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Overall Heat Transfer Coefficient of a Korean Traditional Building Envelope Estimated Through Heat Flux Measurement

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Abstract

The objective of this research is to determine overall heat transfer coefficients (U-value) of the exterior walls, floors, and roof of a Korean traditional residence via field measurement of transient heat flow and temperature difference across each envelope. The acquired U-values are compared with other existing values and those for current residential buildings. As for the field measurement, heat flux sensors and T-type thermocouple are attached on the internal and the external surfaces of each building component. Real-time measurement data are logged for three consecutive summer days. Acquired U-values agree well with other existing values for traditional building envelopes found in the open literature, but they are higher than U-values of current buildings. From this result one may conclude that the Korean traditional building has uncompetitive thermal performance compared with today's buildings. However, the energy simulation performed in this research shows that the traditional building can provide moderate cooling load competitive to current buildings. It comes mainly from the inherent characteristic of the traditional residence including relatively high infiltration rate and reduced solar radiation penetrating the windows.

Keywords: overall heat transfer coefficient; heat flux sensor; building envelope; field measurement

1. Introduction

As a possible solution to realizing green and sustainable buildings and reducing negative impacts on our natural environment, interest in traditional buildings and materials is increasing in many countries, and Korea is no exception[1-3)]. However, a study on thermal and environmental performance of traditional buildings has not been performed intensively so far. Old technologies have simply been ignored without positive consideration. Revisiting traditional building technologies developed based on human experience over a long period would be an effective and economical way of realizing green and sustainable buildings.

For the last decade, studies on Korean traditional buildings have focused on indoor environment variation responding to changes of surrounding conditions[4)], and defining passive technologies and their practical applications to current buildings as passive environmental control tools[5)]. Qualitative and quantitative ratings of thermal comfort and seasonal behavior of the indoor environment have also been performed for some typical floor plans and layouts frequently observed in existing traditional buildings[6-8)]. Natural ventilation performance and a particular passive ventilation mechanism in a typical Korean traditional residence are investigated by CFD simulation and on-site measurement of airflow distributions[9-10)].

Both qualitative and analytical research endeavors on Ondol, a historic Korean floor radiant heating panel system have also been performed extensively[11-14)]. Influence of geometric locations and regional climate conditions on material selection and structural patterns of the Ondol has been investigated. The literature indicated that the principle mechanism of a floor heating system used in current residential buildings is exactly the same as that of the Ondol built a thousand years ago, although its detailed physical form, structure, and material have changed.

The antibacterial effect and far infrared ray emission provided by mud or yellow soil, a typical building material used in traditional buildings, has

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been revisited and has attracted more interest again in both the academic and industrial sectors pursuing sustainable and healthy buildings[15-18]. However, the traditional technologies and thermal characteristics of historic buildings are not well understood. Available data for rating and predicting the thermal and environmental performance of the Korean traditional residence are very limited. It is not because they are old and inapplicable to today's buildings, but because we have been ignoring them for a long time without carrying out intensive studies to reveal the critical mechanism of passive environmental control methods and basic properties of traditional building components which have been satisfying occupants' needs for over a thousand years.

In order to fill the gap, this research performed field measurements to investigate the thermal characteristics of a Korean traditional building. Nakseonjae, a residence located in a historic royal palace called Changdeokgung; a UNESCO World Cultural Heritage was selected for the field test. Overall heat transfer coefficients for the exterior wall, roof, and floor of the test building are determined by measuring the heat flux and surface temperatures of each envelope component. Peak and annual thermal loads of the historic residence are estimated based on acquired thermal properties and then compared with those for another traditional residence and a current apartment house.

2. Test Building

Nakseonjae was a residence for a royal concubine of Heonjong, the 24th king of the Chosun dynasty (Fig.1.). Most recently, the last empress Yun lived in this building until 1966, and princess Deokhye and Madame Bang-Ja Lee both lived there from 1963 to 1989.

Fig.1. Test Building (Nakseonjae in Changdeokgung)

Field measurements of transient heat flux and internal and external surface temperatures were performed in a room with a typical exterior wall, roof, and floor of the test building (Fig.2.). The exterior wall is made of yellow soil mixed with 5-10% thatch and is 0.15-0.25m thick. The roof is a thick, multi-layered structure (Fig.3.) which consists of a wooden frame covered with watertight tiles, oilpaper layer for waterproofing, yellow soil mortar, and quicklime mortar layers commonly found in a typical Korean residence. The eaves of the roof extend enough to block direct sunlight, especially during the summer. The floor of the test building is a traditional Korean radiant floor known as Ondol (Fig.4.)[11]. During the winter, hot combustion gas passes through flue ducts called Gorae, which are made of rocks and yellow soil mortar and heats the floor panel made of flat stones. The floor surface is leveled using clay mortar.

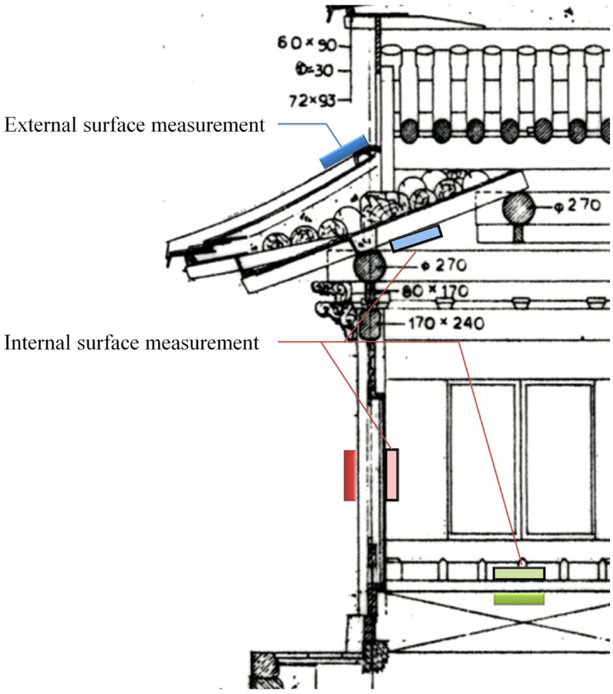


Fig.2. Measurement Point of Surface Temperature

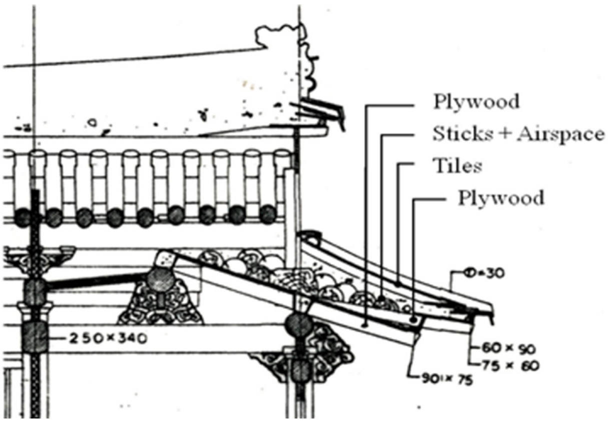


Fig.3. Multi-layer Structure of the Roof

3. Estimation of Heat Transfer Coefficient

A building may gain or lose heat by heat transmission through its envelope structure whenever there is a temperature difference across it. Generally all

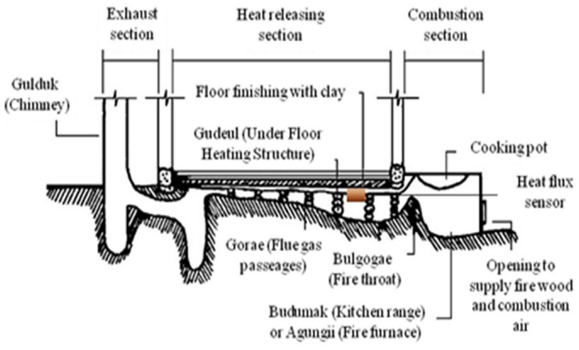


Fig.4. Traditional Korean Radiant Floor (Ondol)

three modes of heat transfer – conduction, convection, and radiation – are important in building heat gain and loss[19].

As for a multi-layered structure under a thermally steady state, the heat transfer coefficient or U-value commonly used in calculating the amount of heat transmission can be determined by Equation (1).

$$U = \frac{1}{\frac{1}{\alpha_i}+\frac{L_1}{\lambda_1}+\frac{L_2}{\lambda_2}+\cdots+\frac{L_n}{\lambda_n}+\frac{1}{\alpha_o}} = \frac{1}{r_1+r_2+r_3+\cdots+r_n+r_i} = \frac{1}{R} \qquad (1)$$

where,

α_i : Interior surface heat transfer rate [W/m^2°C]

α_o : Exterior surface heat transfer rate [W/m^2°C]

$L_1, L_2, \cdots, L_n$: Thickness of each layer [m]

$\lambda_1, \lambda_2, \cdots, \lambda_n$: Heat conduction rate of each layer [W/m^2°C]

$r_1, r_2, \cdots, r_n$: Thermal resistance of each layer [m^2°C/W]

R : Thermal resistance of the structure [m^2°C/W]

The amount of heat transmission is directly proportional to temperature difference across a building component and U-value of the component. The inverse of the U-value is called thermal resistance or R-value. The U-value of a building envelope component can be determined via laboratory tests or on-site measurement approaches.

Laboratory test approach

There are two methods that are well known as laboratory experiments of heat transfer coefficient – the guarded hot box (ASTM C177-97) and the calibrated hot box (ASTM C976) methods. The calibrated hot box method, however, was withdrawn in 2002. According to ASTM, this method can be replaced by the guarded hot box test method. It covers the laboratory measurement of heat flux through a specimen under controlled air temperature, air velocity, and thermal radiation conditions established in a metering chamber on one side and in a climatic chamber on the other. Korean test standards, such as KS F 2277 and 2278 also recommend the calibrated and guarded hot box methods.

Field measurement approach

ASTM C1046–95 "Standard Practice for In-Situ Measurement of Heat Flux and Temperature Building Envelope Components" can be applied to determine the heat transfer coefficient of a building component based on the field measurement data. KS L ISO 9869:2006 is a similar approach recommended in Korea. These test standards cover the in-situ measurement technique and procedure using heat flux transducers and temperature transducers in measurements of the in-situ dynamic or steady-state thermal behavior of opaque components of building envelopes. In this research, the U-value of each envelope component of the test building is determined using the in-situ measurement approach recommended by the ASTM standard.

Heat flux transducers

There are three categories of heat flux sensor which can be applied to the field measurement: (1) contact type (conductive) heat flux sensors, (2) thermal radiative sensors, and (3) convective heat flux sensors. Whereas types 1 and 3 are placed on or embedded in the heat transfer surface, most type 2 sensors are usually suspended in front of a target surface or material. Radiative and convective heat flux sensors are used in the measurement of very high temperature surfaces (e.g. furnace surface) or for studies of fire and flames, which are not very common in building technology[20-21].

Contact-type (conductive) heat flux sensors commonly used in conventional heat flux measurements divide into two types: thin-plate or wafer-type sensors and thin-membrane (foil or film) type sensors. Common applications of this type of heat flux sensor are studies of building envelopes or soil thermal resistance.

Conductive heat flux sensors are generally flat plate and have a sensitivity perpendicular to the sensor surface. The advantages of conductive heat flux sensors are their stability, low resistance value, good signal-noise ratio, and low cost. The disadvantage is the low sensitivity of their output. The thermal resistance and the thermal capacity of the sensor are equal to those of the material of which the sensor is made.

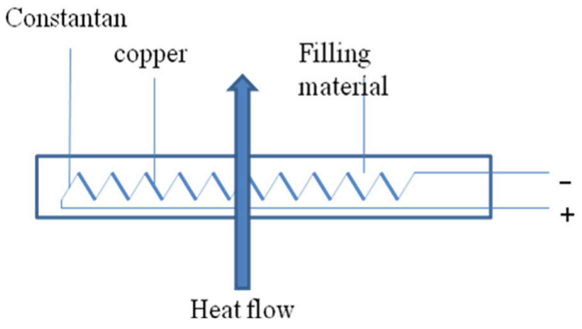


Fig.5. Heat Flux Sensor

As shown in Fig.4., the filling material operates as a thermal resistance, when heat is flowing through the sensor in the indicated direction. Consequently the heat flow goes together with a temperature gradient across the sensor, flowing from the hot to the cold side.

The majority of heat flux sensors are based on a thermopile. A single thermocouple generates an output voltage that is proportional to the temperature difference between the joints (copper-constantan and constantan-copper). This temperature difference is, provided that errors are avoided, proportional to the heat flux, depending only on the thickness and the thermal conductivity of the sensor.

Each individual sensor has its own sensitivity (E_{sen}) expressed in voltage output (V_{sen}) per heat flow in wattage per unit area (W/m^2); that is, heat flux (Φ). Therefore, the flux can be calculated by Equation 2.

$$\Phi = V_{sen} / E_{sen} \qquad (2)$$

Theoretically, it would be better to measure heat flux by inserting heat flux sensors into the envelope component in order to avoid negative impact from the surroundings. However it is almost impossible to insert the sensor when a building envelope should not be damaged by the measurement. Thus in the test building, the heat flux sensor is mounted on the interior surface of each envelope component.

Error sources

As for the heat flux measurement, the thermal resistance of the sensor itself may affect the test result. This is called resistance error22) and the typical value is approximately 5% or less depending on the sensor's material and thickness. This type of error can be easily corrected based on the manufacturer's guideline during the data logging process. The resistance error can also be minimized by using a thin sensor.

In the field measurement, the contact resistance between sensor and material are the biggest error source. It should be noted that the conductivity of the air gap between the sensor and the envelope surface is approximately 0.02 W/m·K, which is ten times smaller than that of the heat flux sensor. This signifies that the air gap would provide the negative impact on the heat flux measurement because of its high thermal resistance. The use of thermal adhesive made of high conductive material is recommended when heat flux sensors are placed on the building envelope surfaces for filling the air gap and minimizing the thermal resistance.

4. Field Measurement

Three portable heat flux sensors with a resolution of $0.012 mV/W/m^2$ are attached on the internal surface of the wall, floor, and roof. The heat flux flowing through each building structure was measured at one-minute intervals for 50 hours from August 25-27, 2008. Internal and external surface temperatures were also measured by attaching T-type thermocouples on both sides of each structure. (Fig.6.)

Overall heat transfer coefficient (i.e. U-value) for each building component is estimated from the collected measurement data using Equation 3.

$$U = \dot{q} / \Delta T \qquad (3)$$

where,

U : overall heat transfer coefficient [$W/m^2{}^\circ C$]

$\dot{q}$: heat flux [W/m^2]

ΔT : surface temperature difference (°C)

In order to obtain reliable overall heat transfer coefficient values from the measurement, it is recommended that constant internal-to-external surface temperature difference should be maintained at a certain level (e.g. 20°C); otherwise, uncertainty of the overall heat transfer coefficient determined by Equation 1 will increase (i.e.$\Delta T \rightarrow 0, U \rightarrow \infty$). However, a practical means to maintain constant surface temperature difference could not be found in this particular case because of strict regulations for preserving the national heritage. Consequently, the field test has been performed without any control of measurement conditions.

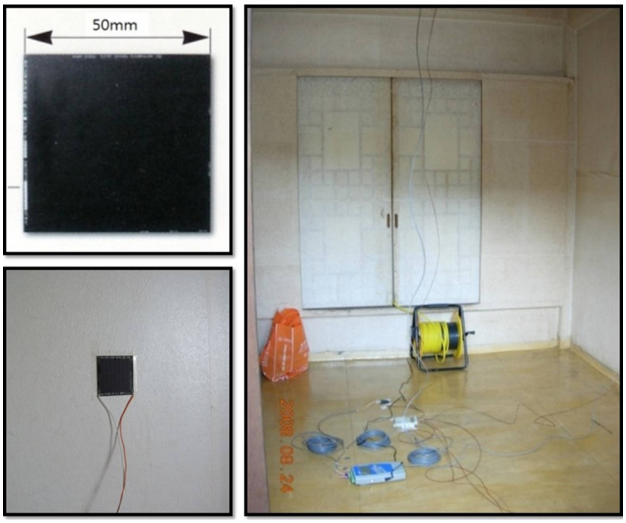


Fig.6. High-resolution Heat Flux Sensor

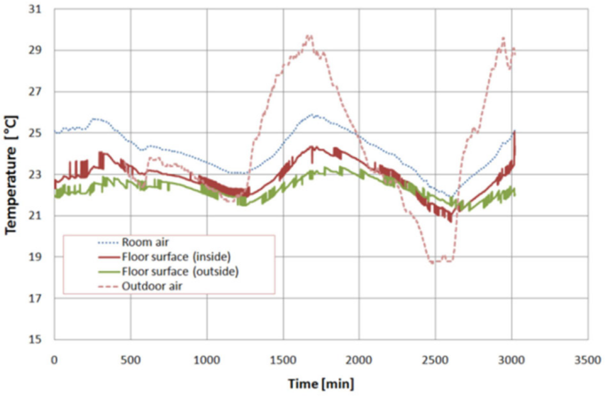
Surface temperature variation

Internal and external surface temperature variations observed from the field measurement for each building structure are shown in Fig.7. As expected, surface temperatures change with the outdoor air temperature variation. Solar radiation also affects surface temperature variation at the wall and the roof (Figs. 7b and 7c) except the floor (Fig.7.a). In the case of the roof, exterior surface temperature increases very quickly after sunrise, and then drops rapidly during the night because of convection and radiation heat exchange between the roof surface and the sky (Fig.7.c).

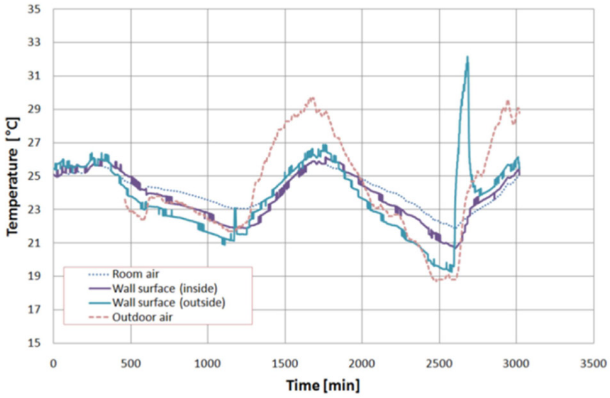
The exterior wall selected for the test faces east and solar radiation may affect surface temperature rise during the morning hours. However, direct sunlight was almost blocked during the whole measurement period by the overhanging eaves and the building nearby. Consequently, internal-to-external surface temperature difference (ΔT) is not significant at the wall and the floor, and relatively high at the roof as shown in Fig.7.

Heat flux variation

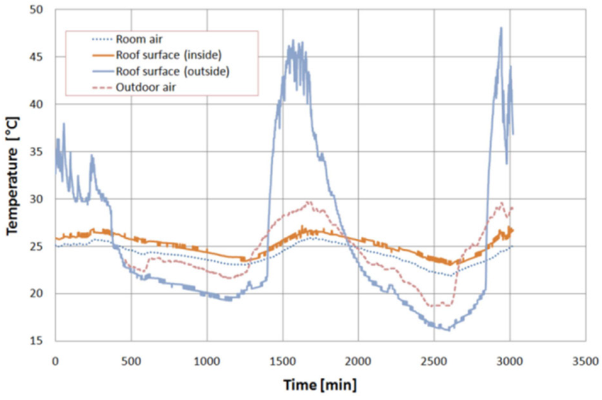
Transient heat flux variation measured at the internal surface of the wall, floor, and roof are presented in Fig.8. Positive heat flux means the thermal energy delivered to the room from outside through unit area of the structure. Fig.9. shows that the floor experienced significant heat flux variation during the measurement period compared with that for the wall and roof. This might be caused by increased radiation heat loss from the floor to the ground surface facing each other during the night.



(a) Floor



(b) Exterior wall



(c) Roof

Fig.7. Surface Temperature Variation

Estimate of overall heat transfer coefficients

Heat flux data collected from the field measurement were sorted and averaged for the surface temperature difference. By replacing acquired heat flux ($\dot{q}$) and surface temperature difference (ΔT) values into Equation 1, overall heat transfer coefficients (U-values) for the wall, roof, and floor were calculated.

Fig.9. shows U-value and ΔT pairs plotted on the x-y plane for each building component. It shows that a numerical problem occurs when ΔT is too small; that is, U-value diverges when ΔT is close to zero. This kind of problem would not be experienced if the test were performed in a laboratory under a controlled condition.

Theoretically, U-value should be constant for a given structure and is not affected by the surface temperature variation. Therefore, data sets returning severely diverged U-value are eliminated from the analysis. In Fig.9.a, U-value diverges significantly when ΔT is less than 2°C, thus U-value for the floor is determined by averaging U-values estimated for higher ΔT. One can see that calculated U-values converge to a certain number when ΔT is higher than 2°C. A similar process is applied to other building components. U-values for the wall and roof are estimated by averaging the U-values for ΔT over 6°C (Fig.9.b) and 10°C (Fig.9.c), respectively. In Table 1., overall heat transfer coefficients derived in this research are summarized.

Open literature for a similar traditional residence[11-23] indicates that the U-value for each envelope component is as follows: 3.27 W/m^2°C for the wall, 0.8 W/m^2°C for the roof. These are within the U-value range shown in Table 1., while the literature for U-value of a Korean traditional floor structure (i.e. Ondol) is very rare.

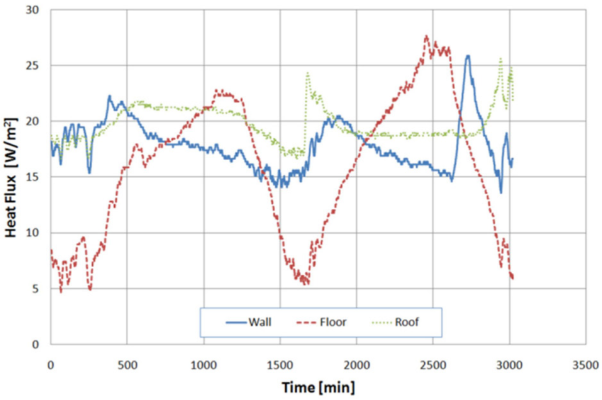


Fig.8. Heat Flux Variation

Table 1. U-values of the Test Building

	Floor	Wall	Roof
U-value, [W/m^2°C]	2.46	2.64	0.57
Standard deviation	±0.35	±0.49	±0.23

Table 2. U-values of Residential Building Envelopes (W/m^{2}K)

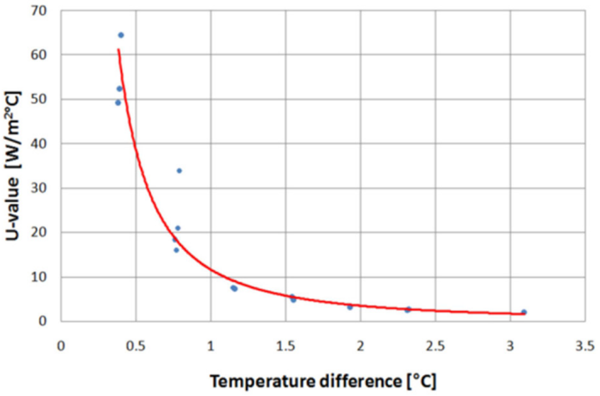
Region	External wall	Roof
Beijing, China	1.16-0.82	0.80-0.60
Russia	0.77-0.44	0.57-0.33
Berlin, Germany	0.5	0.22
Hokkaido, Japan	0.42	0.23
Canada	0.36	0.23-0.4
USA	0.32-0.45	0.19
Sweden	0.17	0.12
Korea	1.26-1.41	0.26-0.29

In Table 2., recommended U-values currently used in several countries found from existing literature[24)] are summarized. By comparing Table 2. values with U-values for the test building, one may conclude that the traditional building envelope may provide more heat gain or loss than current building envelopes.

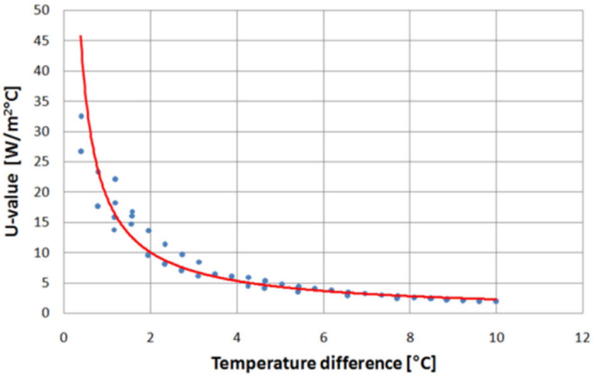
Building thermal load estimation

The peak and annual thermal load of the test building were estimated by using a commercial energy simulation program. U-values determined by the field measurement were applied to the thermal load calculation. On the other hand, each envelope component of the test building model was replaced by those used in two different residential buildings; one is an apartment house commonly found in Korea, and the other is a recently renovated Korean traditional residence. Thermal loads for these two additional cases were estimated and then compared with those for the test building.

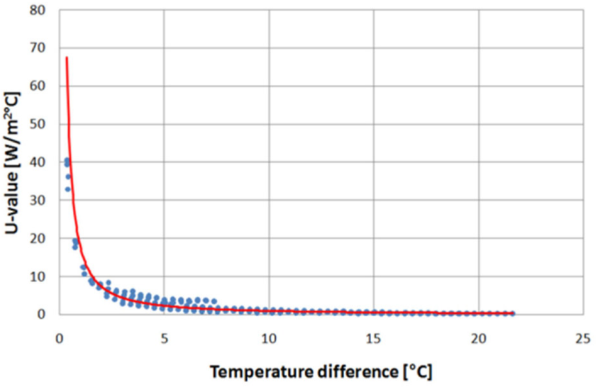
The load calculations for all three cases were performed under the conditions assumed as follows. An occupant generates sensible heat of 67.4W and latent heat of 55.7W. Lighting load density is 20W/m^2, and miscellaneous equipment generates sensible heat by 8W/m^2. A TRY weather data for Seoul city established by the Korean Solar Energy Society (KSES) in 2009 was applied to the thermal load simulation. Based on the open literature, it was assumed that the test building and the renovated Korean traditional residence experience infiltration of 1.17ACH, while the infiltration rate of the apartment house is 0.2ACH. The room temperature was set to 26°C for the cooling load and 21°C for the heating load calculations. Thermal properties of the window for the renovated traditional residence were also applied to the test building because the window materials in both buildings are almost identical. In Table 3., the thermal properties of each envelope component used in all three simulation models are summarized.



(a) Floor



(b) Exterior wall



(c) Roof

Fig.9. Overall Heat Transfer Coefficient (U-value)

Building load comparison

Peak cooling and heating loads estimated for all three buildings are summarized in Table 4. As expected, the test building and the renovated traditional residence which have relatively high U-values show more increased peak cooling and heating loads compared with those for the current apartment house. The peak cooling load and the heating load of the current house are 74% and 54% of the test building, respectively.

Table 5. shows annual heating and cooling loads estimated for each building case. One may see that total annual heating loads for the test building and the renovated traditional residence are more than ten times

Table 3. Thermal Properties of Envelope Components

Building component		Material	Thickness mm	Thermal Conductivity, W/m·K	Specific heat, J/kg·K	Density, kg/m^2	U-value, W/m^2·K
Test Building	Floor	N/A					2.46
	Wall	N/A					2.64
	Roof	N/A					0.57
Renovated Korean Traditional Residence	Wall	Plaster	5	0.73	837	1280	3.27
		Mud-plastered wall	80	0.74	837	1320	
		Plaster	5	0.73	837	1280	
		Plywood	6	0.17	1214	545	
	Roof	Plywood	6	0.17	1214	545	0.8
		Airspace	770	Thermal resistance: 0.53 (m^2·K/W)			
		Plywood	12	0.17	1214	545	
		Sticks	300	0.74	837	1320	
		Tiles	16	0.35	1465	1121	
	Floor	Mortar	10	1.4	836	1857	0.51
		Insulator	50	0.034	1590	24	
		Waterproof	-				
		Floor concrete	150	1.63	836	2241	
		Lean concrete	60	1.63	836	2241	
		Pressed broken stone	200	1.63	836	2241	
	Window	Window paper	0.87	-	-	-	8.16
		Wood Frame	10	0.15	1214	545	0.34
Current Apartment house	Wall	Concrete	200	1.627	879	2198	0.461
		Insulator	50	0.027	837	35	
		Plaster-board	9.5	0.210	1130	910	
	Slab	Mortar	40	1.394	1130	2019	0.733
		Concrete	50	0.084	1130	350	
		Insulator	20	0.037	837	25	
		Concrete	180	1.627	879	2198	
		Plaster-board	9.5	0.210	1130	910	
	Window	Glass	5	0.76	837	2710	3.3
		Airspace	6	Thermal resistance: 0.12 (m^2·K/W)			
		Glass	5	0.76	837	2710	

Table 4. Result of Peak Load Estimation

Building	Cooling load, [kW]	Heating load, [kW]
Test building (Nakseonjae)	11.2	17.6
Renovated traditional residence	11.5	20.3
Current apartment house	8.3	9.5

higher than that of the current building. This signifies that traditional buildings may consume much more heating energy and thus cannot compete against current buildings in terms of thermal performance during the winter.

However, one can find that both the test building and the renovated traditional residence may experience lower cooling load through the year than the current building. The total annual cooling loads of the test building and the renovated traditional residence are only 63% and 77% of the current building, respectively. In this case, small cooling load may be caused by poor insulation performance because internal heat gain can be easily lost through the envelope in summer.

From the detailed simulation data, although not provided in this paper, it was found that the lower annual cooling load experienced in traditional buildings is mainly caused by relatively high room air change rate and reduced solar radiation through the windows. Because of the low air tightness, room air changes more frequently in traditional buildings.

Consequently, the room air in traditional buildings may be naturally cooled and provide reduced cooling load compared with current buildings, especially when the outside air is at moderate temperature. In addition, the windows of traditional buildings are made from wooden mesh covered with Korean traditional wallpaper, called Hanji. Therefore, both direct and diffuse components of solar radiation are blocked in large amounts by the window and cannot be added to the cooling load, while the fenestration used in current buildings allows penetration of solar radiation.

Table 5. Annual Cooling and Heating Loads, [MWh]

Month	Test building (Nakseonjae)		Renovated traditional residence		Current apartment house	
	Cooling load	Heating load	Cooling load	Heating load	Cooling load	Heating load
January	0.0	6.9	0.0	6.3	0.0	1.0
February	0.0	5.1	0.0	4.5	0.0	0.5
March	0.0	2.8	0.0	2.2	0.3	0.0
April	0.0	0.7	0.0	0.3	1.1	0.0
May	0.7	0.0	1.2	0.0	2.1	0.0
June	1.9	0.0	2.4	0.0	2.8	0.0
July	3.3	0.0	3.7	0.0	3.6	0.0
August	3.7	0.0	4.2	0.0	3.8	0.0
September	1.7	0.0	2.1	0.0	2.7	0.0
October	0.3	0.3	0.5	0.1	1.7	0.0
November	0.0	2.6	0.0	2.1	0.4	0.0
December	0.0	5.9	0.0	5.4	0.0	0.6
Total	11.7	24.2	14.2	20.8	18.5	2.1
[MWh/m^2]	1.32	2.73	1.6	2.34	2.09	0.24

5. Conclusion

In this research, overall heat transfer coefficients of Korean traditional envelopes in Nakseonjae at Changdeokgung, a historic royal palace, were determined by in-situ measurement of heat flux flowing through each envelope component. This building was designated as a UNESCO World Cultural Heritage in February 1997. However, a critical thermal characteristic, the U-value of each envelope required for rating energy performance of the building has not been investigated.

The U-value determined for each envelope component of Nakseonjae is as follows: 2.64W/m^2°C for the wall, 0.57W/m^2°C for the roof, 2.46W/m^2°C for the floor. These values are relatively high compared with those for current building envelopes recommended by established building codes applied in many countries.

In the building thermal load simulation, as expected Nakseonjae showed worse thermal performance than a current residential building. The peak cooling and the heating loads of the current house were 74% and 54% of the test building, respectively. The total annual heating load of the current building was only 10% of Nakseonjae.

However, compared with the total annual cooling loads, the test building showed an annual cooling load only 63% of that of the current building. On account of low air tightness, room air changes more frequently, thus the test building could be naturally cooled more than the current residence, especially during the intermediate season. Traditional windows made from wooden mesh covered with Korean traditional wallpaper also contributed to the reduction of total annual cooling load.

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