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Investigation on the influencing factors of energy consumption and thermal comfort for a passive solar house with water thermal storage wall

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ABSTRACT

A passive solar house (PSH) could fully receive and store the incident radiation by the rational arrangement of the building structure and the utility of the massive construction materials. The influence of water thermal storage wall (WTSW) on the indoor thermal environment is analyzed in this paper. Besides, different parts of the building envelope exert varying degrees of impact on the building energy consumption and indoor thermal comfort. Research on the influencing factors could provide references for the building energy conservation design and the retrofit of existing buildings. A PSH with interior walls of WTSW is studied, which is currently being used in North China. Field measurements were carried out in the reference building. TRNSYS was used to simulate the variation of indoor air temperature. The results of simulation and orthogonal analysis indicate that compared to traditional wall the PSH equipped with WTSW can reduce yearly energy consumption by 8.6% and improve indoor thermal comfort evaluation index by 12.9%. Meanwhile, significance of four different structural parameters (namely the shape coefficient, building orientation, glazing ratio of the south wall and the interior wall structure) respectively on the energy consumption and thermal comfort is obtained by the variance analysis.

1. Introduction

Building energy consumption in European countries accounts for 40% of the total social energy use [1], while in New York reaches up to 2/3 [2]. Since building energy consumption is able to be reduced significantly by fully consideration of the heating and cooling loads at building design stage, much more attentions are paid on the optimization of the building envelopes than ever before [3]. The influencing factors of the building envelope generally include the outline dimension, orientation, glazing area and thermo-physical properties of construction materials [4].

Heat exchange area with the outdoor air is determined by the building outline dimension. Wang et al. [5] researched the impact of flat shape on the building life cycle cost. Ourghi et al. [6] considered that a strong correlation existed between the yearly energy consumption and the building shape coefficient, which was defined as the ratio of external surface area over the inner volume. In addition, Depecker et al. [7] regarded the above strong correlation to be effective only in the places with large heating degree days or a short duration of sunshine. Besides, Marks [8] and Adamski [9] optimized the outline dimension from the building costs and yearly heating costs. Mingfang [10] studied the optimal building form basing on the solar heat control in summer and Aksoy et al. [11] researched the influence of shape factor on the heating demand in winter.

Solar energy received by building depends on its orientation and glazing area. Morrissey et al. [12] considered that buildings with high energy efficiency normally owned a wide variation range in orientation. Researches of Shaviv [13] and Florides et al. [14] showed that the wall with a maximum glazing ratio (namely the ratio of window to wall) or with a longer edge should face south in hot and humid areas. Littlefair [15] considered that the optimal orientation can have an angle of less than 20–30° with due south. As to the glazing area, Persson et al. [16] found an appropriate glazing ratio after the optimization on the window. While in the opinion of Leskovar et al. [17,18], the optimal glazing ratio was determined by the heat transfer performance of the building envelope.

Properties of building material directly influence the heat transfer and heat storage capacity of the wall. Oral et al. [19] introduced a method to determine the limit value of the wall heat transfer coefficient. Lollini et al. [20] and Jinghua et al. [21] studied the influence of the wall thermal insulation on the energy consumption. And Çomakli et al. [22] investigated the optimum insulation thickness of the exterior wall. Khalifa [23] analyzed the sensitivity of the indoor air temperature to the change in the thermal storage

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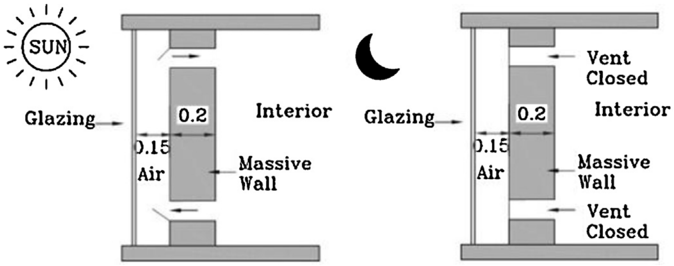

Fig. 1. Typical structure form of the Trombe wall.

wall. Hassanain et al. [24] researched the passive heating effect of heat storage wall in passive solar houses with different roof shapes. While Khalifa et al. [25] and Gregory et al. [26] studied the massive wall with different construction material. Trombe wall is an effective form to exploit the thermal storage capacity. The related researches were conducted in the thermal performance comparison with transparent modular wall [27], the comparison of different types of Trombe wall [28], the winter passive heating effect [29], the summer passive cooling effect [30] and the reduction in energy consumption and CO_2 emissions [31]. Typical structure form of the Trombe wall is shown as Fig. 1 [32].

Kinds of materials are suitable for filling in the massive wall in Fig. 1, one of which is water [33]. During construction process, water thermal storage wall (WTSW) is usually built by enclosing the water with concrete [34] or stainless steel plate. There are little literatures concerning on this kind of high thermal capacity but low-cost wall. Moreover, only single influencing factor of the building envelope was concerned in the previous researches and a comprehensive evaluation is in great need. Thus, a case study was conducted on a passive solar house (PSH) with WTSW in North China. A simulation model is also established with TRNSYS in order to study the influence of WTSW on the indoor thermal environment as well as the energy consumption. Orthogonal analysis is designed to compare the influencing significance of four different structural parameters, including the shape coefficient, building orientation, glazing ratio of the south wall and the interior wall structure, with the help of variance analysis.

2. Description of the reference building

2.1. Introduction of the passive solar house with water thermal storage wall

The single-storey passive solar house faces due south, which has a floor area of 700 m^2 and a shape coefficient (the ratio of external surface area to inner volume) of 0.374. It is located in Tianjin, North China. The house is divided into two zones, which can be seen in Fig. 2. A sun space corridor with a width of 1.4 m lies on the outside margin of the south zone, which can receive solar radiation as much as possible with a glazing ration of 100% in the south wall. The WTSW, outer wall made of steel plate, is processed into modular production with a dimension of 1.1 m × 0.4 m × 2.5 m (length × width × height). WTSW modules are placed along the inner side of the corridor besides some of the interior walls, which are shown by the shaded portion in Fig. 2. Total 29 modules are used in the PSH to store the received solar heat during the daytime. External and other interior walls consist of the steel construction and gypsum boards with a total thickness of 60 mm.

2.2. Simulation and validation of the reference building model

According to the description, a building model was established in TRNSYS to simulate the hourly air temperature in different zones.

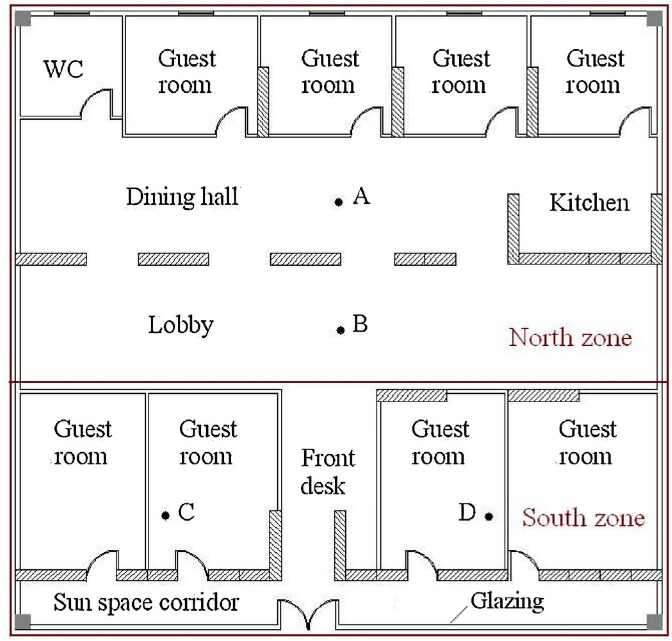

Fig. 2. Floor plan of the passive solar house with water thermal storage wall.

Weather data from the Tianjin Meteorological Bureau was adopted in the simulation. In order to validate simulation results and evaluate the effect of the WTSW, the indoor air temperature has been continuously monitored for more than one week from November 18th to 27th. Four temperature data loggers were fixed at point A–D as shown in Fig. 2.

The average temperature of different zones by simulation and field test in the PSH are shown respectively in Fig. 3. In the condition of no space heating, the measured indoor temperature remained at 13.7 °C mainly because of the high thermal capacity of the WTSWs even when the outside air dropped to −0.4 °C (7:00 am November 23rd). The simulated temperature had a maximum relative error of 24.5% compared to the measured values. Such error is probably related with the randomness of human's activity, such as opening or closing the door, turning on or off the lights and so on. An average relative error of 8.97% reflects the accuracy of the simulation, so this model is suitable for the later orthogonal analysis.

3. Orthogonal analysis

3.1. Test factors and levels

Based on the literature review, four structural parameters are chosen as the test factors, namely the shape coefficient (SC), building orientation (BO), glazing ratio of the south wall (GR) and interior wall structure (IS). The low levels of each factor are the real dimensions of the reference building in North China, while the high levels are the limitations regulated in design standards of energy efficient residential buildings. The medium levels are the average values of the low levels and high levels. All the factor levels are listed in Table 1. Among which, the realistic orientation barely has an angle of more than 30° with due south, and the levels of glazing ratio and shaping coefficient are determined by referring to the energy saving design standard [35] and the original values of the reference building. Besides, the ordinary wall with a layout illustrated in Table 2 is a popular form used in practice, which can meet the requirement of the energy saving standard.