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Reliability Field Test of the Air–Surface Temperature Ratio Method for In Situ Measurement of U-Values

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Abstract: This study proposes the air–surface temperature ratio (ASTR) method as an in situ measurement method to rapidly and accurately measure wall U-values in existing houses. Herein, the wall U-values were measured in situ applying the heat flow meter (HFM) method of ISO 9869-1 and the ASTR method. The results obtained using the HFM and ASTR methods were compared, and the relative error rate and accuracy of the measurements were analyzed. The aging rates of the wall U-values were compared and analyzed by comparing them with the wall U-values before and after the installation of retrofit insulation. Subsequently, the ASTR method was used to analyze the U-value measurement error rates according to the number of measurement days (one day to seven days). In addition, this method calculated the appropriate measurement period required to satisfy the measurement conditions. As a result, the mean relative measurement errors rates of the HFM and ASTR methods were ±3.21%. The short-term (one day) and long-term (seven days or longer) measurement results indicated the average error rates as approximately ±2.63%. These results were included in the tolerance range. Therefore, it was determined that the ASTR method can rapidly and accurately measure wall U-values.

Keywords: energy retrofitting of existing houses; U-value; heat transfer coefficient; quasi-steady state; in situ

1. Introduction

The building energy sector in South Korea accounts for 25% of the total energy consumption. Within the building energy sector, housing consumes approximately 18% of the total energy [1]. The Korean government is currently implementing various policies for energy conservation and greenhouse gas reduction in the housing sector [2].

In the case of existing houses, approximately 50% of the current housing has been in existence for more than 20 years, and thus energy efficiency has declined. These houses require a means of reducing energy consumption and improving energy efficiency [3].

At present, there are not sufficient in situ diagnosis methods to accurately analyze the energy status of existing houses. Therefore, builders are retrofitting existing houses using subjective judgment without accurate diagnosis methods. As a result, the energy efficiency improvements made to the houses decrease; there is therefore a need to further increase the energy efficiency of existing houses. In addition, an in situ measurement methodology is required to quantitatively analyze the thermal performance of a building.

In this study, we perform our analysis with reference to International Organization for Standardization (ISO) 9869-1 (Thermal insulation—Building elements—In situ measurement of thermal resistance and thermal transmittance—Part 1: Heat flow meter method) [4–7] and ISO 6946 (Building components and building elements—Thermal resistance and thermal transmittance—Calculation method) [8].

For the purpose of this study, the following precedent studies were analyzed. First, Giorgio Ficco et al. [9] conducted a study on a method for diagnosing the wall thermal performance of existing houses using the heat flow meter method of ISO 9869-1. In addition, the effect of the wall thermal performance and the error rate were analyzed according to the experimental conditions.

Pier Giorgio Cesaratto et al. [10] evaluated the Heat flow method (HFM) measurement performance of existing residential buildings and evaluated the effect of ambient conditions on wall thermal performance. In addition, an analysis of the uncertainty measurement was conducted through a comparison between the wall thermal performance and the performance calculated via the field measurement. In addition, in theory, simple U-value field measurements indicated several metrological and practical problems that can result in significant errors and uncertainties. Anna Laura Pisello et al. [11] studied the thermal performance of walls using the HFM method and, based on the analysis results, conducted a study on an energy retrofitting strategy for residential buildings. Xuan Cheng et al. [12] conducted a numerical model verification for a quantitative evaluation of long-term insulation performance using the HFM method of ISO 9869-1. Moreover, the effect of the sensor installation position used in the adiabatic diagnosis method on the measurement accuracy was analyzed. Lee et al. [13] presented a study on the practical use of insulation diagnosis technology and the implementation of retrofitted insulation in existing houses through a technical verification of the insulation performance diagnosis of existing wooden houses. In previous studies, the insulation performance of a building was analyzed using the ISO 9869-1 (HFM method). The majority of these studies were conducted via the implementation of the HFM method over a long time period of seven days or more. However, the previous research does not provide a means of measuring the building thermal performance over a short time period. Therefore, this study attempted to improve upon the previous research by investigating the air–surface temperature ratio (ASTR) method of measuring the wall U-values of existing houses over a short time period. In addition, the appropriate measurement period to satisfy the measurement conditions was calculated. Furthermore, the ASTR method was verified as a method that can obtain acceptable measurements in the field over a short time period.

David Bienvenido-Huertas et al. [14] analyzed the viability of the application of the thermometric method (THM), one of the most commonly used methods in Spain. The results indicated that the values obtained via THM are valid for winter environmental conditions with relative uncertainties. However, this study provides limited results only for warm climates using filtered data for temperature differences higher than 5 °C. Therefore, in this study, in-situ measurements were conducted in a winter environment where the indoor and outdoor temperature difference is more than 15 °C. The measurement significance and reliability verification were conducted in this environment.

In previous studies, the improvement methods of the existing buildings were studied based on the results obtained using the HFM method. However, the previous studies lacked examples with regard to improving energy efficiency and actually applying retrofits to houses. Subsequently, the wall U-values were examined in the location of the houses with the lowest thermal performance, and methods for improving the energy efficiency in these areas were suggested. Based on the measurement results, retrofitted insulation work was conducted on the target houses. The wall U-values before and after the installation of the retrofitted insulation were compared and analyzed. Finally, the aging rates of the wall U-values were analyzed.

2. Methodology

The process flowchart for this study is shown in Figure 1. First, the HFM method of ISO 9861-1 [15–18] was studied, and its advantages and disadvantages were analyzed. Additionally, the ASTR measurement method was investigated, and a method to overcome the disadvantages of the HFM method was considered.

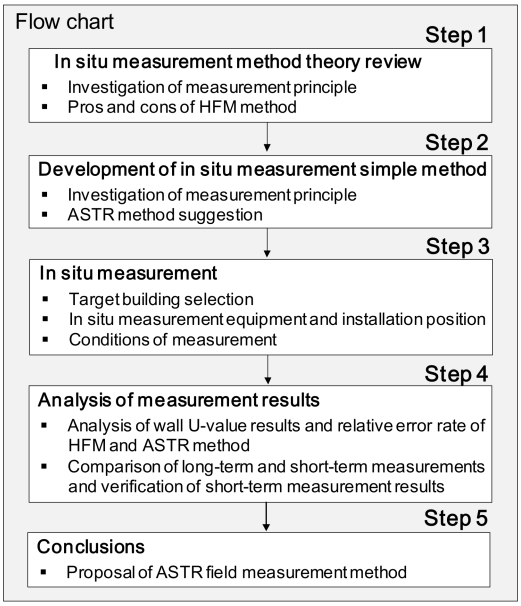


Figure 1. Study process flow.

Second, a devised ASTR method, namely the wall U-value measurement method [19], was proposed based on the difference between the inside and outside air temperatures and the wall surface temperature.

Third, the existing houses were evaluated applying the HFM method of ISO 9869-1 and the ASTR method proposed in this study. In addition, the wall U-values of four existing houses were analyzed. The HFM and ASTR methods were compared to verify the relative error rate and accuracy of the measurements.

Fourth, in this study, four buildings requiring retrofitting were selected. In addition, the wall thermal performance of four buildings was quantitatively analyzed. In addition, methods were proposed to improve the energy efficiency (e.g., building renovation, replacement, and construction) of the target housing. Based on the measurement results, retrofitting work was conducted on the target houses. Subsequently, the U-values of the walls were compared before and after the retrofits, and the aging rates of the wall U-values were analyzed.

Finally, this study analyzed the measurement error rate of the U-values over the measurement period of the ASTR method. This study verified that the ASTR method is capable of measuring in situ wall U-values over a short time period.

2.1. HFM Method

ISO 9869-1 is an exceedingly accurate diagnostic method when the data measured via the in situ measurement of thermal transmittance is in a quasi-steady state [20,21]. A heat flux meter sensor can be applied to specific areas—such as building walls, roofs, and floors—to measure the U-values of the exterior walls of the buildings.

However, certain disadvantages are involved with measuring the insulation performance of a wall, such as the measurement constraints (e.g., the prevention of indoor airflow, meteorological conditions, and the implementation of steady-state conditions) and the complicated process associated with the measurement method. In addition, a long-term measurement duration of 7–14 days is required for an accurate U-value measurement of heavy structures, and the minimum required measurement time exceeds three days. Once determined, the U-value is divided by the indoor and outdoor air temperature difference of the building to calculate the wall U-value (average method). The insulation properties of the building elements in a steady-state condition are calculated using Equations (1) and (2). Figure 2 shows the HFM method in accordance with ISO 9869-1.

$$\mathrm{U} = \frac{q}{(T_{i,air} - T_{e,air})} = \frac{1}{R_T} \tag{1}$$

$$\mathrm{U} = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n} (T_{i,air} - T_{e,air})} \tag{2}$$

where U is the U-value, q is the heat flux of the wall (W/m^2), $T_{i,air}$ is the indoor air temperature (°C), $T_{e,air}$ is the outdoor air temperature (°C), and R_T is the total heat resistance (m^2·K/W).

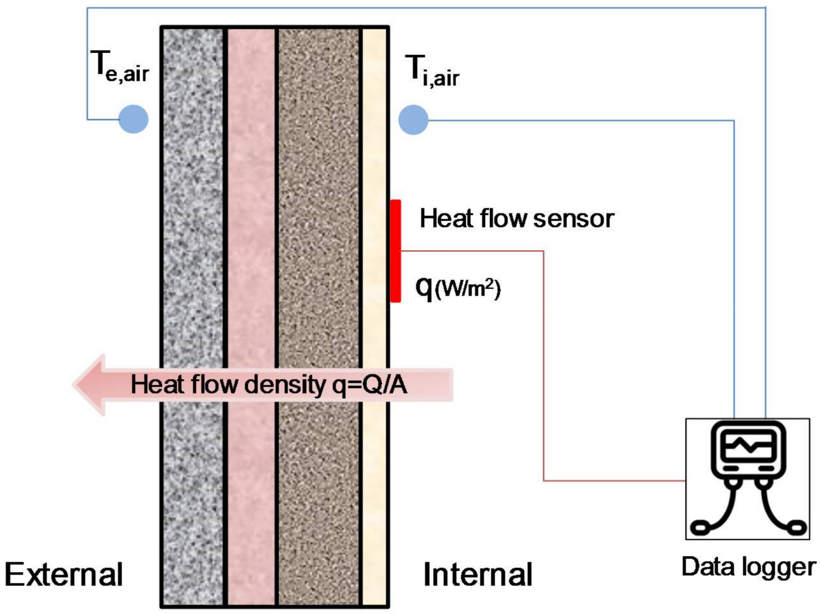


Figure 2. ISO 9869-1:2014—Part 1: HFM method.

2.2. ASTR Method

The ASTR method was devised applying the theory that the heat flux density (W/m^2) flowing through the entire wall and the heat flux density (W/m^2) transferred from the room air to the inner wall surface are equivalent. The ASTR method calculates the wall U-value using the indoor and outdoor air temperatures and the indoor wall surface temperature. The total heat transfer coefficient is calculated using the inner wall surface total heat transfer coefficient, 7.69 W/(m^2·K), which is the reciprocal of the value 0.13 m^2·K/W, the surface total heat transfer resistance value given in ISO 6946 [22–25].

The ASTR method is advantageous owing to the ability to measure the U-value over a short time period. However, the accuracy of the wall U-value measurement is not yet verified, thus, there is a disadvantage with respect to its reliability. In addition, a further limit of the ASTR method is that it measures at a single point. A single point is measured using an Infrared camera to determine where the wall temperature gradient is constant. However, as the ASTR method measures at a single point, there is the disadvantage that the measurement error may increase depending on the measurement position and measurement conditions. Therefore, in this study, precise control of the measurement conditions and measurement positions was performed to reduce the measurement error rate. In addition, the measurement accuracy was verified through a comparison of the HFM and ASTR methods by analyzing the relative error rate of the measurement and the measurement period.

As shown in Equations (3) and (4), the U-value is calculated using the inner wall surface total heat transfer coefficient, indoor/outdoor air temperature difference, indoor air temperature, and indoor wall surface temperature difference. Figure 3 illustrates the ASTR method.

$$\mathrm{U}(T_{i,air} - T_{e,air}) = h_{i,t}\left(T_{i,air} - T_{i,surface}\right) \tag{3}$$

$$\mathrm{U} = h_{i,t}\left[\frac{\sum_{j=1}^{n}\left(T_{i,air_j} - T_{i,surface_j}\right)}{\sum_{j=1}^{n}\left(T_{i,air_j} - T_{e,air_j}\right)}\right] \tag{4}$$

where $T_{i,air}$ is the indoor air temperature (°C), $T_{e,air}$ is the outdoor air temperature (°C), $T_{i,surface}$ is the indoor surface temperature (°C), and $h_{i,t}$ is the inner wall surface total heat transfer coefficient (7.69 W/m^2·K).

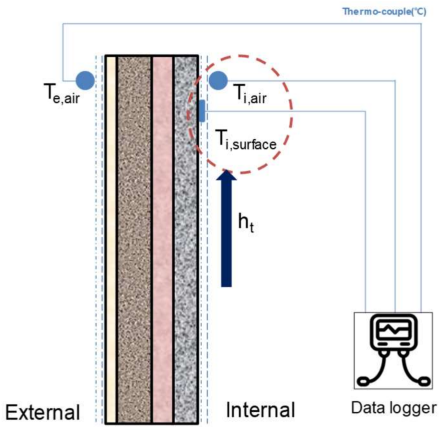


Figure 3. ASTR method.

3. In Situ Measurement of Existing Houses

3.1. Target Buildings

The target buildings in this study were selected from the "Building Energy Efficiency Improvement Project of Low Income Group"; four households were selected that were deemed to be the most similar to the existing housing standard model among the 180,000 households supported [26]. The criteria for the target building selection were based on the analysis of the direction of the building, year of completion of the building, number of rooms, and floor area. The locations of the selected existing houses were Seoul, Pohang, and Gangreung. Each building was constructed between the years 1960 and 1991, and all four houses exceeded 25 years of age. The wall U-values were measured for a period of approximately two months from 1 November 2015 to 31 December 2015.

The buildings located in Seoul (Cases A and B) were built in 1989 and 1991, respectively. The walls have initial design U-value of 0.636 W/(m^2·K) [27].

For the Pohang (Case C) and Gangreung (Case D) houses, the walls were built in 1978 and 1979, respectively. The walls had an initial design U-value of 1.062 W/(m^2·K) [27].

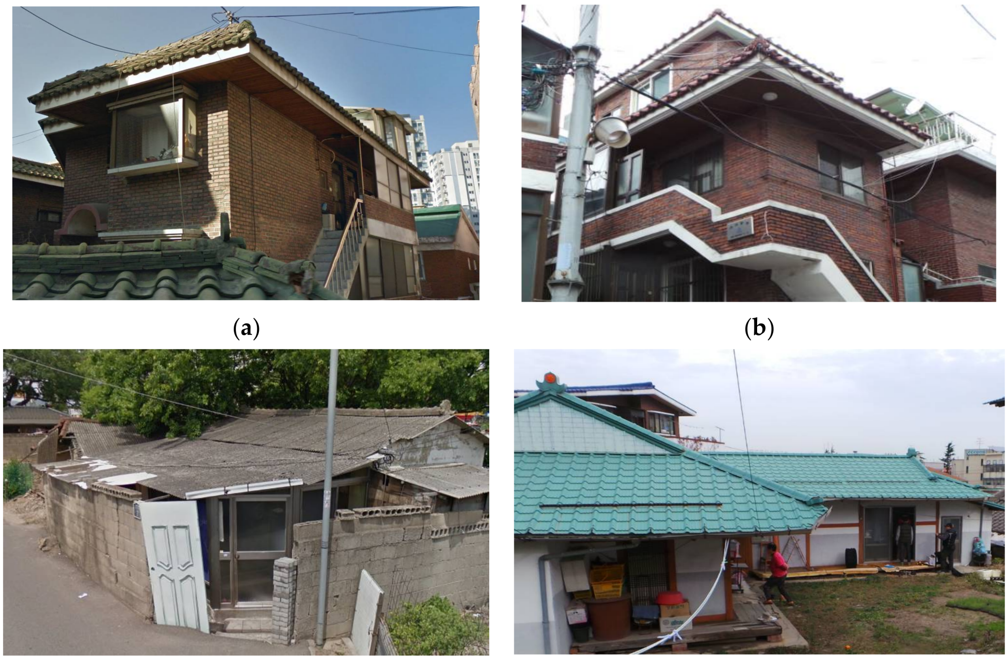
A summary of the buildings, the performance details based on building type, and the views of the buildings are illustrated in Tables 1 and 2, and Figure 4.

Table 1. Overview of the studied buildings.

Categories	Case A	Case B	Case C	Case D
Location	Seoul	Seoul	Pohang	Gangreung
Completion Date	1989	1991	1978	1979
Floor Area	34.97 m^2	45.73 m^2	41.34 m^2	33.52 m^2
Ceiling Height	2.3 m	2.25 m	2.3 m	2.4 m
Orientation	South	West	South	South

Table 2. Thermophysical properties of initial design U-value.

Category		#	Component	d (mm)	λ [W/(m·K)]	R [m^2·K/W]
Initial Design U-value	CASE A, B	1	Indoor surface heat transfer resistance	-	-	0.13
		2	Cement mortar	20	1.4	0.0143
		3	Brick, cement	90	0.6	0.015
		4	Expanded polystyrene No 1. 4	50	0.043	1.1628
		5	Brick, red	90	0.78	0.01154
		6	Outdoor surface heat transfer resistance	-	-	0.04
		#	**Component**	**d (mm)**	**λ [W/(m·K)]**	**R [m^2·K/W]**
	CASE C, D	1	Indoor surface heat transfer resistance	-	-	0.13
		2	Cement mortar	20	1.4	0.0143
		3	Brick, cement	90	0.6	0.015
		4	Air gap	10		0.086
		5	Brick, cement	90	0.6	0.15
		6	Cement mortar	20	1.4	0.0143
		7	Polyurethane (PUR)	10	0.028	0.3571
		8	Outdoor surface heat transfer resistance	-	-	0.04



(**a**) (**b**) (**c**) (**d**)

Figure 4. View of existing buildings: (**a**) Case A; (**b**) Case B; (**c**) Case C; (**d**) Case D.

3.2. In Situ Measurement Equipment

In this study, the equipment detailed in Table 3 was used to conduct the U-value measurements using the HFM and ASTR methods. The heat flux (q) and indoor/outdoor air temperatures around the walls ($T_{i,air}$ and $T_{e,air}$, respectively) were measured in accordance with ISO 9869-1 (HFM method). Each HFM sensor used a G Inc. sensor with high measurement accuracy and reliability, and the U-values of the walls were measured continuously for more than seven days. To measure the proposed ASTR method, T-type thermocouples and a four-channel data logger were used. The indoor wall surface temperature ($T_{i,surface}$), outdoor temperature ($T_{e,air}$), and indoor air temperature ($T_{i,air}$) were measured.

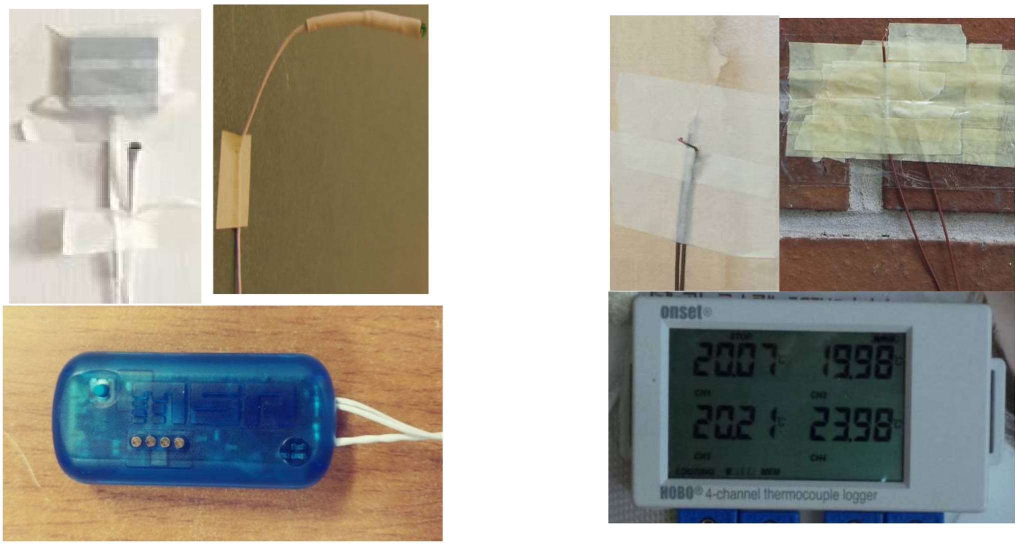
Table 3. Overview of measurement equipment.

Category		Classification	Accuracy	
HFM method	Model Quantity	G. Inc._Heat Flux Kit 16 EA	Heat Flux (W/m^2) < 0.22	Temperature (°C) ±0.5
ASTR method	Model Quantity	H. Inc._4-ch Data Logger + T-type Thermocouples 16 EA	-	Temperature (°C) ±0.5
Air temperature & humidity (reference)	Model Quantity	T. Inc._TR-72wf 4 EA	Humidity (%) ±5 RH	Temperature (°C) ±0.5

3.3. Positioning of In Situ Measurement Equipment

A TR-72wf hygrometer was installed in the representative living spaces of each house to measure the temperature and humidity. In the case of the HFM method, the heat flux meter sensors were installed at four points along each wall to measure the heat flows. In the case of the ASTR method, the T-type thermocouples were installed at four points along each wall to measure the indoor air temperature, outdoor air temperature, and indoor surface temperature of the walls. Figure 5 shows the measurement positions used for measuring the wall U-values of the target buildings in this study. Figure 6 shows an installation image of the in situ measurement equipment.

Figure 5. Measurement positions: (**a**) Case A; (**b**) Case B; (**c**) Case C; (**d**) Case D.



(**a**) (**b**)

Figure 6. Installation image of the in situ measurement equipment for the HFM method and ASTR method: (**a**) HFM method; (**b**) ASTR method.

3.4. Measurement Conditions

This study applied the following measurement procedures and conditions to measure the wall U-values. First, the state of the existing housing walls was visually confirmed using an infrared camera, in accordance with ISO 6781 [28]. This process determined the positions of the wall surface temperature gradients in the rooms. Infrared thermography should be avoided if the surface of the wall is not dry or if it is raining at the time of the test and the wind speed exceeds 8 m/s.

For a minimum of 24 h before the start of the test, the outside air temperature should not change more than ±10 °C from the original temperature at the start of the test. During the test, the outdoor air temperature should not change by more than ±5 °C and the indoor air temperature should be within ±2 °C of the initial value. Subsequently, the heat flux meter sensors and T-type thermocouples were attached to the central portion of the walls using thermally conductive adhesive tape. Each HFM sensor was installed appropriately in locations, except in a cracked wall, a corner that generated heat bridges, and a location where the wall temperature gradient was not constant. In addition, devices that generate airflow, such as fans, ventilation fans, or hoods, were rendered non-operational. The measurements were performed by selecting locations where the heat flow sensors were not exposed to direct sunlight, and the hourly data was analyzed from 2:00 to 6:00 a.m. The ISO 9869-2 [29] defines the quasi-steady-state time zone as 0:00–6:00 a.m. In this study, the time zone was selected by referring to ISO 9869-2. To satisfy the quasi-steady-state conditions, the time period of 2:00 to 6:00 a.m. was selected considering the safety factor.

Through this experimental setup, the U-values were calculated based on the difference between the room temperature and the outdoor temperature, the difference between the room temperature and the wall surface temperature, and the heat flux of the wall surface in both the HFM and ASTR methods. Therefore, the experimental conditions were measured from 2:00 a.m. to 6:00 a.m., which encompassed the time interval with the smallest temperature change, to realize a quasi-stable state. The temperature variation range was analyzed using the hourly data and maintained a range of 0.1–1.2 °C per hour for at least three days (72 h or more), as described in ISO 9869-1. The data was obtained at a measurement interval of 5 min. The indoor temperature was set to approximately 20–22 °C, and the indoor and outdoor temperature difference was maintained at approximately 10–15 °C [30,31].

4. Results and Discussion

4.1. Analysis of Wall U-Values and Relative Error Rates of the HFM and ASTR Methods

This study was conducted to quantitatively analyze the in situ wall U-values of existing houses. The wall U-values of the existing houses were analyzed using the HFM and ASTR methods, and the aging rates of walls exceeding 25 years of age were quantitatively analyzed. The accuracy of the ASTR method was verified by analyzing the measurement relative error rates of the wall U-values according to the measurement method. In addition, the in situ measurement method was used to determine the lowest wall U-values. The walls with the lowest U-values were subjected to insulation retrofitting, and the improvement rates of the wall U-values were analyzed. Finally, the ASTR method was used to analyze the error rates of the wall U-value measurements according to the measurement period (1–7 days). If the measurement conditions were satisfied, the appropriate measurement period was determined. Tables 4 and 5 shows the results of the wall U-value measurements for the existing houses before and after the retrofit.

Table 4. Results of wall U-value measurements prior to retrofit.

(n = 480)		W1 (East) [W/(m^2·K)]	W1 (West) [W/(m^2·K)]	W1 (South) [W/(m^2·K)]	W1 (North) [W/(m^2·K)]
Case A	U_{DESIGN}	0.636	0.636	0.636	0.636
	U_{HFM}	0.928 ± 0.0318 *	0.901 ± 0.0401	-	0.879 ± 0.0383
	U_{ASTR}	0.941 ± 0.0440	0.868 ± 0.0435	-	0.918 ± 0.0482
	U_{HFM}~U_{ASTR} Relative Error (%)	1.42	3.66	-	4.44
Case B	U_{DESIGN}	0.636	0.636	0.636	0.636
	U_{HFM}	0.938 ± 0.0319	0.858 ± 0.0283	1.055 ± 0.0428	1.001 ± 0.0395
	U_{ASTR}	0.894 ± 0.0259	0.893 ± 0.0382	1.030 ± 0.0188	1.030 ± 0.0432
	U_{HFM}~U_{ASTR} Relative Error (%)	4.69	4.08	2.37	2.89
Case C	U_{DESIGN}	1.062	1.062	1.062	1.062
	U_{HFM}	1.618 ± 0.0583	1.577 ± 0.0731	1.679 ± 0.0618	1.618 ± 0.0718
	U_{ASTR}	1.689 ± 0.0647	1.525 ± 0.0651	1.720 ± 0.0794	1.693 ± 0.0872
	U_{HFM}~U_{ASTR} Relative Error (%)	4.39	3.30	2.44	4.64
Case D	U_{DESIGN}	1.062	1.062	1.062	1.062
	U_{HFM}	1.773 ± 0.0481	1.624 ± 0.0414	2.011 ± 0.0832	-
	U_{ASTR}	1.768 ± 0.0524	1.698 ± 0.0389	2.089 ± 0.0799	-
	U_{HFM}~U_{ASTR} Relative Error (%)	0.28	4.56	3.88	-

*: standard deviation.

For Case A (Seoul), the mean wall U-value measured using the HFM method was 0.903 W/(m^2·K), and the mean wall U-value measured using the ASTR method was 0.909 W/(m^2·K). The measured relative error rate was approximately 3.17%, and the U-values of the east and north walls were the lowest.

For Case B (Seoul), the mean wall U-value measured using the HFM method was 0.963 W/(m^2·K), and the average wall U-value measured using the ASTR method was 1.097 W/(m^2·K). The relative error rate was 3.58%, and the U-values of the south and north walls were the lowest.

For Case C (Pohang), the HFM measurement result was 1.623 W/(m^2·K), and the ASTR measurement result was 1.657 W/(m^2·K). The relative error rate was 3.69%, and the U-values of the north and south walls were the lowest.

Table 5. Results of wall U-value measurements after retrofit.

(n = 480)		W1 (East) [W/(m^2·K)]	W1 (West) [W/(m^2·K)]	W1 (South) [W/(m^2·K)]	W1 (North) [W/(m^2·K)]
Case A	U_{HFM}	0.548 ± 0.0225 *	-	-	0.490 ± 0.0203
	U_{ASTR}	0.552 ± 0.0291	-	-	0.511 ± 0.0237
	U_{HFM}~U_{ASTR} Relative Error (%)	0.73	-	-	4.29
Case B	U_{HFM}	-	-	0.589 ± 0.0388	0.579 ± 0.0498
	U_{ASTR}	-	-	0.584 ± 0.0401	0.603 ± 0.0511
	U_{HFM}~U_{ASTR} Relative Error (%)	-	-	0.85	4.15
Case C	U_{HFM}	-	-	0.899 ± 0.0803	0.922 ± 0.0838
	U_{ASTR}	-	-	0.917 ± 0.0907	0.965 ± 0.0888
	U_{HFM}~U_{ASTR} Relative Error (%)	-	-	2.00	4.66
Case D	U_{HFM}	0.757 ± 0.0811	-	0.776 ± 0.0799	-
	U_{ASTR}	0.778 ± 0.0864	-	0.817 ± 0.0819	-
	U_{HFM}~U_{ASTR} Relative Error (%)	2.77	-	5.28	-

*: standard deviation.

For Case D (Gangreung), the HFM method result was 1.803 W/(m^2·K), and the ASTR method result was 1.852 W/(m^2·K). The relative error rate was 2.91%, and the U-values of the east and south walls were the lowest.

For Case A and Case B, the existing houses in Seoul, the results demonstrate that the wall U-values were approximately 36–61% lower than the initial design wall U-values at the time of completion. Case C demonstrates that the U-value of the wall decreased by approximately 43–62%. In addition, Case D demonstrates that the wall U-value decreased by approximately 59–96%.

In this study, the U-values are based on the measurement results prior to the wall retrofit insulation work. In accordance with the results, the walls with the lowest wall U-values were insulated. The insulation material used in the retrofit was approximately 20–30 mm of extruded polystyrene No. 1. As a construction method, the insulation material was tightly adhered to the wall, and subsequently the air gap between the plate materials was filled in a compact manner with urethane foam. After forming the frame, the wall was finished with one sheet of gypsum board.

Table 5 shows the measured results using the HFM method and the ASTR method after the retrofit. Figure 7 shows the measured values of the target building during the experiment. The results indicate the values of the internal air temperature, internal wall surface temperature, and external air temperature of the target buildings. The indoor and outdoor air temperature difference was approximately 10–15 °C. The data were filtered and analyzed under quasi-steady-state conditions.

Case A has an average U-value of 0.519 W/(m^2·K) for the walls measured using the HFM method after retrofitting. The ASTR method determined a U-value of 0.532 W/(m^2·K), and the relative error rate of the HFM and ASTR methods was 2.51%.

The mean U-value for Case B using the HFM method was 0.584 W/(m^2·K). The ASTR method resulted in a mean U-value of 0.594 W/(m^2·K), and the relative error rate was 2.50%.

The Case C measurements indicate that the U-value using the HFM method was 0.911 W/(m^2·K), and the U-value using the ASTR method was 0.941 W/(m^2·K). The relative measurement error rate was 3.33%.

In Case D, the U-value using the HFM method was 0.767 W/(m^2·K), and the U-value using the ASTR method was 0.798 W/(m^2·K). The relative measurement error rate was 4.03%.

The wall U-values prior to retrofitting the houses indicated that the insulation performance for all the cases was exceedingly poor when compared with the initial design at the time of completion. The measurement relative error rate analysis was conducted via a comparison between the HFM and ASTR methods. In addition, the measurement relative error rate was analyzed and found to be less than 10%, satisfying the error tolerance range. Therefore, it is expected that measuring the wall U-values using the ASTR method can be proposed as a method of obtaining accurate data when the measurement conditions are satisfied.

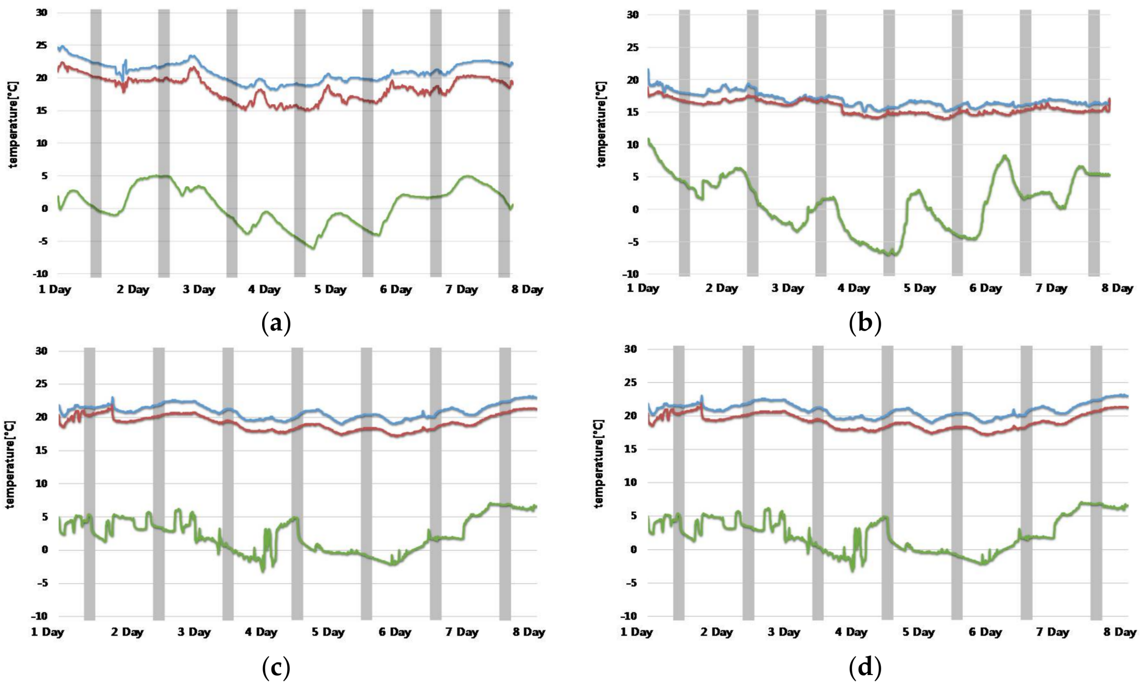


Figure 7. Value of the temperature measured by the ASTR method (**a**) Case A; (**b**) Case B; (**c**) Case C; (**d**) Case D; the internal air temperature (blue); the internal surface temperature of the wall (red); external air temperature (green); 02:00–06:00 a.m.; quasi-steady state zone (black bar).

4.2. Comparison and Validation of Long-Term and Short-Term Measurements

In this study, the results of the long-term and short-term measurements were compared. This section discusses the accuracy and field applicability of the short-term measurements of the in situ wall U-values measured using the ASTR method.

The HFM method (ISO 9869-1) requires a minimum measurement period of 72 h to obtain a stable U-value and temperature around the heat flux sensor. If the conditions are not stable, a longer period of 7–14 days is required because the extra time is necessary to stabilize the measurement conditions. The thermal performance and the thermal resistance values of each structural property are different and vary widely and, therefore, different methods and conditions are required to estimate the period during which the measurement conditions remain in a steady- or quasi-steady state. It is mathematically impossible to maintain steady-state conditions in real environments; therefore, in this study, it was assumed that the experimental condition was a quasi-steady state. The ASTR measurements were performed by selecting the time of the day when the T-type thermocouples were not exposed to direct sunlight, and to implement this measurement condition, the measurements were obtained at 2:00–6:00 a.m. The temperature variation range was extracted from the hourly data, and the temperature difference range was approximately 0.1–1.2 °C per hour.

In the proposed ASTR method, the U-value measurement error rate was analyzed. The values measured using the average method for a period of seven days were calculated and selected as comparative, representative values. In addition, a quasi-steady-state period that satisfied the measurement conditions was selected as five days and compared with the comparative, representative values. The results of the analysis are shown in Figure 8.

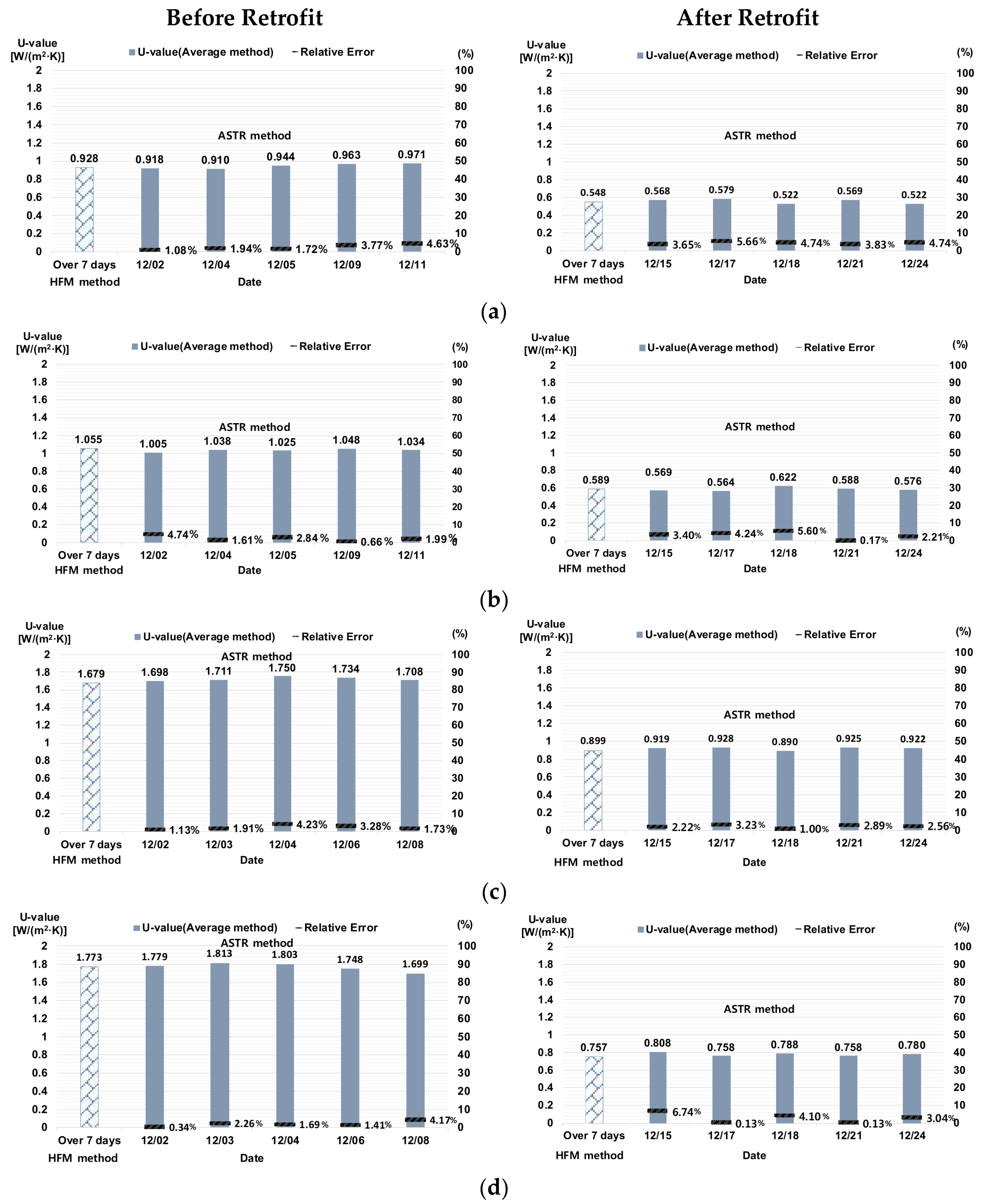


Figure 8. Results of the U-value measurement relative error rates (ASTR method, n = 48): (**a**) Case A; (**b**) Case B; (**c**) Case C; (**d**) Case D.

For each case, the relative measurement error rate was analyzed comparing the results of the long-term measurements of the wall U-values before and after the retrofit with those of the short-term measurements. For Case A, the U-value of the wall measured for the seven-day period was 0.928 W/(m^2·K). The result of the wall U-value data for the short-term period indicated minimum and maximum values of 0.910 W/(m^2·K) and 0.971 W/(m^2·K), respectively. The relative error rate with the representative average value was approximately 1.08–4.63%. After the retrofit measurement for Case A, the measured wall U-value was 0.548 W/(m^2·K). The results of the short-term measurements indicated minimum and maximum values of 0.522 W/(m^2·K) and 0.579 W/(m^2·K), respectively. The relative error rate with the mean value was approximately 3.65–5.66%. For Case B, the long-term wall U-value was 1.055 W/(m^2·K), and the short-term measurements indicated minimum and maximum values of 1.005 W/(m^2·K) and 1.048 W/(m^2·K), respectively. Additionally, for Case B, the relative error rate with the representative average value was approximately 0.66–4.74%. After the retrofit measurement, the measured wall U-value was 0.589 W/(m^2·K).

The results of the short-term measurements indicate minimum and maximum values of 0.564 W/(m^2·K) and 0.622 W/(m^2·K), respectively. The relative error rate with the mean value was approximately 0.17–5.60%.

For Case C, the average wall U-value measured for the long-term period was 1.679 W/(m^2·K). The results of the short-term measurements indicated minimum and maximum values of 1.698 W/(m^2·K) and 1.750 W/(m^2·K), respectively, and the relative error rate with the representative average value was approximately 1.13–4.23%. Following the retrofit measurement, the measured wall U-value was 0.899 W/(m^2·K). The results of the short-term measurements indicate minimum and maximum values of 0.890 W/(m^2·K) and 0.928 W/(m^2·K), respectively. The relative error rate with the mean value was approximately 1.00–3.23%.

For Case D, the long-term average wall U-value was 1.773 W/(m^2·K), and the short-term result indicated minimum and maximum values of 1.699 W/(m^2·K) and 1.813 W/(m^2·K), respectively. The relative error rates of the long-term and short-term measurements were approximately 0.34–4.17%. After the retrofit measurement, the measured wall U-value was 0.757 W/(m^2·K). The results of the short-term measurements indicated minimum and maximum values of 0.758 W/(m^2·K) and 0.808 W/(m^2·K), respectively. The relative error rate with the mean value was approximately 0.13–6.74%.

The wall U-values measured over the long-term period of more than seven days, as suggested by the HFM method, were compared with the results measured over the short-term period using the ASTR method. This comparison confirms the accuracy of the short-term measurement results of the ASTR method. As a result of this analysis, the relative error rates of the results measured using the ASTR method over the short-term period were obtained by calculating the long-term measured values and the periods corresponding to the measurement conditions. The majority of the relative error rates were observed to be less than 5%.

The results of this data analysis indicate that the wall U-values can be determined by extracting only one day of data the time of dawn (2:00–6:00 a.m.) when the indoor and outdoor temperature difference ranges from 10–15 °C and the temperature range deviation is approximately 0.1–1.2 °C. In this study, the measurement accuracy and the measurement relative error rate of the ASTR method developed using the wall U-value in situ measurement method were analyzed and verified. This was verified via experiments where the wall U-value could be measured rapidly in situ, and, therefore, it is considered that this method is suitable for measuring wall U-values.

5. Conclusions

The objective of this study was to propose an ASTR method that can easily and rapidly measure in situ wall U-values facing the external side of an existing house.

First, the wall U-values for existing houses were measured and analyzed using the HFM method described in ISO 9869-1, which is a proven in situ measurement method, and then using the ASTR measurement method proposed in this study. These results were compared with the wall U-values for existing houses exceeding 25 years of age and the initial design values at the time of completion. The results of this analysis indicated that the U-value aging rate of the existing houses was approximately 36–96%.

Second, the relative measurement error rate was analyzed by comparing the measured values for the HFM and ASTR methods that were verified by international standards. The mean relative measurement error rates were 3.32% and 3.091% before and after the retrofit, respectively. The results demonstrated a low relative error rate between the two measurements.

It was possible to analyze the accuracy of the wall U-value measurements and to investigate the applicability of the ASTR method. Subsequently, the improvement effect was analyzed by performing actual insulation retrofitting work on the sites of existing houses with the lowest wall U-values.

Finally, the results of the long-term measurements of the wall U-values were obtained and compared with the results of the short-term measurements. The HFM method calculated the data over a period of seven days using the mean method, whereas the ASTR method was calculated using the averaging method selecting a short time period (one day from 2:00 to 6:00 a.m.). The long-term measured U-values suggested by the HFM method were compared with the short-term measured U-values of the ASTR method. As a result, the short-term and long-term measurement results indicated an average error rate of approximately ±2.63%. These results demonstrate that the ASTR method is capable of obtaining short-term measurements.

In a future study, we will analyze the in situ wall U-values measured in the field with those from an experimental chamber and analyze the effects of different variables—such as wind speed, external environment temperature, internal temperature, external surface temperature, and measurement time—on wall insulation performance. In addition, we plan to implement a measurement significance analysis based on the in situ measurement method.

In addition, as studies regarding the indoor surface heat transfer rate are insufficient in Korea, it is necessary to further study the thermal performance of walls by measuring and analyzing the surface wall heat transfer coefficient suitable for different variables, such as domestic climate, environment, wall properties, and Korean heating systems (ondol floor heating).

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