DAYLIGHTING PERFORMANCE OF TOPLIGHTING SYSTEMS IN THE HOT AND HUMID CLIMATE OF THAILAND

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ABSTRACT

This paper presents the findings of a study that evaluated the daylight performance of three toplighting systems: skylights, lightscoops, and roof monitors for office buildings in Thailand. These toplighting systems were developed through a series of computer-assisted techniques and iteratively refined to respond to a wide range of solar positions. The daylight parameters evaluated were: daylight factor (DF), illuminance level, light distribution and uniformity. This study is part of a research project that examined both the daylighting and thermal performance of the three toplighting systems, which were designed to yield similar annual cooling loads. The daylighting performance evaluation was conducted using physical scale models and the RADIANCE lighting program; and the thermal performance of each system was evaluated using EnergyPlus. Comprehensive sets of computer simulation were used to simulate annual daylighting and energy performance. Results showed that the roof monitor with sun control devices provided the best daylight and thermal performance for a location like Bangkok, Thailand (latitude 13.7°N).

1. INTRODUCTION

1.1 Background

Daylighting is an important factor in the design of buildings, it provides illumination and brightness to interior spaces, and visual links to the outside; in addition it helps to reduce the energy consumption of buildings. In locations near the equator, the use of toplighting systems has significant potential to improve natural lighting in interior spaces due to the high intensity of direct sunlight, and at the same time it is challenging due to high solar heat gains and glare control.

Bangkok is located in a hot and humid climate with no heating season year-round; thus, minimize heat gain is a critical design issue since it can significantly increase the cooling loads and energy consumption in buildings. Sidelighting is the most common daylighting systems used in Thailand. Toplighting is generally avoided due to its excessive heat gains introduced to interior spaces, although it provides more uniform light distribution than conventional sidelight systems and even those with light shelves. Presently in Bangkok the use of large spans of sidelight glazing (curtain walls) with interior blinds is increasingly popular, mainly in new construction, causing an increase of heat gains and a higher demand for electric lighting and air conditioning.

1.2 Previous Studies

Research on integrating toplighting in hot and humid climates such as Thailand is scarce. There has been only few studies of the thermal and lighting performance of toplighting systems; and very few on low latitude hot and humid locations. One of these studies examined the impact of three toplighting systems on the annual energy performance of buildings in Washington DC (latitude 38°N) and concluded that the skylight is more efficient in terms of lighting and thermal performance as compared to sidelight window and clerestory (Treado, Gillette, and Kusada 1984). The results were different in a study which tested three toplighting systems along with their associated heat gains (latitude 0º); skylight performed poorer than clerestory and roof monitor by yielding the lower ratio of light output to heat gain ratio (Cabús and Pereira 1996). Another study analyzed both the visual and energy performance of three toplighting systems: skylights, clerestories, and roof monitors in Argentina (latitude 35°S) concluded that the systems that could save more energy were the clerestories, compared to the roof monitors and skylights (Garcia-Hansen, Esteves, and Pattini 2002). However, the authors defined the same glazing area for each system which yielded to different thermal loads for each system.

E. J. Dewey and P. J. Littlefair compared the daylighting performance of different rooflight systems (Dewey and Littlefair 1998). The objective of their study was to analyze the lighting performance, in terms of the uniformity of illuminance level, of six toplighting systems, including skylight, clerestory, and roof monitor systems. By testing different spacing-to-height ratios for each toplighting system, the authors examined which system gave the most flexibility in meeting CIBSE uniformity criteria. The authors concluded that the roof monitor system provides better uniformity than other systems, even though it had the largest spacing-to-height ratio.

These studies have shown that the thermal and lighting performance of toplighting systems could be different according to the location, weather, and sky conditions. In order to analyze the daylighting performance of toplighting systems more efficiently, we thought that the thermal loads of the systems should be the similar.

The objective of this research was to examine both the thermal and daylighting performance of toplighting systems. We present the results of the daylighting performance of three toplighting systems: skylight, lightscoop, and roof monitor, which were designed to introduce similar heat gain loads to the interior space as well as the most uniform illuminance levels throughout the space.

2. DEVELOPMENT OF PROTOTYPES

A prototypical base case of an office building was defined with dimensions of 15m (50 ft) in width, 25m (82 ft) in depth, 4.5m (14.8 ft) in ceiling height, with a floor area of 375 m^2 (4,100 ft^2). The interior surface reflectances were 0.75 for the ceiling, 0.44 for the walls, and 0.21 for the floor. The daylight and thermal performance of the three toplighting systems were compared using the base case office building. These systems are commonly found in Thailand.

The three systems were designed to intercept sunlight penetration and use the diffuse skylight as the main source of illumination (Fig. 1). The skylight prototype included diffuse glazing to spread daylight evenly in the interior space, with similar visible transmittance values as the clear glazing used in the lightscoop and roof monitor.

The systems were distributed in rows of 12m long throughout the space with a spacing-to-height ratio (SHR) of 1.5:1 (4 units) and 1:1 (6 units) to test the daylighting performance (Fig. 2). According to Dewey and Littlefair (1998), a SHR 1.5:1 ratio in a flat skylight and vertical sawtooth can yield daylight uniformity under overcast skies to meet the uniformity criteria of CIBSE, where the ratio of minimum illuminance to average illuminance is over 0.8, and the diversity of illuminance (ratio of maximum to minimum illuminance) should not exceed 5:1 (CIBSE 1994). On the other hand IESNA suggests a rule of thumb for spacing toplighting system with SHR of 1 to 1 (IESNA 1999). In this study the two SHRs (1.5:1 and 1:1) were tested.

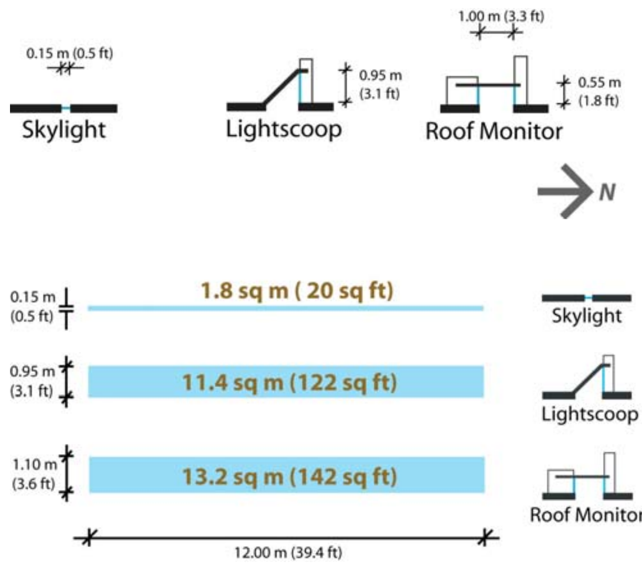

Fig. 1: Cross sections and glazing area comparison of single unit prototypes

3. EVALUATION METHOD

Initially the prototypes were developed using approximate methods to size the overall dimensions and geometry. The design was then refined using the Ecotect program. A reduced scale-model was used to compare illuminance levels with the RADIANCE lighting program. A comprehensive set of computer simulations were done to simulate annual thermal and daylight performance.

3.1 Thermal Performance

The thermal performance of each system was evaluated using the EnergyPlus building energy analysis program. The simulated spaces included a purchased air component to calculate the heating and cooling loads. The construction materials used in the simulations are typical found in Thai buildings (Table 1.) In the thermal performance tests, the three systems yielded similar annual cooling load loads (±2.5%). The annual cooling loads of toplighting systems with SHR 1.5:1 and SHR 1:1 are presented in Fig. 3.

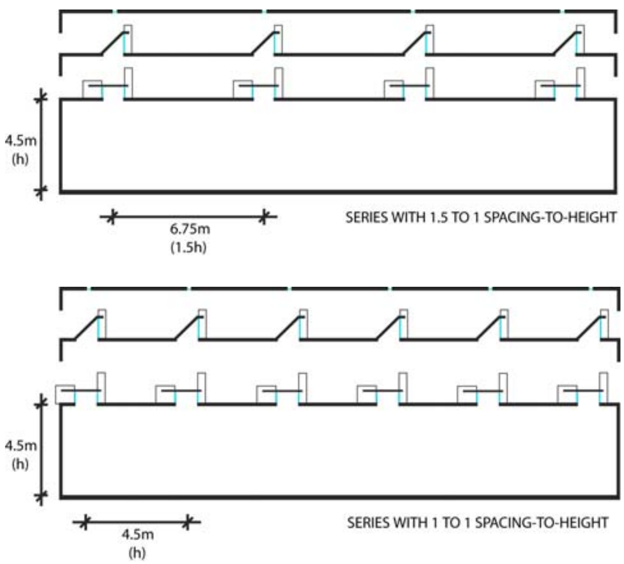

Fig. 2: Cross sections of the prototypes with SHR 1.5:1 (top) and SHR 1:1 (bottom)

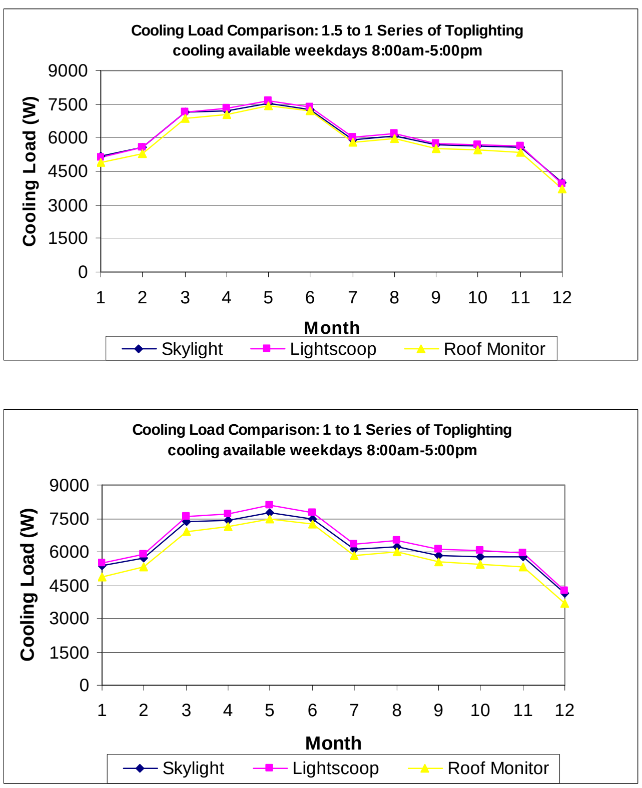

Fig. 3: Comparison of cooling loads, SHR 1.5:1 (top) and 1:1 (bottom)

When the thermal performance of the SHR 1:1 prototype is compared with the SHR 1.5:1 prototype, the glazing area is increased 50% in all the prototypes, but the annual cooling loads increased only 3%, 5%, and 1% for the skylight, lightscoop, and roof monitor, respectively. The roof monitors yielded less cooling loads than the two other systems, while the lightscoop yielded five times this amount.

3.2 Daylighting Performance

The daylighting performance was evaluated using physical scale models (1:40) and the RADIANCE lighting simulation program. The three typical sky types of Bangkok are: 40% overcast, 40% intermediate, and 20% clear sky (Chirarattananon, Chiwiwatworakul, and Pattanasethanon 2003). The tests were done under these sky types during the solstices and equinoxes at 9:00am, 12:00pm and 3:00pm solar time.

TABLE 1: ENERGYPLUS MATERIAL INPUT

Bldg. Element	User Name	Material	Source
Wall	HF-A6	Finish	DOE2.1E
	HF-B2	Insulation 1 inch	
	HF-C4	Common Brick 4 inch	
	AL21	Air Layer ¾ inch	
	HF-C4	Common Brick 4 inch	
	HF-E1	¾ inch Plastic- ¾ inch GYPS	
Ceiling and roof	HF-C10	Concrete HW 8 inch	
	HF-E4	Ceiling Air Space	
	HF-E5	Acoustic Tile	
Floor	0	Finish	Ecotect
	1	Concrete Slab	
Glazing (Low-E)	E178-4.CIG	Low-E glazing	Window5
	AIR 12.7MM	Air space	
	CLEAR_6.DAT	clear glazing layer	

3.2.1 Physical Scale Model

A physical scale model of the office space was constructed at a scale of 1:40 for comparing interior illuminance levels with the RADIANCE model. A replaceable roof was used to test various toplighting options. Photographs of the scale model are shown in Fig. 4. No glazing was used in both the scale model and the computer model, in the latter case a special illum glazing was defined for the RADIANCE runs.

Fig. 4: Daylighting scale model with exchangeable roofs

3.2.2 RADIANCE

RADIANCE lighting program was used in this study because it has the capability to model geometrically complex environments and precisely simulate light behavior within a space with numerical results and sophisticated rendered images. This lighting program has been compared and validated under real sky conditions, and it is able to predict interior light levels with a high degree of accuracy (Larsen and Shakespeare 2003).

3.2.3 Daylighting Evaluation

The performance variables used to assess the daylighting of the three toplighting systems were:

- Illuminance level (lux): Horizontal illuminance was measured at 1.5m. These values were used for comparing daylight levels of the three systems.
- Daylight factor, DF (%) - Ratio of interior horizontal illuminance level to exterior horizontal illuminance level (overcast skies)
- Diversity of illuminance and uniformity – These variables are based horizontal illuminance and CIBSE criteria for uniformity.

Workplane illuminance sensors were taken at seven interior reference points in the scale model. Sensors were placed along the center line at equal distances, 4m in the scale model and 1m in the RADIANCE model (Fig. 5). For the illuminance uniformity evaluation, sensors were placed in a 1m x 1m grid.

4. ANALYSIS AND RESULTS

4.1 Comparison between scale model and RADIANCE

The average difference of the illuminance measured in the scale model and the RADIANCE model was 15% under overcast conditions, and 18% under clear sky conditions. The differences under clear skies were under 20% except during the winter months where differences were higher. Some possible causes for this discrepancy are:

- The daylight model was tested in College Station, TX, which has a different luminance distribution than the CIE clear sky used in RADIANCE.
- The illuminance measurements were taken on the roof of the Langford Architecture Building which has obstructions from surrounding buildings. In the RADIANCE model no obstructions were modeled.
- The model was tilted to match Bangkok's sun positions, then the skydome luminance distribution is different from CIE skies.

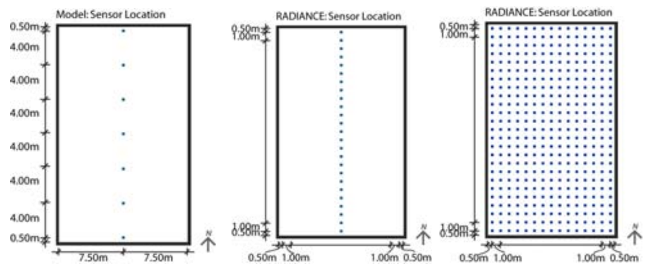

Fig. 5: Plan view of sensor location in scale model (left), RADIANCE model for DF (center), and uniformity analysis (right)

4.2 Single Toplighting Prototypes

Under overcast sky conditions, the single unit toplighting system that introduced the highest DF (2.5%) was the lightscoop, while the roof monitor and skylight introduced a DF of 1.5% and 1%, respectively (Table 2). Under clear sky conditions, the skylight yielded the highest illuminance levels; except during summer that the lightscoop yielded higher values. The roof monitor yielded the lowest illuminance values but with less seasonal variations. Under intermediate sky, all the illuminance levels dropped to about half the values under clear sky, ranging from 300 to 600 lux.

4.3 SHR 1.5:1 and SHR 1:1 Prototypes

Under overcast conditions, the prototypes with SHR 1.5:1 and SHR 1:1 that introduced the highest average DF (2.7% and 3.8%, respectively) was the lightscoop; while the skylight introduced the lowest average DF (1.2% and 1.7%, respectively). The average DF introduced by the roof monitors varied from 2.5% to 3.6% for SHR 1.5:1 and 1:1, respectively (Table 2). Under clear skies, the lightscoop introduced higher illuminance levels than the two other systems except in winter, when the roof monitor introduced higher illuminance values.

Under intermediate sky conditions the lightscoop introduced the highest illuminance levels in summer with both SHRs, while the roof monitor introduced the highest illuminances in winter with both SHRs (Fig. 6). In the equinox, the lightscoop and roof monitor introduced similar illuminance levels. In general, the illuminance levels introduced by the roof monitor remained fairly constant throughout the year. The skylight introduced the lowest illuminance levels at all times. The overall illuminance distribution was similar with SHR 1.5:1 and SHR 1:1, the latter one in general introduced around 50% higher illuminance levels with less variations of the maximum and minimum values.

TABLE 2: MAXIMUM AND AVERAGE DAYLIGHT FACTORS

	Max. DF Single Unit	Average DF SHR 1.5:1	Average DF SHR 1:1
Skylight	1.5	1.2	1.7
Lightscoop	2.6	2.7	3.8
Roof monitor	2.0	2.5	3.6

The roof monitor had lower diversity of illuminance ratios than the skylight and lightscoop, ranging from 3-5 for both SHRs. This indicated that, for the roof monitor prototype, the SHR 1.5:1 was sufficient to meet the CIBSE uniformity criteria (less than 5:1). The diversity of illuminance ratio for the lightscoop varied from 6-10 for SHR 1.5:1, and 5-7 for SHR 1:1, while the ratios for the skylight were 10-15 for a SHR 1.5:1, and 6-9 for a SHR 1:1. The roof monitor also performed better in terms of the uniformity, with higher uniformity ratios than the two other systems; even though these values did not meet the CIBSE criteria of 0.8 (see Tables 3 and 4). Fig. 7 depicts illuminance distribution over the floor area for SHR 1.5:1 and SHR 1:1 under overcast conditions. Fig. 8 shows the interior space with roof monitors and skylights with SHR 1.5:1.

5. CONCLUSIONS

From the results of the study, we concluded that the roof monitor with sun control devices provided the best overall daylight and thermal performance for a location like Bangkok, Thailand with variable sky distribution, and hot and humid conditions. The illuminance levels introduced by the roof monitor remained above 400 lux with SHR 1.5:1 and above 500 lux with SHR 1:1. The roof monitor provided uniform light distribution with the lowest cooling load.

The need for electric lighting during peak hours is reduced with the roof monitor, which has the potential for higher energy savings. The lightscoop system can also be an effective strategy, although it will require supplemental electric lighting in the dark areas in between rows. The diffuse skylight is the least recommended of all the toplighting systems due to its poor daylight performance, which may require a SHR less than 1:1 to improve the daylight uniformity. SHR of 1:1 or less increases the construction and maintenance costs, cooling loads, and the energy consumption of buildings.

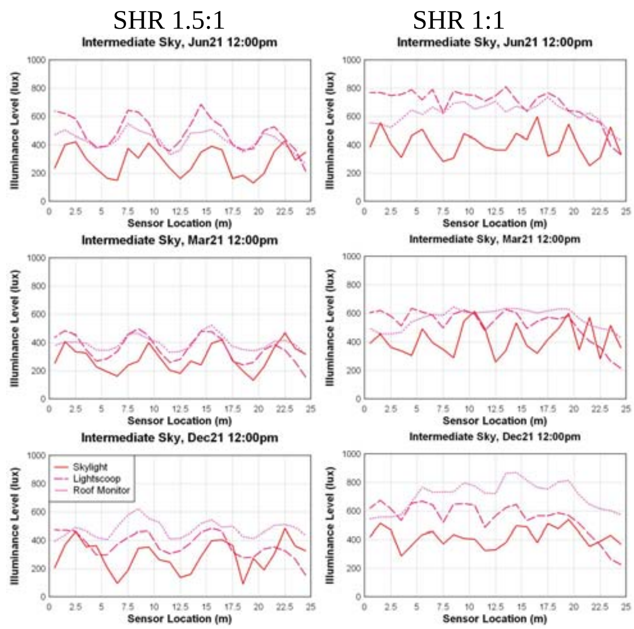

Fig. 6: Comparison of illuminance levels of SHR 1.5:1 and 1:1; under CIE intermediate skies, 12:00pm

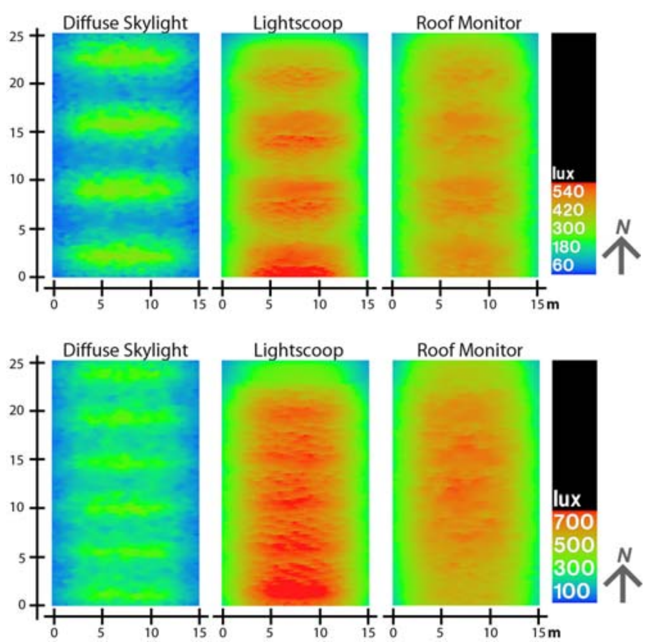

Fig. 7: Illuminance distribution over floor plans rendered with RADIANCE of SHR 1.5:1 (top) and SHR 1:1 (bottom), overcast sky

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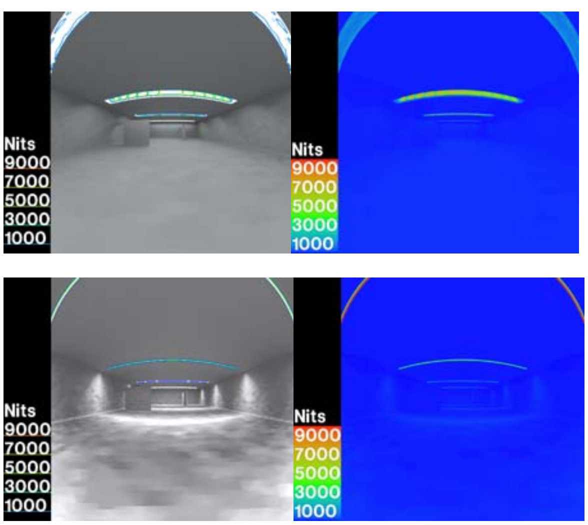

Fig. 8: RADIANCE images of interior space with roof monitor (top) and skylights (bottom) with SHR 1.5:1, June 21 at 12:00pm, CIE clear sky

TABLE 3: DIVERSITY OF ILLUMINANCE AND UNIFORMITY OF SHR 1.5:1 PROTOTYPES

		Illuminance Diversity			Illuminance Uniformity		
		A	B	C	A	B	C
Overcast Sky		13	8	4	0.18	0.23	0.35
Intermediate Sky							
Jun21	9:00	13	7	5	0.17	0.25	0.31
	12:00	14	8	5	0.16	0.24	0.34
	15:00	12	6	5	0.19	0.26	0.33
Mar21	9:00	10	7	4	0.22	0.24	0.38
	12:00	11	7	3	0.20	0.25	0.43
	15:00	10	6	4	0.21	0.25	0.37
Dec21	9:00	12	7	4	0.17	0.23	0.41
	12:00	12	7	3	0.19	0.23	0.45
	15:00	13	9	4	0.18	0.24	0.41

A: skylight; B: lightscoop; C: roof monitor prototype

TABLE 4: DIVERSITY OF ILLUMINANCE AND UNIFORMITY OF SHR 1:1 PROTOTYPES

		Illuminance Diversity			Illuminance Uniformity		
		A	B	C	A	B	C
Overcast Sky		7	7	5	0.29	0.21	0.29
Intermediate Sky							
Jun21	9:00	8	6	4	0.26	0.25	0.33
	12:00	7	7	5	0.27	0.24	0.33
	15:00	7	6	5	0.27	0.26	0.30
Mar21	9:00	7	7	4	0.25	0.22	0.36
	12:00	8	7	4	0.24	0.20	0.40
	15:00	5	7	5	0.33	0.23	0.34
Dec21	9:00	7	7	4	0.29	0.21	0.42
	12:00	6	7	4	0.32	0.21	0.40
	15:00	8	7	4	0.27	0.23	0.39

A: skylight; B: lightscoop; C: roof monitor prototype