1 *Article*

2 Development of Window-Mounted Air Cap Roller
3 Module

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12 **Abstract:** While previous research has shown the use of attachable air-caps on windows to
13 efficiently reduce a building's energy consumption, the air-caps considered had to be attached to
14 the entire window's surface, thus limiting the occupants' view and creating the inconvenience of
15 needing to detach and attach the air-caps. In this study, a window-mounted air-cap roller module
16 using Velcro tape that may be easily attached, detached, and rolled up or down was developed and
17 performance tested in a full-scale test bed. It was found that as the area of the air-caps attached on
18 a window increased, the required indoor lighting energy increased. However, the window
19 insulation improved, thus reducing the cooling and heating energy needed. Attaching the air-caps
20 to the entire window surface effectively reduced the building's energy consumption, but views
21 through the window may be disturbed. Thus, the developed window-mounted air-caps enable an
22 occupant to reduce the building energy consumption and maintain their view according to their
23 need. The findings of this study may contribute to a reduction in building energy consumption
24 without sacrificing a pleasant indoor environment. Further studies may be needed to verify their
25 efficacy under varying indoor and outdoor conditions.

26 **Keywords:** Air cap, Roller module, Energy saving, Performance evaluation, Building envelope
27

28 **1. Introduction**

29   The "2015 Renewable Energy Data Book," published by the United States Department of Energy,
30 reported that the energy consumption by buildings accounted for 39.8% of the overall energy
31 consumption in the United States [1]. It also predicted that the energy consumption of the buildings
32 would continue to increase. The energy usage of buildings for space heating, lighting, and cooling is
33 as high as 20.8%, 11.3%, and 10.0% of the total energy usage in the United States, respectively [2].
34 Therefore, there is an increased requirement to develop technologies and methods to reduce the
35 energy consumed by buildings. Further, high energy consumption is related to the poor insulation of
36 building skins, especially that of windows. Various studies have been conducted to investigate
37 potential approaches for improving the thermal performance of windows, including the use of
38 double skins [3–12], phase change materials (PCM) [13–19], window blinds [20–29], awnings [30–32],
39 and light shelves [33–38]. Although several of these apparatuses may be efficiently used to reduce
40 the energy consumption of the buildings, they often have high installation costs or are difficult to be
41 applied to the existing buildings.
42   Air caps, originally developed by the Sealed Air Corporation [39] as a packaging material,
43 comprise a regular pattern of air pockets that are sealed between two sheets of polyethylene film and
44 have been depicted to improve the window insulation. In previous studies, air caps were attached to
45 the entire window surface [40–42], which may have efficiently improved the insulation performance
46 of the window; however, this may disturb the view through the window and increase the amount of

47 energy required to ensure indoor lighting. Additionally, water or double-sided adhesive tape was
48 used to adhere the air caps [40, 41], which caused problems while attaching and detaching the air-
49 caps.
50   In this study, a window-mounted air cap roller module was developed for easy attachment,
51 detachment, and adjustment of the air caps. A full-scale test bed was used to verify the effectiveness
52 of the module in reducing the energy consumption that is required for heating, lighting, and cooling
53 a building.

54 *1.1. Previous Research on Air Caps and their Specifications*

55   According to the information provided by the manufacturer [39], air cap pockets are generally
56 circular and their dimensions vary depending on the thickness of the air-filled layer, as shown in
57 Table 1. In this study, Type 2 air caps with 10-mm diameter circular air-filled pockets were used. This
58 choice was based on a previous study, in which the thermal performance of a window was improved
59 using air caps [42].

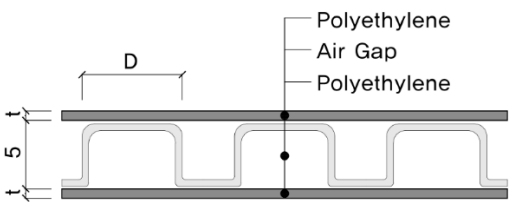60 **Table 1.** Air cap specifications provided by the manufacturer

Type	D (Diameter of Air Layer)	t (Thickness of Coating Layer)	Air Cap Section
1	10 mm	0.2 mm	
2		0.4 mm	
3	20 mm		
4	25 mm	0.6 mm	
5	30 mm		

61
62   Table 2 presents a summary of previous work improving building insulation by implementing
63 air caps. In previous studies, researchers suggested attaching air caps directly onto the glass surfaces
64 or frames of windows to achieve an air-tight fit and improve insulation performance. However,
65 attaching air caps directly onto a window may impair viewing through the window, which is its
66 original function. Moreover, attaching air caps onto a window may decrease the amount of natural
67 light entering the building, thereby reducing the indoor illumination and increasing the energy
68 demand for lighting.

69 **Table 2.** Previous studies on air caps for the improvement of window insulation performance

Title of study (year)	Materials for attachment of air caps	Parts to which air caps are attached	Area of window to which air caps are attached	Consideration of views through windows depending on air cap coverage
A Comparative Evaluation on the Thermal Insulation Performance of Windows according to the Temporary Improvement Method (2015) [40]	Water or double-sided adhesive tape	Glass surface or window frame	Entire surface	Not considered
Thermal Performance Evaluation of the Window Systems with Air Bubble Sheets (2015) [41]	Water	Glass surface of window	Entire surface	Not considered
Development of Detachable Air Cap Module for Improving the Performance of Windows (2017) [42]	Linear magnet and insulation tape	Window frame	Entire surface	Not considered

70   *1.2 Appropriate Indoor Temperature and Illumination Standards for Performance Evaluation*

71   Indoor temperature and illumination are factors that determine the pleasantness of an indoor
72   space. Maintaining them at a constant level contributes to a reduction in total building energy
73   consumption by preventing unnecessary energy consumption for cooling, heating, and lighting [43].
74   Therefore, setting appropriate standards for indoor temperature and illumination is important in
75   controlling cooling and heating devices and lighting. A summary of the appropriate indoor
76   temperature and illumination standards for various countries is presented in Tables 3 and 4. Based
77   on these standards, the performance evaluation in this study was conducted for maintaining the
78   summer and winter indoor temperature standards of 26°C and 20°C, respectively. The appropriate
79   indoor illumination standard was determined as 500 lx [32]. The reasons for selecting this indoor
80   illumination standard for the performance evaluation in this study were the following. Upon
81   examining the illumination standards of the United States, Japan, and Korea, the values of 500 and
82   600 lx were found to be used interchangeably as the illumination for a "normal" task grade. In the
83   cases of Japan and South Korea, 600 lx is designated as the maximum allowed illumination. In light
84   of this, the 600-lx value was excluded as an appropriate indoor illumination standard. Therefore, this
85   study set 500 lx as the appropriate indoor illumination standard and proceeded to carry out the
86   performance evaluation under this condition.

87   **Table 3.** Appropriate indoor temperature standard

Standard	Summer (°C)	Winter (°C)
ANSI/ASHRAE Standard 55-2013 (USA) [44]	23.0–26.0	20.0–23.5
ISO Standard (Europe) [45]	23.0–26.0	20.0–24.0

88   **Table 4.** Appropriate indoor illumination standard

| Reference Standards	Task Grade	Minimum Allowed Illumination (lx)	Standard Allowed Illumination (lx)	Maximum Allowed Illumination (lx)
IES (USA) [46]	Normal	500	750	1000
	Simple	200	300	500
JIS Z 9110 (Japan) [47]	Normal	300	500	600
	Simple	150	200	300
KS A 3011 (Republic of Korea) [48]	Normal	300	400	600
	Simple	150	200	300

89   **2. Proposal and Performance Evaluation Methods**

90   *2.1 Proposal of Window-Mounted Air Cap Roller Module*

91   The proposed window-mounted air cap roller module shown in Figs. 1, 2, and 3 allows a user
92   to roll the air cap sheets up or down to vary the window area to which the air caps are attached in
93   accordance with the desired view and illumination through the window. However, decreasing this
94   area may reduce the insulation performance of the windows, resulting in an increase in the building's
95   energy consumption. To overcome this limitation, the window-mounted air cap roller module was
96   attached to the window frame. This was based on the findings of a previous report, which indicated
97   that the insulation performance of a window was improved more when the air caps were attached to
98   the window frame than when they were attached to the glass surface of the window [40]. Velcro™
99   tape and dual-sided insulation tape were used to attach the air caps to the window frame to improve
100   the insulation and allow easy attachment and detachment of the air cap sheet. An aluminum
101   insulating rod, prepared by insulating treatment, was attached to the lower part of the window-
102   mounted air cap roller module to allow an indoor occupant to easily adjust the air cap sheet.

103   Additionally, an insulation bar was inserted between the air cap sheet and the glass surface of the
104   window to resolve the gap caused by attachment of the air cap to the window frame. The aluminum
105   insulation bar was prepared by inserting an extruded polystyrene insulation board into it for
106   insulation and air-tightness. Springs were placed at both ends of the insulation bar for solid and
107   convenient attachment to the inside of the window frame. A test bed of the proposed window-
108   mounted air cap roller module was installed for the performance evaluation (shown in Fig. 4).

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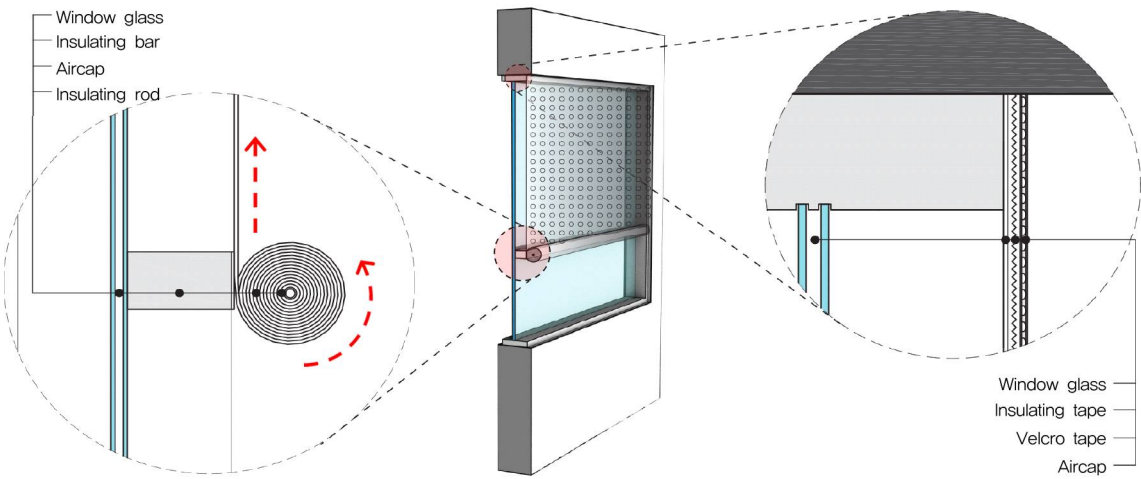
110   **Figure 1.** Control of the coverage area by the window-mounted air cap roller module

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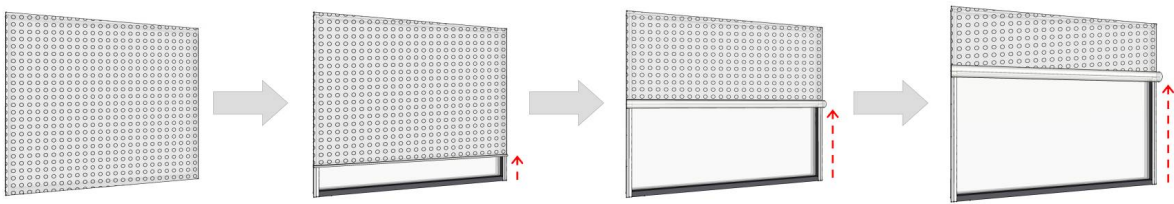
112   **Figure 2.** Control of the coverage area by the window-mounted air cap roller module (air cap sheet
113   rolling)

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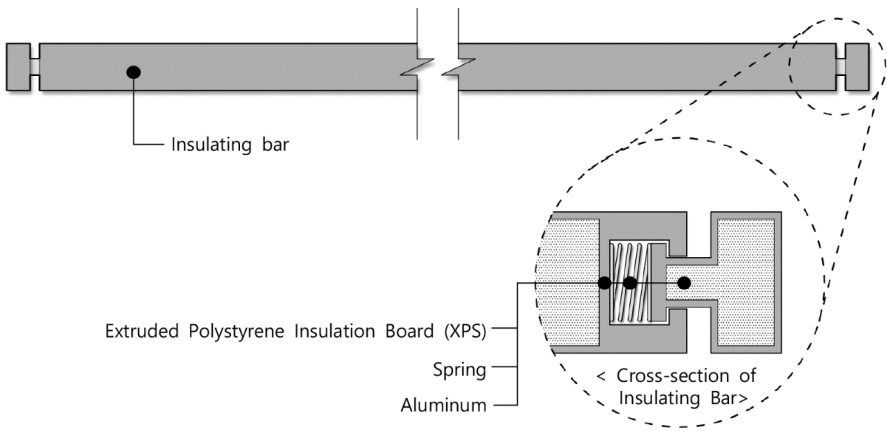
115   **Figure 3.** Configuration and function of the insulating bar included in the window-mounted air cap
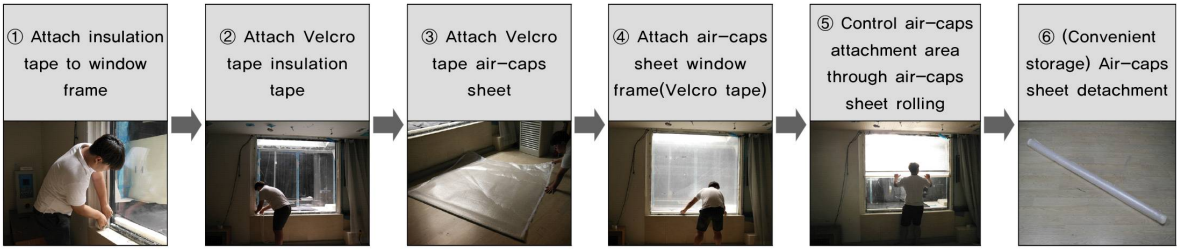116   roller module

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Figure 4. Process of installing the window-mounted air cap roller module

2.2 Environment for Performance Evaluation

The developed full-scale test bed for performance evaluation of the window-mounted air cap roller module is detailed in Table 5 and illustrated in Fig. 5. The test bed was 4.9 m wide, 2.5 m high, and 6.6 m long. The window to which the air caps were attached was 2.2 m wide, 1.8 m high, and included transparent double glazing. To form an external environment for the performance evaluation, an artificial climate chamber was installed outside the window to control the temperature. The external temperatures for the performance evaluation were determined to be –11.3°C and 36.5°C for winter and summer, respectively [49]. The artificial climate chamber included an artificial solar radiation apparatus to control the light intensity, height, and angle of the artificial light source to form various external environmental conditions. Because the artificial solar light radiation apparatus employed an artificial light source, the environmental conditions created for the performance evaluation were different from the actual conditions. However, the artificial light source satisfied the Grade A measurement homogeneity standards, according to the ASTM E927-85 international standard. This ensured that uniform external environmental conditions were maintained between the performance evaluation cases. Due to the characteristics of the artificial solar light radiation apparatus used in this study, the performance evaluation was performed only with the windows in question facing south.

Temperature and illumination sensors were installed as shown in Fig. 6 to collect indoor environmental information. A temperature sensor was installed at the center of the indoor space, whereas four illumination sensors were installed at positions 2.2 and 4.4 m away from the window at a height of 750 mm, in accordance with their optimal measuring distance [50].

Table 5 . Overview of test bed

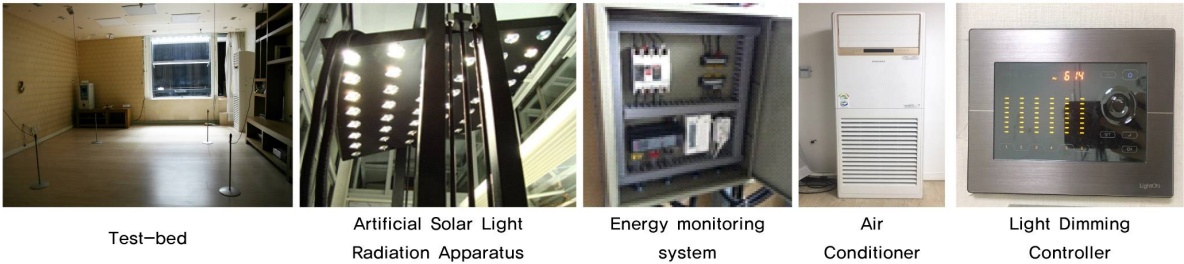|	
Room size, material	· Size: 4.9 m (W) × 6.6 m (D), 2.5 m (ceiling height) · Reflectability: Ceiling (86%), wall (46%), floor (25%) · Material: Insulation panel (thickness: 100 mm)
Window size, material	· Size: 1.9 m (W) × 1.7 m (H) · Type: Double glazed 24 mm (6CL + 12A + 6CL) · Thermal transmittance: 2.83 W/m²K (summer), 2.69 W/m²K (winter) · Transmissivity: 80%
Artificial solar light radiation apparatus	· Precision of solar light radiation: Grade A (according to ASTM E927-85) · Range of illumination: 0–80,000 lx · Directions: South aspect
Temperature sensor	· Sensing element: silicon photo sensor, with filter · Detection range: 0–200,000 lx · Precision: ±3%
Illuminance sensor	· Sensing element: NTC 10 KΩ; AN type · Detection range: –40℃ to +90°C · Precision: ±0.3℃
Energy monitoring system	· Model: SPM - 141 · Measurement capacity: Single phase (220 V, 1–50 A) · Measurement items: Power/voltage/current, real-time, and accumulated amount · Error rate: within 2.0%

| Test-bed | Artificial Solar Light Radiation Apparatus | Energy monitoring system | Air Conditioner | Light Dimming Controller |

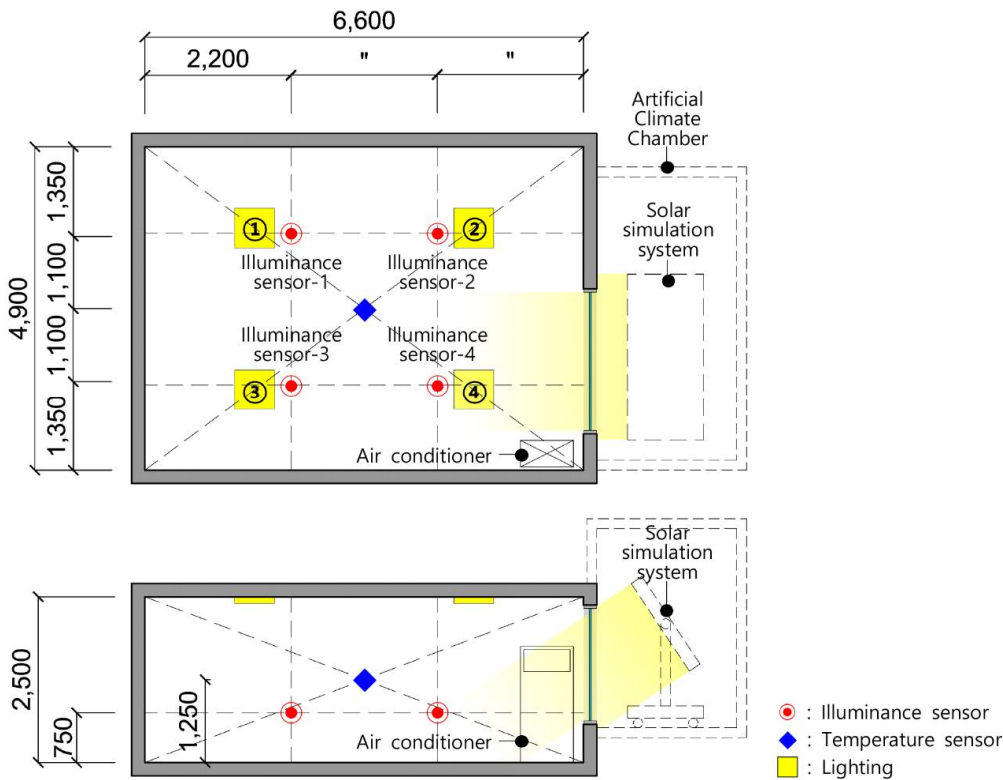**Figure 5.** Overview of test bed and measurement apparatus

Figure 6. Floor plan and sectional view of test bed

As shown in Table 6, to undertake the performance evaluation in this study, air-conditioning and lighting appliances were installed in the test bed, and automated control of the air conditioner and lighting device was also established. The air conditioner employed in this study allowed home network-based control, and the rated power for cooling and heating was 11,000 and 13,200 W, respectively. On/off control of the air conditioner to maintain the appropriate indoor temperature was performed automatically in coordination with the indoor temperature sensor. In the off mode, the air conditioner operated at minimum power without cooling or heating the indoor space but was never entirely turned off. For example, cooling of the indoor space was performed in summer when the indoor temperature was higher than 26°C; however, when the indoor temperature was below 26°C, the air conditioner operated at minimum power with only the fan running and did not perform cooling duty. Heating of the indoor space was performed in winter when the indoor temperature was lower than 20°C; however, when the indoor temperature was below 20°C, heating was not performed, and the air conditioner continued to operate at minimum power. An LED lighting device allowed control in eight levels of illumination. The position of the lighting device was determined based on a four-point method recommended by the Illuminating Engineering Society [46]. Illumination sensors 1, 2, 3, and 4 were connected to lights 1, 2, 3, and 4, respectively, to control the

163   indoor illumination values. When the measured illumination value was below 500 lx, the lights were
164   automatically brightened, beginning with the illumination sensor that showed the lowest
165   illumination value, until an illumination of 500 lx was reached. For example, when an indoor
166   illumination value of 400 lx was measured by illumination sensor 1, the light connected to that sensor
167   was brightened from level 1 up to level 8, until the value reached 500 lx or higher. If the minimum
168   indoor illumination value did not reach 500 lx even after the brightness control of light No. 1 to level
169   8, the brightness level of light No. 3, which was the light nearest to the illumination sensor, showed
170   the lowest illumination value, was sequentially elevated from level 1 to level 8 until the minimum
171   indoor illumination value measured by the illumination sensors exceeded 500 lx. This brightness
172   control was repeated until the minimum indoor illumination value exceeded 500 lx.

173   **Table 6.** Specifications of the lighting devices and air conditioner

Lighting	· Type: 8-level dimming (LED type) · Electricity consumption according to the level of dimming lighting control: lv 1 (12 W), lv 2 (18 W), lv 3 (22 W), lv 4 (28 W), lv 5 (34 W), lv 6 (39 W), lv 7 (43 W), lv 8 (51W) · heating temperature: 35℃
Air conditioner	· Model: AP-SM302 (EHP) · Heating/cooling capacity: 13,200 w / 11,000 w · Heating/cooling energy consumption: 3.90 kw / 3.90 kw · COP: heating: 3.38 / cooling: 2.82

174   *2.3 Method of Performance Evaluation*

175   In this section, the performance evaluation method for the proposed window-mounted air cap
176   roller is detailed. As shown in Table 7, the evaluation was conducted for six cases: Case 1) air caps
177   attached to the entire window surface; Case 2) air caps attached from a height of 1,200 mm,
178   corresponding to eye level at a sitting position, to the top of the window; Case 3) air caps attached
179   from a height of 1,500 mm, corresponding to eye level at a standing position, to the top of the window;
180   Case 4) air caps attached from a height of 1,800 mm from the floor to the top of the window; Case 5)
181   air caps attached from a height of 2,100 mm from the floor to the top of the window; and Case 6) no
182   air caps attached. The settings for Cases 4 and 5 were established by adjusting the settings of Cases 2
183   and 3, which considered the eye level of building residents. In other words, the heights of the air caps
184   in Cases 2, 3, 4, and 5 were adjusted in 300-mm increments to make it possible to undertake
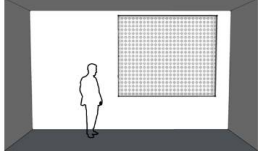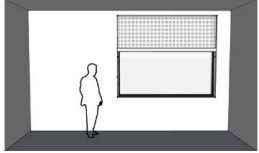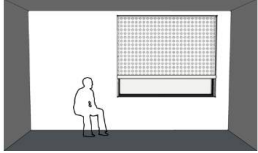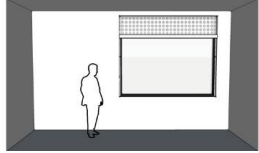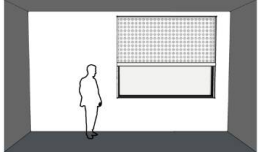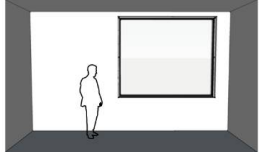185   performance evaluations according to the area of air cap coverage.

186   Because the lighting devices and air conditioner were automatically switched on and off to
187   maintain the appropriate lighting and temperature levels, the power consumed by these devices was
188   used as a performance indicator for each case. The thermal properties of the air cap sheets were
189   dependent on the position of the internal air layers, thus limiting the calculation of thermal
190   conductivity, heat transmission coefficient, and thermal resistance.

191   Furthermore, the power consumed by the lighting devices was calculated by setting the
192   minimum illumination measured by the indoor illumination sensors to 500 lx. In addition, to evaluate
193   the reduction of the energy consumption for cooling and heating in each case, the temperature sensor
194   located at the center of the indoor space was connected to the air conditioner, which was
195   automatically controlled to maintain the predetermined appropriate indoor temperature. In this
196   study, the power consumed by the automatically controlled air conditioner was used as a quantitative
197   performance evaluation indicator. However, the cooling and heating energy consumption was
198   measured while performing dimming control of the lights to satisfy the appropriate indoor
199   illumination standard.

200   The performance evaluation was limited to summer and winter, when air conditioners and
201   heating are most used, between 10 a.m. and 3 p.m. The selected external illumination and
202   temperature conditions for summer and winter are shown in Table 8 [49] and were simulated by
203   varying the input solar radiation and artificial lighting.

204   **Table 7.** Cases for the performance evaluation

Case	Ratio of Air Cap Coverage Area to Entire Window Area (%)	Case	Ratio of Air Cap Coverage Area to Entire Window Area (%)
(Case 1) Air caps covering the entire window surface	100	(Case 4) Air caps attached from a height of 1,800 mm to the top of the window	27.5
(Case 2) Air caps attached from a height of 1,200 mm to the top of the window	73	(Case 5) Air caps attached from a height of 2,100 mm to the top of the window	9.1
(Case 3) Air caps attached from a height of 1,500 mm to the top of the window	46	(Case 6) No air caps attached	0

205   **Table 8.** External illumination, solar radiation, and outdoor temperature conditions in each time
206   zone

Season		Time Zone		
		10:00–12:00	12:00–13:00	12:00–14:00
Summer	External illumination	70,000 lx	80,000 lx	70,000 lx
	Solar radiation	429 W/m²	503 W/m²	429 W/m²
	Altitude		76.5 m	
	External temperature		34°C	
Winter	External illumination	20,000 lx	30,000 lx	20,000 lx
	Solar radiation	283,429 W/m²	340,429 W/m²	283,429 W/m²
	Altitude		29.5°	
	External temperature		−10°C	

207   **3. Results and Discussion of Performance Evaluation**

208   In contrast to Case 6, which did not have air cap attachments, Cases 1 through 5, all of which
209   had air cap attachments, presented lower average indoor illumination. This was due to the reduced
210   amount of natural light introduced into the indoor space by the air caps attached to the windows. In
211   addition, increases in the air-cap coverage area reduced the amount of natural light being introduced
212   indoors, resulting in lower average indoor illumination. It was also possible to confirm this through
213   the indoor images of each case, as presented in Table 10. As shown in Table 9, the results indicated
214   that increases in the air cap coverage area resulted in increases in energy consumption for indoor

215 lighting purposes. For example, Cases 1 through 5 presented an increase in energy consumption
216 between 4.3% and 17.8% during the summer season and an increase between 12.3% and 52.1% during
217 the winter season compared with Case 6. To summarize the above, an increase in the air cap coverage
218 area reduced the natural light volumes, which in turn increased the energy consumption required to
219 maintain the appropriate indoor illumination levels. With regard to Cases 1 through 5, which had air
220 cap attachments, an increase in energy consumption between 5.6% and 25.7% during the summer
221 and winter seasons compared with Case 6 was needed to reach the appropriate 500-lx indoor
222 illumination level. In light of this, these cases were considered inappropriate to reduce the energy
223 consumption for lighting purposes.

224 **Table 9.** Lighting device control and power consumption for maintaining appropriate indoor
225 illumination

		Summer			
Case	**External Illuminance (lx)**	**Illumination (lx)**		**Lighting Level**	**Power Consumption (kWh)**
		Min.	**Ave.**		
1	80,000	76.0	285.1	1(8) + 3(8) + 2(3)	0.642
	70,000	66.1	188.2	1(8) + 3(8) + 2(5)	
2	80,000	78.8	311.3	1(8) + 3(8) + 2(3)	0.630
	70,000	68.4	202.2	1(8) + 3(8) + 2(4)	
3	80,000	82.2	339.9	1(8) + 3(8) + 2(2)	0.591
	70,000	70.2	224.4	1(8) + 3(8) + 2(3)	
4	80,000	84.7	483.2	1(8) + 3(8) + 2(1)	0.589
	70,000	73.1	243.7	1(8) + 3(8) + 2(3)	
5	80,000	87.5	509.2	1(8) + 3(8)	0.552
	70,000	74.9	251.9	1(8) + 3(8) + 2(3)	
6	80,000	90.4	559.2	1(8) + 3(7)	0.528
	70,000	76.1	280.2	1(8) + 3(8) + 2(3)	

		Winter			
Case	**External Illuminance (lx)**	**Illumination (lx)**		**Lighting Level**	**Power Consumption (kWh)**
		Min.	**Ave.**		
1	30,000	386.2	5130.4	1(3)	0.192
	20,000	270.3	3727.5	1(8) + 3(1)	
2	30,000	391.5	5257.1	1(3)	0.168
	20,000	274.1	3800.2	1(8)	
3	30,000	401.7	5391.8	1(2)	0.140
	20,000	289.4	4065.9	1(7)	
4	30,000	407.2	5474.5	1(1)	0.114
	20,000	284.5	4140.3	1(6)	
5	30,000	409.6	5680.5	1(1)	0.105
	20,000	293.1	4546.2	1(5)	
6	30,000	415.8	5800.1	1(1)	0.092
	20,000	292.2	4695.6	1(4)	

226   **Table 10.** Images of individual cases and sum of electrical power consumption for each case

Case	Indoor Images for each Case		Sum of Electrical Power Consumption by Lighting Devices(kWh)	Case	Indoor Images for each Case		Sum of Electrical Power Consumption by Lighting Devices(kWh)
	Summer (External Illuminance : 80,000 lx)	Winter (External Illuminance : 30,000 lx)			Summer (External Illuminance : 80,000 lx)	Winter (External Illuminance : 30,000 lx)	
1			0.834	4			0.703
2			0.798	5			0.657
3			0.731	6			0.620

227
228   The effects on the heating and cooling energy consumption of attaching the air cap roller module
229 are shown is presented in Table 11. The greatest reduction in the cooling and heating energy
230 consumption occurred when the air caps were attached to the entire window surface (Case 1).
231 However, the cooling and heating energy consumption was lower in all cases except Case 6, in which
232 no air caps were attached. When the air caps were only attached to a part of the window surface
233 (Cases 2, 3, 4, and 5), the cooling and heating energy consumption decreased by 2.0% to 21.9% for
234 summer and by 8.3% to 27.5% for winter when compared with Case 6. In the summer simulation, the
235 cooling energy consumption notably increased in Case 4, in which the air caps were attached from a
236 height of 1,800 mm above the floor to the top of the window. In the winter simulation, the heating
237 energy consumption notably increased in Case 3, in which the air caps were attached from a height
238 of 1,500 mm above the floor to the top of the window. Therefore, the proposed window-mounted air
239 cap roller module may effectively reduce the cooling and heating energy consumption even if the air
240 cap coverage area is adjusted to permit viewing through the window and allow light into the room.
241 Additionally, the module enables an occupant to choose the level of viewing possible through the
242 window and reduces the cooling and heating energy consumption, depending on the circumstances.

243   **Table 11.** Air conditioner power consumption required to maintain appropriate indoor temperature
244   for each case

Summer						
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Power consumed by air conditioner (KWH)	1.955	2.072	2.129	2.483	2.599	2.653
Reduction of energy consumption in comparison with the case without air cap attachment (Case 6)	26.3%	21.9%	19.8%	6.4%	2.0%	-
Winter						
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Power consumed by air conditioner (KWH)	2.595	2.665	3.095	3.195	3.370	3.676
Reduction of energy consumption in comparison with the case without air cap attachment (Case 6)	29.4%	27.5%	15.8%	13.1%	8.3%	-

245

246   When considering only the reduction in total energy consumption, the best method of applying
247   the window-mounted air cap roller module proposed in this paper is that of Case 1, in which air caps
248   were attached to the entire window surface; however, that case did not allow viewing through the
249   window. However, the energy consumed did decrease as the air cap coverage area was reduced, as
250   shown in Fig. 7. The energy consumption dramatically increased in Case 4 during the summer and
251   in Case 3 during the winter. Therefore, considering the energy savings and viewing performance, the
252   optimal height for the air cap module is 1,500 mm. This is the height at which occupants can still see
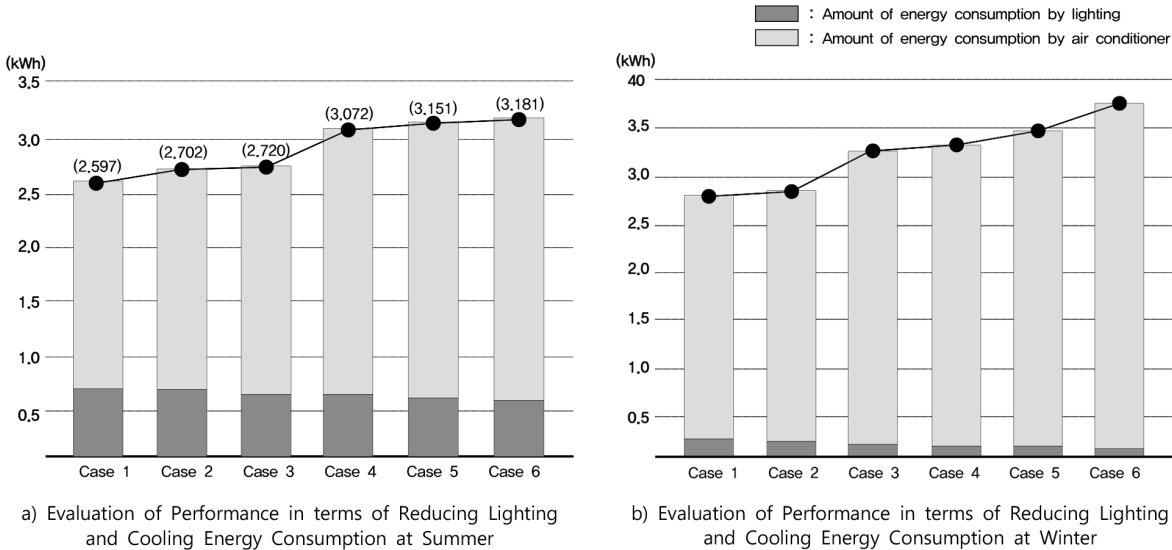253   through the windows and energy consumption is significantly decreased.

254

a) Evaluation of Performance in terms of Reducing Lighting and Cooling Energy Consumption at Summer

b) Evaluation of Performance in terms of Reducing Lighting and Cooling Energy Consumption at Winter

255   **Fig. 7.** Evaluation of performance in terms of reducing energy consumption by lighting device and
256   air conditioner for each case

4. Conclusions

258   A window-mounted air cap sheet roller module was proposed and evaluated to address the
259   impairment of viewing caused by the application of air caps on windows while still reducing building
260   energy consumption. The proposed module was first designed as an air cap attachment module that
261   allowed the air cap sheet to be rolled up and secured with Velcro™ tape. An insulation bar was used
262   to resolve the gap between the air caps and window glass surface caused by the attachment of the air
263   caps to the window frame.
264   A performance evaluation of the proposed model was then completed using a full-scale test bed.
265   Lighting energy consumption increased by 4.3% to 17.8% in summer and by 12.3% to 52.1% in winter
266   compared with the case in which no air caps were attached; therefore, the use of air cap sheets is not
267   appropriate for reducing the lighting energy consumption. Heating and cooling energy, however,
268   were significantly decreased through the use of the module. The greatest reduction in heating and
269   cooling energy usage was found when the air caps were attached to the entire window surface (Case
270   1). However, when the air caps were only attached to part of the window surface (Cases 2, 3, 4, and
271   5), the cooling and heating energy consumption decreased by 2.0% to 21.9% for the summer and by
272   8.3% to 27.5% for the winter compared with Case 6, indicating that the proposed window-mounted
273   air cap roller module was effective. Cooling energy consumption notably increased during the
274   summer in Case 4, in which the air caps were attached from a height of 1,800 mm above the floor to
275   the top of the window. Heating energy consumption notably increased during winter in Case 3, in
276   which the air caps were attached from a height of 1,500 mm above the floor to the top of the window.
277   Therefore, the air caps may be attached to the entire surface of a window to reduce the energy
278   consumption but may also be effectively attached from the top of the window to a height of 1,500
279   mm above the floor to allow viewing through the window, while still reducing the amount of energy

consumed. Therefore, the window-mounted air cap roller module may enable a building occupant to choose the level of viewing secured through windows and reduce the cooling and heating energy consumption, depending on the circumstances.

The proposed window-mounted air cap roller module allowed air caps to be conveniently attached to a window while resolving the problem of the impairment of views caused by the attachment of air caps onto the entire window surface. However, the performance evaluation in this study was carried out in an artificial environment by controlling specific variables. Further studies may be needed to overcome this limitation by considering various variables, such as air cap dimensions, heat transmission coefficient, time lag, material properties, and the effectiveness of air cap applications under different climate characteristics. In addition, although this study was conducted to improve viewing through a window when air caps were attached, the view from an indoor space depending on various external environmental conditions was not analyzed. Therefore, further studies may also be needed to analyze the views through windows from an indoor space.

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