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Research paper

Feasibility experiment on the simple hot box-heat flow meter method and the optimization based on simulation reproduction

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HIGHLIGHTS

- A new method (SHB-HFM) is proposed to test the wall *U*-value in situ.
- The SHB-HFM has the adequate accuracy and a certain tolerance on in-situ operation.
- The source of the in-situ test error is analyzed by the numerical simulation.
- The perfect in-situ conditions do not improve the test accuracy obviously.
- The effective ways to improve the in-situ test accuracy are pointed out.

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ABSTRACT

This paper proposes a simple hot box-heat flow meter method (SHB-HFM) and verifies its feasibility by an in-situ measurement of wall thermal transmittance. The experimental results show that even under very unfavorable test conditions, the test error of the wall thermal transmittance by the SHB-HFM is only −5.97% relative to the design value, which proves that the SHB-HFM has the adequate test accuracy, thereby proving that this method is feasible. And through arranging reference test sensors, 15 cm up and down from the central primary test sensors, the test errors due to location deviation increase to −8.14% and −9.60% respectively, which basically meets the accuracy requirement and thereby demonstrates the SHB-HFM has an acceptable tolerance for the in-situ operation. To further explore the influence of various factors on the test accuracy, a mathematical model is established and verified by the experimental data. The simulation results indicate that the perfect in-situ measurement conditions do not improve the measurement accuracy obviously, while moderately enlarging the box dimensions or simultaneously arranging heat flow meters on the inner and outer surfaces is more effective in improving the test accuracy.

1. Introduction

With the continuous improvement in living standards and indoor comfort, building energy consumption is increasing very rapidly and improving building energy efficiency is a very urgent task [1,2]. In order to promote the building energy efficiency, design standards, in which the thermal performance indices of building envelopes are compulsory provisions, have already been promulgated successively according to the different climate subareas in China [3–6] and exerted a very good effect. The total new floor space completed in buildings is up to 1.067 billion m^2 in China [7], which is equivalent to all the sum of the western developed countries. In order to ensure that a huge amount of the new building constructions strictly abide to the energy conservation designs and avoid those phenomena, such as the poor quality of building materials, cutting corners and bad quality of workmanship during the construction, close monitoring and management are of vital importance and the in-situ measurement of wall thermal transmittance has been an important and indispensable link in a series of acceptance management standards, which have been successively promulgated in China [8,9].

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The measurement method for the wall *U*-value in the lab has become relatively mature, and many standards, such as ISO [10–12] and ASTM [13,14], have been formulated since 1991. China also issued relevant standards [15] in 2008. At present, the heat flow meter method (HFM), the guard hot box method (GHB) and the calibrated hot box method (CHB) are three main methods in the lab [16]. The common characteristic of above methods is that the environmental temperature on two sides of the measured object is carefully controlled to ensure the measurement accuracy.

The HFM is internationally recognized and most widely used. But the HFM has the high requirement on the indoor and outdoor air temperature difference. Therefore, the HFM is only used in heated buildings in winter or air-conditioned buildings in summer, demonstrating that the HFM has a great dependence on seasons and heating & air-conditioning equipments [9,17]. Actually in China, the completion time of many buildings is spring or autumn, and most buildings haven't any heating & air-conditioning equipments at the period of completion inspection and acceptance. So the realistic condition is exceedingly difficult to meet the in-situ temperature difference demand of the HFM.

The GHB is not limited by indoor and outdoor air temperature environment, but it needs many measurement equipments, such as the metering box and the guard boxes which are very big [18]. Therefore, this method has much workload, poor operation and high energy consumption. On the other hand, owing to the increasing of building structure's diversity, the present wall has not large area enough to install such big guard boxes. Therefore, the GHB only suits some special buildings.

Moreover, when the CHB is used to measure wall thermal transmittance in the lab, it needs to utilize a standard wall to calibrate the boundary heat loss of the hot box under the certain environment. However, in-situ environment is complex and varied, so it is impossible to calibrate the boundary heat loss exactly [18].

Aiming at the in-situ measurement of wall thermal transmittance, some international scholars did some related researches. Desogus et al. [19] conducted a comparative analysis about the measured and theoretical thermal transmittance for a three-layer wall, containing one layer of the 100 mm fired perforated brick and two layers of 15 mm cement plaster. Their study shows that the measurement uncertainty of by the HFM is 10% with temperature difference of 10 °C between outer and inner surfaces, and the higher the temperature difference, the higher the measurement accuracy. Ahmad et al. [20] measured the thermal transmittance of hollow reinforced precast concrete walls by the HFM under the average ambient air temperature of 35 °C–40 °C and the set point of the air-conditioner of 22 °C. They had an accurate test result owing to the high temperature difference. Cesaratto and Carli [17] and Cesaratto et al. [21] measured the thermal transmittance of an exterior insulation wall over a period of four years by the heat flow meter method. Their study finds that the measurement location has a great influence on the measurement accuracy for the same wall. The increase in the measurement temperature difference between the indoor and outdoor environment can weaken the influence of the temperature fluctuation and decrease the test error. Meng et al. [22] researched the influence caused by the wall non-uniformity on the measurement error of the HFM. Their finding shows the test error can be up to 26% when the heat flow meters are improperly pasted. In addition, Biddulph et al. [23] and Jiménez et al. [24,25] studied the data processing methods to increase the measurement accuracy respectively.

From above research [17,20–25], most in-situ measurements of wall thermal transmittance used the HFM, although this method had the high requirement on the temperature difference [9,17,19–22]. To solve this problem, many scholars try to explore some new methods to measure wall thermal transmittance in situ. Peng and Wu [26] studied some different methods of wall thermal transmittance experimentally. Their researches showed that heat flow measurement error was the main source for the heat flow meter method, and thereby, they proposed the frequency response method, which avoided the low accuracy influence. However, this method has a bigger limitation owing to that it requires an accurate knowledge of the frequency response factor of the wall inner surface in absorbing heat [27]. Fokaides et al. [28] used the infrared thermograph method to measure the wall thermal transmittance, but their measurement error reached to 10%–20% and the assumed emissivity of building surface had most influence on the final measurement accuracy.

As can be seen, above three common methods are only suitable to wall thermal transmittance measurement in labs or some special buildings under certain in-situ conditions. And some new proposed methods have a larger limitation or a lower accuracy. However, the situation of China's continuous urbanization is that there are too many new buildings [7], vast constructions needing to be measured and very complex in-situ conditions. Therefore, in China, in-situ measurement methods must be relatively simple to operate, easy to transport, quick to install for measurement instruments, low in measurement cost and not complicated for the data processing method on the condition that the measurement accuracy should meet the essential engineering requirement.

Facing to this severe condition, some Chinese scholars have proposed a temperature control box-heat flow meter method (TCB-HFM) [29–32], which is based on the heat flow meter method and has a relatively stable thermal environment created by the temperature control box. The temperature control box, which is installed on the inner surface, can switch between cooling and heating according to the season and air temperature in the temperature control box can be accurately controlled by the PID. The temperature difference between indoor and outdoor air is created by cooling operation in summer, while it is created by heating operation in other seasons. Tian [29] systematically investigated the in-situ measurement of the wall thermal transmittance by the TCB-HFM earlier and measured the thermal transmittance of a 430 mm sintered clay brick wall in the non-heating period. The result showed the deviation between measurement and design values was only 0.7%. Pan et al. [30,31] investigated the TCB-HFM by numerical simulation and induced the correction factors suited to the thermal resistance of different insulation forms according to simulation results. Zhu et al. [32] measured the thermal transmittance of a 240 mm concrete masonry wall by the TCB-HFM. The experimental result showed the measurement thermal transmittance is 55% higher than the design thermal transmittance and that the measurement error was attributed to high moisture, which readily increased its thermal conductivity. A number of studies show the TCB-HFM is basically feasible in the theory principle [30–33], but the TCB-HFM, which was proposed lately, is at an exploration stage and it is not clear about many important problems closely related to the widespread use. In addition, the temperature control box of the TCB-HFM has a certain restriction in the in-situ measurement especially for the cooling operation in summer, as it needs an auxiliary refrigeration system and becomes more complex.

Based on the research status, this paper firstly puts forward to an easier method named as the simple hot box-heat flow meter method (SHB-HFM). The feasibility of the SHB-HFM is investigated by the theoretical analysis and an experiment. Moreover, the numerical simulation is done to analyze the error sources. And based on the error analysis, the further optimization methods on the SHB-FHM are proposed.