Guo et al. (2012) [14] studied the energy-saving effect of coating exterior walls with heat-reflective insulation and found an obvious saving in energy with this insulation in Hangzhou. Li and Li (2007) [15] analyzed the heat transfer principle of architectural cladding structure in the hot summer and cold winter zone and proposed a new method for calculating the heat load of a building in this area. Xu et al. (2007) [16] analyzed the effects of the thermal properties of exterior walls on the annual energy consumption in Shanghai. Their results showed that during transitional seasons, insulation of the walls actually increased energy consumption. Wang and Wu (2008) [17] pointed out that the economically optimal insulation thickness depends on the specific region of the building, the air conditioning operating time, and the price of the insulation material. Most of the studies listed above, like those mentioned in the previous paragraph, focused on the thermal performance of the insulated wall and examined energy consumption using simulation methods, and only a few of these studies investigated the effects of the indoor thermal environment. Moreover, the models used in simulations are always simplified, which will lead to some differences between the model and the real system. Another consideration is that the error for simulation data is bigger because the meteorological parameters in the simulations are primarily obtained via statistical analysis [18]. Therefore, the results produced by simulation software are not very accurate and only roughly reflect the actual situation. Another complicating factor is that the weather in the hot summer and cold winter zone of China is severe. The hot summer and cold winter zone including the Middle–Lower Yangtze River and the surrounding area is defined by the mean temperature of annual coldest month and the mean temperature of annual hottest month [19]. In this zone the mean temperature of annual coldest month should be in the range of 0–10 °C and the mean temperature of the hottest month being 25–29 °C. In addition, the relative humidity in most cities in this zone is 75–80%. The entire winter is cold and without much sunshine (2008) [20]. Chongqing city is located in the hot summer and cold winter zone in China. Its climate is characterized by high dry bulb air temperatures and high moisture levels in the summer [21,22].

The building industry is developing rapidly in China, which is having a serious impact on the country's energy consumption. Considering the limitations of the past research described above, it is particularly important to use experimental tests to study the influence of an external insulation system on building energy consumption and the indoor environment. The aim of the present study was to analyze the effects of the insulated wall on the indoor temperature and relative humidity as well as the energy consumption of the air-conditioning system in experimental tests.

2. Experiment

2.1. Experimental system

To conduct the comparative experiment, two experimental chambers were constructed in the Urban Construction and Environmental Engineering Laboratory of Chongqing University. It located at latitude 29.35°, longitude 106.33°. One was called the basic chamber and was designed on the basis of a 1980s–1990s residential building envelope design standard consisting of brick and single glazed windows. For comparison, another chamber called the energy efficient chamber was constructed, in which the envelope was built using hollow brick, external insulation material, and double glazed windows. The materials used in constructing the two experimental chambers are listed in Tables 1 and 2.

The basic design of the two experimental chambers was as follows: the chambers faced south and were 3000 mm high with an area of $3600 \times 3000\ mm^2$. Two square holes were placed at a position 2400 mm high in the south and north walls. One ventilation fan was installed in the south wall with sealant around the edges to keep the amount of ventilation constant while fan was running. Before installing the ventilation fan, the dynamic pressure of the outlet of the ventilation fans was tested, and the velocity was calculated for use in determining the natural ventilation rate. The hole in the north wall was left open for natural ventilation. The natural ventilation rate is kept 1 time h^{-1} by the ventilation fans in both of chambers. To simulate the environment of a house, a bed and computer desk were installed inside both chambers, and the layout of the chambers is shown in Fig. 1(i) and (ii).

This study focused on comparing the impact on the indoor environment and air conditioning energy consumption caused by the thermal properties of the walls and windows, and thus, all other materials used in constructing the chamber envelopes were the same. For security considerations, the roofs of the experimental chambers were built using lightweight materials to reduce the weight of the roofs. To ensure the indoor environments of the chambers were as similar as possible, indoor air conditioner units with the same power were installed on the east wall of both experimental chambers above the beds. The outdoor air conditioner units with the same power were installed outside the chambers against the north wall shown in Fig. 1(i). During the experiment process the indoor set point temperature was 26 °C, and the control mode of the air conditioner was automatic mode in both chambers. When the indoor dry bulb air temperature is higher than 27 °C, the air conditioning system turns on. When lower than 25 °C, it will turn off. The power consumption of the air conditioners was measured using a power meter.

2.2. Experimental apparatus

The Tinytag data acquisition instrument was produced by Gemini Data Loggers and offers high accuracy, high resolution, high storage capacity, fast download speeds, and a low level indicator and other features. It is ideal for measuring indoor and outdoor dry bulb air temperature and relative humidity.

The wall surface temperature was measured using a copper–constantan thermocouple (T type) with a potentiometer, for which the reference node was an ice bottle filled with ice water to keep the temperature constant at 0 °C. The potentiometer was a UJ33a type with high accuracy and resolution characteristics.

All thermocouples were verified rigorously using a constant temperature water bath method before measuring the experimental temperature [24]. The absolute values of data error between each thermocouple and the standard thermometer were within the allowable range which is from 0 to 0.2 °C[24]. The compressor power consumption was measured using an electricity meter.