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STUDY ON THERMAL INSULATION AND HEAT TRANSFER PROPERTIES OF WOOD FRAME WALLS

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ABSTRACT

Steady-state heat transfer performance of wood frame wall is an important index to assess its energy efficiency. In order to study the factors that affect the heat transfer coefficient of wood frame wall, the method of improving the thermal insulation property of the wall was studied. In this paper, 12 wall specimens with different structures were manufactured, and the effective heat transfer coefficient was measured by the hot box-heat flow meter test method. The reliability of the theoretical calculation value of thermal resistance was verified by the experimental value. The results showed that the moisture content of Spruce-pine-fir (SPF), insulation materials, spacing and thickness of studs had influence on the heat transfer coefficient of walls. The effective heat transfer coefficient values of three walls ranged from 0.325 to 0.398 $W•m^{-2}•K^{-1}$, which met the thermal level It of the severe cold area. The linear correlation between the theoretical calculation value and the test value was up to 0.9587, effective thermal resistance value of wood frame wall can be estimated by calculating without extra experiment.

KEYWORDS: Wood frame wall, insulation, heat transfer coefficient, thermal resistance.

INTRODUCTION

Wooden construction residence can provide a well living environment with its outstanding advantages of environment-friend, energy-efficiency, quake-proof, structural safety, health and comfort. To create such functioning objects, several factors must be met. One of the factors is to maintain the best possible thermal insulation properties of the building envelope, which is achieved both by the use of suitable materials and their proper combination and wall constitution. When used in practice innovative concept will improve the thermal insulating performance of the construction and in compliance with the other principles of the construction of low-energy buildings (i.e. reduce the heat transfer coefficient, improve the thermal resistance, use the exterior insulation etc.) reduces the overall energy consumption of the building (Blazek et al. 2016). Innovative concept of composite wall material was based on dimension lumber as framework material. The inside and outside sheathings are applied, making up of multi-layer materials which possesses the characters of thermal insulation, sound-proof, moisture-proof and meeting the load requirement. As a vital component of building envelope, steady-state heat transfer performance of wood frame wall has a remarkable influence on thermal insulation and energy consumption of buildings.

The thermal insulating properties of wooden construction were represented by heat using heat transfer coefficient U and thermal resistance R. These two values were measured and calculated in the practical part of this study. For purposes of measuring guarded hot box according to DIN EN ISO 8990: 1996 was used to determine heat transfer coefficient U. This method was commonly used in the world for detection of thermal insulation properties of building components and structures (Burch et al. 1990, Gao et al. 2004, Asdrubali and Baldinelli 2011). Nussbaumer and Wakili (2006) used a similar method to determine thermal transmittance of structures from concrete and vacuum insulation. Measured values of U ranged from approximately 0.16 to 0.18 $W\bullet m^{-2}\bullet K^{-1}$, which showed that composite wall had good application reference value in thermal storage and thermal insulation. Nyers et al. (2015) analysed the optimum energy-economic thickness of thermal insulation layer for external wall by adopting a new method investment-savings, developing an appropriate mathematical model, which could obtain the temperature variation at the interface of the external wall by different methods. In another study Wakili and Tanner (2003) presented results of three methods to determine the value of coefficient U. One was tested in a hot box according to EN ISO 8990: 1996 and the other two methods were theoretical calculations according to EN 1745: 2002 during examination of the walls made of perforated porous clay bricks. The results of this study showed the measured value of coefficient U at approximately 0.115 to 0.128 $W\bullet m^{-2}\bullet K^{-1}$ and calculated values of U were approximately 3-5% higher. Isaev (2005) applied unsteady heat transfer theory and computer simulation to study heat transfer coefficient of the wall and further improved the calculation method of it. Skujans et al. (2007) used equipment similar to hot box (also according to the aforementioned standards) for measurement of heat transfer coefficient. There has also been steady and controlled flow of heat through walls made by using polystyrene foam and plaster.

The measured the value of U ranged from 0.35 to 0.37 $W\bullet m^{-2}\bullet K^{-1}$. The lowest recommended values of U for passive buildings were reported in the range from 0.12 to 0.18 $W\bullet m^{-2}\bullet K^{-1}$. Kucerova et al. (2014) studied the condition of timber building envelope in terms of the thermal transmittance coefficient after years of use, the value of coefficient U determined by measuring was of 0.04 $W\bullet m^{-2}\bullet K^{-1}$ higher than the value determined by the calculation software, a deviation from expected value can be calculated, and it proved that the envelope construction of the designed wooden buildings met current thermal requirements of technical standards.

With the wide application of wood frame construction in different climate areas and the surge of new materials, thermal insulation and steady-state heat transfer properties of wood frame walls were attached great importance (Zarr et al. 1995, Dalgliesh et al. 2005). The research on thermal insulation and steady-state thermal transmission properties of wood frame wall was beneficial to reveal heat-transfer mechanisms, whether the thermal insulation properties met national standards were testified by analyzing influencing factors on the heat transfer coefficient of composite wall, they all laid solid foundation for further development of new-type wall materials as well as architectural structures.

In this paper, 12 wood frame walls with different types using various sheathings, thermal insulation materials and studs in different thickness and spacing were manufactured with Canadian spruce-pine-fir (SPF) dimension lumber, Chinese larch OSB, thistle board and other materials.

Hot box-heat flow meter method was adopted to detect and evaluate the thermal insulation performance of walls, and the effects of thermal insulation, steady-state heat transfer properties, different materials and wall structures on heat transfer coefficient were investigated, which were compared with theoretical calculation values of thermal resistance R. Attempting to develop cost-effective and practical retrofit systems to reinforce existing wooden construction for specific stud-wall deficiencies of thermal insulation (Pantelides et al. 2004), including wall constitutions, thermal insulation materials, outer protective coatings and sheathings. The results were anticipated to offer reference for future design of prefabricated wood frame walls, especially in thermal insulation and heat transfer properties.

MATERIAL AND METHODS

Experimental materials and connecting manners

Wall materials and frame structure design

Dimension lumber of SPF was employed as the studs of wood frame walls, whose section size were 38 × 89 mm, 38 × 140 mm, respectively. 12 mm larch oriented strand board (OSB) and 12 mm thistle board finish (TB) in thickness were used as sheathings. Glass wool (GW) was chosen as insulation material in wall insulating layer; 30 mm expanded polystyrene foam sheet (EPS) or extruded polystyrene foam sheet (XPS) was applied as external insulation material. Fig. 1 and Fig. 2 illustrate the wall frame and its structure, materials and connecting manners of all the walls are given in Tab. 1, which all refer to the Canadian Wood-Frame House Construction (Burrows 2005), Chinese GB 50005 – 2003 and GB/T50361–2005.

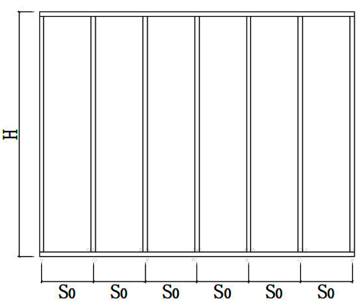


Fig. 1: The wall frame.

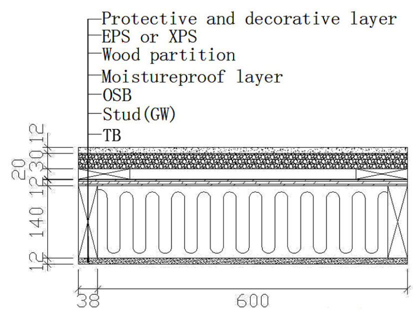


Fig. 2: The wall frame structure.

Tab. 1: The materials and connecting manner of all walls.

Wall structure and materials \ Wall number	1	2	3	4	5	6	7	8	9	10	11	12
TB	√	√	√	√	√	√	√	√	√	√	√	√
GW	√	√	√	√	√	√	√	√	√	√	√	√
SPF	√	√	√	√	√	√	√	√	√	√	√	√
OSB	√	√	√	√	√	√	√	√	√	√	√	√
EPS		√			√			√			√	
XPS			√			√			√			√
Stud spacing 400	√	√	√				√	√	√			
Stud spacing 600				√	√	√				√	√	√
Section size of stud 38×89mm	√	√	√	√	√	√						
Section size of stud 38×140mm							√	√	√	√	√	√

Note: √ means yes.

The structures of walls

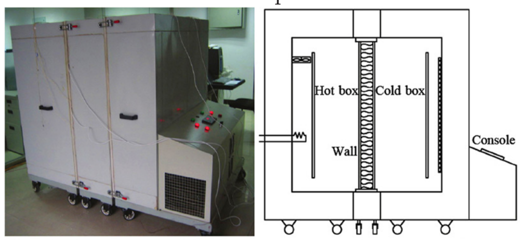
The structures of wood frame walls were shown in Tab. 2, stud spacing of samples 1–3 and 7–9 were 400 mm, samples 4–6 and 10–12 were 600 mm, respectively. Section size 1–6 were 38 × 89 mm, 7–12 were 38 × 140 mm. The proposed structural systems met all the requirements of technical standards in terms of stability, endurance, technical properties of the shells of buildings, fire resistance and requirements for hygienic safety of living space.

Tab. 2: The structures of walls.

Samples	Stud spacing (mm)	Wall materials	Stud thickness (mm)
1	400	TB+GW+Stud+OSB	89
2	400	TB+GW+Stud+OSB+EPS	89
3	400	TB+GW+Stud+OSB+XPS	89
4	600	TB+GW+Stud+OSB	89
5	600	TB+GW+Stud+OSB+EPS	89
6	600	TB+GW+Stud+OSB+XPS	89
7	400	TB+GW+Stud+OSB	140
8	400	TB+GW+Stud+OSB+EPS	140
9	400	TB+GW+Stud+OSB+XPS	140
10	600	TB+GW+Stud+OSB	140
11	600	TB+GW+Stud+OSB+EPS	140
12	600	TB+GW+Stud+OSB+XPS	140

Experimental methods

The thermal insulation properties of wood frame wall was measured by guarded hot box according to Chinese GB/T 13475 – 2008. The structure of guarded hot box is made up of three parts that were cold box, hot box and specimen box respectively, as shown in Fig. 3. In order to ensure the temperature distribution of the internal environment as uniform as possible, stirring fan, vapor chamber, temperature measurement and control sensor were installed in cold and hot boxes. The steady thermal transmission was controlled by temperatures of cold and hot boxes for constant temperature difference of wall's cold and hot surface. Automatic itinerant measuring instrument of temperature and heat flow was adopted to collect and record temperature data.



(a) Hot box on working (b) Schematic diagram of hot box

Fig. 3: The structure of hot box.

When heat flow got through the wall structures, the temperature gradient was in the process of decay in thickness direction, and the steady temperature difference was kept on both sides of the wall due to the existence of thermal resistance. As can be seen from the Fig. 4, three heat flow meters were attached to the stud surface and the position between two adjacent studs of the wall's hot surface, whose surface were surrounded by 9 T-type thermocouples. On the cold surface, 9 T-type thermocouples were also arranged at the corresponding positions. Testing signal was input to automatic itinerant measuring instrument of temperature and heat flow, 10 hours after heat transference continued in steady state. The values of temperature and electromotive force were both achieved and stored, then the thermal conductivity can be calculated with the measured value of electromotive force.

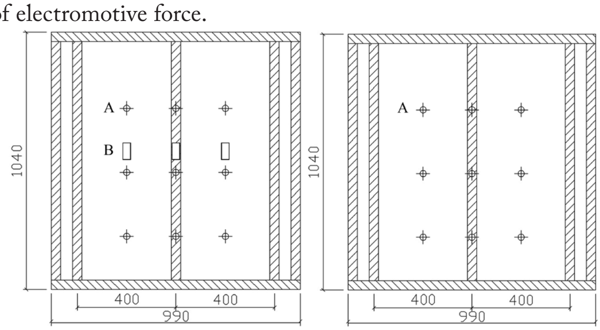


Fig. 4: The schematic diagram of measuring points. (A is T-type thermocouple; B is heat flow meter.)

Calculations

The heat transfer calculation of composite wall was based on the principle of one-dimensional steady-state thermal transmission. The condition of steady state, the temperature, air speed and radiation condition were satisfied in two side boxes (cold and hot), the thermal transmission properties of the specimens can be calculated according to the data measured from air temperature, surface temperature of the inner wall of boxes and specimen and power inputted to the metering box. The total power of the input value Q_p was amended in terms of the heat flow of box wall value Q_2 and lateral circuitous heat loss value Q_3. The heat flow of box wall value Q_2 and lateral circuitous heat loss value Q_3 were demarcated by a known thermal resistance of the specimen, which are shown in calculating Eq. 1:

$$U = \frac{Q_p - Q_2 - Q_3}{A\,(T_h - T_c)} \tag{1}$$

where: Q_P - the total power of the input (W),
Q_2 - the heat flow of box wall (W),
Q_3 - lateral circuitous heat loss (W),
U - heat transfer coefficient ($W \bullet m^{-2} \bullet K^{-1}$),
A - the specimen area (m^2),
T_h - ambient air temperature of the hot box (°C),
T_c - ambient air temperature of the cold box (°C).

When the planar heating source on the wall plane came from a constant power heat source, variation in temperature merely occurred in X direction (Hammerschmidt 2003). The entity part of composite wall took the form of heat conduction mainly, whose heat transfer process was complicated. For further study on thermal transmission of wall, the thermal conductivity detection from the component was simplified into an ideal thermal test, which was calculated by the quasi-steady-state test method of thermal conductivity, as shown in Eqs. 2 and 3:

$$\lambda = \frac{q_c \delta}{2\Delta t} \tag{2}$$

$$q_c = \frac{IU}{F} \tag{3}$$

where: λ - thermal conductivity ($W \bullet m^{-1} K^{-1}$),
q_c - heat flux density ($W \bullet m^{-2}$),
δ - specimen thickness (m),
Δt - temperature difference (°C),
I - current (A),
U - voltage (V),
F - the size of the specimen cross section (m^2).

RESULTS AND DISCUSSION

Influence of moisture content on thermal conductivity

The thermal conductivity was calculated based on computational formula (Eqs. 3 and 4), which was obtained from the electromotive force value (voltage value U, current value I), contact areas and thickness of the specimens that were measured by the quasi-steady-state thermal conductivity analyzer, as given in Tab. 3.

Tab. 3: Thermal conductivity of materials.

Specimens	Voltage (V)	Current (A)	Temperature difference (°C)	Thermal conductivity ($W \cdot m^{-1}K^{-1}$)
Moisture SPF 15%	20	0.12	12	0.156
Moisture SPF 12%	20	0.12	11.4	0.152
Moisture SPF 8%	20	0.12	10.6	0.147
TB	20	0.12	18	0.342
OSB	20	0.12	11	0.173
EPS	20	0.12	3	0.035
XPS	20	0.12	2.5	0.026
GW	20	0.12	4	0.042

Materials with thermal conductivity value less than 0.233 $W \cdot m^{-1}K^{-1}$ can be termed as thermal insulation materials at room temperature of 20°C (Cech et al. 2016). As described in Tab. 3, all the wall materials met requirements except thistle board in thermal conductivity. What's more, moisture content had an influence on stud's thermal conductivity. Especially, thermal conductivity decreased with the reduction of moisture content, because thermal conductivity of water was 25 times of air. With the increase of moisture content in wood, some air was replaced by water which led to thermal conductivity increase. In practical building of wooden construction, moisture content of SPF was controlled under 19%. Referring to the above comparison and contrast, when moisture content was less than 19%, there was no apparent influence of moisture content on thermal conductivity, which revealed the SPF moisture content didn't have obviously influence on thermal conductivity of the entire wall because of small proportion of SPF in the whole structure.

Influence of external thermal insulation on heat transfer coefficient

Different component materials and connecting manners generated difference in thermal insulation properties of 12 wood frame walls. The heat transfer coefficient and thermal resistance values of all walls (Tab. 4) were figured out based on Eqs. 1 and. 4.

Tab. 4: Heat transfer coefficient and thermal resistance values of all walls.

Wall number	Temperature of cold box (°C)	Temperature of hot box (°C)	Thermal resistance R $m^2 \cdot K \cdot W^{-1}$	Heat transfer coefficient U ($W \cdot m^{-2} \cdot K^{-1}$)
1	5.2	26.7	1.626	0.563
2	5.5	26.9	1.903	0.487
3	5.1	26.5	2.295	0.409
4	5.1	26.5	1.838	0.503
5	5.8	26.1	2.248	0.417
6	5.7	26.2	2.344	0.401
7	5.4	26.4	1.758	0.524
8	6.1	25.9	2.138	0.437
9	5.8	26.7	2.560	0.369
10	5.6	26.6	1.862	0.497
11	5.2	26.2	2.441	0.386
12	5.2	26.3	2.927	0.325

External thermal insulation technology that insulating layer set in outboard of composite walls kept the temperature of wood frame major structure near that of indoor (Kotaskova et al. 2016, Armando 2010), and buffered structural stress brought by changes in outer circumstance temperature, which avoided the wall construction damage from various environmental conditions, such as rain, snow, freeze and melt. Among them, wall samples (2, 3, 5, 6, 8, 9, 11 and 12) were covered with external thermal insulation boards. Fig. 5 displayed the influence of presence or absence of external thermal insulation materials on wall heat transfer coefficient.

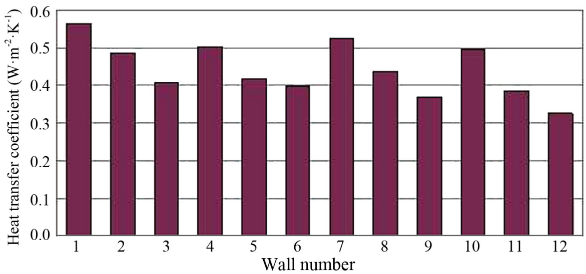


Fig. 5: Effect of external thermal insulation materials on heat transfer coefficient.

As shown in Fig. 5, heat transfer coefficient value of walls without external thermal insulation layer is more than 0.5 W•m^{-2}•K^{-1}, while those with outer insulation materials are 15% – 30% less than those without external thermal insulation layer, which indicate that external thermal insulation manners can improve the thermal insulation properties of walls obviously. Besides, heat transfer coefficient of walls with EPS was larger than that with XPS, which revealed thermal insulation capacity of EPS was less than XPS. Thermal insulation performances of EPS and XPS increased with the increasing thickness. In order to achieve the same heat preservation effect, the thickness of EPS should be greater than XPS, because the heat transfer coefficient of EPS and XPS are 0.035 and 0.026 W•m^{-2}•K^{-1}, respectively.

Influence of stud spacing on heat transfer coefficient

Two walls with same construction mode were classified as one group with the only difference in stud spacing, one was 400 mm, the other was 600 mm (Fig 6). It can be seen clearly from Fig. 6 that the heat transfer coefficient of walls with 600 mm stud spacing was less than those with 400 mm, which resulted from the increasing stud spacing and decreasing studs, lessened stud cavity was filled with glass wool. Heat transfer coefficient of glass wool was far less than stud, hence walls with 600 mm stud spacing were superior to those with 400 mm in thermal insulation properties.

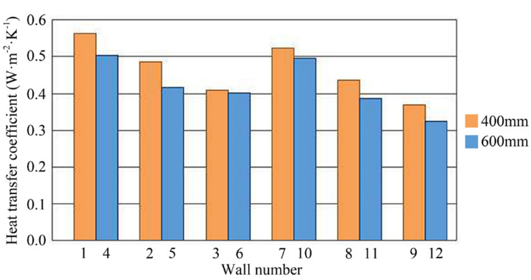


Fig. 6: Effect of stud spacing on heat transfer coefficient.

The reduced stud cavity filled by glass wool accounted for 2.9% (sectional dimension of stud was 38 × 39 mm) and 3.5% (sectional dimension of stud was 38 × 140 mm) of the whole space, respectively, and heat transfer coefficient of the whole walls reduced by 9.3% and 10.7%, respectively, which illustrated effects of the amount of studs on heat transfer coefficient of wall. Therefore, it can be taken into account to change wall heat transfer coefficient by altering stud spacing without affecting the strength of the building.

Influence of stud thickness on heat transfer coefficient

Two walls with stud thickness of 89 mm and 140 mm were classified as one group, other construction modes were the same (Fig. 7). When stud thickness increased 51 mm, temperature difference between two sides enhanced 0.4 – 1.6°C and heat transfer coefficient reduced 0.006 – 0.073 $W{\cdot}m^{-2}{\cdot}K^{-1}$, thermal resistance increased 0.11 – 0.59 $m^2{\cdot}K{\cdot}W^{-1}$. The increasing glass wool thickness improved the thermal insulation properties of walls effectively, because of the increase of stud thickness, which enhanced the effect of thermal resistance on frame and offered larger space for glass wool. Meanwhile, more thickness offered larger air interlayer that led to less heat loss. Heat transfer coefficient of wall 9, 11 and 12 are less than 0.4 $W{\cdot}m^{-2}{\cdot}K^{-1}$ with no exception, meeting standard of thermal transmittance coefficient in severe cold areas (It level). Therefore, adding the thickness of stud is a critical measure for energy-efficiency in severe cold areas.

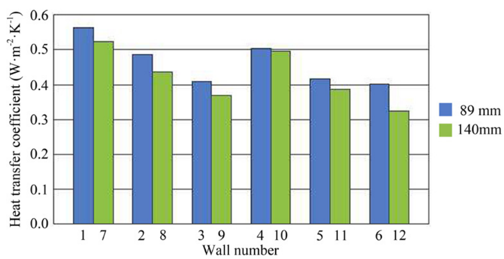


Fig. 7: Effect of studs thickness on heat transfer coefficient.

Comparison between the measured and calculated values of thermal resistance

Based on computational method regulated in ASHRAE Handbook of Fundamentals (ASHRAE 2001) and Chinese GB50176: 2015, the thermal resistance value of a composite wall was calculated by adding the effective R-values of each of the layers of the wall (Tab. 5) with the computational formula of the average thermal resistance of a non-homogeneous envelope with multi-layer structure, thermal resistance and the average one can be calculated according to the following formulas:

$$R = \frac{1}{U} - R_i - R_e \tag{4}$$

$$R_n = \frac{\delta}{\lambda} \tag{5}$$

$$\overline{R} = [\frac{F_0}{\frac{F_1}{R_1} + \frac{F_2}{R_2} + \ldots\ldots \frac{F_n}{R_n}} - (R_i + R_e] \, \varphi \tag{6}$$

where: R and R_n - thermal resistance of walls and materials respectively ($m^2{\cdot}K{\cdot}W^{-1}$),

U - heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$),
R_i and R_e - heat resistance of inner and outer surface with R_i=0.11 ($m^2 \cdot K \cdot W^{-1}$), R_e=0.04 m2$\cdot K \cdot W^{-1}$),
δ - materials thickness (m),
λ - thermal conductivity ($W \cdot m^{-1} K^{-1}$),
`R - average thermal resistance ($m^2 \cdot K \cdot W^{-1}$),
F_0 - total heat transfer areas vertical with heat flow direction (m^2),
F_1,F_2...F_n - represent separate heat transfer area parallel to heat flow direction (m^2),
R_1,R_2...R_n - thermal resistance of each heat transfer section ($m^2 \cdot K \cdot W^{-1}$),
R_i and R_e - heat resistance of inner and outer surface, which is 0.11 and 0.04 ($m^2 \cdot K \cdot W^{-1}$),
φ - corrective factor, which is 0.93.

Tab. 5: Thermal resistance of all materials.

Materials	Thickness (mm)	Thermal conductivity λ ($W \cdot m^{-1} K^{-1}$)	Thermal resistance R ($m^2 \cdot K \cdot W^{-1}$)
Moisture SPF 12%	89 140	0.156	0.571 0.897
TB	12	0.342	0.035
OSB	12	0.173	0.069
EPS	30	0.035	0.857
XPS	30	0.026	1.154
GW	89 140	0.042	2.119 3.333

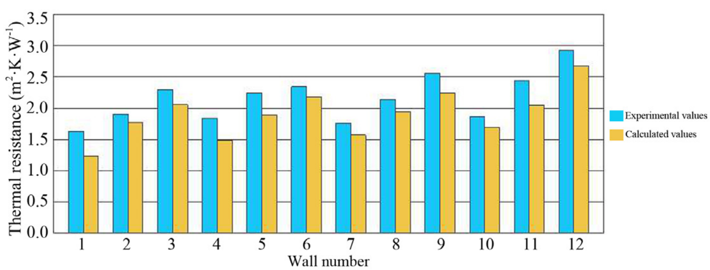


Fig. 8: Contrast of experimental and theoretical calculation.

Due to the difficulty in calculating actual heat release of the fan and the increase of thermal resistance brought by the interspace between each layer of the wall, thermal resistance values of theoretical calculation were smaller than those of experimental values with the relative error about 7% – 21% (Fig. 8), but their correlation coefficient was highly consistent, up to 0.9587. Therefore, effective thermal resistance values of wooden composite wall can be got by calculating thermal conductivity of materials without extra experiment.

CONCLUSIONS

The major conclusions can be drawn based on the above study and analysis as following:

(1) When SPF's moisture content was less than 19%, moisture content didn't have obvious effect on thermal conductivity, which was similar to that of the whole wall.

(2) External thermal insulation manners can improve the thermal insulation properties of walls

obviously. In addition, insulation performance of XPS was superior to those of EPS.

(3) Thermal insulation property can be increased by increasing stud spacing to decrease wall's heat transfer coefficient under the guarantee of building intensity.

(4) Thermal resistance can be enhanced to improve thermal insulation performance of wall by increasing stud thickness, especially in severe cold areas.

(5) The correlation coefficient between theoretical calculation and experimental values were highly consistent, effective thermal resistance value of wall can be calculated by measuring thermal conductivity of materials without extra experiment.

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