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Analysis of Indoor Thermal Comfort and Energy Saving Based on Changes in the Office Building Envelope

Cho, Jong-Soo * · Kim, Young-Min **

* *Graduate School of Architecture, Konkuk University, South Korea(profcho@konkuk.ac.kr)*
** *Corresponding author, Technology Division, GS E&C, South Korea(lisang2@hanmail.net)*

ABSTRACT

Purpose: The heating, cooling, and lighting loads of buildings are very closely related to the buildings' performance. Here, we provide a guide for effective window design by examining the cooling and heating load reduction and indoor comfort according to the type of the building envelope. **Methods**: In this study, the heating and cooling loads were calculated using Energy Plus, while varying the envelope of the G-Tower. By analyzing the constituent elements of the envelope, items with excellent insulation and shielding performance that affected the heating and cooling loads were selected and classified. **Results**: Residential environment was evaluated using the building envelope systems. Eight types of envelope systems were evaluated, and the evaluation items of the residential environment were the heating and cooling loads, lighting load, thermal comfort, and condensation. The results of the evaluation showed that the system with the PCM glass showed excellent overall performance; however, direct applicability is limited owing to high cost. The envelope system will very likely become more widespread with reduction in PCM material cost.

KEYWORD

Environmentally friendly architecture design
Indoor thermal comfort
Energy reduction
Living condition analysis
Environmental Architecture Design
Indoor Thermal Comfort
Energy Plus
PCM (Phase Change Material)
Prism Plate

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1. Background

1.1. Introduction and motivation

In architecture design, the environmental aspect serves the basic purpose of constructing an architectural space and plays an important role in preserving a sustainable environment and advancing the quality of life, even prior to the financial issue of reducing the use of energy. This indicates that the fundamental goal of architectural design is to create beauty through understanding technology. Focusing on the technical aspect, the application of energy-saving technologies to the architectural design process can minimize the negative impact on the environment associated with architecture, and can help create functional designs.

Domestically, buildings (residential and commercial) have accounted for 23% of national energy use in Korea; therefore, reducing the buildings' energy use by 30~40% is equivalent to reducing the overall national energy use by 8~10%.

Based on normal energy usage patterns, architectural buildings can largely be divided into residential and commercial categories. In the case of residential buildings, there have been real pilot projects aiming to analyze the annual energy use for usage reduction, with examples such as zero-energy houses and passive houses; moreover, a large volume of research on this topic exists. On the other hand, while the topic of environment-friendly buildings for energy use reduction is very interesting, more attention has been given to the residential sector problems; as a result, not much research has been performed on environment-friendly buildings. Unlike residential buildings, commercial buildings are characterized by a vertical core that divides the service and work areas; work areas tend to be open in nature, and come in direct contact with a large external area. This is based on office landscaping for effective work and responding to future changes in an architecturally spatial manner; given spatial characteristics, the heating, cooling, and lighting loads of office building envelopes are more closely related to the buildings' exterior performance. This indicates that if the building's envelope is designed to respond flexibly to the external environment and to control the physical aspects of the building's interior, significant reduction in the building's energy use is possible.

Therefore, this study aims to categorize building envelopes according to their type and to analyze the reductions in the heating and cooling loads for summarizing their differences.

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Moreover, this study aims to compare the living conditions, or the thermal comfort, to provide a more technical and effective guide for designing building envelopes depending on the nature of the space in addition to the energy savings aspect.

1.2. Study methodology and scope

The main purpose of this study is to compare and contrast the differences in universal heating load reductions based on changes to the building envelopes for general office architecture; as such, the target buildings are universal in nature, rather than being significant in terms of architectural characteristics, such as the size and space of the buildings. Therefore, this study has applied the energy reduction items selected in this study to the G-Tower, a general office building located in Seoul, and used a computer program Energy Plus, which measures the energy volume, to comparatively analyze the heating and cooling loads. Based on these calculations, the differences were analyzed and organized.

Energy Plus is a software module developed by the U.S. Department of Energy (DOE) that combines the advantages of existing programs (DOE-2, BLAST). Using this software module, the present study aimed at analyzing the functions of changing building envelopes to select insulation and solar screening functions that can significantly influence heating and cooling, and to organize the differences in performance of these functions based on items.

The present study has used glass, Al bars, gas, and thermal storage as aspects that influence insulation; the factors influencing solar screening were selected as blinds, projections, films, and solar control. Figure 1 shows the selection of items and the aforementioned technologies studied [1][2][3].

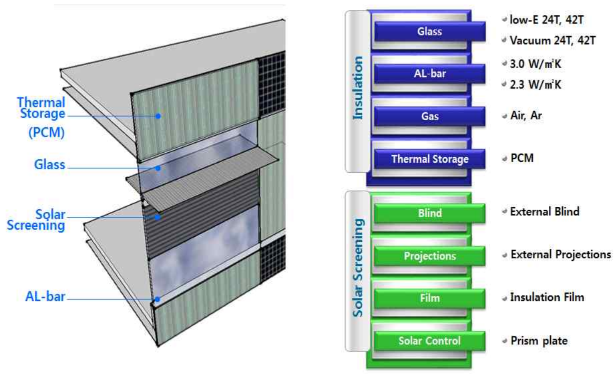


Fig. 1. Energy Saving Items

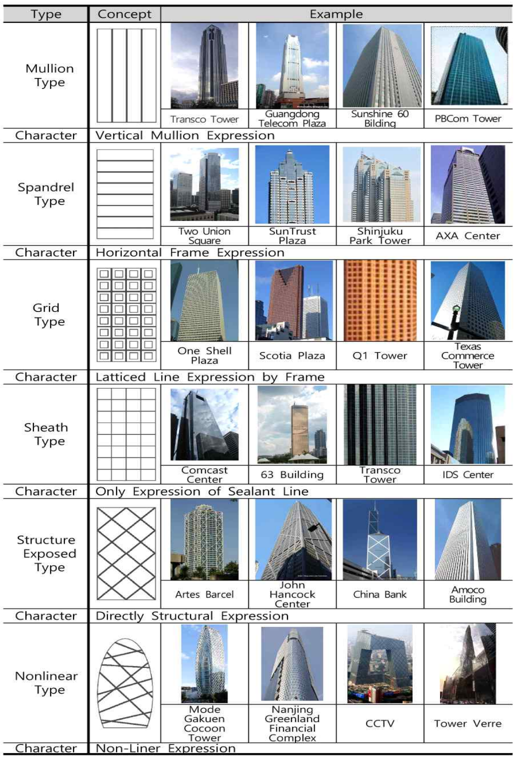
2. Facade of office architecture

2.1. The architectural significance and present status of facades

The facade of a building is an architectural factor that directly influences the building's viewers, with significant design implications of distinguishing the interior and exterior of the building, controlling the environment and expressing the artistic value of the building. It is the primary aspect of a building that helps to understand it, and its design is critical as it must functionally express the cultural situation of the era.

Facade became independent from structure after modernism, working towards a liberalist attitude, which then led to the development of the envelope system called a curtain wall, which is the most widely used today. However, even though the envelope system is now independent of the structure, it cannot be defined outside the basic thesis of internal environment control, which is the ultimate objective of the exterior. Therefore, there have been attempts to divide the internal environment control with design, as office architecture has largely been subject to the mechanical style of evolution, along with developments of air conditioning and fluorescent lighting. In a way, this is akin to the inability to carry out the merging of art and technology, which is a key responsibility of architects.

As such, office facades are being planned with changes of the curtain wall at their core. Figure 2 shows the literature review on the characteristics of facade design.



Type	Concept	Example			
Mullion Type		Transco Tower	Guangdong Telecom Plaza	Sunshine 60 Bilding	PBCom Tower
Character	Vertical Mullion Expression				
Spandrel Type		Two Union Square	SunTrust Plaza	Shinjuku Park Tower	AXA Center
Character	Horizontal Frame Expression				
Grid Type		One Shell Plaza	Scotia Plaza	Q1 Tower	Texas Commerce Tower
Character	Latticed Line Expression by Frame				
Sheath Type		Comcast Center	63 Building	Transco Tower	IDS Center
Character	Only Expression of Sealant Line				
Structure Exposed Type		Artes Barcel	John Hancock Center	China Bank	Amoco Building
Character	Directly Structural Expression				
Nonlinear Type		Mode Gakuen Cocoon Tower	Nanjing Greenland Financial Complex	CCTV	Tower Verre
Character	Non-Liner Expression				

Fig. 2. The Classification of Office Facade Design

As seen from the literature review [4], facade designs in a diverse range are used in office high-rise buildings, and analysis shows that these designs are based on the curtain wall system. Certainly, there are cases in which facades are formed based on structural materials and systems; however, in many cases, curtain walls accompany these facades, with a nod to financial and buildable aspects of the building. Given the reality that curtain walls constitute the majority of office facade designs, the facades vary significantly in terms of the types and volumes of energy use, determined by the technical knowledge of the architect. Therefore, analyzing and organizing the differences in heating load reductions based on changes to facades in office buildings can be used by architects as important information, for applying energy saving methods in the early design phases.

3. Analysis of heating and cooling load reductions

3.1. Building modeling

This study has selected the G-Tower building located in Seoul to analyze the heating and cooling load reduction effects based on items that may influence the insulation and solar screening functions. As mentioned in 1.2, this building was selected because it enables a more accurate simulation through adjustments to real data-based simulation values (error margin ±5%) such as operating conditions and schedule, sublicensing rates, heating conditions [5][6] and energy use, along with the fact that this building is representative of office buildings located in Korea. The modeling was conducted so as to ensure maximal possible similarity to actual buildings, as shown in Figure 3.

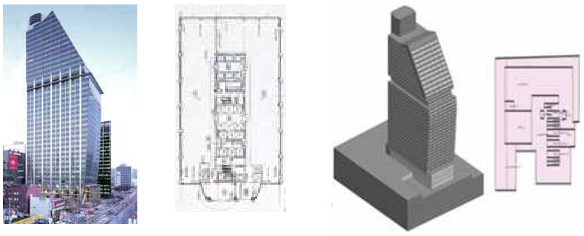


Fig. 3. G-Tower Modeling

3.2. Calculation of heating and cooling loads for the baseline model

This study has utilized Energy Plus, the energy analysis software program, to analyze the G-Tower as modelled in 3.1, with respect to its heating and cooling loads. The windows and doors that are in place today are made up of aluminum frames, 24 T Low-E multiple floor glass, and the gas is air; the U-Value is 2.6 W/㎡K and the G-value is 0.6. These conditions were set as the baseline to calculate the heating and cooling loads; the cooling load was 94.13 kW/㎡, while the heating load was 67.36 kW/㎡. As such, the total heating and cooling load was 161.49 kW/㎡.

Based on these values, this study aimed at analyzing the changes in the heating and cooling loads, using the methods presented above.

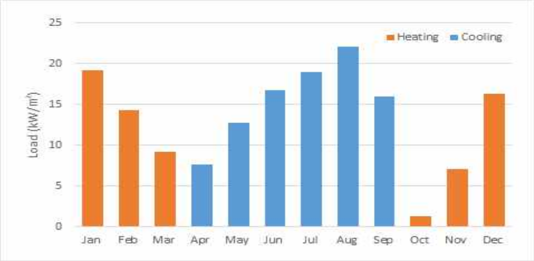


Fig. 4. Heating & Cooling Load of Baseline Model

Table 1. Heating & Cooling Load Saving and Cost of Windows

Item	Base-line	Alt1	Alt2	Alt3	Alt4	Alt5	Alt6	Alt7	Alt8	Alt9	Alt10	Alt11	Alt12	Alt13	Alt14
Glass	low-E (24T)	low-E (24T)	low-E (24T)	low-E (24T)	Double low-E (24T)	low-E (42T)	low-E (42T)	Double low-E (42T)	Vacuum (24T)	Vacuum (24T)	Vacuum (24T)	Vacuum (24T)	Vacuum (42T)	Vacuum (42T)	Vacuum (42T)
Gas	Air	Air	Air	Ar	Ar	Air	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar
AL bar	3.0W/㎡K	2.3W/㎡K	3.0W/㎡K	3.0W/㎡K	3.0W/㎡K	3.0W/㎡K	3.0W/㎡K	3.0W/㎡K	3.0W/㎡K	3.0W/㎡K	3.0W/㎡K	3.0W/㎡K	2.3W/㎡K	2.3W/㎡K	2.3W/㎡K
Film			Insulation film							Insulation film					
Solar Screening											External Blind	External Projections	External Blind		
Thermal Storage														PCM (40%)	PCM (40%)
Solar Control															Prism plate
U-Value (W/㎡K)	2.6	2.4	2.6	2.3	2.1	1.5	1.3	1.2	1.0	1.0	1.0	1.0	0.8	0.7	0.6
G-Value	0.60	0.60	0.52	0.58	0.47	0.40	0.38	0.35	0.42	0.30	0.42 (0.10)	0.42	0.42 (0.10)	0.25	0.20
Saving(%)	-	2.7%	-4.1%	-1.8%	3.6%	0.69%	5%	10%	-0.4%	-0.9%	20%	19.5%	28%	35%	48%
Cost (1,000Won/㎡)	-	30	50	20	40	30	50	110	200	250	300	270	420	1,920	2,500

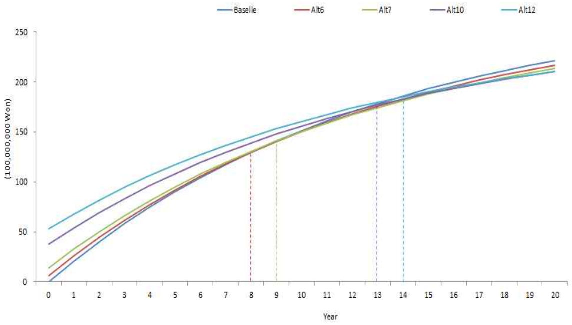


Fig. 5. LCC Analysis of Windows System

3.3. Analysis of heating and cooling load reduction effects

A total of 14 Alts were selected by combining the heating and cooling load reduction items; for each Alt, the heat transfer rate, the U-value (U -value of 2.6 W/㎡K), and the solar screening coefficient of G (G-value of 0.6) were proposed. Based on the above-proposed values, simulations of the modeled G-tower were conducted to calculate the heating and cooling loads and the initial investment for each Alt. As shown in Table 1, the maximal heating and cooling load reduction was 48%, and the increase in the initial investment was found to be KRW 2.5 million per unit area. Alt-specific effects indicate that PCM applied on Alt 13 and 14 were significantly advantageous; however, these Alts have used imported products (Glass X company, 獨) and tend to be very costly. Moreover, this study estimated the return period for the initial investment as shown in Figure 4 for Alt 6, 7, 10, and 12, with an effective investment-to-reduction ratio. The results suggest that Alt 6 requires 8 years to recover the initial investment, while 9 years are required for Alt 7, 13 years are required for Alt 10, and 14 years are required for Alt 12; based on the model recovery period of 10 years, Alt 7 was determined to be the most advantageous, and based on the model period of 20 years, Alt 14 was determined to be the most cost-efficient.

4. Analysis of indoor thermal comfort

4.1. Test bed construction experiment

The simulation was conducted on the energy test bed in the architectural environment experiment facility located in the research and development facilities of G Construction; as shown in Figure 6, the sizes of the 3 identical experimental chambers were 3 m (width, Rm 1), 5 m (depth, Rm 2) and 2.4 m (height, Rm 3).

The construction items applied to each test bed were Low-E (24T), AL Bar 2.3 W/m^{2}K, and external blinds, as shown in Table 2.

Fig. 6. Test Cell

Table 2. Windows System for The Test

	Windows System
Room1	- loe-E (42T) - AL bar 2.3W/m^{2}K - External Blind
Room2	- Vacuum (24T) - AL bar 2.3W/m^{2}K - External Blind
Room3	- loe-E (24T) - AL bar 2.3W/m^{2}K - External Blind

4.2. Measurement of the cooling energy usage

As a basic condition for measuring the cooling energy per window system constructed on the test bed, the measurements were conducted during overcast days, to prevent the influence of sunlight; the internal temperature was maintained at 26.0℃ for ensuring the most standard environment.

The exterior conditions of the Test Bed were varied using the most commonly used triple glass, vacuum glass, and Low-E glass; as external blinds are not commonly used in the actual design process, they were not used in the experiment.

Figure 7 shows the results of the experiment conducted using the Test Bed. Among the measurement times, the energy consumption was comparatively low, depending on the descending order of the heat transfer rate; among these, the vacuum glass showed the best performance. Moreover, the energy measurements indicated that the energy reduction of vacuum glass is 19.6%; the triple glass exhibited the reduction rate of 10.7%. The results are listed in Table 3.

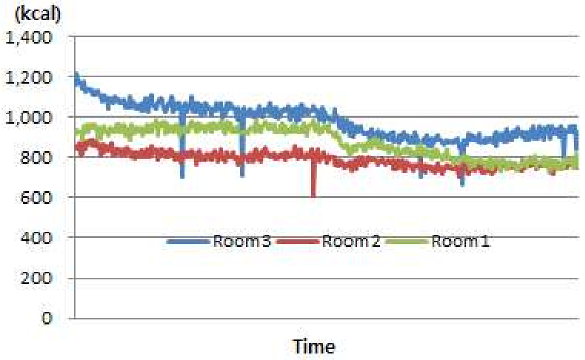


Fig. 7. Cooling Energy Consumption

Table 3. Cooling Energy Saving by Windows System

Cooling	Indoor Temp.	Energy Consumption	Energy Saving
Room1	25.3℃	368.78kcal	10.7%
Room2	25.3℃	332.01kcal	19.6%
Room3	25.4℃	412.75kcal	0%

4.3. Measurement of the heating energy usage

Following the measurement and analysis of cooling energy, the heating energy use by the window system was measured. The measurement dates and conditions were the same as the ones for the cooling energy measurements, namely, overcast conditions. The internal temperature was maintained at 22.0℃.

The exterior conditions were also maintained the same as the ones in the cooling energy measurements using triple glass, vacuum glass, and Low-E glass; as shown in Table 4, vacuum glass, with its superior insulation, exhibited the best performance, with the reduction rate of 47.8%. Moreover, triple glass exhibited the reduction rate of 34.7%.

Table 4. Heating Energy Saving by Windows System

Heating	Indoor Temp.	Energy Consumption	Energy Saving
Room1	21.9℃	18,99kcal	34.65%
Room2	21.9℃	15,18kcal	47.76%
Room3	21.8℃	29.07kcal	0%

4.4. Thermal comfort from changes in internal temperature

After measuring heating and cooling, the internal thermal comfort owing to glass and shade were measured. Typically, the horizontal temperature difference for thermal comfort is below 10℃ per ANSI / ASHRAE Standard, ISO 7730 (1984). According to the results of these measurements, listed in Table 5, vacuum glass exhibited the best performance, with a low period of discomfort at 3.4%. Moreover, in terms of shade, installing external blinds led to the complete elimination of discomfort periods; the installation of roll screens inside resulted in a 6% reduction in the periods of discomfort, compared with the absence of roll screens. Therefore, this test indicated that shades yield superior results in terms of thermal comfort. This indicates that it would be most effective to design the exterior design and shade in a comprehensive manner, to maintain internal thermal comfort in office buildings, and that the differences in characteristics and thermal comfort between exterior and interior shades suggests the inclusion of shades in exterior design.

In modern buildings, the exterior is expressed in new designs using interactive design. This involves the introduction of various changes to walls for internalization of new spatial characteristics by presenting a diverse range of lights in the interior. This can be advantageous for heating and cooling energy savings and for internal thermal comfort; as such, it is an item of architectural design that is environmentally friendly and presents new possibilities of visual effects in exterior design. Unlike a shade that is built for blocking out direct lights from the south and west directions, the results of this study allow for a comprehensive exterior design along with associated machinery and electrical devices, thus constituting an environmentally friendly approach.

Table 5. Indoor Thermal Comfort by Temp. Difference

Windows System		Indoor Temp. (℃)	Glass Surface Temp. (℃)	Temp. Difference (℃)	Over 10℃
Ioe-E (24T)	Ave.	23.3	25.2	1.9	7.8%
	Max.	29.7	40.4	12.4	
	Min.	21.5	22.0	-1.1	
Ioe-E (42T)	Ave.	23.3	25.0	1.7	3.6%
	Max.	29.2	40.0	12.2	
	Min.	22.2	21.6	-1.5	
Vacuum (24T)	Ave.	23.4	25.9	2.6	3.4%
	Max.	30.2	44.9	16.9	
	Min.	21.4	20.8	-2.4	
Ioe-E (24T) + Internal Blind	Ave.	23.3	24.5	1.2	1.8%
	Max.	27.5	38.8	11.3	
	Min.	21.5	20.3	-1.3	
Ioe-E (24T) + External Blind	Ave.	23.3	25.2	1.9	0%
	Max.	27.1	35.7	8.6	
	Min.	21.5	23.2	1.7	

4.5. Analysis of PCM glass performance

In this study, we conducted tests to identify the effects of PCM glass that was manufactured by the Glass X company [10].

The test method involved the use of thermal imaging cameras at noon, when the incoming sunlight is at its highest, to measure the surface temperature as shown in Figure 8; second, temperature sensors were installed on the surface of each glass to record temperature changes over the period of 2 days.

The test results are shown in Table 6, Figure 9, and Figure 10. Comparison of the surface temperatures of Low-E triple glass and PCM glass shows that during the beginning of sunlight intake, Low-E triple glass exhibited a rapid increase in its surface temperature; however, PCM glass exhibited consistent temperature. These results are shown in Figure 9. These results explain the delay in the temperature hikes from thermal storage by the PCM material, resulting in an increase in the surface temperature after ~4 hours.

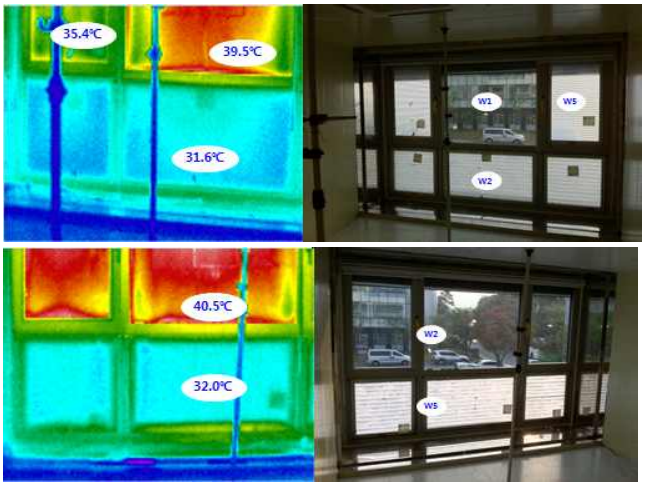


Fig. 8. Thermal Infrared Image

Table 6. Effect of Thermal Storage by PCM Glass

Windows System		Glass Surface Temp.(℃)	Performance
R1_W1	Double low-E (42T)	39.5	-
R1_W2	PCM+Prism plate	31.6	Solar Screeming
R1_W3	Prism plate	35.4	
R1_W4	low-E (24T)	40.5	
R1_W5	PCM	32.0	Theraml Storage

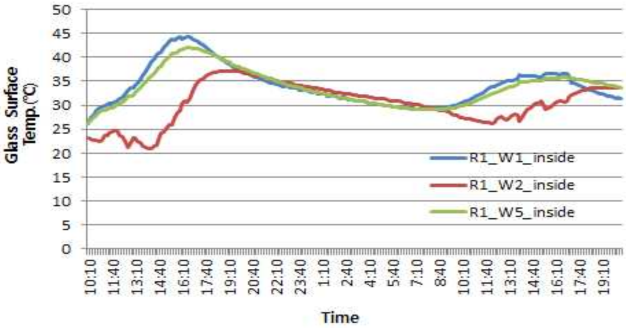


Fig. 9. Inside Surface Temp. Difference of Glass

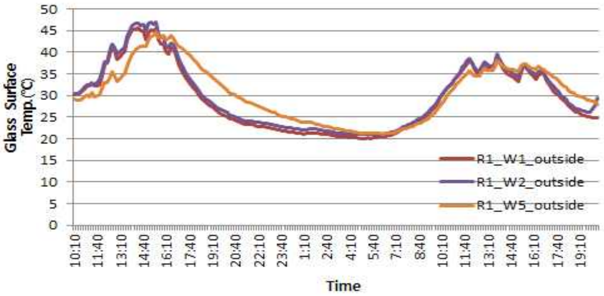


Fig. 10. Outside Surface Temp. Difference of Glass

PCM glass enables to maintain surface temperature that is 6~8℃ lower than that of Low-E triple glass, which implies that it can be used for lowering the cooling load. Figure 10 shows the results of measuring exterior surface temperature simultaneously. In the early phases of the experiment with sunlight intake, the surface temperature of PCM glass was lower than that of Low-E triple glass; however, the surface temperature of PCM glass was ~5℃ higher. This appears to be owing to the PCM material slowly releasing the stored heat over time. Utilization of this thermal storage could help reduce the heating load during wintertime.

4.6. Condensation test

The window condensation test was conducted based on the interior humidity. The window sizes and insulation characteristics of frames were kept consistent during the test, and changes were made to glass performance.

Tests were conducted using general thermopanes, Low-E thermopane, Low-E triple glass, and vacuum glass. The interior humidity was set to 60%, 70%, and 80%; the internal and external temperatures were maintained at −15℃ outside and at 25℃ inside.

Table 7. Condensation Test

Cooling	Humidity (%)		
	60	70	80
low-E (24T)	LEVEL 2	LEVEL 3	LEVEL 3
low-E (42T)	LEVEL 1	LEVEL 2	LEVEL 3
Vacuum (24T)	LEVEL 1	LEVEL 1	LEVEL 2

The results of the condensation test were divided into Level 1 (Caution), Level 2 (Warning), and Level 3 (Danger). The caution stage indicates mist condensation, where the condensed water naturally evaporates. The warning stage indicates the presence of a small amount of dew, and the user must remove the accumulated dewwater within 5 days. Lastly, the danger stage was defined as a stage of mass dewwater, which overflows and makes a secondary contamination possible.

As shown in Table 7, the condensation test indicated that a general thermopane was at level 3 when the internal humidity was above 60%; in the case of vacuum glass, it was at level 2 even when the internal humidity was at 80%, exhibiting superior performance.

As such, the selection of glass used in the exterior appears to be important for condensation, which occurs owing to the heat produced in the space and the outside environment. As such, glasses can be chosen depending on the building use; these results can be applied to design – such as selecting vacuum glass when significant condensation is expected.

4.7. Analysis of internal illumination

Internal illumination was tested as well. To minimize the heating and cooling loads, it is important to control sunlight; however, this strongly affects internal illumination. Therefore, to measure the influence of the envelope system on the internal illumination, six envelope systems were tested by combining glass, PCM, and blinds.

The results of the above-described tests are listed in Table 8. Notably, the results indicate that using external blinds, which exhibited a strong reduction in the heating and cooling energy, only weakly affected illumination at 13.35 Lux. Technically, this indicates that the exterior envelope for cooling and heating is not necessarily correlated with the lighting energy. This indicates that architects must have a deep understanding of the relationship between heating, cooling, and lighting, for constructing an appropriate envelope system depending on spatial characteristics when aiming to design a space using the technical content of the envelope. The experimental results in Table 8 can be used as a reference for architects that design envelopes and spaces.

Table 8. Average Illumination

Windows System	Average Illumination	Remarks
Ioe-E (24T)	453.6 Lux	-
Vacuum (24T)	442.2 Lux	-
Ioe-E (24T) + PCM Glass	460.5 Lux	Apply to 40% of Window Area
Ioe-E (24T) + Internal Blind	286.6 Lux	Apply to 70% of Window Area
Ioe-E (24T) + Internal Blind	168.1 Lux	-
Ioe-E (24T) + Ecternal Blind	13.3 Lux	-

5. Conclusion

This study has led to the following conclusions.

(1) Fourteen alternatives by energy reduction item application were categorized and analyzed in this study, and the differences between the alternatives were presented. Moreover, to ensure that this approach is practical, the energy reduction values of each Alt, as well as the initial investments required, were compared to derive actual differences for each Alt. The results indicated that a maximal energy reduction of 48% was possible, with a corresponding increase in the initial investment at KRW 2.5 million per unit area. Assuming that the recovery period of the initial investment is 10 years from the LCC perspective, Double Low-E triple glass (42 T), or Alt 7 of this study, exhibited the best performance. If the recovery period is set to 20 years, the application of Alt 14 would be the most effective.

(2) sed on the test results, this study has also analyzed the living conditions associated with the envelope system; for this purpose, this study has tested the heating and cooling loads, the lighting load, the thermal comfort and the condensation, analyzing the eight previously mentioned envelope systems.

Table 9. Total Evaluation of Windows System

Windows System	Heating Load	Cooling Load	Lighting Load	Thermal Load	Conden sation
Ioe-E (24T)	△	△	◎	△	△
Ioe-E (42T)	○	○	◎	○	○
Vacuum (24T)	◎	○	◎	○	◎
Ioe-E (24T) + PCM Glass	◎	◎	○	◎	◎
Ioe-E (24T) + Prism plate	○	◎	○	○	○
Ioe-E (24T) + PCM + Prism plate	◎	◎	○	◎	◎
Ioe-E (24T) + Internal Blind	△	◎	△	◎	△
Ioe-E (24T) + Ecternal Blind	△	○	△	○	△

Very good :◎, Good :○, Fair :△

The results are listed in Table 9. The results indicate that the system with PCM glass exhibits the best performance; however, these alternatives are costly and cannot be applied immediately. However, a drop in the price of PCM material would make it a superior envelope system.

(3) Environment has long been considered one of the most basic approaches to architecture, which expresses life; however, it is true that the reality after modernism does not have a clear boundary between architectural design and the technical aspects of the environment. This indicates that the environmental approach to architectural design is based solely on abstract theories and experiential images, excluding technical aspects. Ultimately, the approach to environment must begin from the theoretical standpoint in architectural work that is connected to life; to this purpose, architects must strive to apply cutting-edge technologies and their implications to architectural design. Therefore, this study allows architects to technically perceive the material and components of the envelope design, learn methods and apply them during design, and support data based on practical experiments and comparisons.

Acknowledgements

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