Experimental Study on Insulation Performance and Condensation Characteristics of a Vacuum Insulated Glass Window

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Abstract
Through a mock-up test the surface temperature distribution and condensation characteristics were analyzed for a vacuum insulated glass (VIG) window, manufactured through an in-vacuum method, and compared with a double-glazed (DG) window. The outside air temperature was -21.2°C for a VIG window, at which the inside surface condensation begins to occur, given an inside air temperature of 20°C and an inside relative humidity of 50%; thus, given the typical weather conditions for Seoul, a VIG window is not likely to have condensation. The surface temperatures of the VIG window were found to be approximately 4 K–6 K higher than those of the DG window. In the case of the VIG window, the surface temperature of the center of glass is higher than that of the frame, because the vacuum insulated glass (VIG) has a superior insulation performance compared with the frame. However, the surface temperature of the edge of the vacuum insulated glass is lower than that of the frame, by approximately 0.9 K–1.5 K. Thus, to reduce heat loss and improve condensation resistance, measures to reduce heat loss at the glass connection should be established and frames should be utilized that have insulation performance equal to or better than VIG.

Keywords: window system; surface temperature; surface condensation; temperature ratio value; vacuum insulated glass window

1. Introduction
Windows play an important role in the view, ventilation, skylights, and architectural design of a building. Recently, because of various building trends in exterior architecture and a desire to secure better views, there has been an increasing frequency in the use of glass and windows.

However, Jang et al. (2010) reported that the insulation performance of windows is six or seven times lower than that of opaque walls, and furthermore, approximately 45% of a building’s total heat loss occurs at windows. For that reason, increasing the size of glass and windows will inevitably lead to heat loss in a building.

Heat loss through windows has an effect not only on the energy consumption but also on the temperature drop of inside surfaces; as a result, it may be a cause of discomfort to the occupants because of cold drafts, etc., as well as condensation on a window’s surface. In particular, window surface condensation may not only cause discomfort and health issues for occupants, such as interior pollution, mold, or insalubrious odors, but also damage the finishing materials, degrade the performance of insulating materials through moisture absorption, and cause structural corrosion. Thus, at the design stage, surface condensation on the window system needs to be predicted and prevention measures must be established.

Inside surface condensation on windows during the winter may be caused by a low interior surface temperature because of heat loss via windows and an increase of the inside humidity. Inside humidity may be decreased through ventilation and dehumidification; however, the vapor that inevitably results from the activities of occupants (e.g., breathing, cooking, washing) is hard to reduce, and it is difficult for a ventilation system to get rid of interior vapor because of the efficient airtight construction of buildings to address the need for energy conservation (Kim et al., 2011). In particular, the reduction in ventilation rate, to reduce heat loss during the winter, has a negative effect on the condensation resistance through the elimination of inside vapor. One practical approach to reducing condensation is to adjust the inside surface temperature by improving the insulation performance of windows.

To improve the energy consumption and condensation issues caused by the thermal vulnerability of the window system, various window systems are being developed, such as double-glazed (DG) windows and triple-glazed windows, as well as low-e coating, and gas injection technology. Furthermore, there has been an increasing interest in vacuum insulated glass (VIG) windows, which have an excellent insulation performance.
For a high insulation window system, one focus has been improving the thermal transmittance of the glass and frame. However, the insulation performance of windows is affected not only by the insulation performance of the components, such as glass, frame or spacer, but also by the quality of construction and assembly of those components. In addition, manufacturers generally provide data on the thermal transmittance for the center of glass; however, the thermal performance and condensation resistance of the overall window system is affected more by the frame, the edge of glass, and the connection area, rather than by the center of glass (Behr, 1995). Thus, prior to an application of a window system, it is imperative that an analysis be undertaken about a window system part that is vulnerable to condensation, so that the appropriate condensation reduction measures can be implemented.

For these reasons, this research is aimed at evaluating the insulation performance and surface condensation characteristics of the whole system of the VIG window, which is one of the most promising recent high insulation window systems. From this experimentation, the actual surface condensation potential of the VIG window as a whole system can be analyzed, and ways can be derived for improving the thermal performance of a high insulation window system, such as a VIG window.

In this study, the insulation performance and condensation resistance of the VIG window, compared with the DG window, were analyzed through a mock-up test, and measures to improve the insulation performance and condensation resistance of each window system were derived.

To achieve the research objective, the surface temperature of each window system was measured and analyzed. The surface temperature is an important factor that is related to thermal performance and also affects the surface condensation.

Furthermore, the temperature ratio value ($\tau$) was selected as a condensation resistance index and calculated for some parts of each window system. The temperature ratio value ($\tau$) enables a quantitative comparison of the condensation resistance of window systems and a prediction of the condensation under various inside and outside conditions (temperatures and humidity) that can occur in the real world.

2. Analysis of Methods for Testing Condensation Resistance of Window Systems
2.1 Previous Experimental Studies on the Condensation Resistance of Window Systems

Lee et al. (2004) analyzed the condensation characteristics of double-glazed windows with aluminum fiber reinforced plastic, or hard polyurethane spacers. For that experimental study, a 2,000 mm x 2,000 mm sized specimen was used. While the temperature of the warm chamber was maintained at 20°C (RH 50%), the temperature of the cold chamber was decreased from 20°C to -20°C by lowering by 5 K every two hours. Through Lee's (2004) observations, it was found that the double-glazed windows with FRP or hard polyurethane spacers showed slightly better condensation resistance than those with aluminum spacers.

Jung et al. (2005) compared the condensation characteristics, through a scaled-down experiment, in the glass and frame of an aluminum curtain wall, based on the heating method, inside and outside temperature conditions, and inside relative humidity. The test specimen was composed of two sheets of glass with a size of 600 mm x 800 mm. The experiment was conducted with the inside temperature at 20°C and the outside temperature at -5°C and -10°C, and the inside relative humidity was consistently increased from 30% to evaluate the condensation at an interval of ten minutes. The result showed that regardless of the heating method, the condensation of the glass started at the bottom and rose to the top. However, considering the condensation of the frame, with convective heating, it progressed from the bottom to the top, while for radiant floor heating it progressed from the top to the bottom. Also, compared with convective heating, in the case of radiant floor heating, the condensation occurred under relatively high humidity conditions.

Song et al. (2013) analyzed the surface temperatures, through simulation and a mock-up test, for three curtain wall frame types: aluminum, steel, and scagliola frames. Through these analyses, the insulation performance was evaluated for each curtain wall with each frame type.

2.2 Test Methods for Condensation Resistance of Window Systems

(1) AAMA 1503-09 (USA)

The AAMA 1503-09 presents methods for testing the condensation resistance of window systems under specific conditions at steady state. Also, the Condensation Resistance Factor (CRF), which can estimate condensation characteristics, is recommended as the performance index of condensation resistance. A higher CRF value means superior condensation resistance. The CRF is estimated by measuring the inside surface temperature of a specimen.

For the test, the warm chamber and cold chamber should be maintained at a consistent level of 21.1°C ± 0.3°C, and -18.0°C ± 0.3°C, respectively. Also, to prevent condensation during the test, the relative humidity of the warm chamber should be maintained at 25% or less.

The surface temperatures are measured with respect to glass (6 points) and frame (14 points) according to the given method. In addition, four roving location thermocouples are used in order to find the point with the lowest temperature on the sash or frame surface. The test specimen size and surface temperature measurement points are suggested not only for a fixed window or casement window, but also for windows with a combination of those two types.

(2) CAN/CSA-A440-00 (Canada)

The CAN/CSA-A440-00 presents the temperature index (I) as a performance index for condensation resistance. The lowest surface temperature at the temperature for a warm chamber and cold chamber set at 20°C ± 1°C and -30°C ± 1°C, respectively, is measured. Based on the measured lowest surface temperature, a temperature index (I) is calculated, which is utilized to evaluate the condensation resistance.
of windows under various temperature and humidity conditions. The CAN/CSA-A440-00 also suggests a test specimen size and surface temperature measurement points for a fixed window or casement window.

(3) KS F 2295 (Korea)

The Korean Industrial Standard KS F 2295 suggests a method for testing the condensation resistance of windows by measuring air and surface temperature. The temperature difference ratio \( P_e \) is suggested as a performance index.

While the air temperature of a warm chamber is maintained at 20°C (relative humidity at 40%), the air temperature of a cold chamber is reduced to -10°C, by lowering it 5 K from 5°C. The air temperature, surface temperature, and condensation status of the test specimen are observed.

2.3 Analysis of Test Methods for Condensation Resistance of Window Systems

(1) Performance Indexes on Condensation Resistance

The three test methods on condensation resistance of window systems were reviewed. The temperature difference ratio \( P_e \), condensation resistance factor (CRF, AAMA 1503-09), and temperature index (I, CAN/CSA-A440-00) are suggested as the performance indexes for condensation resistance. Each index is similar, yet different. The \( P_e \) has the same concept as the TDR, introduced by Roaf and Hancock (1992), and it is expressed as the ratio of the difference between the inside and outside surface temperature to the difference between inside air temperature and outside air temperature. The CRF and I are the ratio of the difference between inside surface temperature and outside air temperature. As for each frame, the suggested measurement points are: the center of the overall window, and the left and right edges of the glass. As for each frame, the suggested measurement points are: the center of the overall window, and the left and right edges of the glass. As for each frame, the suggested measurement points are: the center of the overall window, and the left and right edges of the glass.

Lombardi and Aghemo (1989) introduced temperature ratio value \( \tau \) as an index that enables a determination of the occurrence of surface condensation, given various inside humidity and outside temperature conditions at the given inside temperature condition. It can be calculated by a one-time measurement of the lowest inside surface temperature under specific inside and outside temperature conditions. The \( \tau \) is defined as the ratio of the difference between the lowest inside surface temperature and outside air temperature to the difference between inside air temperature and outside air temperature, and is fixed at a certain value as long as thermal resistance is fixed for a certain part, although the inside and outside temperatures are changed. Thus, if it is calculated once under certain inside and outside temperature conditions, the index enables one to predict the occurrence of condensation under various combinations of inside humidity and outside air temperature conditions. This \( \tau \) is more similar to the CRF of AAMA 1503-09 and the I of CSA-A440-00 than the \( P_e \) of KS F 2295.

The \( \tau \) is calculated using Equation 1. In addition, after rearranging Equation 1 for the outside air temperature \( \vartheta_e \), if the inside surface temperature \( \vartheta_{st} \) is substituted with the dew point temperature of inside air \( \vartheta_d \), Equation 2 can be obtained. According to Equation 2, \( \vartheta_e \) means the outside air temperature \( \vartheta_{st} \) at which inside surface condensation starts to occur, under various inside humidity conditions, at the given inside temperature \( \vartheta_i \) is the inside air temperature).

\[
\tau = \frac{\vartheta_{st} - \vartheta_e}{\vartheta_i - \vartheta_e}
\]  
\[
\vartheta_e = \frac{\tau \times (\vartheta_i - \vartheta_d)}{\tau - 1}
\]

2) Inside and Outside Conditions and Test Specimen

The inside and outside conditions (temperature and humidity) for the test are guided by the standard or the guide for test methods of condensation resistance. The conditions are slightly different because the characteristics of local climate are reflected. Also, because the type or size of window for a test is suggested based on the kind of windows usually used in a certain region, the conditions will differ for each standard or guide. Hence, if there are no big differences in the conditions for the test, according to each standard or guide, the inside/ outside conditions and specimen can be decided based on the local climate and application trends for the test.

(3) Measurement Points for Surface Temperature

The KS F 2295 suggests that the surface temperature should be measured at the center of the glass, the center of the overall window, and the left and right edges of the glass; however, it does not provide the exact location for the edge of glass. As for each frame, the suggested measurement points are: the center of the top part, bottom, left, and right of the frame. However, there is no measurement for the bottom edge of glass, which is expected to show the lowest temperature in the measurement of surface temperature.

However, the AAMA 1503-09 or CAN/CSA-A440-00 mandates the measurement of the surface temperature on the bottom edge of glass. The AAMA 1503-09 recommends the measurement of a certain point at the bottom edge of the glass and the bottom center of the frame, as well as the center and top parts of the window system. The CAN/CSA-A440-00 mandates three measurement points for both the glass and frame at the bottom of the window system; however, no measurements are mandated with respect to the top part of the window system.

The AAMA 1503-09 suggests a point 13 mm from the glass-frame connection to the direction of the center of glass as the representative point for measurement of the edge of the glass.

The surface temperature measurement focuses on a casement window for KS F 2295, AAMA 1503-09, and CAN/CSA-A440-00 are summarized in Fig. 1.

3. Overview of Evaluation Experiment

Simulation-based evaluation has the advantages of fewer limitations and less time and expenses; however, it also has the disadvantages of not accurately reflecting the real world because of various hypotheses and simplifications during the interpretation process. To address this disadvantage, Kim et al. (2004) and No and Kim (2005) developed an improved computer simulation model and evaluated the inside surface condensation of
However, the heat transfer at the edge of glass and the connection may be still inaccurate in a simulation. Thus, in this study, a mock-up test was conducted to analyze the surface temperature of general double-glazed (DG) windows, which are usually standard in domestic apartment housing in South Korea, and vacuum insulated glass (VIG) windows manufactured via an in-vacuum method. Based on the surface temperature measured through the mock-up test, the temperature ratio value (τ) is calculated to evaluate the condensation resistance of each window system. Also, there are suggested measures to improve the surface temperature distribution for each window system, through an analysis of surface temperature.

### 3.1 Characteristics of VIG and Cases for Test

A VIG maintains the narrow space between two sheets of plate glass in a vacuum state, thus preventing heat loss by convection via the gas or air that exists between the sheets of plate glass, or by conduction. A VIG reduces the thermal transmittance of glass to the level of a wall. Heat transfer through glass is directly influenced by air pressure between sheets of glass, and thus as the pressure decreases, heat loss prevention effects increase.

A VIG is manufactured by a depression or an in-vacuum method. In a depression method, before sealing, the gas or air between two sheets of glass is removed through a small orifice or tube. In an in-vacuum method, a VIG is assembled at room temperature in a vacuum chamber, where the processes of sealing and exhausting are simultaneously conducted. As the vacuum pressure is formed up to $10^{-5}$–$10^{-6}$ torr, the insulation performance further increases, and as the processes of sealing and exhausting are conducted simultaneously, the manufacturing time is reduced.

In general, when the gap between two sheets of glass is maintained as a vacuum, there is a big air pressure difference between the inside vacuum state and outside air pressure. Hence, a fine pillar is installed as a prop. Also, to sustain the stress caused by the difference between the inside and outside temperatures, the edge of the glass is welded with glass materials, thus maintaining a perfect sealing state. In addition, low-e coating may be applied inside a window in order to block out radiation that enters through the windows. For VIG manufactured through depression, a tube removing the air inside the window may be installed in the glass.

In this study, a VIG window manufactured through an in-vacuum method was selected and a low-e coating was applied on one side. The composition of the VIG window for the test is shown in Fig.2.

### 3.2 Evaluation Conditions and Methods

Through a preliminary study, it was found that the types or sizes of windows for the test differed depending on the standard or guide. This is because the types or sizes of windows for the test are recommended based on the prevalent local usage of window systems. Thus, in this study, taking into consideration the kind of apartment housing, the type and size of the window system for the test was determined and the test specimen was composed as follows: the size of the overall window system was 1930 mm x 1930 mm, by combining the fixed window and casement window.

For a comparison between window systems, the same frame (U-value 1.85 W/m²K) made of PVC is applied for all window systems, in order to exclude the effects driven by factors other than the glass and identify the characteristics depending on the performance of the glass itself.

Some detailed information on each window system is summarized in Tables 1. and 2.

### Table 1. Window System for Mock-up Test (Case)

| Layer of Window System | U-value (W/m²K) |
|------------------------|-----------------|
| 22 mm DG Window 5CL-12A-5CL | 2.71 |
| 27.25 mm VIG Window 5CL-12A-5CL-0.25V-5LE | 0.56 |

### Table 2. Size of Glass (unit: mm)

| Width | Fixed Window (Left) | Fixed Window (Right) |
|-------|---------------------|----------------------|
| 560   | 660                 | 1,030                |
| 860   | 730                 | 1,790                |

The test chamber for the evaluation was composed of a room side chamber and outside chamber, and the test specimen was installed between two chambers (Fig.3. and Fig.4.). A dry-bulb temperature and the humidity of the room side chamber can be adjusted by a HVAC system and humidifier. An outside chamber to simulate the outside environment can be maintained with a dry-bulb temperature of -15°C–40°C and relative humidity of 20%–90% using a thermo-hygrostat.

When the inside surface temperature is below the dew point temperature of the ambient air, vapor condensation occurs on the inside surface. This phenomenon is referred to as inside surface condensation. Thus, in this study, if the inside surface temperature was less than or
equal to the dew point temperature of the ambient air, it was considered surface condensation.

The inside surface condensation depends upon the inside temperature and humidity and outside temperature, hence, an experimental evaluation for all possible conditions is almost impossible. Also, the inside and outside temperatures and humidity conditions suggested by a standard or guide for the condensation resistance test are slightly different because these conditions reflect the characteristics of local climates. However, because the inside set temperature during the winter is less changeable, compared with the outside temperature condition, predicting the inside surface condensation in accordance with an outside temperature change with respect to an inside temperature is useful for the purpose of evaluating the condensation resistance of windows. Given this point, in this study, so that condensation resistance under the other conditions can be predicted and compared, the temperature ratio value (τ) was selected as the performance index.

As aforementioned, a TRV (τ) can be calculated by a single measurement of the lowest inside surface temperature under specific inside and outside temperature conditions, and enables a determination of the occurrence in condensation with respect to various conditions of inside humidity and outside temperature at a given inside temperature; thus, in this study, the room side chamber was maintained at 20°C and the outside chamber was maintained at -11°C, with a control deviation of ± 1°C, considering the inside and outside design conditions for Seoul, South Korea. After the set conditions for each chamber were maintained for one day, the surface temperatures were measured during the following day. Using these measured values, there was an analysis of the lowest inside surface temperatures for each location.

4. Condensation Characteristics and Surface Temperature Distribution for Each Window System

4.1 Lowest Surface Temperature and Condensation Characteristics for Each Window System

(1) Lowest Surface Temperature

The lowest inside surface temperatures of the DG window and the VIG window are shown in Table 3. The lowest inside surface temperature of each part of a VIG window is as follows: 13.5°C (left bottom, ⑦) for a frame, 11.9°C (bottom edge, ◐) for a top left casement window glass, 12.5°C (left bottom edge, e) for a left bottom fixed window glass, and 13.5°C (left bottom edge, E) for a right fixed window glass. Also, the lowest inside surface temperature of each part of a DG window is as follows: 12.6°C (bottom, ⑦⑧) for a frame, 6.7°C (left bottom edge, ◐) for a top left casement window glass, 7.2°C (bottom edge, e) for a left bottom fixed window glass, and 7.8°C (left bottom edge, E) for a right fixed window glass.

For every part of a window, the lowest surface temperature of a VIG window was higher than a DG window, and the deviation between the lowest surface temperatures of a VIG window and a DG window was 0.9 K for a frame, 5.2 K for a top left casement
window glass, 5.3 K for a bottom left fixed window glass, and 5.7 K for a right fixed window glass.

Also, for the identical spot, the surface temperature of a VIG window was found to be approximately 4-6 K higher than that of a DG window. As a result, compared with a DG window, the surface temperature of a VIG window was higher; thus demonstrating its superior thermal performance and condensation resistance.

(2) Temperature Ratio Value (τ)

By substituting the lowest surface temperature of each part of a window (see Table 3.) into Equation 1, a TRV (τ) was calculated for each part of the window. The calculation outcomes are summarized in Table 3.

The lowest TRV of each window type was found at the bottom edge of the left top casement window in which the surface temperature was the lowest, and the lowest TRV of a VIG window was calculated at 0.74, whereas the lowest TRV of a DG window was 0.57.

(3) Condensation Characteristics of Each Window System

For the analysis of the condensation occurrence conditions for each window type, the calculated TRV for each window system was utilized to calculate the outside temperature at which the surface condensation started to occur for each window system at an inside temperature of 20°C and a relative humidity of 50%, based on Equation 2 and Fig.6. As a result, for the VIG window, the inside surface condensation started to occur when the outside temperature was -21.2°C, whereas it occurred at -4.9°C for the DG window.

The occurrence hours of condensation for each window system were analyzed, based on the outside air temperature for the four months during the winter (November, December, January, and February) using the typical weather data for Seoul, South Korea (KSES, 2010). During the experimental period, the outside temperature was -21.2°C or below for zero hours, while it was -4.9°C or below for 471 hours.

Thus, under the conditions of an indoor air temperature of 20°C and a relative humidity of 50%, a VIG window is not likely to have surface condensation during the winter; whereas a regular DG window is likely to have an inside surface condensation for 471 hours, thereby accounting for 16.4% of the total time during the four winter months (2,880 hours).

In general, the indoor relative humidity during the winter is in the range of 50% or less. Given the analysis results in this study, under the winter climate conditions in Seoul, South Korea it is expected that almost no inside surface condensation will occur on a VIG window.

However, as heating and cooling energy savings have recently received great attention, the airtightness of buildings has been improved, and in particular, because of the reduction of the ventilation rate during the winter, there are some instances of increased indoor relative humidity (Kim et al., 2004; Yoshino and Lou, 2002). The outside temperature at which inside condensation started to occur for each window system, at an indoor air temperature of 20°C and a relative humidity of 60%, was -10.8°C for a VIG window and 1.4°C for a DG window. Based on the typical weather data for Seoul, the surface condensation occurrence hours were estimated in relation to outside temperature. The results are as follows. Of the 2,880 hours in the four winter months, the outside air temperature was -10.8°C or below—the temperature at which surface condensation on a VIG window is likely to occur—for 53 hours, or 1.8% of the time. However, the outside air temperature was 1.4°C or below—the temperature at which surface condensation on a DG window is likely to occur—for 1,579 hours, or 54.8% of the time.

4.2 Analysis of Surface Temperature Distribution

(1) Surface Temperature Distribution depending on Location

The measurements of the lowest surface temperature, for each part of a window with the same frame (Table 3.), showed that the surface temperature for the bottom was lower than the top for both a frame and glass. Regardless of the glass type used and the installed location, the surface temperature for the top and bottom in each component showed a similar pattern, and the surface temperature of the top was higher than that of the bottom because of the air temperature differences between the top and the bottom. For both window types, glass, rather than frame, showed a relatively lower surface temperature, and this seemed to have been caused by the relatively superior thermal performance of the frame, compared with glass.

(2) Surface Temperature Distribution Characteristics depending on the Type of Windows

The surface temperature distribution (Table 4., Fig.7.), at the edge of the glass of the top left casement

![Fig.6. Temperature Ratio Value (τ)](image)

![Fig.7. Surface Temperature Characteristics in accordance with the Type of Glass and the Structure of a Window](image)
window and bottom left fixed window (i.e., I, II measurement points, Fig.5.), showed that the surface temperature at the bottom edge is lower than that at the top edge for each window, which seemed to be caused by the vertical difference in the air temperature between the top and the bottom. In this regard, the surface temperature at the top edge of a fixed window should be lower than that at the bottom edge of a casement window (Fig.7., dotted arrow). However, the surface temperature at the top (or bottom) edge of a fixed window was higher than that at the top (or bottom) edge of a top casement window.

This phenomenon is considered to have been caused by the structural differences between a fixed window and casement window. In short, this means that an openable casement window is thermally vulnerable, compared with a fixed window. Therefore, under the same conditions, a casement window is more likely to be exposed to the risk of surface condensation than a fixed window.

### 4.3 Measures to Improve Surface Temperature Distribution

The surface temperatures for the frame, edge of glass, and center of glass were compared and analyzed (Table 4., Fig.8.). The measurement points of the analysis, for both a top left casement window and for a fixed window, were the identical locations, mutatis mutandis: the top frame (①), top left edge of a glass (②), and center of a glass (③) and a left frame (④), top left edge of a glass (a), and the center of a glass (c) (III, IV measurement points, Fig.5.).

For a DG window, the surface temperature was the highest for the frame with a relatively superior thermal performance, and the surface temperature for the edge of a glass and frame showed differences of 3.5–3.7 K. However, the center of a glass showed a 0.6–1.3 K higher surface temperature than the edge of a window because of its window structure. Thus, more measures are necessary to improve the glass insulation performance under which the surface temperature of glass can be maintained at a frame level (single-point dashed line on the right graph, Fig.8.). Moreover, further measures are required to reduce heat loss at the glass-frame connection point, in order to improve the insulation performance and condensation resistance.

For a VIG window, because of the utilization of a vacuum insulated glass with excellent thermal performance, the surface temperature of the center of a glass was the highest or at a similar level with the frame. The edge of glass showed the lowest surface temperature. The surface temperatures of the edge of a glass and frame showed differences of 0.9 K–1.5 K, specifically, 43% for a casement window and 24% for a fixed window, compared with the DG window. All these results showed that a VIG with excellent thermal performance could maintain a relatively high inside glass surface temperature under the same conditions, thus reducing the differences between surface temperature for a frame and the edge of a glass. However, the differences between a surface temperature for a frame and an edge of glass added to the thermal performance of each casement window and fixed window; and thus, concerning casement windows, there was a reduction in the excellent thermal performance effects of the VIG.

For a VIG window, the center of a glass showed a 1.4 K–4.3 K higher surface temperature than the edge of a glass because the edge of a glass is thermally vulnerable. Hence, measures are needed to reduce heat loss at the glass-frame connection point, in order to improve the thermal performance and condensation resistance of a window system.

The frame surface temperature for a VIG window, which utilized an identical frame, is 1.7 K and 1.9 K higher than a DG window, as summarized in Table 4. A comparison of each point for a frame (Table 3.) shows that the surface temperatures of a VIG window are 0.2 K–1.9 K higher than those of a DG window.

These data seem to suggest that the thermal performance improvement effects of glass have an effect on the surface temperature of a frame. Furthermore, the surface temperature of the center

### Table 3. Lowest Surface Temperature (Ts, °C) and Temperature Ratio Value (τ, -)

| Frame | Casement Window | Fixed Window (Left) | Fixed Window (Right) |
|-------|-----------------|---------------------|---------------------|
| VIG Window | Ts | 14.5 | 15.2 | 13.5 |
| Window | τ | 0.82 | 0.86 | 0.79 |
| DG Window | Ts | 12.8 | 15.1 | 12.5 |
| Window | τ | 0.77 | 0.86 | 0.76 |

### Table 4. Surface Temperature for the Main Parts (unit: °C)

| Vacuum Insulated Glass Window (VIG Window) | Double Glazed Window (DG Window) |
|-------------------------------------------|----------------------------------|
| Casement Window | Frame | Edge of Glass | Center of Glass | Frame | Edge of Glass | Center of Glass |
| Fixed Window | 15.0 | 14.1 | 18.4 | 13.1 | 9.4 | 10.7 |

For a DG window, the surface temperature was the highest for the frame with a relatively superior thermal performance, and the surface temperature for the edge of a glass and frame showed differences of 0.9 K–1.5 K, specifically, 43% for a casement window and 24% for a fixed window, compared with the DG window.
of a glass was higher than the surface temperature of a frame. This shows that to improve the thermal performance and condensation resistance of a high insulation window system, like a VIG window, the following important measures are required: 1) reduction of heat loss at a glass-frame connection point; and 2) the application of a frame with a thermal performance equal to or higher than a high insulation glass to improve the surface temperature distribution.

5. Conclusion

Through a mock-up test, the surface temperature and condensation characteristics were analyzed for a vacuum insulated glass (VIG) window, manufactured through an in-vacuum method, and compared with a general double-glazed (DG) window. The results of this study are summarized as below.

1) The inside surface temperature for each part of a VIG window was approximately 4 K–6 K higher than a DG window. Furthermore, temperature ratio value (τ) for the VIG window was higher than for the DG window. In short, this means that the VIG window has a superior thermal performance to the general DG window.

2) Under the conditions of an indoor air temperature of 20°C and a relative humidity of 50%, the inside surface condensation started to occur at an outside air temperature of -21.2°C for a VIG window and -4.9°C for a DG window. The analysis of the outside air temperature during the winter, based on the typical weather data for Seoul, showed that a VIG window was not likely to have surface condensation, whereas the DG window was likely to have inside surface condensation for 471 hours, thereby representing 16.4% of the winter experimental period.

3) For a DG window, the surface temperature of a frame was higher than a center and an edge of glass, and the surface temperature differences between an edge of glass with the lowest surface temperature and a frame was 3.5 K–3.7 K. To enhance the surface temperature distribution for a DG window, it will be necessary to enhance the thermal performance of glass so that the surface temperature of glass is maintained at the level of the frame; furthermore measures will be needed to reduce the heat loss at a glass-frame connection point.

4) For a VIG window, because of the excellent thermal performance of an applied vacuum insulated glass, the surface temperature of the center of a glass was similar to or higher than that of a frame, but it was still 0.9 K–1.5 K lower than that of the edge of a glass.

5) When the frames were identical, the frame surface temperature of a VIG window was 0.2 K–1.9 K higher than that of a DG window because the thermal performance improvement effects of the glass also seemed to have an effect on the surface temperature of the frame.

6) For a VIG window, in which the thermal performance of glass is relatively superior to that of the frame, the following important measures are required: 1) the reduction of heat loss at a glass-frame connection point; 2) the application of a frame with a thermal performance identical to or even higher than a high insulation glass to improve the surface temperature distribution.

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