Applied Thermal Engineering 83 (2015) 48–56

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research paper

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

Xi Meng [a], Yanna Gao [b], Yan Wang [c], Biao Yan [a], Wei Zhang [a], Enshen Long [a, c, *]

[a] *College of Architecture and Environment, Sichuan University, Chengdu 610065, PR China*
[b] *Faculty of Environmental Engineering, The University of Kitakyushu, Kitakyushu 808-0135, Japan*
[c] *Institute of Disaster Management and Reconstruction, Sichuan University-Hong Kong PolyU, Chengdu 610065, PR China*

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.

ARTICLE INFO

Article history:
Received 9 November 2014
Accepted 2 March 2015
Available online 18 March 2015

Keywords:
Thermal transmittance
In-situ measurement
Simple hot box
Heat flow meter
Measurement error

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].

* Corresponding author. Room 112, Administration Building, Sichuan University, No. 24, First Loop South First Section, Chengdu 610065, Sichuan Province, China. Tel./fax: +86 028 85401015.
E-mail address: longes2@163.com (E. Long).

http://dx.doi.org/10.1016/j.applthermaleng.2015.03.010

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.

2. The simple hot box-heat flow meter method (SHB-HFM)

The SHB-HFM, which is based on the basis of the HFM, creates a relatively stable thermal environment by the simple hot box and has advantages of the TCB-HFM. It not only avoids the seasonal restriction of the HFM but uses simple experimental equipments, because the simple hot box is simply a temperature control device and there is neither the huge guarded hot box to eliminate the influence of the boundary heat loss nor the calibrated hot box to demarcate the boundary heat loss. The difference between the SHB-FHM and the TCB-FHM is that no matter in what season, the SHB-HFM always creates a wall temperature difference by the heating operation, and the box is always installed on the higher temperature side. This means the box is installed on the inner surface in winter, while it is installed on the outer surface in summer. In this way, this box can further increase the temperature difference of both wall sides on the basis of the original temperature difference between the inside and outside environment. Therefore the THB-FHM can get rid of the refrigeration device of the TCB-FHM, save the cost of measurement system and reduce the measurement difficulty.

Fig. 1 shows the measurement principle of the wall thermal transmittance by the SHB-HFM in summer. As shown in this figure, when the simple hot box is installed on the outer surface and heats the measurement wall with the indoor temperature still maintaining the natural temperature, thereby there will be a relatively stable high temperature difference. If the box dimension is large enough to form a 1-D heat transfer in the central area of the wall corresponding to the simple hot box, the wall thermal transmittance can be detected by arranging thermocouples and heat flow meters on the 1-D heat transfer area on the inner and outer surfaces.

The data processing method of the SHB-HFM is the same as the traditional heat flow meter method. The wall thermal transmittance can be obtained by the following equation:

$$U=\left(\frac{1}{h_{\text{out}}}+\frac{\sum_{n=1}^{N}\left(T_{\text{l,in,n}}-T_{\text{l,out,n}}\right)}{\sum_{n=1}^{N}q_{in,n}}+\frac{1}{h_{\text{in}}}\right)^{-1} \tag{1}$$

where, $T_{\text{l,in,n}}$ and $T_{\text{l,out,n}}$ are the nth measurement values of temperature on inner and outer surfaces respectively, °C; $q_{\text{in,n}}$ is the nth measurement value of heat flow on inner surface, W/m^2; h_{out} and h_{in} are outside and inside convection heat transfer coefficients, W/(m^2 K); N is the sum of the measurement number during one data processing cycle, which is integral multiple of 24 h.

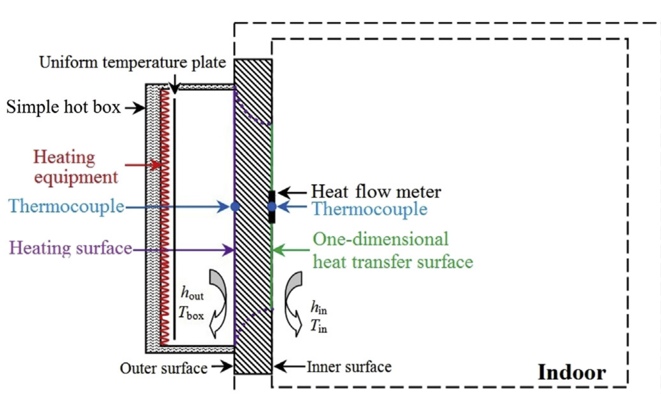

Fig. 1. The schematic diagram of the SHB-HFM in summer.

3. Experiment subject and measurement system

3.1. Experiment subject

The experimental subject is a new two-storey rural building, which belongs to an energy-saving demonstration project of the United Nations as shown in Fig. 2(a). This building had complete design drawings and was constructed under the good construction management, which enables a fair comparison as the measurement value with the design value. The measurement wall d is the east gable of the new building. Fig. 2(b) shows the structure of the measurement wall consisting of one 240 mm self-insulation brick layer and two 20 mm plaster layers.

3.2. Structure of the simple hot box

Fig. 3 shows the appearance and the section of the simple hot box. The box has the external dimensions of 900 mm × 900 mm × 300 mm ($L \times W \times H$) and the internal dimensions of 820 mm × 820 mm × 260 mm. From outside to inside, the box consists of 15 mm wood composite board and 25 mm rubber sponge plate with thermal conductivity of 0.034 W/(m K), which has good thermal insulation and fireproofing properties. The electrical heating element of 100 W is uniformly paved at the box bottom and a voltage regulator is used to increase or decrease the heating power. On the contact line between the box and the measurement wall, the seal belt is used to reduce air outflow and improve the temperature stability of the air in the box.

3.3. Calibration of measurement equipments

In the in-situ measurement, the accuracies of heat flow meters and T-thermocouples are 5% and 0.5 °C respectively. Heat flow meters were calibrated according to the standards by a special agency and T-thermocouples were calibrated using a constant temperature water bath. Thermocouples and heat flow meters, with errors lower than 0.3 °C and 3% respectively, were selected for in-situ measurement. All measurement data were recorded by JTRG-II building thermal temperature automatic tester with the data-collection interval of 2 min.

3.4. Measurement location arrangement

Fig. 4 shows the arrangement diagram of the simple hot box and measurement equipment. The simple hot box is installed on the east gable and 2.0 m away from the corner and floor of the south wall. There are no components (such as beams and columns), which may cause thermal bridge. One thermocouple (T1) is laid at the center of the simple hot box to measure the air temperature in the box, and three thermocouples (T2–T4) are laid at an equal distance of 15 cm to measure the outer surface temperature, in which T3 is the primary location. Three heat flow meters (HF1–HF3) of size 10 cm × 5 cm are laid at the place of inner surface corresponding to locations of T2–T4 to measure the outer surface heat flow, in which HF2 is the primary location of the heat flow. Two thermocouples (T5–T7, T5′–T7′) are symmetrically arranged on both sides of each heat flow meter to measure the inner surface temperature, in which T6 and T6′ are primary locations.

4. Variation rules of temperature and heat flow in the in-situ measurement

The in-situ measurement of the wall thermal transmittance may encounter very complicated climate conditions and a complex

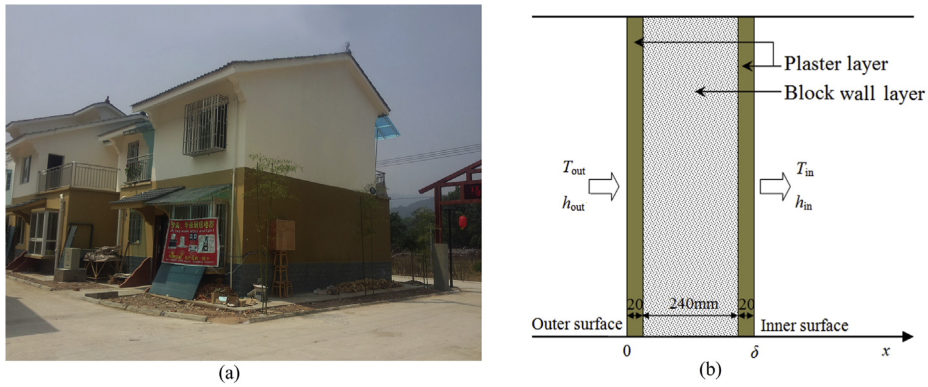

Fig. 2. Experimental subject: (a) architectural appearance and (b) the wall structure.

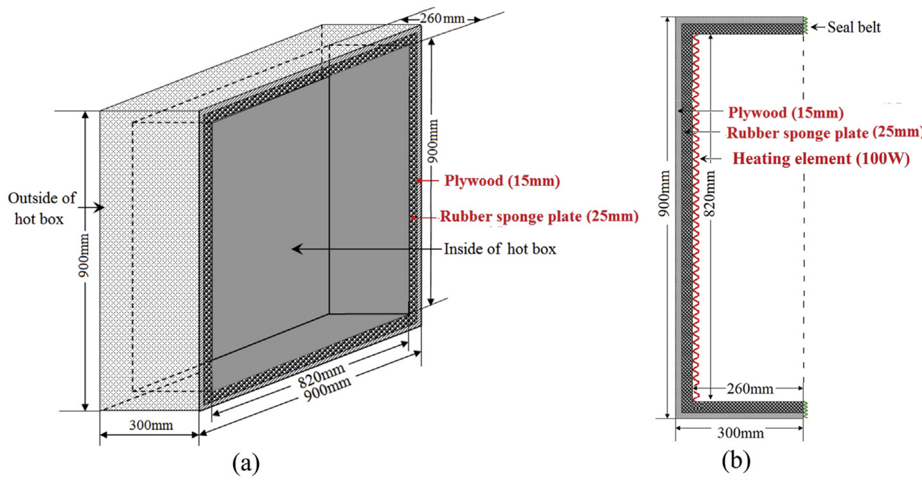

Fig. 3. (a)The appearance and (b) the section of the simple hot box.

diversity of building walls. In order to measure the adaptability and reliability of the SHB-HFM under the most unfavorable conditions, the experiment was carried out from 7th to 15th in August 2013. During the measurement period, there were rainy, cloudy and sunny days, and the ambient temperature of the wall and the box fluctuated naturally with weather conditions.

Fig. 5(a) shows the variation of the inside and outside air temperature and air temperature in the simple hot box with time and the maximum, minimum and average values after the 72 h heating period are also shown in the figure. As shown in figure, the outside air temperature had a big fluctuation of 15 °C due to the alternations of day and night, local weather and the solar radiation, while

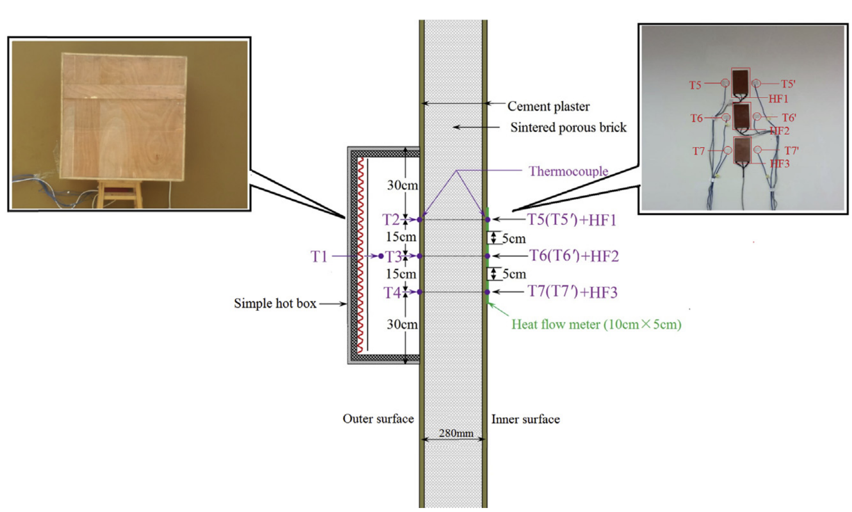

Fig. 4. The arrangement diagram of the simple hot box and measurement equipment.

the inside air temperature fluctuation was obviously less than that of the outside due to the thermal inertia of the building envelope. Comparing the inside and outside air temperature, the average temperature difference was less than 2 °C after the 72 h heating period, and even the inside air temperature was higher than outside some times, so it was difficult to form the unidirectional heat transfer. However, the air temperature in the box (T1) easily obtained 60 °C and has only a small fluctuation of 3 °C, so the temperature difference between inside air temperature and air temperature in the box can keep more than 30 °C, which makes the in-situ measurement possible and effective.

Fig. 5(b) shows the outer surface temperature variation (T2–T4) with time. As shown in the figure, the surface temperature rose rapidly during the initial heating stage, this rate slowed down after 12 h and the air temperature was basically stable after 24 h. And the outer surface temperature also had the fluctuation of around 2 °C after 72 h. The temperatures of three locations had the same varying tendency and their average difference was less than 1.6 °C. And T3 at the center was the highest.

Fig. 5(c) shows the inner temperature variation (T5–T7) with time. As shown in the figure, the inner surface temperature did not rise as the outer surface temperature owing to the wall thermal inertia effect. On the contrary, it decreased with the inside air initial stage and then rose rapidly. And the inner surface temperature had the fluctuation of around 2.2 °C after 72 h. The temperatures of three locations had also the same varying tendency and their average difference was less than 0.5 °C, which was obviously lower than that of outer surface. And T6 at the center was the highest.

Fig. 5(d) shows inner heat flow variation (HF1–HF3) with time. As shown in the figure, the inner heat flow rose rapidly with a

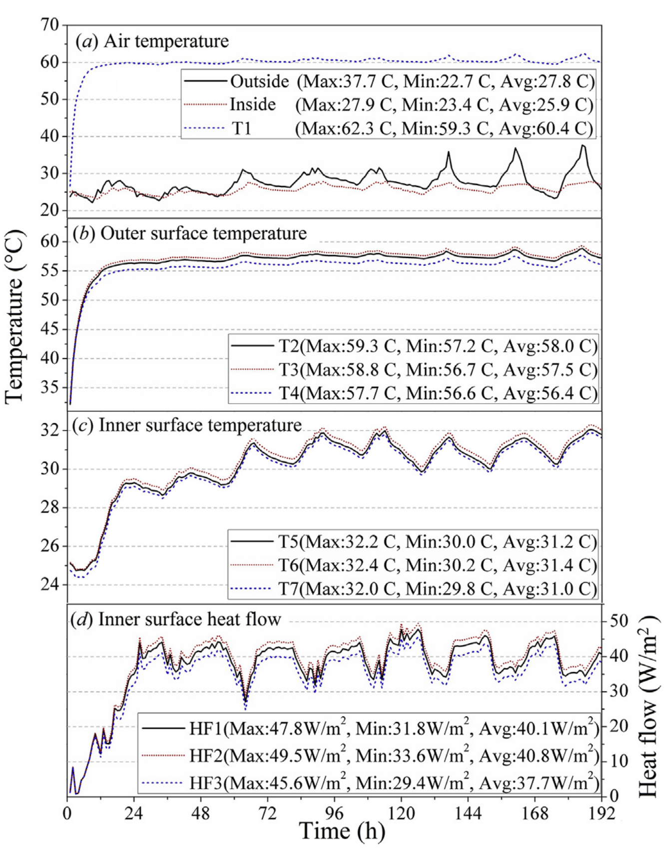

Fig. 5. Variation of (a) air temperature, outer surface temperature (b), inner surface temperature (c) and inner surface heat flow (d) with time.

certain fluctuation and the sharp increase was not obvious any more after the 24 h heating. During the stable heat transfer period, heat flow was more than 30 W/m^2 and always unidirectional the outer surface to the inner surface, which was very favorable for improving the measurement accuracy. The average difference among various locations was up to 4 W/m^2 and it may be resulted from the boundary heat loss. And HF2 at the center was the highest.

It should be pointed out that the effective locations were T3, T6 and HF2. The auxiliary measurement locations (T2, T4, T5, T7, HF1 and HF3) shown in Fig. 5 provides the important information about the influences of the locations arrangement on the measurement accuracy and lay the experiment data foundation for the subsequent error analysis.

5. Feasibility of the SHB-HFM

According to building design information, the measurement wall consists of a one block layer and two plaster layers as shown in Fig. 2(b) and their thermal physical properties are shown in Table 1. Outside and inside convective heat transfer coefficients were assumed as 19 W/(m^2 K) and 8.7 W/(m^2 K). The design value of wall thermal transmittance was calculated as 1.315 W/(m^2 K). In order to quantify the measurement accuracy of wall thermal transmittance, relative error ε is introduced and described as follow:

$$\varepsilon = \frac{U - U_D}{U_D} \times 100\% \tag{2}$$

where, U_D and U are the design value and the measurement value of wall thermal transmittance respectively, W/(m^2 K).

The measurement value of wall thermal transmittance can be obtained by Equation (1) according to the relevant data in Fig. 5. Fig. 6 shows measurement values and relative errors of five days (72 h–192 h) with the data processing cycle of 24 h (one day). It is seen that for the primary sensors, the measurement value range of wall thermal transmittance is 1.22–1.26 W/(m^2 K) and their average relative error is −5.97% for five data processing cycles, which indicates that even under the influence of unfavorable factors of the natural fluctuation of ambient temperature, apparent variation of indoor air temperature with the external large fluctuation and the slight variation of the air temperature in the hot box without any temperature control measure, the SHB-HFM still has the higher accuracy and satisfies the requirement of engineering detection. Moreover, through arranging reference test sensors, 15 cm up and down from the central primary test sensors, errors caused by location deviation have increased just to −8.14% and −9.60%, which basically meet the accuracy requirement. On the other hand, it also indicates that the SHB-FHM has a tolerance for the in-situ operation errors and the error increased by the location deviation is also in the acceptable range of engineering.

Table 2 shows a comparison of five present measurement methods. As shown in Table 2, the CHB is not applicable for the in-situ measurement due to the complex and varied in-situ conditions, while the GHM is rarely applicable to in-situ measurement due to the heavy equipment and the difficult in-situ operation. In addition, the HFM has obvious limitation for buildings and test season. The TCB-HFM and the SHB-HFM has the easy in-situ measurement and not obvious limitation, but the SHB-HFM has the easier equipment, due to the absence of the refrigeration device of the TCB-FHM, and the lower cost for the equipment production and the in-situ test cost. Meanwhile, the TCB-FHM has the higher measurement accuracy and tolerant in-situ operation as sown above.

Although the SHB-HFM has some obvious advantages and the above experiment results have proved its feasibility and availability,

Table 1
Thermal physical properties of wall materials.

Wall material	Density (kg/m^3)	Heat capacity (J/(kg K))	Thermal conductivity (W/(m K))
Block	1654	750	0.44
Cement plaster	1860	840	0.84

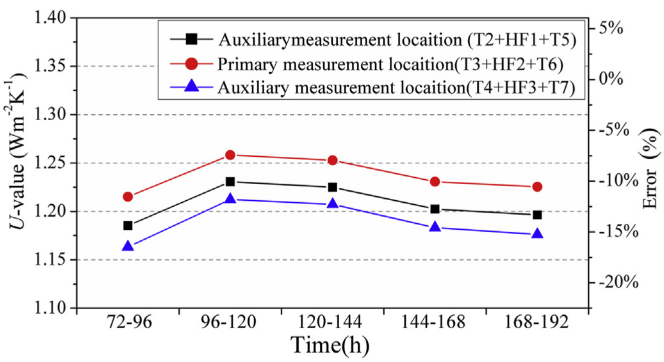

Fig. 6. Variation of wall thermal transmittance and relative error for different measurement cycles.

but it should also be noted that the measurement value of wall thermal transmittance is always lower than the design value, which is worthy of the further study from the view point of the academic exploration.

6. Simulation reproduction and error analysis of the in-situ measurement

In order to improve the measurement accuracy of the SHB-FHM, a theoretical modeling method is supposed to be resorted in order to verify the actual experiment results and explore the error sources.

6.1. Heat transfer model of the SHB-HFM

In the in-situ measurement, the simple hot box was installed to heat the measurement wall. The ambient temperatures of outer surface covered by the box and that uncovered must be different, while the ambient temperature of inner surface is lower. So the wall heat transfer is three-dimensional (3-D). However, as the wall heat transfer is symmetrical about the vertical central section of wall covered by the box, there is only heat transfer along the wall thickness and height. Therefore, a 3-D problem can be approximately simplified to 2-D heat transfer along the directions of thickness and height. Fig. 7 shows the physical model of the measurement wall. H and δ are the height and thickness of the wall model and L is the qualitative box dimension. In addition, the monitoring locations of the temperature and the heat flow are at the center of the inner and outer surfaces in accord with the test locations so as to compare the simulation values with the experiment values.

If a 2-D coordinate system is established with the coordinate origin at the center of wall surface corresponding to the box, the thickness direction x and the height direction y, according to the energy conservation law, the dynamic heat transfer of the wall is described as the following equation:

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\frac{\lambda}{\rho C_p}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\lambda}{\rho C_p}\frac{\partial T}{\partial y}\right) \tag{3}$$

where, T denotes the material temperature, °C; t is the simulation time, s; λ is the thermal conductivity, W/(m K); ρ is the material density, kg/m^3; C_p expresses specific heat, J/(kg K);

Convective heat transfer boundary conditions are adopted on the outer and inner surfaces ($x = 0$ and δ) and the adiabatic boundary conditions can be used on top and bottom surfaces ($y = \pm H/2$) and they can be expressed as:

$$\text{On the outer surface}(-\mathrm{L}/2 \le y \le \mathrm{L}/2): -\lambda\left.\frac{\partial T}{\partial x}\right|_{x=0} = h_{\text{out}}(T_{\text{box}} - T_{\text{l,out}}) \tag{4}$$

$$\text{On the outer surface}(-H/2 \le y \le -L/2) \text{ and } (L/2 \le y \le H/2) : -\lambda\left.\frac{\partial T}{\partial x}\right|_{x=0} = h_{\text{out}}(T_{\text{out}} - T_{\text{l,out}}) \tag{5}$$

$$\text{On the inner surface}: -\lambda\left.\frac{\partial T}{\partial x}\right|_{x=\delta} = h_{\text{in}}(T_{\text{l,in}} - T_{\text{in}}) \tag{6}$$

$$\text{On the top and bottom surfaces}: -\lambda\left.\frac{\partial T}{\partial y}\right|_{y=\pm H/2} = 0 \tag{7}$$

where T_{in}, T_{out} and T_{box} are the inside and outside air temperature and the air temperature in the box respectively, °C; $T_{\text{l,out}}$ and $T_{\text{l,in}}$ are temperatures of the outer and inner surface temperature, °C;

6.2. Simulation of temperature and heat flow on wall surfaces

For the in-situ measurement, the box dimensions are 900 mm × 900 mm × 300 mm. Namely, the box length (L) is 0.9 m in the numerical simulation. In order to reproduce in-situ measurement data, the inside and outside air temperature and the air temperature in the box are the same with the in-situ measurement data shown in Fig. 5(a) during the simulation. The wall structure

Table 2
Comparison of the measurement methods on wall thermal transmittance.

Method	In-situ test	Requirement	Limitation	Operation	Equipment	Accuracy	Cost
CHB	Inapplicable	–	–	–	–	–	–
GHB	Applicable	Big test area	No	Difficult	Heavy	High	High
HFM	Applicable	Heated building	Only winter	Easy	Simple	Low	Low
TCB-HFM	Applicable	No	No	Easy	Heavy	High	High
SHB-HFM	Applicable	No	No	Easy	Simple	High	Low

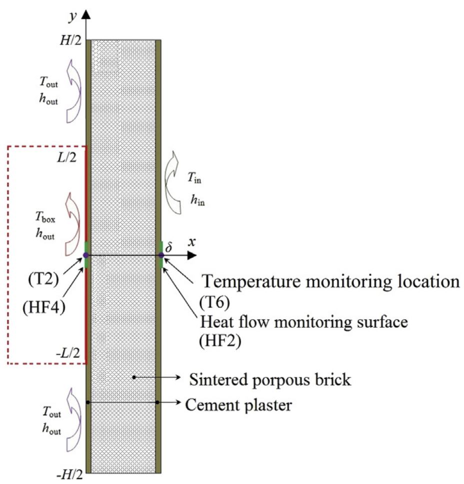

Fig. 7. A physical model of the measurement wall.

and the material thermal physical properties are shown in Fig. 2 and Table 1 respectively. Outside and inside convective heat transfer coefficients are 19 W/(m^2 K) and 8.7 W/(m^2 K) respectively. The wall height (H) of 4 m is sufficiently high to eliminate the influence of the boundary heat loss.

For the numerical simulation based on the heat transfer model of Equation (2), the finite volume method is utilized to discrete the heat transfer equation in the simulating region. For the discretization, a central differencing algorithm is used for the two-order implicit scheme. Meshing chooses the structured grid and the grid of plaster layer is carried out by the encryption processing. In addition, a grid-independent solution is tested and the final quantity of the grid is 99400.

Fig. 8 shows a comparison of the simulation values with the measurement values of primary locations (T2, T6 and HF2). It can be seen that the varying tendencies of the simulation and measurement are approximate the same and the maximum deviation is only 0.46 °C for the temperature, which is less than the measurement precision of thermocouple of 0.5 °C, and 2.73% for the heat flow, which is also much less than the measurement precision of heat flow meter of 5%. The above mathematical simulation has well reproduced the experimental results of the surface temperature and heat flow. It demonstrates that the heat transfer model is effective and accurate, and indicates that predicted conclusions are verified in this further investigation by means of the mathematical model.

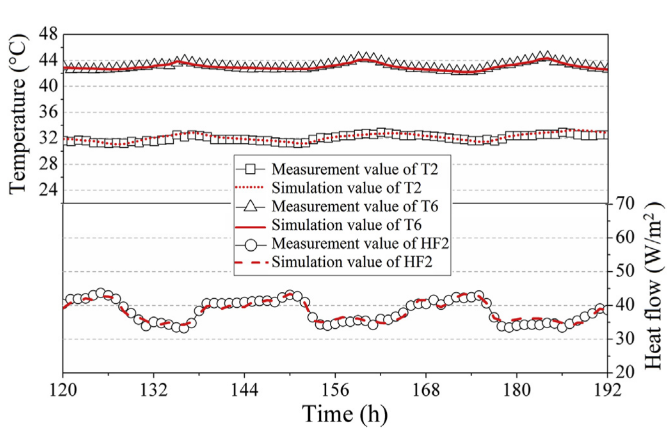

Fig. 8. Comparison of measurement value and simulation value for T2, T6 and HF2.

6.3. Error analysis of the in-situ measurement

In the above simulation, the simulation and measurement values have a good consistency under the same measurement conditions, which shows that the material thermal physical properties of the actual wall agree with those of the building design. Therefore, the possibility can be excluded that utilizing wall materials with better thermal performance during construction results in good thermal insulation properties of the actual wall. In addition, the good consistency between simulation and measurement values also shows thermocouples and heat flow meters have the high accuracy and that the influences of the sensor error can be eliminated.

However, what on earth are the primary reasons leading to the phenomenon that the measurement value of the wall thermal transmittance is slightly lower than design value? During the in-situ measurement, any heat flow meter was not arranged on the outer surface corresponding to the box. In order to further analyze the error source, it was assumed that a monitoring surface (HF4) is at the center of outer surface in the box shown in Fig. 7. Fig. 9 shows the simulation comparison of HF2 on the inner surface and HF4 on the outer surface. It can be clearly seen that heat flows on outer and inner surfaces are very close during certain time intervals, while there exists an obvious "scissor difference" in other time intervals. Heat flow on the outer surface is higher than that on the inner surface at other time and thereby, an obvious “scissor difference” of heat flows has been formed. By the computation, the average values of heat flows on the inner and outer surfaces were 41.8 W/m^2 and 46.8 W/m^2 respectively from 120 h to 192 h. The in-situ measurement values of the heat flow are only for the inner surface, which is a key reason why test result is slightly lower than design value.

If heat flow meters are arranged on both inner and outer surfaces in the in-situ measurement, the higher measurement accuracy should be obtained. In addition, there is the "scissor difference" between heat flows on the inner and outer surfaces even after 120 h, which implies that the existing SHB-HFM may have some flaws, and the problems need to be identified to make further improvement.

7. Optimization of the SHB-FHM

7.1. Moderate dimensional enlargement of the box

Why does the “scissor difference” phenomenon exist for heat flows on the inner and outer surfaces? A preliminary speculation is that it is related to the box dimensions except for the fluctuation of

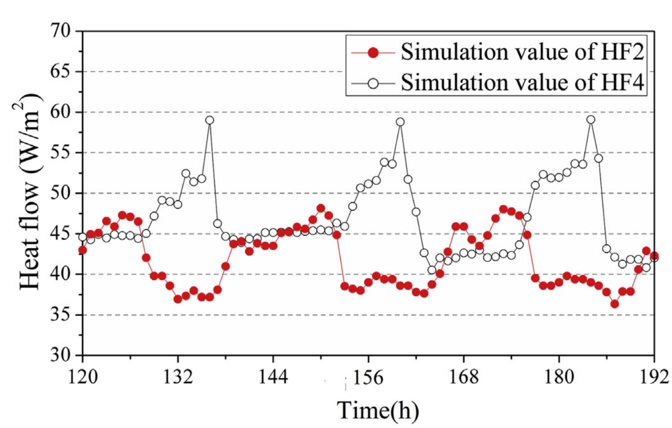

Fig. 9. Variations of heat flows of HF4 on outer surface and HF2 on inner surface with time.

the temperature boundaries. When the box dimension increases to a certain degree, the central area of the wall corresponding to the box will form a 1-D heat transfer zone, and the larger the box dimensions, the larger the 1-D heat transfer zone. In order to further find out the relationship between the "scissor difference" phenomenon and the box dimensions, the simple hot boxes with two dimensions of 0.9 m and 2.0 m were respectively selected to simulate, under the assumptions that the inside and outside air temperature and the air temperature in the box are 20 °C, 30 °C and 45 °C respectively so as to eliminate the fluctuating influence of the temperature boundaries.

Table 3 presents the comparison of the design, measurement and simulation values on wall thermal transmittance for different box dimensions and different temperature boundaries. As shown in figure, when the box dimension is 0.9 m, even under the ideal in-situ test conditions ($T_{box} = 45$ °C, $T_{in} = 20$ °C and $T_{out} = 30$ °C), the predicted error is still close to −5% if the heat flow meter is pasted on the inner surface, while the predicted error is close to 3.7% if the heat flow meter is pasted on the outer surface. Compared with adverse conditions, the ideal constant boundaries cannot obviously decrease the measurement error as expected. In addition, when the box dimension increases to 2.0 m, regardless of the inner or outer surface where heat flow meters are installed, the predicted values of thermal transmittance are almost the same and only have a deviation of 0.36% relative to the design value. Therefore, it can be seen that the box dimension has a significant influence on the measurement accuracy.

The above investigation shows that a larger box is conducive to forming the 1-D heat transfer zone and to improving the measurement accuracy, but box dimensional enlargement increases the box cost and adds the in-situ measurement difficulty. In order to obtain the optimum box dimensions according to the measurement wall, thirteen sizes of the boxes are selected at the equal interval from 0.9 m to 2.0 m. The simulation is carried out to find the zone dimensions where heat flows on inner and outer surfaces are the same under different box dimensions, and the simulation conditions are the same as the above. This zone can be defined as the 1-D heat transfer zone.

Fig. 10 shows the variation of the 1-D heat transfer zone with the box dimension. As shown in the figure, when the box dimension is less than 0.9 m, the 1-D heat transfer zone cannot be fully formed. And when the box dimension increases to 1.0 m, the 1-D heat transfer zone of 0.09 m has formed and then, the 1-D heat transfer zone linearly increases with the box dimension enlargement. If the pasting area of the heat flow meters is 0.1 m × 0.05 m, the minimum box dimension is 1.20 m for three heat flow meters on the measurement wall.

7.2. The double heat flow meters

In-situ measurement may encounter many complex situations. For example, the box dimension carried might be somewhat small and it may be difficult to install heat flow meters at the central area, corresponding to the box. Therefore, for the sake of safety, heat flow meters should be arranged on the inner and outer surfaces, and the average value of both heat flow values is final test value. Table 4 shows the comparison of the simulation value by double heat flow meters, the measurement value by the single heat flow meter and the design value. It can be seen that double heat flow meters can decease the test error significantly, no matter what the ideal or natural temperature boundaries. Namely, even when there are some flaws in the in-situ test hardware, the inevitable human faults or the in-situ test conditions, it is always helpful that heat flow meters are simultaneously arranged on the inner and outer surfaces, because they not only verify each other but improve the test accuracy.

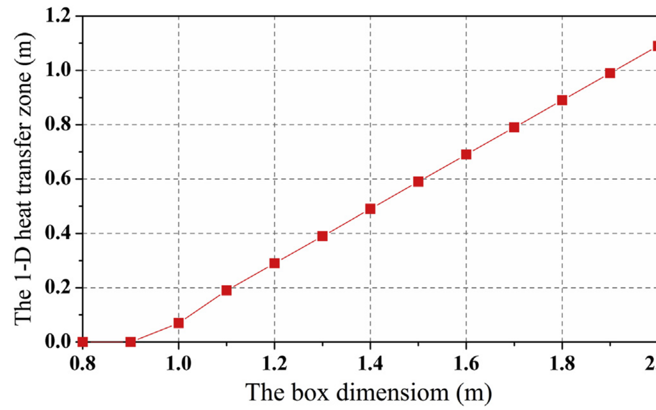

Fig. 10. Variation of 1-D heat transfer zone with the dimension of the simple hot box.

8. Conclusions

The practice of determining China's building energy efficiency urgently calls for a simple and accurate in-situ measurement method for testing the wall thermal transmittance. This paper proposes the SHB-HFM, which has the higher measurement accuracy than the HFM and overcomes its seasonal limitation, and has the simpler measurement equipment, the lower wall requirement and the smaller in-situ operation difficulty than the GHB, the CHB and the CTB-HFM. The following conclusions have obtained.

(1) Since the simple hot box can maintain a high enough temperature difference, the test error of the wall thermal transmittance by the SHB-FHM is only −5.97% relative to the design value even under the most unfavorable in-situ conditions, thereby proving that this method is feasible.
(2) Through arranging reference test sensors, 15 cm up and down from the central primary test sensors, the test errors due to the location deviation increased just to −8.14% and −9.60% respectively, which basically meet the accuracy requirement and thereby demonstrates the SHB-HFM has a certain tolerance. The reason for the effectiveness of SHB-FHM in in-situ measurement is that it grasps the main contradiction and creates an enough high temperature difference.

Table 3
Comparison of design, measurement and simulation values on wall thermal transmittance.

Design value	Measurement value	Simulation value				
		Unsteady state		Steady state		
	$L = 0.9$ m	$L = 0.9$ m		$L = 0.9$ m		$L = 2.0$ m
	Inner surface	Inner surface	Outer surface	Inner surface	Outer surface	Inner or outer surface
1.315	1.235	1.241	1.359	1.257	1.362	1.3197
Error (%)	−5.97%	−5.63%	3.35%	−4.91%	3.67%	0.36%

Table 4
Comparison of design, measurement and simulation values on of thermal transmittance when $L = 0.9$ m.

Design value	Measurement value	Simulation values	
		Unsteady state	Steady state
	Inner surface	Double heat flow meters	Double heat flow meters
1.315	1.235	1.301	1.310
Error (%)	−5.97%	−1.08%	0.37%

(3) The ideal in-situ test conditions cannot improve significantly the measurement accuracy and arranging heat flow meters on two wall surfaces is an important way to improve the test accuracy. The box dimension has a significant influence on the test accuracy and a moderate enlargement of the box dimension is an efficient way to improve in-situ test accuracy. The optimum box dimension is 1.20 m for the measurement wall (280 mm in thickness with specific thermal performance).

As a simple in-situ test method, there are many problems worthy of studying in order to find application and achieve popularization.

Acknowledgements

The authors gratefully acknowledge the financial support from the National Natural Science Foundation of China under Grant No. 51478280 and No. 51178282.

References

[1] E.S. Long, General descriptions of research method, buildings, analysis object, assumptions and weather conditions of background cities, Build. Environ. 40 (4) (2005) 443–450.
[2] C. Barreneche, A.D. Gracia, S. Serrano, M.E. Navarro, A.M. Borreguero, A.I. Fernández, M. Carmona, J.F. Rodriguez, L.F. Cabeza, Comparison of three different devices available in Spain to test thermal properties of building materials including phase change materials, Appl. Energy 109 (2013) 421–427.
[3] GB 50176-93, China Standard, Thermal Design Code of Civil Buildings, MOHURD, Beijing, October 1993.
[4] JGJ134-2010, China Standard, Design Standard for Energy Efficiency Design of Residential Buildings in Hot Summer and Cold Winter Zone, MOHURD, Beijing, August 2010.
[5] JGJ50198-2005, China Standard, Standard for Energy Efficiency Design of Public Buildings, MOHURD, Beijing, April 2005.
[6] JGJ268-2010, China Standard, Design Standard for Energy Efficiency Design of Residential Buildings in Severe Cold and Cold Zones, MOHURD, Beijing, March 2010.
[7] http://www.jssb.gov.cn/jstj/djgb/sxndtjgb/201101/t20110128_114796.htm.
[8] GB/T 23483-2009, China Standard, Test Standard for Overall Heat Transfer Coefficient of Building Envelope and Heat Supply for Space Heating, MOHURD, Beijing, December 2009.
[9] JGJ 132-2001, China Standard, Standard for Energy Efficiency Inspection of Heating Residential Buildings, MOHURD, Beijing, February 2001.
[10] ISO standard 8301-1991, Thermal insulation – determination of steady-state thermal resistance and related properties – heat flow meter apparatus.
[11] ISO standard 8302-1991, Thermal insulation – determination of steady-state thermal resistance and related properties – guarded hot plate apparatus.
[12] ISO standard 8990-1994, Thermal insulation – determination of steady-state thermal resistance and related properties – calibrated and guarded hot box.
[13] ASTM C1199-00 Standard, Test Method for Measuring the Steady-State Thermal Transmittance of Fenestration Systems Using Hot Box Methods.
[14] ASTM C518-04 Standard, Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus.
[15] GB/T 13475-2008, China Standard, Thermal Insulation – Determination of Steady-state Thermal Resistance and Related Properties – Calibrated and Guarded Hot Box, AQSIQ, Beijing, June 2008.
[16] G.F. Jones, R.W. Jones, Steady-state heat transfer in an insulated, reinforced concrete wall: theory, numerical simulations, and experiments, Energy Build. 29 (3) (1999) 293–305.
[17] P.G. Cesaratto, M.D. Carli, A measuring campaign of thermal conductance in situ and possible impacts on net energy demand in buildings, Energy Build. 59 (2013) 29–36.
[18] F. Asdrudali, G. Baldineli, Thermal transmittance measurements with the hot box method: calibration, experiment, and uncertainty analyses of three different approaches, Energy Build. 43 (2011) 1618–1626.
[19] G. Desogus, S. Mura, R. Ricciu, Comparing different approaches to in situ measurement of building components thermal resistance, Energy Build. 43 (2011) 2613–2620.
[20] A. Ahmad, M. Maslehuddin, L.M. Al-Hadhrami, In situ measurement of thermal transmittance and thermal resistance of hollow reinforced precast concrete walls, Energy Build. 84 (2014) 132–141.
[21] P.G. Cesaratto, M. De Carli, S. Marinetti, Effect of different parameters on the in situ thermal conductance evaluation, Energy Build. 43 (2011) 1792–1801.
[22] X. Meng, B. Yan, Y.N. Gao, J. Wang, W. Zhang, E.S. Long, Factors affecting the in situ measurement accuracy of the wall heat transfer coefficient using the heat flow meter method, Energy Build. 86 (2015) 754–765.
[23] P. Biddulpha, V. Goria, C.A. Elwella, C. Scottb, C. Rye, R. Lowea, T. Oreszczyna, Inferring the thermal resistance and effective thermal mass of a wall using frequent temperature and heat flux measurements, Energy Build. 78 (2014) 10–16.
[24] M.J. Jiménez, B. Porcar, M.R. Heras, Application of different dynamic analysis approaches to the estimation of the building component U value, Build. Environ. 44 (2009) 361–367.
[25] M.J. Jiménez, B. Porcar, M.R. Heras, Estimation of building component UA and GA from outdoor tests in warm and moderate weather conditions, Sol. Energy 82 (2008) 573–587.
[26] C.H. Peng, Z.H. Wu, In situ measuring and evaluating the thermal resistance of building construction, Energy Build. 40 (2008) 2076–2082.
[27] C. Peng, Z. Wu, Thermoelectricity analogy method for computing the periodic heat transfer in external building envelopes, Appl. Energy 85 (2008) 735–754.
[28] P.A. Fokaides, S.A. Kalogirou, Application of infrared thermography for the determination of the overall heat transfer coefficient (U-value) in building envelops, Appl. Energy 88 (2011) 4358–4365.
[29] S.B. Tian, Study on In-situ Measurement Method of Heat Transfer Coefficient of Building Envelop (Master Thesis), Xi'an University of Architecture and Technology, Xi'an, 2006.
[30] L. Pan, B.M. Chen, Z.H. Fang, Y.T. Zhen, Field measurement and data processing method of envelope's thermal resistance, Build. Energy Environ. 6 (2005) 80–84.
[31] L. Pan, B.M. Chen, Z.H. Fang, B.F. Han, Y.T. Zhen, Measurement of thermal resistance of building enclosures by means of the heat box method, Build. Energy Environ. 2 (2005) 74–77.
[32] X.F. Zhu, L.P. Li, X.B. Yin, An in-situ test apparatus of heat transfer coefficient for building envelope, Build. Energy Effic. 256 (2012) 57–60.