Design and Analysis of a New Natural Illumination Device through Lumen Method Approach

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Abstract. The design and development of a natural illumination device (NID) for Malaysian roofing system is explored and improved with the aid of Lumen Method Approach at the analysis stage. The aim of this research is to channel and distribute natural sunlight from exterior to interior building to enlighten the required space in a daytime. It is made up of three main parts; dome as light collector, light tube as light reflector and light diffuser as light distributor. The result shows illuminance level for the NID in full summer sun and overcast summer sun conditions are higher than T8 fluorescent lamp.

Introduction

Modern natural illumination device was invented in the middle of 1980s. It is also known as tubular daylight device (TDD), light pipe or sun pipe. The NID presents a way to collect, transport, distribute, and control daylighting. Introducing natural light into buildings, users can not only minimize electricity consumption during daytime but also improve productivity, health, and even retail sales [1]. Daylight is harvested through a roof-mounted acrylic or polycarbonate dome with diameters ranging from about 10 inches for residential applications to 22 inches for commercial buildings. According to Wanda [1], acrylic or polycarbonate is used because the materials are formulated to block ultraviolet rays.

Daylight or natural light has several benefits over electric light. It radiates with perfect blend of colors [2]. About 2.5 times as many lumens per kWh of cooling load are produced by spectral content of natural light. Almost three times more illumination for the same cooling load of electric light can be produced by natural light if it introduced through modern high-performance glazing with low emissivity coating [3].

Zonal Cavity Method or Lumen Method is an accurate hand method for indoor applications because it takes into consideration the effect that inter-reflectance has on the level of illumination. It is used to calculate average level of illumination in the room determining the number of luminaires necessary to achieve a design illumination level. Assumptions for these calculations are uniform distribution of luminaires and diffuse surface reflectances for the walls, ceiling, and floor of the space. Average illuminance at the work plane gives impact to this method [4]. Fig. 1 illustrates the basis of Lumen Method which consists of three spaces or cavities of a room.

Recent trend towards natural daylighting over electric lighting is about to install basic skylights or the rooftop windows. Based on MacLellan and Wolfson [5] skylights can be either fixed (inoperable) or can be opened (operable). Skylights bring in twice the light of a conventional window of the same size. Users often think that skylights or 'roof windows' are the most effective way for letting daylight penetrate into the interior or buildings. Since skylights typically come in a flat shape, the incoming lights is just focused on one area and not distributed evenly. The other problems encountered from installation of skylights are like it requires a large hole in a roof which

later might leads to water infiltration and damage as stated by Hren and Hren [6], causes warm environment in residential area due to heat received from the sun, needs high maintenance cost to clean-up the dirt or moss formed on skylights which used for a long time and requires heading off roofs or ceiling joists [6]. Due to these constraints, NID installation might be the best solution and therefore, this study has been conducted to modify and analyse the NID design specifically for the Malaysian market.
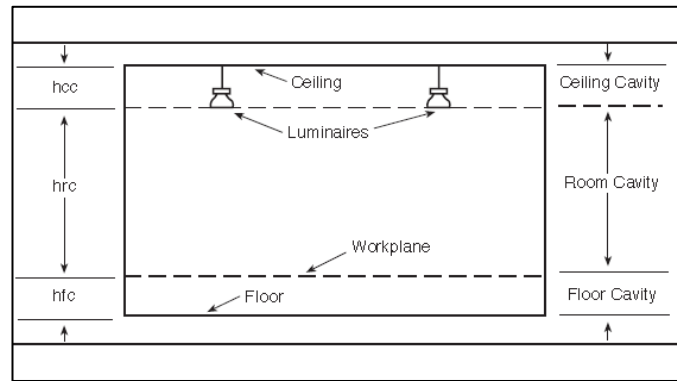

Figure 1: Cavities in a room [8]

Method & Procedures

Questionnaire survey questions were distributed among 30 residents of terrace houses at Taman Iftitah and Taman Haji Wan Ngah, Kemaman, Terengganu in order to forecast the market demand and gather their preferences for the upcoming NID design. Griffin and Hauser as stated in [7] mention that a low number of respondents (<10) would contribute to inadequate survey data while more than 50 (>50) are too many. Based on the survey result, 77 % of the respondents showed good interest with this invention while the rest were not. Voice of customer (VOC) was translated in the House of Quality and five designs were proposed with regard to customer demands, technical requirements and benchmarking of the competitors.

The final design was finally selected with the aid of Pugh Concept Selection matrix and each component of this NID was analyzed by using the CES Edupack 2010 Software for the material selection stage. SolidWorks 2011 software was used in modeling and the average illuminance level for the NID was calculated by using Lumen method and standard formula as follows:

Ceiling Cavity Ratio (CCR) = [5 h_{cc} (L + W)] / (L x W)   (1)
Room Cavity Ratio (RCR) = [5 h_{hrc} (L + W)] / (L x W)   (2)
Floor Cavity Ratio (FCR) = [5 h_{hfc} (L + W)] / (L x W)   (3)
Illuminance = [(lumen / luminaire) x no of luminaire x CU x LLF] / Area   (4)

h_{cc} and h_{rc} are the distance in feet from luminaire to ceiling and to work plane respectively. Meanwhile h_{hfc} is distance in feet from work plane to floor. The L and W represent length and width in feet unit. LLF and Cu are the light loss factor and coefficient of utilization respectively.

Results and Discussion

Table 1 shows A to E proposed NID concepts with a reference to the skylight panel (F). After the screening and scoring stages based on the Pugh Selection Matrix, concept A was finally chosen.

Table 1: Several proposed NID concepts

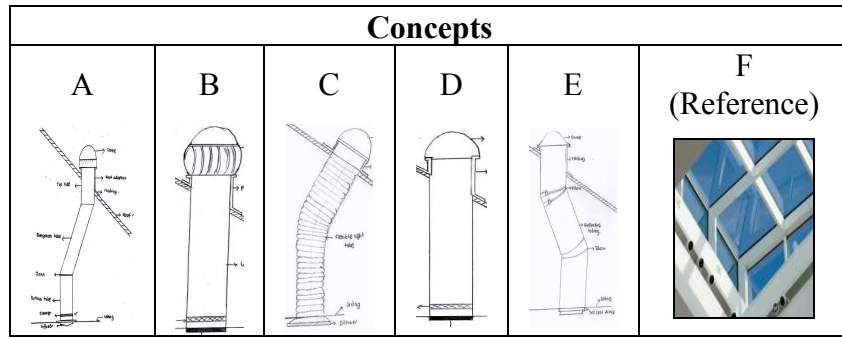| Concepts					
A	B	C	D	E	F (Reference)

Fig. 2 indicates the NID components which consist of a dome, a flashing, a light tube and a diffuser (below the ceiling).
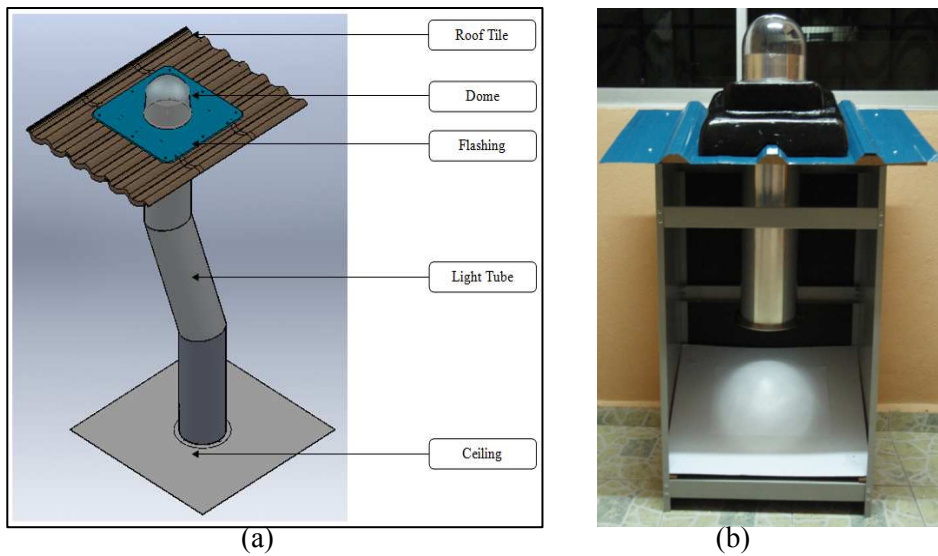

Figure 2: Natural illumination device (a) isometric drawing components, (b) actual prototype.

CES Edupack 2010 Software suggested the best material for each component as summarized in Table 2.

Table 2: The proposed materials for NID

Part	Material
Dome	Polycarbonate (PC)
Flashing	CFRP
Light tube	Age-hardening wrought Al-alloy
Diffuser	PMMA

Lumen method was used for the analysis on average illuminance level and the result obtained was compared with a typical 17 watts T8 fluorescent lamp. This type of lamp was chosen due to its longer lifetime and low operating cost. Most common reflectance values have been used in the analysis. According to [4], reflectance for ceiling is usually 80%, 30% for wall, and 10% for the floor. Room dimensions for the analysis involve width, length, height, h_{cc}, h_{hrc} and h_{hfc} are 9.84 ft, 8.86 ft, 12.17 ft, 1 ft, 9.19 ft and 2 ft respectively.

The value of CCR, RCR and FCR obtained using Eq. 1 until Eq. 3. From calculation the value of CCR, RCR and FCR are 1.1, 9.8 and 2.1 respectively.

The effective cavity reflectance was determined for the ceiling cavity and for the floor cavity. The percent of effective ceiling cavity reflectance (ρ_{cc}) is 60% and floor cavity reflectance (ρ_{fc}) is 47%. The values were obtained from the standard table by referring to percent ceiling reflectance (CR) or percent floor reflectance (FR) value of 80% and percent ceiling wall reflectance (CWR) or percent floor wall reflectance (FWR) value of 30%.

The coefficient of utilization (CU) or correction factor for luminaire in the room having RCR of 9.8 was then accomplished by interpolating the values. Floor cavity reflectance (ρfc), wall reflectance (ρ_w) for the room is 30% and ceiling cavity reflectance (ρ_{cc}) is 60%. The values obtained are shown in Table 3.

Table 3: CU related to w, cc, and values of RCR

RCR	ρ_{cc}=70%, ρ_w=30%	ρ_{cc}=60%, ρ_w=30%	ρ_{cc}=50%, ρ_w=30%
9	0.989		0.990
9.8	$CU_{9.8}$ = 0.9898	0.9903	$CU_{9.8}$ = 0.9908
10	0.990		0.991

The illuminance level for the NID was calculated. Compact T8 fluorescent lamp was used in comparison to NID. Related values that will be used in calculating the illuminance level for both types of lighting system are depicted in Table 4.

Table 4: Output and LLF for the NID and T8 fluorescent lamps

Parameters		NID	T8 Fluorescent Lamp
Output (Lumen)	Full summer sun	2796	1260
	Overcast summer	1302	
	Overcast winter	473	
Light Loss Factor (LLF)	Lamp Lumen Depreciation (LLD)	0.997	0.95
	Luminaire Dirt Depreciation (LDD)	0.995	0.90
	Ballast Factor (BF)	-	0.10

Table 4 shows output for NID is varied by time as sunlight position always changes. Total LLF for the NID is 1.992 while fluorescent lamp has total LLF value of 1.95. By using Eq. 4, illuminance level serves by both type of lighting system was determined and stated as in Table 5.

Table 5: Illuminance level calculation for NID and T8 fluorescent lamps

Lighting System	Condition	Illuminance Level (lm/ft^2)
NID	Full summer sun	63.26
	Overcast summer	29.46
	Overcast winter	10.70
T8 Fluorescent Lamp	-	21.47

Comparisons of illuminance level for the NID and T8 fluorescent lamp can be done after four steps of Lumen Method was performed for both lighting systems. From the calculations, illuminance level for the NID in full summer sun and overcast summer sun conditions are higher than T8 fluorescent lamp. However, illuminance level for T8 fluorescent lamp is better than the NID in overcast winter resulting from low amount of sunlight captured by dome during the season.

Conclusion

This study has proposed the best design concept of the NID based on customers' needs which comes with the suitable material for each component. The analysis of NID by using Lumen Method or Zonal Cavity Method was successfully explored which finally proven that NID is a better choice to enlighten dark spaces during daytime.

Acknowledgement

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