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A Large Sky Simulator : A Reproduction of CIE Sky Condition and Daylighting Evaluation using Scale Model

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Abstract

KH University has developed a large sky simulator which is its scale suits international standard. To verify the reliability of the sky simulator, the luminance of 36 points on the inner sky surface was measured and compared with the CIE standard overcast sky model. It was found that the sky simulator can reproduce the CIE standard overcast sky condition with 1.8[%] of mean difference. To identify the differences of daylighting performance, scale model measurements were taken under a real sky and in a sky simulator. Under overcast sky conditions, two kinds of scale model experiments were conducted by using the photometric sensor Li-cor. Firstly, a 1/20 scale model of a side-lit office room 4.9[m] wide, 7.2[m] long, and 2.6[m] high was created. Five measurement points were set at 1.2[m], 2.4[m], 3.6[m], 4.8[m], and 6.0[m] from the window. The mean difference of the light factor between the sky simulator and real sky was 7.1[%]. Secondly, a 1/30 scale model of a top-lit atrium 15[m] wide, 15[m] long, and 15[m] high was created. The measurement point was set at center of the room and the well indexes of the model were set in 5 types. The mean difference of the light factor between the sky simulator and real sky was 1.7[%]. This proved that the sky simulator is fully accurate and usable for daylighting research.

Key Words : Sky Simulator, Artificial Sky, CIE Standard Overcast Sky, Luminance Distribution

1. Introduction

For daylighting performance experiment, maintaining constant sky condition is essential. However, since real sky conditions vary, it is necessary to have a specific standard to draw an objective conclusion. Because of this, CIE provides the standard skies for natural lighting designs such as the CIE Standard Overcast Sky and CIE Standard Clear Sky.

Sky Simulators are evaluation facilities that represent these standards. In scale model experiments, they enable daylighting research under consistent sky conditions by randomly controlling these conditions. Such sky simulators are developed in variable forms mainly by advanced universities and research centers, and

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advanced universities and research centers, and are used in research. This thesis inquires into these existing sky simulators by dividing them into Full Covering Sky simulators and Partial Sky simulators.

KH University has developed a hemispherical sky dome based on the existing sky simulators.

In this paper, the luminance inside the dome was measured to verify whether KH University's sky simulator represents the CIE Standard Overcast Sky.

Following the verification mentioned above, the light environment of the sky simulator was compared with that of real overcast sky conditions to evaluate the accuracy of the artificial sky under Korean sky conditions. To achieve this comparison, a comparison experiment was carried out by using a scale model in artificial sky conditions and in real sky conditions. That is, two scale models(i.e. a 1/20 scale model of a side-lit office and a 1/30 scale model of a top-lit space) were produced, and the light atmosphere in those two models was compared by measuring the interior and exterior illuminance upon the changes in depth of the room and the changes in well index.

2. The Outline of K University's Sky Simulator

2.1 Configuration

The sky simulator designed and produced by K University is of a Sky Dome form and has a scale of 6 meters in diameter and 3.7 meter in height (Hereinafter, the K University sky simulator will be referred to as KSS). The interior surface of the simulator is finished with highly diffusible white matte paint to optically distribute light uniformly when reproducing an overcast sky condition. The

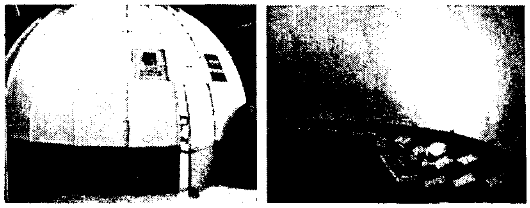


Fig. 1. Exterior and Interior view of KSS

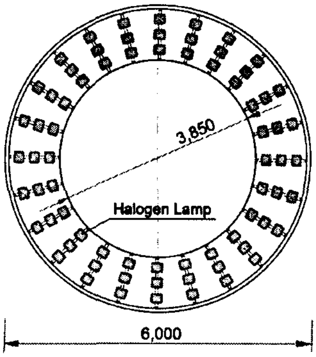


Fig. 2. Floor plan of KSS

hemispherical shell consists of 133 insulated parts while the radius of curvature of each part is milled, formed and executed by computer so that the sky simulator has a completely curved surface. In scale model experiments, data are acquired by the Li-cor illuminance measurement equipment and the HP data logger. Also, to support a daylighting model, an adjustable height table is utilized.

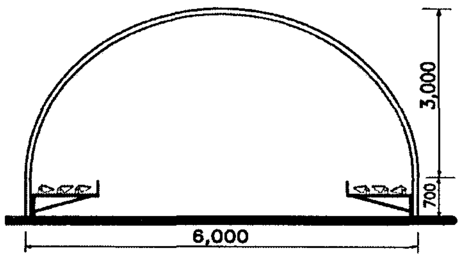
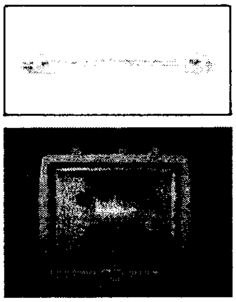


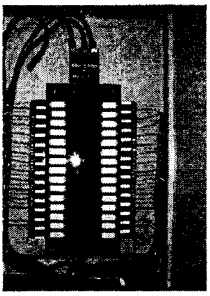
Fig. 3. Section plan of KSS

2.2 Lighting and Dimming System

A total of 72 halogen lamps in 3 rows and 24 lines are installed on the horizontal edge of the inner dome. The installed halogen lamps have are 500[W] with a 9,500[lm] luminous flux. When all lamps are activated, they represent nearly 9,740[lx] of maximum horizontal illuminance and 3,890[cd/m^2] of sky zenith luminance. The angle of each luminaire can be controlled individually so that a variety of sky conditions are reproduced. The brightness of the luminaire can also be controlled on an individual level using lamp control dimmers, which enable the representation of skies that are tailored for each purpose.

Table 1. Lamp Specifications

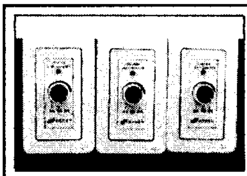
	Lamp Type	Halogen Lamp
	Electricity consumption	500[W]
	Intensity of Radiation	9,500[lm]
	Color Temperature	3,000[°K]



Number of electric circuit
Lamp: 24
Air conditioner: 2
Spare: 2

Fig. 4. Electric control panel

Table 2. Specification of Dimmer switch

	Model No.	SD-500
	Rated Voltage	220[V]
	Electricity Consumption	500[W]

The heat generated by the halogen lamps is managed by two air conditioners inside the dome and through an upper ventilation opening. The ventilation opening is connected to a round, flexible duct which vents to the outside.

3. Optical Characteristics of KSS

3.1 Reliability Test

Measurement was taken as mentioned below to verify the reliability of the sky simulator. The measurement was taken after activating all 24 lines of lamps and adjusting their brightness and angles, so that the luminous distribution of the sky simulator resembles that of the CIE Standard Overcast sky. A CS-100 luminance meter and ProMetric1400 were used in this measurement, and the measured luminance inside the sky simulator was compared with the luminance distribution of the CIE Standard Overcast value.

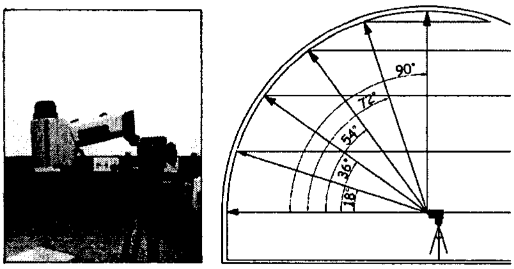


Fig. 5. CS-100 Luminance meter and measuring point

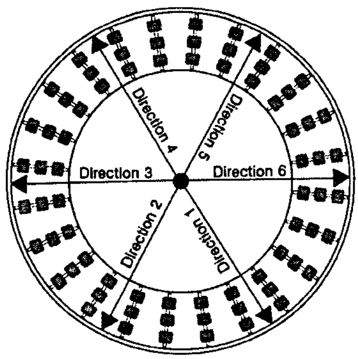


Fig. 6. Location of measuring point

The measurement using the CS-100 luminance meter selected 6 directions(Figs.6, 7) and measured the luminance of 6 angles by dividing the surface between the ceiling and the ground into fifths.

The ProMetric1400 is a digital optical measurement instrument which creates numerical values such as luminance, chromaticity and color temperature using a photographed image analysis program. Compared with traditional equipment that measure luminance and chromaticity by a single point, the ProMetric system measures 1,500,000 points simultaneously and is capable of showing the measurement values of color temperature and chromaticity both in 2D and 3D graphs. The ProMetric1400 was used to measure the interior to verify the numerical data of the luminance distribution and the visual luminance distribution inside the sky simulator. The measurement was taken by dividing the interior of the sky simulator into 3 spheres(Fig. 8).

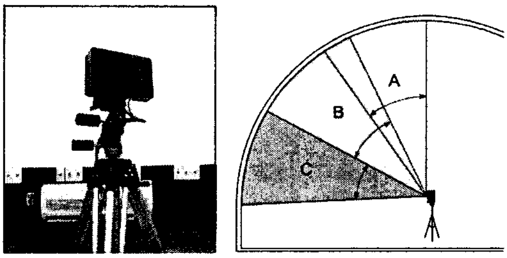


Fig. 7. ProMetric1400 and measuring range

3.2 Verification of Surface Luminance

In the luminance measurement, the zenith luminance was 3,487[cd/㎡] and the work plane horizontal illuminance was 8,720)[lx].

3.2.1 Verification of Luminance Using the CS-100 Luminance Meter

The luminance values of each location inside the KSS was measured and compared to that of the CIE Standard Overcast Sky. The mean difference was 1.81[%] with a minimum of 0.2[%] and a

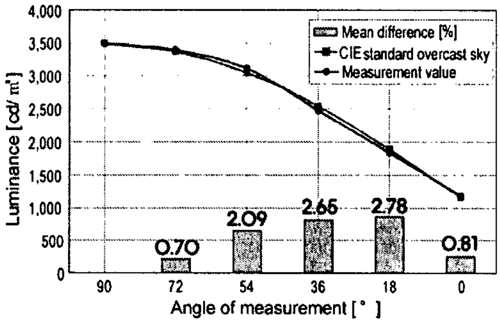


Fig. 8. Comparison of KSS with CIE model[cd/㎡]

Table 3. Comparison of KSS with CIE mode[cd/㎡]

Classification		90[°]	72[°]	54[°]	36[°]	18[°]	0[°]
CIE Standard Overcast Sky [cd/㎡]		3,487	3,373	3,043	2,529	1,881	1,162
Measuring . Location 1	Luminance [cd/㎡]	3,487	3,390	3,080	2,390	1,800	1,180
	Difference From Average [%]	0	0.50	1.22	5.50	4.31	1.55
Measuring Location 2	Luminance [cd/㎡]	3,487	3,380	3,120	2,510	1,850	1,190
	Difference from Average [%]	0	0.30	2.53	0.75	1.65	2.41
Measuring Location 3	Luminance [cd/㎡]	3,487	3,410	3,130	2,450	1,830	1,130
	Difference from Average [%]	0	1.10	2.86	3.12	2.71	2.75
Measuring Location 4	Luminance [cd/㎡]	3,487	3,430	3,130	2,460	1,820	1,160
	Difference from Average [%]	0	1.69	2.86	2.73	3.24	0.17
Measuring Location 5	Luminance [cd/㎡]	3,487	3,390	3,150	2,530	1,840	1,190
	Difference from Average [%]	0	0.50	3.52	0.04	2.18	2.41
Measuring Location 6	Luminance [cd/㎡]	3,487	3,380	3,030	2,430	1,830	1,180
	Difference from Average [%]	0	0.21	0.43	3.91	2.71	1.55

maximum of 5.5[%]. Sorted by measuring angles, the difference showed the smallest average value of 0.7[%] at 72[°] and the highest of 2.8[%] at 18[°]. The luminance ratio between the ceiling and the ground was 2.96:1, which was similar to that of the CIE Standard Overcast Sky luminance distribution.

3.2.2 Verification of Luminance Using the ProMetric1400

The measurement of luminance using the interior surface of the dome was carried out by dividing the surface between the ceiling and the level surface into three. The ProMetric1400 was used for this measurement. The data are shown in Fig. 14.

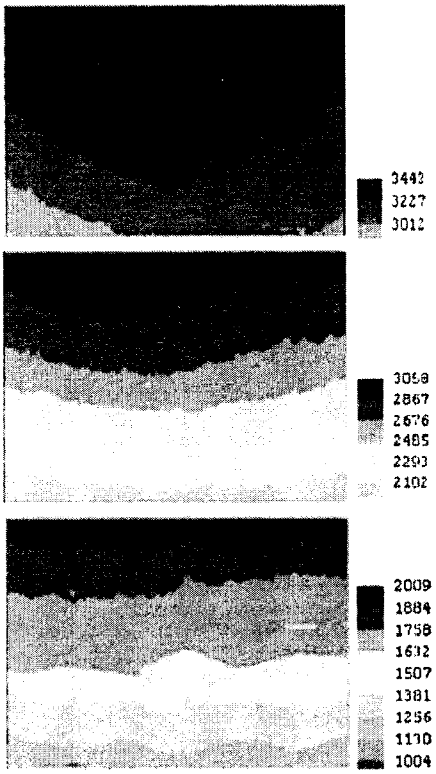


Fig. 9. Luminance distribution of ProMetric

The measured luminance rates had a distribution ranging between approximately 1,000[cd/m²] of horizontal luminance and 3,400[cd/m²] of zenith luminance, which was equivalent to the values measured with the CS-100. The change in luminance was verified as evenly distributed over the interior surface.

4. Measurement of the Daylight Illuminance Ratio between the Artificial Sky and the Natural Sky

4.1 Evaluation Model and Measurement Points

4.1.1 Scale Model of a Side-lit Office

The scale model that was built for the daylight illuminance measurement appears as a typical office space with an actual width of 4.8[m], an actual depth of 7.2[m] and an actual height of 2.6[m], complete with a 4.7[m] wide and 1.7[m] high window opening in the front. The scale of the model was chosen to be 1:20, after consideration of the size of the photometer, the internal area of the KSS and the practicability of measuring. Form board was selected as the material for the model because of its advantages in light diffusibility and manufacturing.

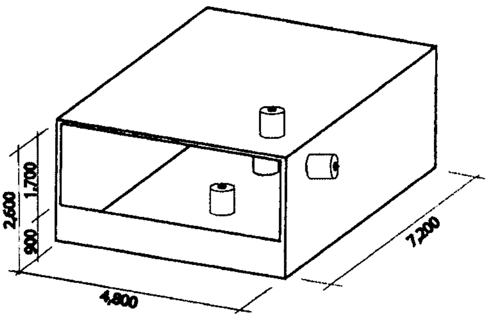


Fig. 10. Configuration of side-lit office model

The interior measurement spot is located at

0.85[m]-work plane height-perpendicular to the window. Five sensors were installed at 1.2[m] intervals from the window. Additionally, both the horizontal and the vertical plane were chosen as exterior measurement points. To verify the accuracy of the photometer, the exterior horizontal illuminance was measured by a TOPCON IM-5 illuminance meter and the value was compared with that of the Li-cor.

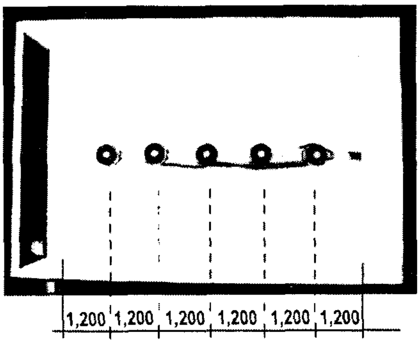


Fig. 11. View of installed photometers in Side-lit model

4.1.2 Scale Model of a Top-lit Atrium

The scale model of the top-lit atrium is square, 15×15×15[m], and is 1/30th of the actual atrium size. Paper and wood were used as materials for the uniform distribution of light inside the model. The well index was altered to 1.25, 1.0, 0.75, 0.5 and 0.25 by adjusting the height of the interior floor surface, and the illuminance under each index was measured.

One point on the center of the atrium floor and one on the exterior horizontal illuminance were chosen as the measurement points. Although the illuminance of both the exterior horizontal plane and the interior floor were measured simultaneously for the real overcast sky, a different approach was taken for the artificial sky since it showed an extreme change of illuminance upon change of location. Thus the illuminance of interior floor was taken first, and, after removal of the scale model, the illuminance of the exterior horizontal plane was measured at controlled heights using the plane.

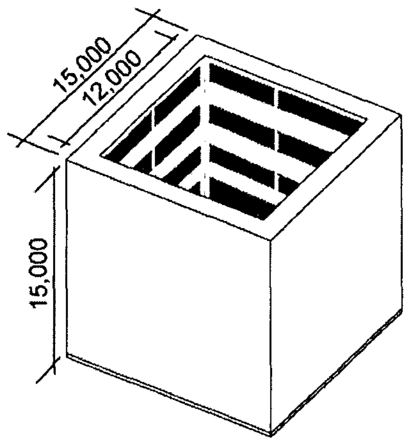


Fig. 12. Configuration of top-lit atrium model

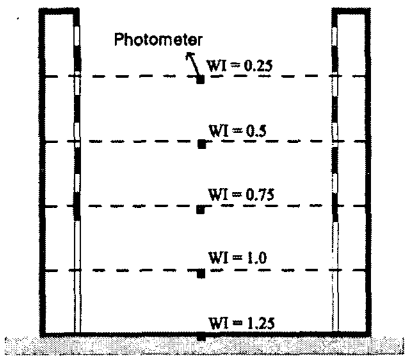


Fig. 13. Measurement points of top-lit atrium model

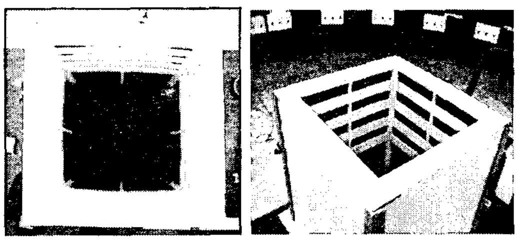


Fig. 14. View of top-lit atrium scale model

4.2 The Monitoring System

The acquisition of illuminance data inside the scale model was configured with a measuring system and a data acquisition system based on the monitoring protocol of IEA Task21. The measuring system consists of the LI-210 SA, which is an illuminance sensor by Li-cor, and a Millivolt Adaptor, which converts mA into mV.

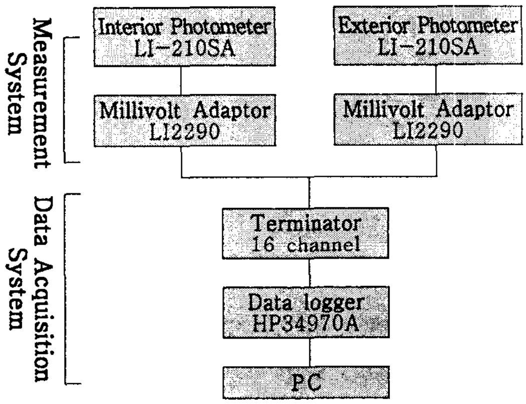


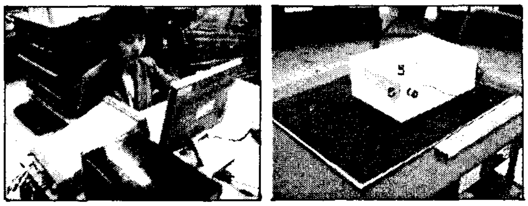
Fig. 15. Monitoring system

The data acquisition system is made up of 16 terminal channels that link Agilent sensors and data loggers, HP34970A data loggers that collect and save the values measured by the sensors, and a PC. The whole monitoring system is then controlled by the Agilent Version4.1 program.

4.3 Measurement Methods

4.3.1 Scale Model of a Side-lit Office

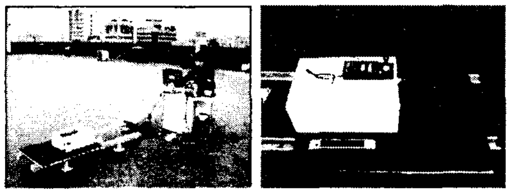
The illuminance of the sky simulator inside the 1/20 side-lit scale model and of the real overcast sky was measured and compared with each other. The illuminance inside the sky simulator was measured 3 times over 2 minutes each for 10 seconds on the 9th of November, 2005. The measuring was processed with all the lamps of the 24 lines active so that the luminance distribution inside the sky simulator resembles that of the CIE Standard Overcast sky model. The measured sky zenith luminance was 2,550[cd/m²] and the measured horizontal luminance was 851[cd/m²]. The measured illuminance was verified to have an error rate less than 0.1[%] when compared with the measurement taken by the TOPCON IM-5 illuminance meter.



(a) View of measurement system (b) View of model

Fig. 16. Measurement of illuminance of side-lit model in the sky simulator

The daylight illuminance under a real overcast sky was measured on the roof of the K University Engineering Center to minimize obstructions. Measurements were taken between twelve noon and 12:30 on the 13th of November, 2005. Cloud cover was 7.1 and the measurements were taken in four directions--north, south, east and west--considering the effects of the daylight. The time used for each measurement was 2 minutes at 10 second intervals. The mean zenith luminance was 11,479[cd/m²] and the mean horizontal luminance was 3,283[cd/m²] at the time and place of the measurement.



(a) View of measurement (b) View of model

Fig. 17. Measurement of illuminance of side-lit model under real sky

4.3.2 Scale Model of the Top-lit Space

The experiment inside the sky simulator for the top-lit scale model was carried out on the 16th of February, 2006. All 24 lines of lamps were used to produce a similar luminance distribution to that of the CIE Standard Overcast Sky. The luminance was 2,550[cd/m²] and the horizontal luminance was 851[cd/m²] inside the sky simulator when measured. The measurement was taken for 2 minutes at 10 second intervals.

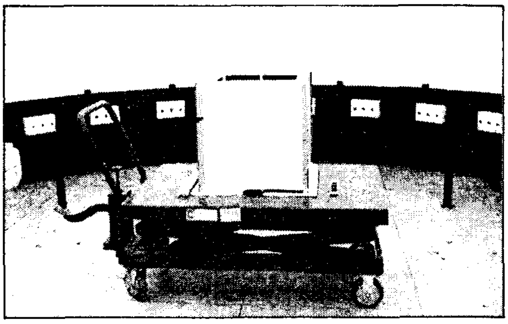


Fig. 18. Measurement of illuminance of top-lit model in sky simulator

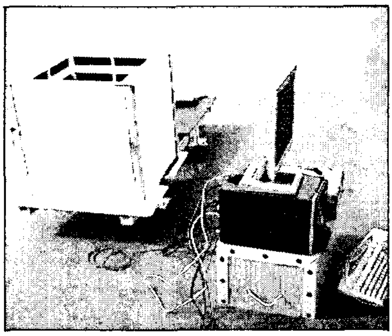


Fig. 19. Measurement of illuminance of top-lit model under real sky

Daylight illuminance under a real overcast sky was measured on the roof of the K University Engineering Center at 14:00 on the 20th of March, 2006. The sky was fully covered with a cloud cover of 10, and measurements were taken for 2 minutes at 10 second intervals for each well index. The mean zenith luminance was 6,737[cd/m²] and the mean horizontal luminance was 2,643[cd/m²] at the time of measurement.

5. Comparison of the Illuminance Ratio between the Artificial Sky and Natural Sky

5.1 Scale Model of the Side-lit Office

Due to the difference between the sky conditions of the sky simulator and the real overcast sky, the acquired illuminance was compared after having been converted into a daylight illuminance ratio (LF-light factor-= interior horizontal illuminance /exterior horizontal illuminance×100[%]), which is a relative value. The measured illuminance and LF are shown in Fig. 3. The average difference between the LF values of the artificial sky and the real sky was 7.1[%].

Table 4. Iluminance and LF of side-lit model

Classification		Exterior Illuminance	Interior Illuminance				
			1.2[m]	2.4[m]	3.6[m]	4.8[m]	6.0[m]
Artificial Sky	Illuminance[lx]	5,080	1,363	999	877	766	738
	LF[%]	·	26.8	19.7	17.2	15.1	14.5
Natural Sky	Illuminance [lx]	24,156	6,603	4,527	3,833	3,309	3,124
	LF[%]	·	27.3	18.7	15.7	13.7	13.0

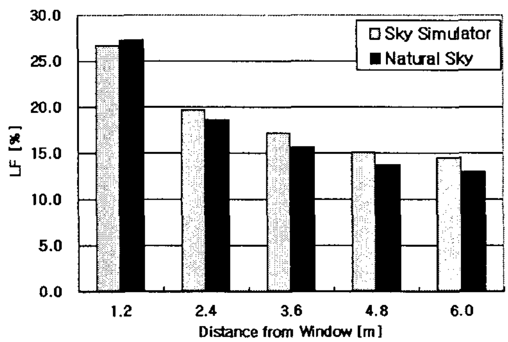


Fig. 20. Distribution of LF of the Side-lit Model

Although the daylight illuminance distribution varies depending upon the measuring points and directions, the change in LF value for each measuring point turned out to be similar. Among the four directions, the LF value in the west was closest to that of the sky simulator while the difference was the greatest in the east.

5.2 Sale Model of the Top-lit Space

Table 5. Illuminance and LF of top-lit model

Well index		1.25	1.0	0.75	0.5	0.25
Artificial Sky	Interior Illuminance [lx]	1,387	1,973	2,539	3,334	4,370
	Exterior Illuminance [lx]	4,414	4,496	4,561	4,613	4,749
	LF[%]	31.4	43.9	55.7	71.8	92.0
Natural Sky	Interior Illuminance[lx]	7372	9374	10962	13035	15094
	Exterior Illuminance [lx]	23803	21766	19133	17685	16425
	LF[%]	31.0	43.1	57.3	73.7	91.9

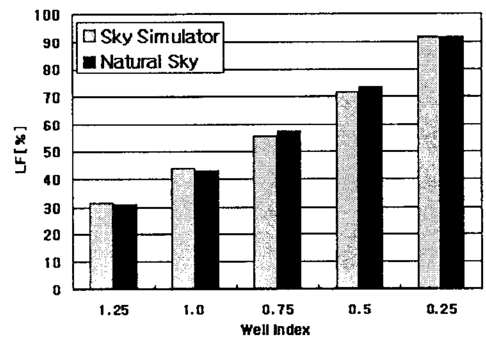


Fig. 21. Distribution of LF of top-lit model

Illuminance distribution and LF for the well index inside the sky simulator for the atrium scale model and under a real overcast sky are shown in Table 5 and Fig. 22. The sky conditions between the interior sky simulator and the real overcast sky were very different, as the exterior horizontal illuminance was 4,573[lx] for the former and 19,798[lx] for the latter. Nevertheless, the mean difference between the relative values for interior and exterior(i.e. LF) was 1.7[%] regardless of the well index.

6. Conclusion

Sky simulators are core evaluating facilities for objective daylight studies. Through a detailed process, K University designed and produced a large sky dome type sky simulator which meets international standards. To verify the reliability of this sky simulator, this study reviewed whether the sky simulator reproduces the standard sky(i.e., the CIE Standard Overcast Sky) by measuring the luminance inside the dome. Also, to evaluate the utility of the KSS, LF values of the sky simulator and the real overcast sky were compared through side-lit and top-lit scale model experiments. The results are as follows:

The mean difference of the luminance values inside the sky simulator and the CIE Standard Overcast sky was 1.8[%], which proves that the sky simulator offers a very useful sky as a daylight evaluation facility.

For the scale model of the side-lit office, an illuminance of 5 points was measure by active depth under a partial sky with 7.1 cloud cover. The mean LF difference between the artificial sky and the real sky was 7.1[%] which indicates the proximity of the artificial sky and the real sky.

For the scale model of the top-lit space, the illuminance was measured with five varied well indexes under a fully covered sky with a cloud cover of 10. The mean difference of the measured daylight illuminance ratio of the artificial sky and real sky was 1.7[%], which shows those values are very similar.

As a result of these two scale model experiments, the utility of the developed sky simulator was proven since it showed a change of daylight illuminance slopes that is very similar to that of real sky. The sky simulator that was verified by this study will offer reliable daylight performance evaluations.

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References

[1] Kim, Jeong Tai et al., 2005, Development and its Validation of Sky Simulator Facilities for Daylighting Evaluation, Journal of the Korea Institute of Ecological Architecture and Environment, Vol. 5 No. 4, pp.51-57.
[2] Song, Kyoo-Dong et al., 2002, Calibrating the Luminance Distribution and Analyzing Major Factor for Measurement Error in an Artificial Sky Dome for Daylighting Studies, Journal of the Architectural Institute of Korea, Planning & Design Section, Vol. 18 No. 12, pp.207-214.
[3] In Hye Yu, Jeong Tai KIM, Comparative Daylighting Performance of Real Sky and Sky Simulator by Scale Model Experiments, Proceedings of 5th International Conference on Sustainable Energy Technologies, 2006, pp.111-116.
[4] Boyer L.L. and Degelman L.O., "A Large Sky simulator for Daylighting Studies at a Texas University", Proc. II of Int'l Daylighting Conference, Long Beach, CA, pp.125~133, 1989.
[5] Evans, B.H. Daylight in Architecture, McGraw-Hill, Inc., New York, NY. 1981.
[6] Littlefair P J , "Constraints on reflectance in artificial sky domes", Lighting Res. Technol. 19(4) pp.115~118.

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