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Thermal Performance Optimization and Experimental Evaluation of Vacuum-Glazed Windows Manufactured via the In-Vacuum Method

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Abstract: Windows are essential in buildings; however, they have poor thermal performance, so extensive research has been conducted on improving their performance. In this study, we developed vacuum-glazed windows with excellent insulation via the in-vacuum method, which shortens the manufacturing time and vacuuming degree considerably. In addition, the configuration of the pillars, low-emissivity (low-e) coating, and frame from a thermal performance perspective was experimentally optimized. The results revealed that the optimal pillar placement spacing is 40 mm and that the low-e coating surface must be located inside the vacuum layer to maximize insulation performance. The vacuum-glazed window produced by the in-vacuum method was applied to an actual residential building to investigate its thermal performance, which was compared with that of a triple-glazed window. The results showed that the center-of-glazing heat flow of the vacuum-glazed window was approximately 0.8 W/m^{2}K lower than that of the triple-glazed window. The difference between the average indoor and outdoor surface temperatures during the nighttime was found to be up to 35.1 °C for the vacuum-glazed window and 23.1 °C for the triple-glazed window. Therefore, the energy efficiency of the building can be greatly improved by applying vacuum windows manufactured via the in-vacuum method and optimized for the best thermal performance.

Keywords: vacuum glazing; in-vacuum method; pumping decompression method; vacuum-glazed window; thermal performance; U-value; guarded hot box method; building heating and cooling energy

1. Introduction

Carbon dioxide emissions from buildings account for approximately 30% of total emissions, based on data from developed countries [1], and it has been reported that 60% of energy consumption is lost through windows (based on a window area ratio of 30%) [2,3]. While the U-value of a typical windows is 2.00 W/m^{2}K, the U-values of the ceiling, ground, and outer walls are 0.16, 0.25, and 0.30 W/m^{2}K, respectively [4]. Therefore, the U-value of windows must be reduced to decrease the energy consumption of buildings. In particular, for buildings with large window area ratios, their cooling and heating energy demand is determined depending on the performance of the windows. Thus, the development of high-performance windows is essential for the improvement of building energy performance.

Despite their low thermal performance, windows are a very important element in buildings. Windows provide building occupants with daylight and external vision, which has proven to be important for human well-being [5]. Esch et al. [6] found that having access to nature via a window view produces beneficial effects for employees who spend much of the working day inside. Farley et. al. [7] reviewed the effect of windows on work and well-being. They found a window with a view of nature can improve work and well-being in a number of ways including increasing job satisfaction, interest value of the job, perceptions of self-productivity, perceptions of physical working conditions, life satisfaction, decreasing intention to quit, and the recovery time of surgical patients. Despite this importance, in terms of energy savings, the thermal performance of windows is still lower than in other building structures. Therefore, windows are essential for human well-being in buildings, and the thermal performance of windows must be improved to reduce energy consumption.

The building energy performance depends greatly on the U-value as well as the solar heat gain coefficient (SHGC) of the windows. Shakouri et al. [8] compared the building energy reduction depending on the window size and orientation of double glazed (2.5 W/m^{2}K) and triple glazed windows (1.4 W/m^{2}K). The results showed that the annual energy consumption of triple glazed windows is always higher than double glazed windows, regardless of the window wall ratio. Sadrzadehrafiei et al. [9] investigated the possibility of cooling energy reduction when applying single clear glass and triple glazing (0.6 W/m^{2}K) in Malaysia. The analysis showed that triple glazing can save 6.3% of electric energy consumption compared to single clear glass. Jaber and Ajib [10] investigated the cooling and heating energy demands for performance of single glazing (5.68 W/m^2), double glazed L (2.83 W/m^2), double glazed H (1.4 W/m^2) and triple glazed (0.68 W/m^2). The results showed that the annual energy demand is greatly increased when the U-value decreases. Therefore, the thermal performance of windows in the building must be maximized to reduce the building energy consumption.

U-values depending on the composition of glazing are shown in Table 1. The U-value of single glazing is 5.9 W/m^{2}K and that of air-filled double glazing with one low-e coating is 1.7 W/m^{2}K. The triple glazing window system, currently widely used as a high-performance window, ranges from 0.9 W/m^{2}K to 1.3 W/m^{2}K depending on the type of coating and gas.

Table 1. Thermal performance of glazing depending on the configuration [11].

Glazing Configuration		U-Value (W/m^{2}K)
Number of Glazing	**Coating and Gas**	
Single glazing	Clear float	5.9
	One low-e coating	5.7
Double glazing	One low-e coating and air	1.7
	One low-e coating and krypton	1.1
	Two low-e coating and krypton	1.0
Triple glazing	One low-e coating and air	1.3
	One low-e coating and krypton	0.9
	Two low-e coating and krypton	0.9

In this study, a vacuum-glazed window was fabricated using the in-vacuum method, a new vacuum glazing manufacturing method. The in-vacuum method requires less time to manufacture vacuum-glazed windows because it is manufactured in a vacuum chamber. In addition, the in-vacuum method can produce vacuum glazing with excellent insulation performance because it can significantly reduce the vacuuming degree compared to the existing pumping decompression method. In addition, thanks to the low temperature during the manufacturing process, the soft-coated low-e glass can be applied to a new vacuum-glazed window. Therefore, it is hypothesized that the thermal performance of the vacuum window manufactured by the in-vacuum method would be better than the conventional high-performance windows, since it can produce the vacuum window with a lower degree of vacuum and low emissivity coating. This study first optimized pillar spacing, and low-e coating position of the vacuum glazing developed using the in-vacuum method. The thermal performance was then tested using the standard test method for thermal resistance for windows. The thermal performance of the vacuum window was experimentally evaluated and compared to the triple window, which is widely used as a high-performance window.

2. Performance of Vacuum-Glazed Windows

Vacuum-glazed windows with maximized insulation performance can significantly reduce energy loss compared to conventional windows. The thermal performance of vacuum glazing generally varies depending on the presence of low-e coating, the material and spacing of pillars, the edge seal, and the vacuum pressure. When one internal low-e coating is applied to double glazing with a vacuum, the U-value of the center of the vacuum glazing is approximately 1.2 W/m^{2}K [12]. Fang et al. [13] examined changes in the performance of vacuum glazing according to the emittance of low-e coating and simulated the thermal performance of triple vacuum glazing (TVG) according to the emittance of the low-e coating [14]. The research results showed that when the emittance of the TVG with two vacuum gaps and low-e coating applied to four sides was reduced from 0.18 to 0.03, the U-value was reduced to 0.41–0.22 W/m^{2}K. Moreover, when low-e coating with an emittance of 0.03 was applied to one side of each vacuum layer in TVG, the center-of-glazing thermal conductance could be reduced to 0.25 W/m^{2}K. The thermal conductance was found to be 0.5 W/m^{2}K when low-e coating was applied to both sides of the vacuum gap on the cold side and 0.33 W/m^{2}K when low-e coating was applied to both sides of the vacuum gap on the warm side.

As such, the emissivity of the vacuum layer must be lowered to enhance the thermal performance of the vacuum glass, where only heat transfer by radiative heat transfer occurs. Eames [15] investigated the radiative heat transfer rate depending on the emissivity of the surface of vacuum glass when the internal and external temperature difference of 0.15 mm vacuum was 20 degrees. As shown in Figure 1, the lower the emissivity of the surface of the vacuum layer, the lower the radiation heat transfer performance. In addition, if the emissivity is low on only one side, the radiant heat transfer rate is significantly low (minimum 80%). Therefore, applying the low-e coating to only one surface in the vacuum layer can greatly improve the thermal performance of vacuum glazing.

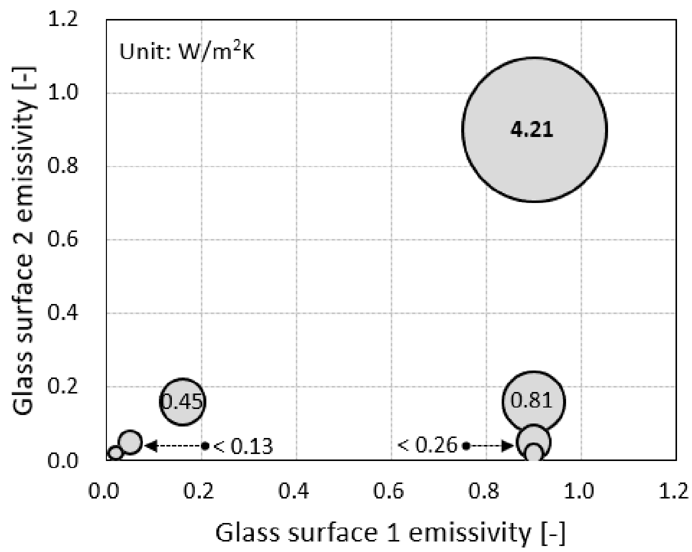


Figure 1. The effect of low-emittance coatings on radiative heat transfer rate (bubble size) in a vacuum glazing [15].

Meanwhile, the thermal performance of vacuum glazing varies depending on the material and spacing of the pillars. Cho et al. [16] examined changes in the U-value while adjusting the pillar spacing from 20 mm to 30 mm and 50 mm. The analysis results showed that the U-values of the vacuum glazing with pillar spacings of 30 and 50 mm were 11% and 25% lower compared to a spacing of

20 mm; as can be seen, the thermal performance of vacuum glazing increases as the number of pillars decreases. Fang et al. [17] decreased the U-value by reducing the number of pillars using tempered glass (T-glass) with 4–10 times higher strength than annealed glass (A-glass). According to their study, the U-value of the double evacuated glazing (DEG) that used T-glass was 47.4% lower than that of the DEG that used A-glass. In the case of triple evacuated glazing, its U-value was 60.7% lower when T-glass was used than when A-glass was used.

Moreover, the performance of a vacuum-glazed window varies depending on the magnitude of the vacuum pressure. Memon et al. [18] verified the thermal performance of TVG according to the magnitude of the vacuum pressure and found that the thermal performance of a vacuum-glazed window is significantly affected by the magnitude of the vacuum pressure. They determined that the total U-values of center-of-glazing and the TVGs were 0.28 and 0.94 W/m^{2}K, respectively, when the vacuum pressure was 0.001 Pa; however, those values became 2.4 and 2.58 W/m^{2}K when the pressure was 100 kPa (atmospheric pressure).

In addition, for vacuum-glazed windows, the thermal performance of glazing is very high. Thus, the thermal performance of the entire vacuum-glazed window significantly varies depending on the performance of the glazing edge and frame [19]. Among them, the U-value of a vacuum-glazed window by the glazing edge is more affected by the thickness of the edge seal than by its material [20].

A lowered U-value can significantly contribute to reducing the energy consumption of the building. Memon [21] investigated the possibility of reducing energy when replacing triple air-filled glazed windows to TVG, which is applied to houses in the United Kingdom through simulation. The research results showed that the annual heating energy consumption to be approximately 1.6% for a house with un-insulated solid walls and 3.0% for a house with an externally insulated solid walls. Kim et al. [22] investigated the energy reduction potential of vacuum-glazed windows for offices and residences in South Korea through simulation and found that the energy consumption of office buildings could be reduced by 2.7%, indicating that the effect of introducing vacuum-glazed windows was not large. In the case of residences, however, cooling and heating energy was reduced by approximately 30% and 24%, and the annual energy consumption was reduced by 12%.

Recently, vacuum-glazed windows integrated with renewable energy systems, such as photovoltaics (PVs), have been developed, and studies have been conducted to secure power generation performance in addition to insulation performance [23–25]. When PVs are integrated, it is possible to manufacture vacuum-glazed windows with a low solar heat gain coefficient that reduces the cooling load by preventing the inflow of solar radiation in addition to generating power [24]. Qiu et al. [26] proposed a vacuum PV insulated glass unit (VPV IGU) that combined a vacuum-glazed window with building integrated PVs (BIPVs). They suggest that VPV IGUs can achieve a U-value of up to 1.5 W/m^{2}K and unnecessary solar radiation can be blocked. In the summer, in particular, a low indoor temperature was maintained due to high insulation and low transmittance. A simulation showed that the cooling load can be reduced to 14.2% if a VPV IGU is applied to the southern side.

Vacuum glazing has excellent insulation performance, but its production is difficult. This is because its main material is glass, which is vulnerable to external and internal stress. It is also not easy to maintain a vacuum state because the perfect bonding of glass edges to maintain the vacuum is difficult [27,28]. Moreover, it is difficult to apply coatings, such as low-e coatings capable of improving thermal performance, to the internal surfaces of multi-layer glass [4]. Nevertheless, studies have been conducted to develop vacuum-glazed windows with excellent performance [29–32].

3. Materials and Methods

3.1. Vacuum Glazing Manufacturing Technology

3.1.1. Vacuum Glazing Manufacturing by the Pumping Decompression Method

Vacuum glazing was first proposed approximately 100 years ago. It was first fabricated and disclosed to the public via the University of Sydney in 1989 and commercialized after 1996 [33]. Most of the currently available vacuum-glazed windows are manufactured using the pumping decompression method. In this method, pillars are placed at regular spacings between two glass sheets to create a space, and the edges are sealed using solder glass or metal bonding. The air is then removed by decompression of the pump, as shown in Figure 2. This also removes the conductive and convective heat transfer between the two glass sheets by the air.

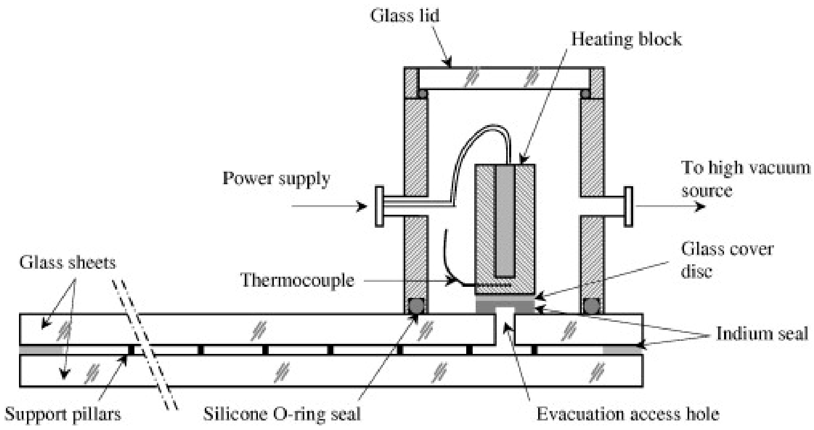


Figure 2. Schematic diagram of the pump-out system [34].

The manufacturing process via the pumping decompression method involves approximately 15 processes, as shown in Figure 3, and it takes approximately 10–12 h to produce one vacuum glaze. This is because vacuum glazing is produced via the vacuum glazing assembly, sealing, evacuation, and evacuation hole capping processes.

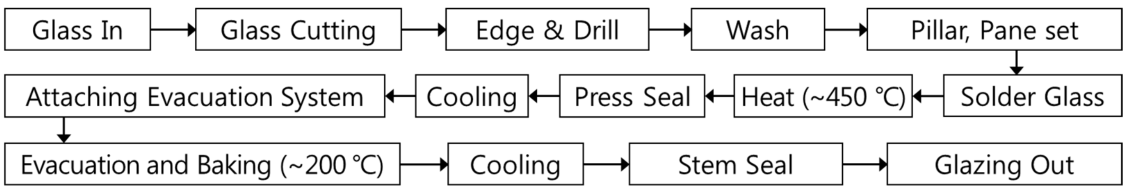


Figure 3. Vacuum glazing manufacturing process via the pumping decompression method [5].

3.1.2. Vacuum Glazing Manufacturing Technology via the In-Vacuum Method

Vacuum glazing manufacturing via the in-vacuum method as shown in Figure 4 is in a vacuum chamber. An assembly in vacuum glazing form is directly placed in the vacuum chamber, and evacuation is performed simultaneously with heating for sealing. After the evacuation and sealing processes, the cooling process to room temperature is performed. When approximately 300 °C is reached, evacuation holes are blocked using the same sealing material (frit glass) as the vacuum glazing sealing material. Finally, the inside of the vacuum chamber is cooled to approximately 100 °C, and the vacuum glazing is removed from the chamber to complete the production of the vacuum glazing. The vacuum layer of the vacuum glazing produced using the in-vacuum method can maintain a high vacuum state of less than 0.0013 Pa. As the manufacturing process is simpler than the pumping decompression method, approximately six hours are required to produce the vacuum glaze, as shown in Figure 5. Therefore, the in-vacuum method can reduce the production time by at least three hours compared to the pumping decompression method. The vacuum layer thickness of the vacuum glaze made using this method is approximately 0.25 mm. To reinforce building structural performance and thermal performance, one glass sheet is usually added, and vacuum multi-layer glass is produced.

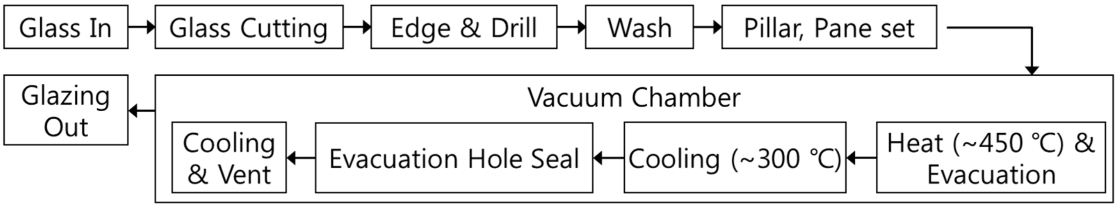


Figure 4. The vacuum glazing manufacturing process via the in-vacuum method.

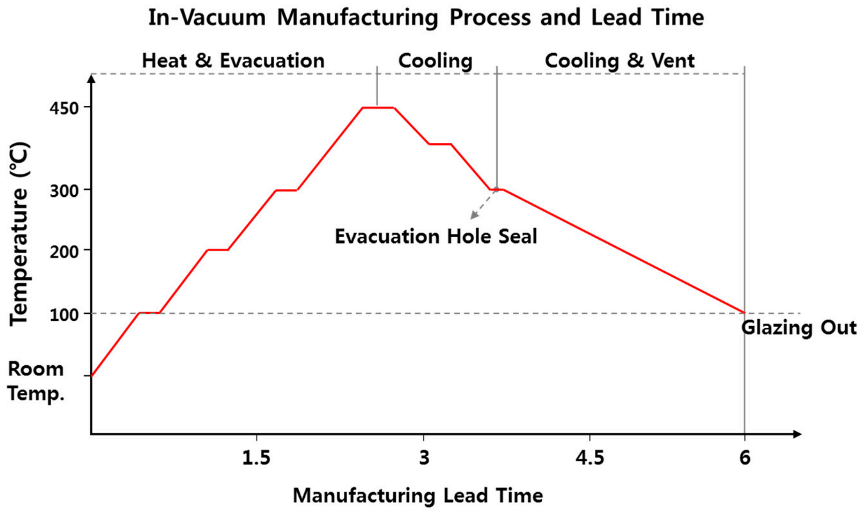
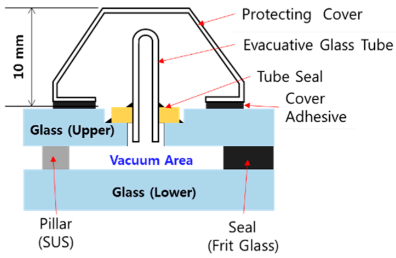
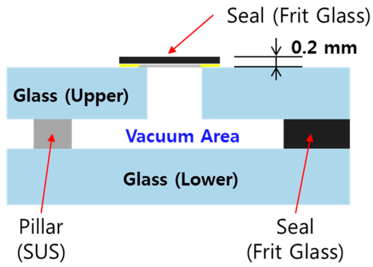
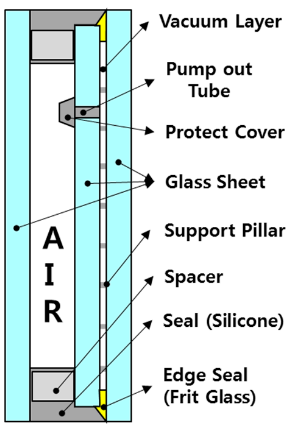
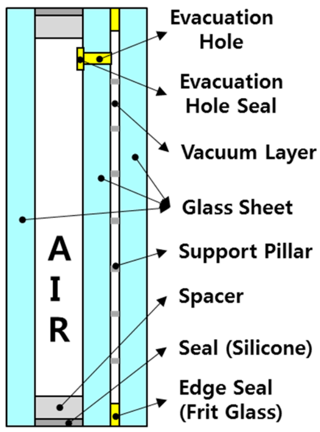


Figure 5. Time required for each process in the in-vacuum method.

3.1.3. Characteristics of the Vacuum Glazing Produced by the In-Vacuum Method

The most notable characteristics of vacuum glazing manufacturing via the in-vacuum method are as follows. First, the vacuum glazing manufacturing time can be reduced to approximately six hours, and, thus, the production amount can be significantly increased compared to that when using the pumping decompression method. Second, the simple evacuation hole sealing method can reduce the vacuuming degree inside the vacuum layer to 0.0013 Pa–0.00013 Pa (1.3 Pa–0.13 Pa for the pumping decompression method). In the in-vacuum method, all the evacuation and sealing processes are performed in a vacuum chamber. Thus, the process of attaching separate evacuation tubes or sealing evacuation tubes is omitted, and there is no loss in the vacuuming degree. Moreover, only the process of blocking the evacuation holes on the glass surface is required. Thus, the degree of vacuuming inside the chamber is the same as that of the vacuum glass, and high-performance vacuum glazing can be manufactured when the vacuuming degree in the chamber is reduced. As in the study results of Memon et al. [18], the insulation performance of vacuum-glazed windows can be significantly increased by significantly lowering the vacuuming degree. Third, soft coating low-e glass can be used as a raw material (pane). Unlike the hard coating low-e glass, the low-e function of the soft coating low-e glass is destroyed as the metal materials on the coating surface are oxidized at a high temperature (450 °C during the manufacture of vacuum glazing. Therefore, hard coating low-e glass is used instead of soft coating low-e glass. In the in-vacuum method, however, since all air has been removed before the temperature is raised to 450 °C, the oxidation reaction at high temperatures does not occur. Thus, when soft coating low-e glass is used, its functions and performance can be maintained. Fang et al. [29] made soft coating low-e glass applicable by enabling sealing at 200 °C using a sealing material made from indium. In the in-vacuum method, however, vacuum glazing can be manufactured using glass frit, a conventional low-cost material, without using costly materials, such as indium. Table 2 compares the characteristics of vacuum glazing by using the pumping decompression and in-vacuum methods.

Table 2. Comparison of vacuum glazing characteristics by the pumping decompression and in-vacuum methods.

Manufacturing Method	Pumping Decompression	In-Vacuum
Vacuuming degree (Pa)	~1.3–0.13	~0.0013–0.00013
Manufacturing time (hours)	~10–12	~6–7
Raw material	Float glass, low-e glass (hard coating; soft coating low-e glass can be used when indium sealing material is used)	Float glass, low-e glass (hard coating, soft coating), color glass, etc.
Evacuation hole		
Vacuum multi-layer glazing geometry		

3.2. How to Assess the Insulation Performance of Vacuum Multi-Layer Glass

In order to determine the exact thermal performance of vacuum windows and to compare them with each other, guaranteed results must be obtained under controlled and identical conditions. Therefore, the U-value of the vacuum window should be calculated in a controlled and guaranteed manner [35].

In this study, the insulation performance of windows and glass was assessed using the guarded hot box method. This is because the guarded hot box method follows ISO 12567-1 [36], an international standard on thermal transmittance performance assessment for windows, and it also follows KS F 2278, an authorized window thermal performance assessment method of South Korea. In this study, however, performance assessments were conducted while the frame was removed to assess the performance of vacuum glazing alone and not the performance of the window set including the frame. Therefore the frame was replaced with an extruded polystyrene foam (XPS) insulation material with a thermal conductivity of 0.028 W/mK and a thickness of 300 mm, as shown in Figure 6. The four edges of the vacuum glazing were inserted into the XPS insulation material at a depth of more than 80 mm. The edge-of-glazing affecting the thermal performance of the glazing has an impact on the thermal transmittance of the entire glazing process. Although the degree of impact varies depending on the size of the glazing, the National Fenestration Rating Council of the United States specifies the edge-of-glazing as being around 63.5 mm [37]. Therefore, in this study, approximately 80 mm of the edge of the glazing specimen was inserted into the insulation material to minimize the impact of the edge-of-glazing.

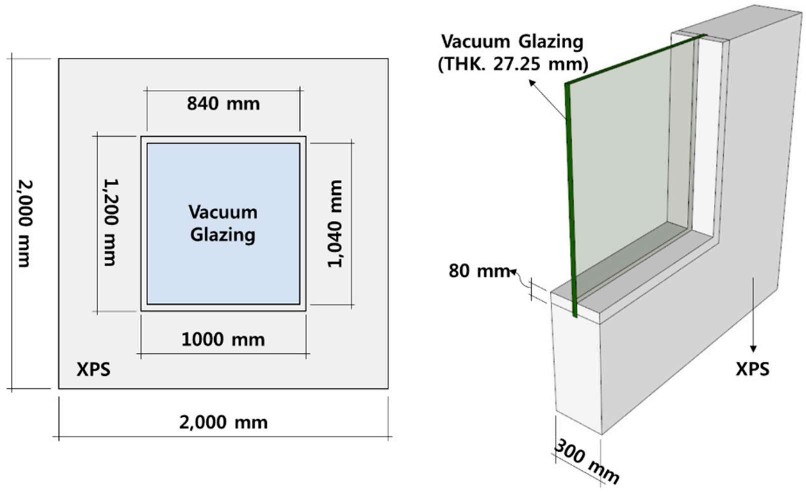


Figure 6. Vacuum multi-layer glass specimen.

The experimental setup consisted of a constant-temperature chamber, low-temperature chamber, and heating box according to the guarded hot box method. A specimen was installed between the constant-temperature chamber and the low-temperature chamber for the experiment. The set temperature for the inside of the constant-temperature chamber was 20 ± 1 °C while that of the low-temperature chamber was 0 ± 1 °C. When the heat of the constant-temperature chamber moves to the low-temperature chamber through the specimen (vacuum glazing), the thermal transmittance is calculated by measuring the heat supplied by the heater to maintain the set temperature of the constant-temperature chamber.

4. Results

4.1. Thermal Performance Optimization according to the Vacuum Multi-Layer Glass Construction Method

In this section, the insulation performance of the vacuum glazing fabricated using the in-vacuum method was optimized through experiments by varying the types of glass constituting the vacuum glazing (general glass and low-e glass), the layer locations of each glass sheet, and the placement and spacing of the support pillars. Moreover, the insulation performance was assessed by applying the optimized vacuum glazing to the thermally broken aluminum frame and PVC frame.

U-value of the Vacuum Multi-Layer Glass According to the Pillar Spacing

In vacuum glazing, support pillars are placed at regular spacings between the two glass sheets to maintain the vacuum layer. Such pillars not only maintain the thickness of the vacuum layer in a stable manner, but they also act as heat transfer paths between the two glass sheets through conduction. To maintain a stable vacuum layer from a structural perspective, regular spacings must be maintained between pillars. As the spacing decreases, a more stable vacuum layer can be maintained. When the spacing is reduced, however, the number of pillars increases, and this can lower the insulation performance by increasing heat conduction. Moreover, the insulation performance of vacuum glazing may vary depending on the thermal conductivity of the pillar material [2]. Stainless steel materials are usually used for pillars. This is because they are relatively strong, easily available, and economical.

In this study, the stainless steel (STS)-based pillar shown in Table 3 was used to measure the insulation performance of the vacuum glazing according to the pillar spacing. In addition, the thermal transmittance was measured according to the pillar spacing, and the results were compared. The pillar spacings were 25, 30, 40, and 50 mm.

Table 3. Overview of the vacuum multi-layer glass support pillar.

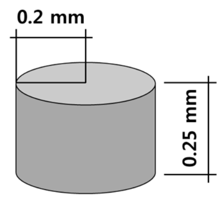
Feature	Description	Size
Shape	Cylindrical	
Height	0.25 mm	
Diameter	0.4 mm	
Projected area	0.126 mm^2	
Material	Stainless Steel	
Placement spacing	24 mm, 30 mm, 40 mm, 50 mm	

Figure 7 shows the experimental results from the guarded hot box method. The vacuum glazing with low-e glass (emissivity of 0.087) located on the inner surface of the glass on the indoor side (see LE-5 in Table 3) was used for the experiment. The U-value of the vacuum glazing was found to be 0.918 W/m^{2}K for a pillar spacing of 25 mm, 0.557 W/m^{2}K for 30 mm, 0.428 W/m^{2}K for 40 mm, and 0.415 W/m^{2}K for 50 mm. Compared to the pillar spacing of 50 mm, the U-values of 40, 30, and 25 mm were found to be approximately 4%, 44%, and 57% higher. The U-value difference was not large for the pillar spacings of 50 and 40 mm. The experimental results showed that the heat transfer area was in proportion to the number of pillars, and the insulation performance of the vacuum multi-layer glass changed as the number of pillars changed. The insulation performance significantly changed based on a pillar spacing of 40 mm. Therefore, for the vacuum glazing fabricated using the in-vacuum method, the optimal pillar spacing from a thermal performance perspective was 40 mm. In this instance, the insulation performance was approximately 0.428 W/m^{2}K.

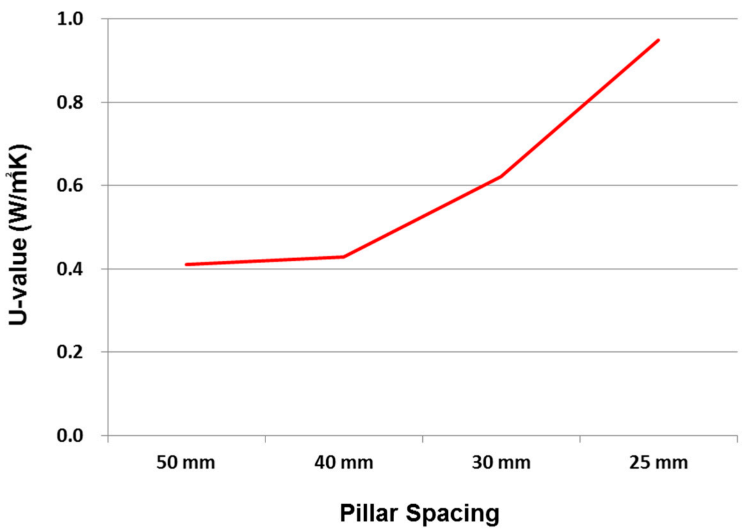
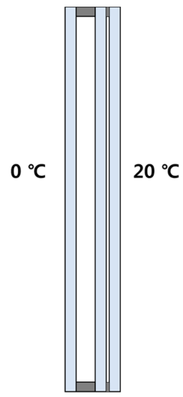
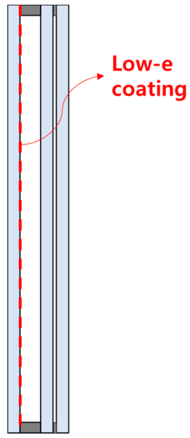
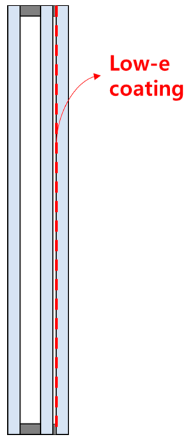


Figure 7. Measured thermal transmittance according to the pillar spacing.

4.2. U-value of the Vacuum Glazing According to the Low-e Coating Location

The heat transfer of a building structure is performed through conduction, convection, and radiation. Vacuum glazing secures its insulation performance by minimizing the air particles in the air layer (vacuum pressure: 0.0013 Pa–0.00013 Pa), thereby blocking conductive and convective heat transfer. If low-emissivity coating is applied, the insulation performance can be further improved because radiation heat transfer can also be blocked. For the in-vacuum method, vacuum glazing can be done by applying a soft low-e coating with lower emissivity than the hard low-e coating. Therefore, in this study, the U-values of the vacuum glazing with low-e glass located on the inner surface of the glass on the outdoor side (LE-2) and the vacuum glazing with low-e glass located on the inner surface of the glass on the indoor side (LE-5) were measured for performance optimization of the vacuum glazing. At the same time, the results were compared with those of the vacuum glazing without low-e glass (soft coating) (LE-0). Table 4 shows the specimens used in the experiment. The low-e glass used for the specimens was a commercial product from company H in South Korea, and its emissivity was 0.087. A pillar spacing of 40 mm was applied to the specimens based on the results of Section 4.1.

Table 4. U-Value test specimens with different low-e coating locations.

Category	LE-0	LE-2	LE-5
Glazing composition	5CL + 12A + 5CL + 0.25V + 5CL	5LE + 12A + 5CL + 0.25V + 5CL	5CL + 12A + 5CL + 0.25V + 5LE
Geometry			

※ CL: Clear glass, A: Air layer, V: Vacuum layer, LE: Low-emissivity coating glass.

The experimental results showed that the U-values were 1.711 W/m^{2}K for LE-0, 1.369 W/m^{2}K for LE-2, and 0.428 W/m^{2}K for LE-5, as shown in Figure 8. The U-value of LE-5 was approximately 69% and 75% lower than those of LE-0 and LE-2, respectively. In particular, the U-value was significantly reduced when the low-e coating surface was located inside the vacuum layer. This indicates that the low-e coating surface must be located inside the vacuum layer to maximize the insulation performance when low-e coating is applied to a vacuum-glazed window.

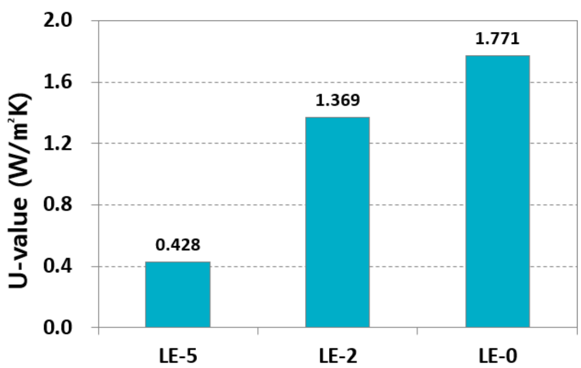


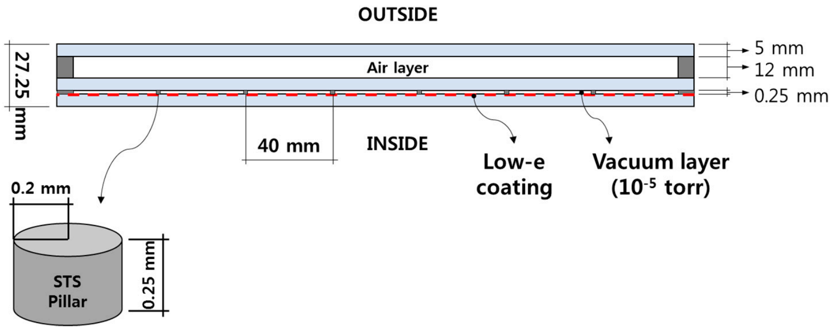
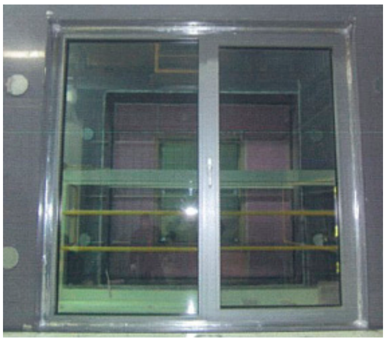
Figure 8. The measured U-value according to the low-e coating location.

Meanwhile, LE-5 (1 vacuum layer + 1 low-e coating surface) exhibited an insulation performance similar to that (0.41 W/m^{2}K) of the TVG (2 vacuum layers + 4 low-e coating surfaces with an emittance of 0.18) produced by Fang et al. [14] using the pumping decompression method. In other words, LE-5 exhibited similar insulation performance even though it had one vacuum layer and three low-e coating surfaces less than the TVG.

4.3. U-value of the Vacuum Multi-Layer Glass According to the Frame Type

In general, the thermal performance of a window is significantly affected by the material of the frame. In this study, the insulation performance of LE-5, which exhibited excellent performance in the experimental results, was measured for each frame type using KS F 2278 (Korea national standards), which follows the guarded hot box method. The frames used for performance measurement were the thermally broken aluminum frame and PVC frame, which were most commonly used in South Korea. The pillars of the vacuum glazing were made of STS, and the pillar spacing was 40 mm. Moreover, the low-e coating surface was located on the inner surface of the vacuum layer of the vacuum glazing on the indoor side (LE-5). Table 5 shows the window specimens fabricated for the experiment and the measurement results.

Table 5. Vacuum-glazed window specimens for testing and their structures.

Category	Thermally Broken Aluminum Frame + Vacuum Glazing	PVC Frame + Vacuum Glazing
Structure of the vacuum multi-layer glazing		
Specimen		
U-value (W/m^{2}K)	0.866	0.690

In the experimental results, for the vacuum glazing produced using the in-vacuum method, the insulation performance (i.e., U-value) according to the frame type was 0.886 W/m^{2}K when the thermally broken aluminum frame was applied and 0.69 W/m^{2}K when the PVC frame was applied. When the PVC frame was applied, the insulation performance was improved by approximately 22% compared to when the aluminum frame was applied. Through this experiment, it was revealed that high-insulation windows with a U-value of less than 1.0 W/m^{2}K can be made by applying the vacuum glazing produced using the in-vacuum method to either the thermally broken aluminum frame or the PVC frame, which are the most commonly used frames in South Korea.

Currently, the South Korean government specifies the first-grade thermal performance of windows as having a U-value less than 1.0 W/m^{2}K to reduce energy consumption in buildings. In particular, for all residential buildings, the use of windows with first-grade thermal performance is actively recommended. According to Table 1, less than 1.0 W/m^{2}K can only achieve triple glazing with one or more low-e coatings filled with gas (argon or krypton). Therefore, the application of vacuum glazing to actual buildings is expected to be effective in reducing building energy consumption by significantly decreasing indoor heat loss through windows.

4.4. Thermal Performance Comparison between Vacuum-Glazed Windows and Triple-Glazed Windows through Building Application

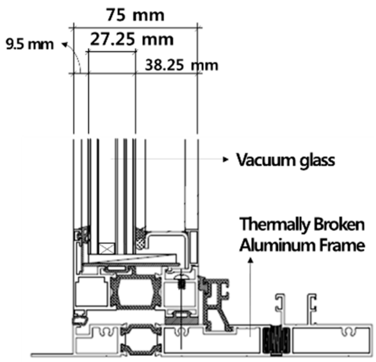
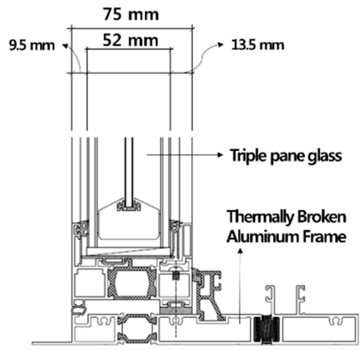
4.4.1. Thermal Performance Comparison Experiment Methods

In this section, the thermal performance of the vacuum-glazed window fabricated using the in-vacuum method was assessed through an experiment in which it was applied to an actual building by referring to the research results of Kim et al. [22]. In other words, the thermal performance of the triple-glazed window, which is most widely used in South Korea as a high-insulation window, was compared with that of the vacuum-glazed window. The building upon which these two windows were installed was a residential building located in South Korea (Table 6). They were installed on the southern side of the building, as shown in Table 6, and the experiment was performed under the same indoor temperature conditions. The two windows were sliding window systems with a size of 2.1 m (W) × 2.3 m (H). This building was completed in 2009. At the time of completion, all windows had triple glazing (low-e coating on one surface) with a thickness of 52 mm and a thermally broken aluminum frame. For the experiment, the glazing of the center window on the southern side (first floor) was replaced with vacuum glazing, while the frame was maintained as it was, and the performance of the window was compared with that of the triple glazing window next to it. Table 7 shows the structures of the two windows. The experiment for comparing the insulation performance of the windows was performed in winter (February) when the indoor and outdoor temperature difference was large. The measurement items were the heat flow through glazing and indoor/outdoor surface temperatures for each part.

Table 6. Specification of the residential building for the performance comparison between vacuum-glazed and triple-glazed windows.

Item	Specifications	Location of Vacuum and Triple Glazed Windows
Location	Daejeon, Korea	
Completion	2009. Jul.	
Stories	1 basement & 2 ground floors	
Structure	Reinforced concrete	
1st Floor	103.86 m^2 (Living room, Kitchen, Dining room, 2 bedrooms)	
2nd Floor	55.80 m^2 (Living room, 2 bedrooms)	

Table 7. Composition of vacuum-glazed and triple-glazed windows for a comparative experiment.

Item	Vacuum-Glazed Window	Triple-Glazed Window
Glazing composition	5 CL + 12 A + 5 CL + 0.25 V + 5 LE	6 CL + 18.5 A + 3 CL + 18.5 A + 6 LE
Window cross-section		

4.4.2. Results of the heat flow comparison experiment

To compare the thermal performances of the vacuum-glazed and triple-glazed windows, heat flow sensors (testo 635) that meet ISO 9869-1 [38] were installed at the center of the glazing of each window, as shown in Figure 9, and the center-of-glazing heat flow was measured. The heat flow was measured in the nighttime between 19:00 and 07:00 to accurately measure the heat flow by conduction and convection, excluding the influence of solar radiation. The experiment was performed for a day under heating conditions with the indoor temperature set at 28 °C.

Figure 9. Installed heat flow sensors for each window.

The heat flow variation will be higher for the parts of the window with low insulation performance and lower for the parts with high insulation performance due to the indoor and outdoor temperature difference. This will be the heat lost through the window glazing. Figure 10 shows the heat flow measurements over time changing according to the outdoor temperature at night. The triple-glazed window exhibited higher heat flow variation than the vacuum-glazed window did as the indoor and outdoor temperatures varied during the experimental period. For the vacuum glazing, the heat flow ranged from 0.3 to 0.5 W/m^{2}K during the experimental period, and the difference was 0.2 W/m^{2}K. For the triple-glazed window, however, the heat flow ranged from 1.0 to 1.5 W/m^{2}K, and the difference was 0.5 W/m^{2}K. It was also found that the triple-glazed window discharged approximately 0.8 W/m^{2}K more heat to the outside than the vacuum-glazed window did throughout the night. Figure 11 shows the average/minimum/maximum heat flow values. The average heat flow was 0.372 W/m^{2}K for the vacuum glazing and 1.273 W/m^{2}K for the triple-glazed window. The triple-glazed window also exhibited higher max/min heat flow variations than did the vacuum-glazed window. When the center-of-glazing heat flow was measured, it was found that the indoor heat loss of the vacuum-glazed window was significantly lower than that of the triple-glazed window.

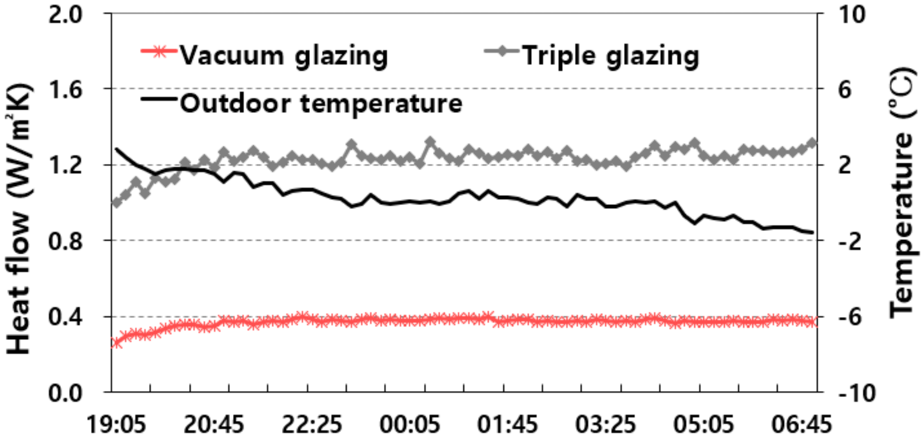


Figure 10. Heat flow measurements and outdoor temperature over time.

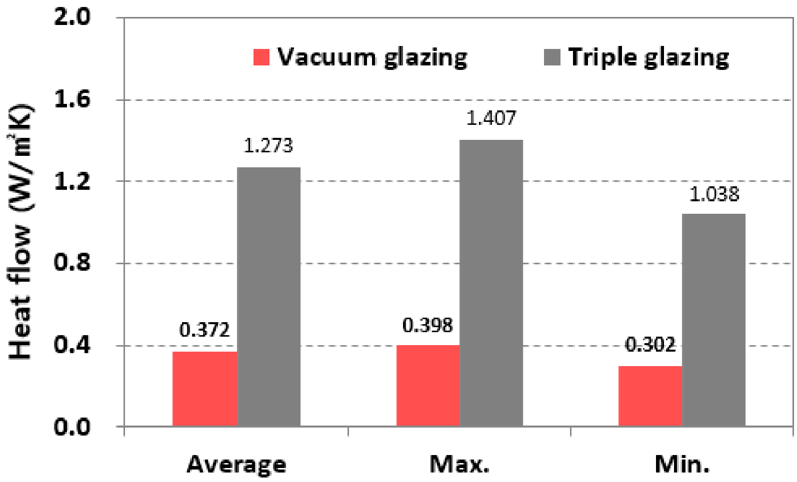


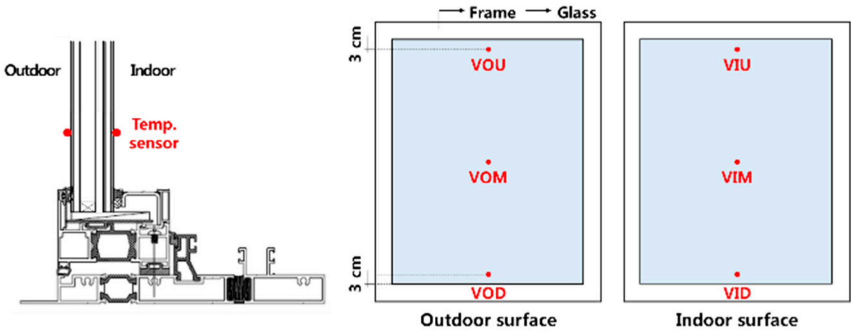
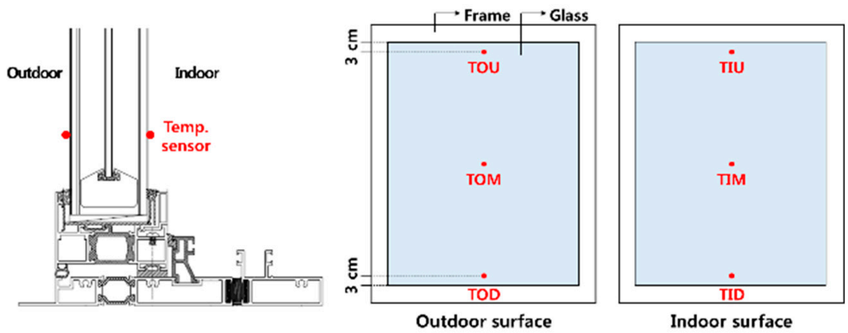
Figure 11. The average, minimum, and maximum heat flow.

4.4.3. Results of the Surface Temperature Comparison Experiment

As mentioned previously, glazing is the major cause of indoor heat loss through a window. Moreover, for the indoor and outdoor environmental conditions surrounding a window, the loss of heat is different for each glazing section. In this study, to examine the heat loss for each section of the vacuum glazing, the indoor and outdoor surface temperatures were measured for each part of the vacuum-glazed window applied to the residential building. The results were then compared with those of the triple-glazed window. The indoor and outdoor surface temperatures were measured by installing temperature sensors (type T thermocouple) at three spots on the indoor side and at three spots on the outdoor side of each window, as shown in Table 8. The experiment was performed for four days. To examine the heat loss for each part of the windows, temperatures were measured at night between 19:00 and 07:00 when the indoor and outdoor temperature difference was large.

When heat loss occurs from the inside to the outside, the insulation performance is higher since the indoor surface temperature of the glazing is closer to the indoor temperature and because its outdoor surface temperature is close to the outdoor temperature. Figure 12 shows the center-of-glazing indoor/outdoor temperature distributions of the two windows obtained from the four-day temperature measurement experiment. According to the experimental results, the difference between the surface temperature of the vacuum glazing on the indoor side, VIM, and the indoor temperature was less than 2 °C, but the difference between the surface temperature of the triple-glazed window on the indoor side, TIM, and the indoor temperature ranged from 5–7 °C. As for the surface temperature on the outdoor side, the vacuum glazing VOM also showed a temperature difference of less than 1.5 °C from the outdoor temperature, but the triple-glazed window TOM exhibited a temperature difference of approximately 4 °C.

Table 8. Surface temperature measurement sensor installation positions on a window.

Glazing Type	Temperature Sensor Installation Position
Vacuum glazing	
Triple glazing	

These experimental results were obtained under the same indoor/outdoor temperature conditions. Thus, it can be interpreted that the insulation performance improves as the indoor and outdoor surface temperature difference of the window increases. As shown in Figure 12, the maximum indoor and outdoor surface temperature difference was 35.1 °C for the vacuum-glazed window and 23.1 °C for the triple-glazed window during the measurement period, indicating that the center-of-glazing thermal performance of the vacuum-glazed window was excellent.

As mentioned earlier, the top, bottom, left, and right sections of glazing are affected by the frame. Thus, it can be said that the characteristics of the center-of-glazing represent the characteristics of the glazing itself. Figure 13 shows indoor and outdoor average temperature differences at the upper edges, which are affected by the frame, and at the center-of-glazing. The average air temperature difference between indoor and outdoor during the experimental period was 32.4 °C. The center-of-glazing indoor and outdoor surface temperature difference was 30.3 °C for the vacuum glazing and 21.0 °C for the triple glazing on average, showing that the difference was approximately 9.3 °C larger for the vacuum glazing. The average temperature differences at the upper and lower edges of the vacuum glazing, which are affected by the frame, were found to be 21.3 °C and 22.2 °C, while those of the triple glazing were found to be 16 °C and 16.5 °C, respectively. Therefore, the temperatures of the vacuum glazing at the edges were approximately 5.3–5.8 °C higher.

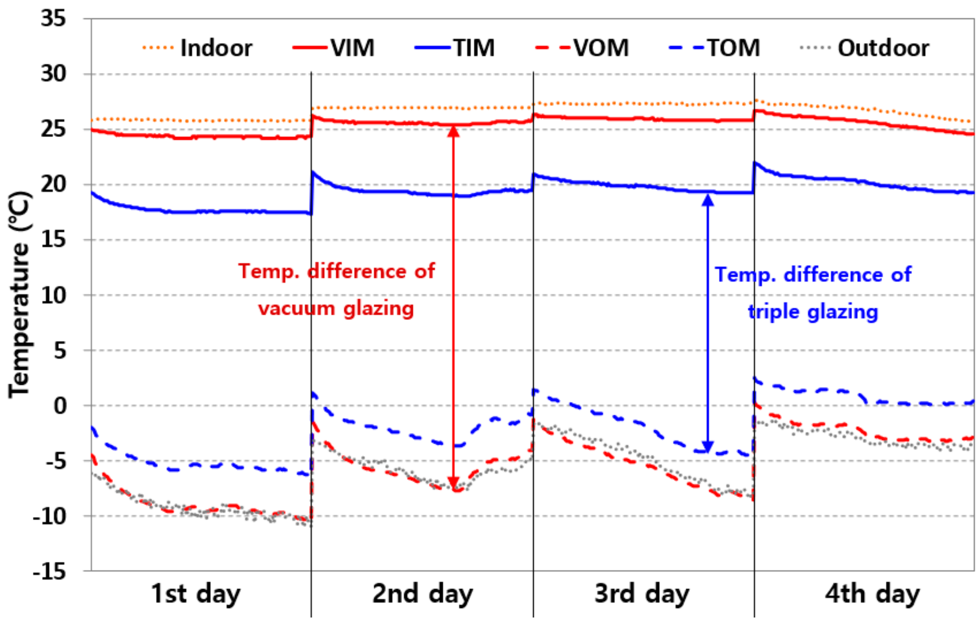


Figure 12. Center-of-glazing surface temperatures of two windows at night (19:00–07:00).

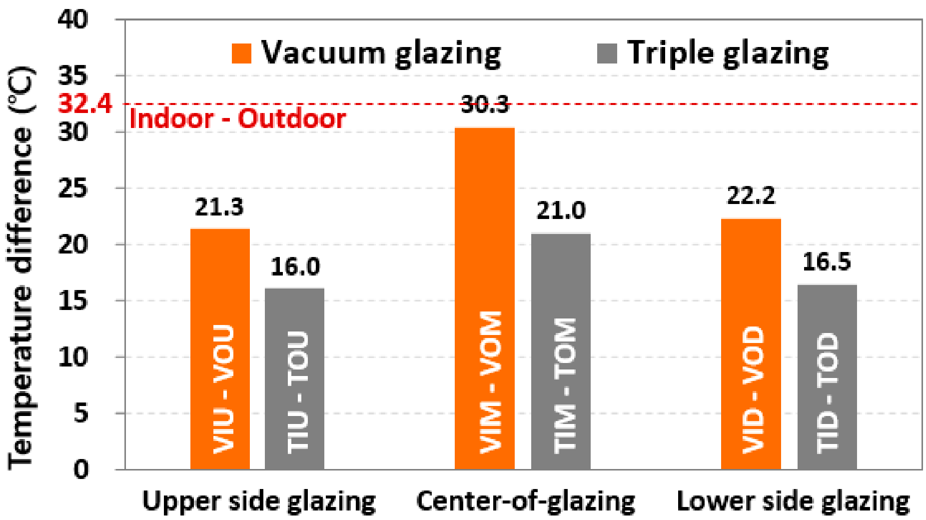


Figure 13. Average indoor and outdoor surface temperature differences of vacuum and triple glazing.

The experiment on the center-of-glazing performance, which is not affected by the frame, revealed that the insulation performance of the vacuum-glazed window is superior to that of the most widely used high-performance window. For the edge sections that are affected by the frame, insulation performance and condensation are also expected to be significantly improved by applying vacuum glazing manufactured using the in-vacuum method.

5. Conclusion and Discussion

This study introduced a vacuum-glazed window manufacturing technology using the new in-vacuum glazing method. The in-vacuum method can reduce manufacturing time by approximately 4–6 h compared to the existing pumping decompression method. Moreover, it can reduce the vacuuming degree to 0.0013 Pa–0.00013 Pa, making it possible to develop vacuum glazing with excellent insulation performance. Insulation performance was assessed via the guarded hot box method, which was adopted by the international standard for windows (ISO 12567-1 [36]) and Korean national standards. Results revealed that if vacuum-glazed windows are manufactured using the in-vacuum method, it is possible to produce high-insulation windows with better thermal performance than that of conventional windows.

The performance of the vacuum glass fabricated using the in-vacuum method was assessed according to the pillar spacing, low-e coating location, and frame type to optimize the thermal performance of the vacuum glazing (the major components).

- To optimize the pillar spacing, the U-value was measured, and the results were compared for pillar spacings of 25, 30, 40, and 50 mm. The experimental results showed that the performance of the vacuum glazing varied significantly depending on the number of pillars due to the pillar spacing and that the insulation performance of the vacuum multi-layer glass significantly changed in proportion to the heat transfer area. The optimal pillar spacing was found to be 40 mm, considering the structural stability and insulation performance.
- To optimize the low-e coating application locations, the U-values of the vacuum glazing with the low-e coating located on the inner surface of the glass on the outdoor side (LE-2) and the vacuum glazing with low-e coating located on the inner surface of the glass on the indoor side (LE-5) were measured and compared. The results were compared with those of the vacuum glazing without low-e coating (LE-0). The experimental results showed that the U-value of LE-5 (0.428 W/m^{2}K) was approximately 69% and 75% lower than those of LE-0 (1.711 W/m^{2}K) and LE-2 (1.369 W/m^{2}K), respectively. Therefore, the low-e coating surface, when it is applied, must be used inside the vacuum layer to maximize insulation performance.
- When the pillar spacing was 40 mm and the LE-5 vacuum multi-layer glass was produced using the in-vacuum method, the insulation performance (i.e., U-value) according to the frame type was found to be 0.886 W/m^{2}K when the thermally broken aluminum frame was applied and 0.69 W/m^{2}K when the PVC frame was applied.

The vacuum-glazed window fabricated using the in-vacuum method was applied to an actual residential building, and its performance was compared with that of a triple-glazed window. The performances were compared by measuring the heat flow values and surface temperatures at night in the winter. The main results are as follows:

- The heat flow measurement results showed that the heat flow of the vacuum glazing ranged from 0.3 to 0.5 W/m^{2}K, while that of the triple glazing ranged from 1.0 to 1.5 W/m^{2}K, during the experimental period. Throughout the night, the triple glazing discharged approximately 0.8 W/m^{2}K more heat to the outside than did the vacuum glazing. This indicated that the insulation performance of the vacuum-glazed window was superior.
- The surface temperature measurement results showed that the maximum indoor and outdoor surface temperature difference was 35.1 °C for the vacuum-glazed window and 23.1 °C for the triple-glazed window, confirming that the center-of-glazing thermal performance of the vacuum-glazed window was excellent. Moreover, the vacuum glazing exhibited 5.3–5.8 °C higher average surface temperatures at the edges than did the triple glazing.

In this study, it was verified that the performance of the vacuum glazing fabricated using the in-vacuum method is better than that of the vacuum glazing produced using the existing pumping decompression method through the experiment. Moreover, a high-performance vacuum-glazed window was fabricated by optimizing the pillar spacing and low-e coating locations. If the vacuum glazing is applied to either the thermally broken aluminum frame or the PVC frame, which are the most commonly used frames in South Korea, it is possible to produce high-insulation windows with a U-value of less than 1.0 W/m^{2}K. A comparative experiment with the triple-glazed window, one of the windows with the highest insulation performance, verified the potential and applicability of the vacuum-glazed window to reduce energy consumption in buildings. In future studies, optical and thermal properties of the vacuum-glazed windows should be investigated such as Visible Light Transmittance (VLT), and Solar Heat Gain Coefficient (SHGC). In addition, the production cost of the vacuum glazing fabricated using the in-vacuum method must be analyzed, and its economic feasibility upon application to buildings must be assessed for the commercialization and mass distribution of the vacuum glazing. Moreover, the comprehensive performance of vacuum glazing as a building material must be assessed in thermal and light environments by applying it to actual buildings.

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