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Experimental Investigations of Solatube Daylighting System for Smart City Applications in Saudi Arabia

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The smart cities programme is at the core of Saudi Arabia's Vision 2030. The development of smart cities is based on adapting innovative technologies and solutions to meet local needs and possibilities in order to reduce both cost and energy resources consumption. In smart cities, more than 40% of electrical energy consumption should be saved. One of the most important electrical energy saving techniques is the application of the Solatube daylight system in sustainable buildings. In the present paper, an experimental investigation into the Solatube daylight system is performed according to the local climate conditions of Taif city, Saudi Arabia. A test chamber was designed with dimensions of 1 m^3, made from medium density fibreboard. The model of Solatube used in the present research is Solatube 160 DS, 10" in diameter and with a length up to 30'. The HS1010-LCD digital light meter is used for measuring light intensity. A comparison of illumination obtained from the Solatube with that obtained from artificial bulbs of standard ratings was made at two different vertical distances inside the test chamber (z = 0.8 m, z = 1.0 m). The results showed that the Solatube, at both vertical distances, gave a better illuminance than standard artificial bulbs. Moreover, the results indicated that the Solatube daylight system converted about 60% of sunlight to passive light inside the test chamber. Generally, it is concluded that the Solatube daylight system can be efficiently used in residential, commercial, or industrial buildings in smart cities according to the available solar characteristics.

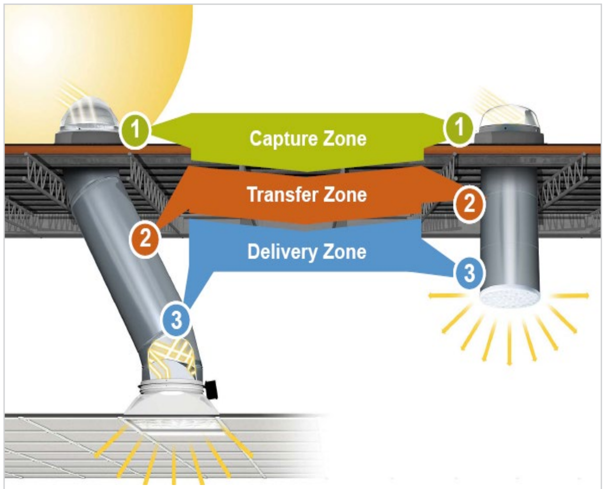
Keywords: energy saving, experimental investigation, Solatube daylighting system, smart cities, Saudi Arabia.

Introduction

In the context of Saudi Vision 2030, smart cities development plays an important role in achieving the goals of the announced vision of Saudi Arabia. The expression *smart city* includes many categories, including the application of different elements of sustainability in all life sectors (Eremia et al., 2017). The importance of the new approach of sustainability in architecture has been noticeable in terms of how it will be beneficial for the environment and the next generations. Electrical energy saving is a hot topic in sustainable buildings used in smart cities due to climate change and energy challenges globally (Bhati et al., 2017). Lighting accounts for about 17% of energy use in residential buildings and 18% in commercial buildings. Both conserving lighting use and adopting more efficient technologies can yield substantial energy savings in the building sector. Recently, new lighting technologies in building sectors have been developed, e.g., skylights, clerestories, external shading systems, light shelves and Solatube systems. These lighting technologies can be efficient in energy savings, in addition to traditional lighting technologies. Switching to newer technologies can result in substantial net energy use reduction up to 50% and, consequently, associated reductions in greenhouse gas emissions (Von Wachenfelt et al., 2015). The Solatube technology can be used in lighting of all building sectors, and in farm animal production.

The main function of the Solatube daylighting systems is to collect the sun's rays efficiently and transfer them into the home. The result is brighter, more colourful rooms that cost nothing to light with no structural changes. It is the fastest and simplest solution to a more beautiful home. For builders and roofers, offering Solatube daylighting systems is a way to increase revenue, add value, and increase customer satisfaction (Spacek et al., 2018). The Solatube system is considered the oldest type of natural day lighting used by ancient Egyptians. Thereafter, further developments of the Solatube system have been made in order to widely use them in different applications where areas are not usually covered by skylights. Solatube can deliver daylight without solar heat gains that give suitable health conditions for working and living. More recently, investigation of the Solatube daylight system performance has been increased, especially in sunny and cloudy climate conditions (Williams et al., 2014; Malet-Damour et al., 2017). The Solatube system consists of three main parts, as can be seen from Figure 1; the collector, the tube and the diffuser. The collector, or the capture zone, is usually hemispheric and made up of clear glazing in order to gather the sunlight. The tube, or the transfer zone, is made up of aluminium sheets with highly reflective interior lining. The diffuser, or the delivery zone, may be hemispherical or flat with preferably glazing in order to diffuse light to the indoor space.

Fig. 1. *The different parts of a Solatube system*



The performance of a Solatube is affected by three important factors: namely the collector efficiency, the transmission of light through the tube, and the diffusion of the light. In addition to that, the external weather conditions play a significant role. Investigation into the Solatube has recently increased due to its importance in energy saving in smart buildings. The Solatube was judged as the most innovative technology in daylighting by Littlefair (1990). An experimental study was performed by Shao et al. (1998) to investigate the performance of Solatubes in winter. The results showed an energy decrease of 30%. The most effective characteristics of Solatube were investigated by Oakley et al. (2000). They found that the Solatube should have a large diameter, and a straight and short pipe in order to obtain high performance. The hybrid lighting system (coupling of light-pipe and artificial lighting (LED)) gave an annual energy saving of 60.4% (Ji et al., 2016). However, if the Solatube is used alone, it could deliver the equivalent of 10 incandescent bulbs or five compact fluorescent bulbs (Malet-Damour et al., 2016). Through the measurements of the light-pipe system installed in an air-conditioned corridor (Li et al., 2010), it is found that the integration of the light-pipe system with proper lighting controls can reduce the lighting energy use. The transmission of beam and diffuse daylight through straight circular light-pipes with and without bends has been investigated analytically and validated with performed experimental results (Samuhatananon et al., 2011). It is concluded that the developed analytical model can be applied for designing light-pipes as well as the economic decision on the size, configuration, and choice of surface materials to be used. The effects of various sizes and geometries of commercial light-pipe systems on their performance have been experimentally evaluated (Su et al., 2012). Moreover, a mathematical model is proposed to correlate the obtained experimental results. It is found that the derived mathematical formula can be considered as a useful design tool for prediction of the lumen output of a light-pipe system. Furthermore, the performance of the light-pipe system in the winter season under sunny and cloudy conditions has been experimentally evaluated (Wu and Li, 2012). It is found that the light-pipe system can substitute partially or totally the artificial light to decrease the energy consumption of lighting required.

In the present paper, a Solatube model 160 DS daylighting system of 10” in diameter and with tube length up to 30’ is used. For the current research, the Solatube price in the Saudi Arabia market is about 270$, and one can simply install it in the test model. This model is applied to light a test chamber with dimensions 1 m^3 according to the local climate conditions of Taif city, Saudi Arabia. Experimental measurements of light intensity inside as well as outside the test chamber are performed, and the obtained results are compared with an artificial lighting system.

Test model design

In the present research, a test chamber was designed of size 1 m^3 and made from medium density fibreboard (MDF). The Solatube system is installed directly in the middle section of the chamber surface, while the side walls of the chamber are totally closed. Figure 2 shows the sequential steps of Solatube installation in the test model. In the test model, a circular

Fig. 2. *The sequential steps of Solatube installation in the test model*

opening of 11" diameter was made on the roof of a small enclosure located over the test chamber for fixing the Solatube system. The small additional enclosure is designed so that the end of the Solatube (diffuser section) is located exactly on the interior roof of the test chamber, as shown in Figure 1. The Solatube system is totally placed in a black enclosure to prevent the loss of sunrays. The place of the experiment is chosen in an open space so that there will be no effect of shadows on the experiment. The place of performing the proposed experiment is in College of Engineering, Taif University, Taif, Saudi Arabia.

Measuring devices

In order to measure the light intensity, a digital Light Meter HS1010 Professional Illuminance is used. The specifications of such a device are given in Table 1.

Table 1. *The specifications of the measuring light intensity device HS 1010*

Specification:	
Product name:	HS1010 HS1010A LCD Digital Light Meter
Model:	HS1010, HS1010A
Material:	plastic
Measurement range:	(1~200000Lux)
Repeatability:	±2%
Accuracy:	±4%±10dgts(<10000Lux) ±5% ±10dgts(>10000Lux)
Temperature characteristic:	±0.1%/°C
Measuring rate:	Approximately 2.0 time/sec
Photo detector:	One silicon photo diode with filter
Weight:	130g
Size:	(16.2 cm x 5.9 cm x 3.1 cm)(HS1010A)
	(10.8 cm x 5.9 cm x 3.1 cm)(HS1010)

Results and Discussion

The experimental procedure was carried out by first measuring the outside solar light intensity. The internal light intensity was measured at three vertical distances: directly below the diffuser, z = 0.0, z = 0.8 m and z = 1 m away from the diffuser. The data was collected every ten minutes as a fixed period. The readings were taken from 09:00 to 14:00. Some experimental measurements are presented in the following figures. The period of the measurements was from 09:00–14:00 on the day of 12/4/2018. Figure 3 shows the average monthly maximum/minimum temperature of Taif city. It can be shown that the average temperature during the day of measurements was about 40°C.

Figure 4 shows the distribution of the external solar light intensity compared with that measured inside the test chamber directly below the Solatube (z = 0.0). The results indicate that the maximum solar light intensity outside the test chamber is about 128,800 lux located at about 12:40 PM. At the same time, Solatube intensity is about 78,500 lux, with a percentage of 61% of solar light conversion. It can also be seen that the minimum values at 9:00 AM are 89,180 lux for external solar light and about 30,300 lux for the Solatube system. It is well expected that increasing the external solar light intensity may increase the Solatube light intensity within the range of the conversion ratio of 61%. This is considered as a good conversion ratio.

Figure 5 shows the Solatube light intensity measured at two vertical distances (z = 0.8 m, and z = 1.0 m) downwards in the diffuser. The results indicated that the light intensity reaches its maximum value of 3100 lux at z = 0.8 m, and about 1950 lux for z = 1.0 m. Moreover, the maximum values are obtained at about 12:30 PM. The percentage reduction in light intensity is about 0.36% for a distance reduction of 0.25%, which may indicate that the reduction of light intensity is proportional linearly with the distance.

In order to indicate the effectiveness of the Solatube system, a comparison was made with bulbs of four standard ratings, as shown in Table 2. From the collected experimental results in Table 2, it can be shown that a LED bulb (20W) has a better performance than the Solatube system for a direct measure (z = 0.0), while by increasing the vertical distance away from the light source, the Solatube system gives high performance. Also, the Solatube system gives better performance than LED bulb (4.5 W) for all distances (z = 0.0, z = 0.8 m, z = 1.0 m). This high performance of the Solatube system is also noticed when compared with halogen bulbs of 60 W and 100 W. Therefore, it is important to notice that, in case of building a Solatube, the internal area of the place determines the number of Solatube systems used. In general, for a room of 10 m^2, two Solatube systems can be considered more than enough.

Fig. 3. *The maximum/minimum average monthly temperature in Taif city*

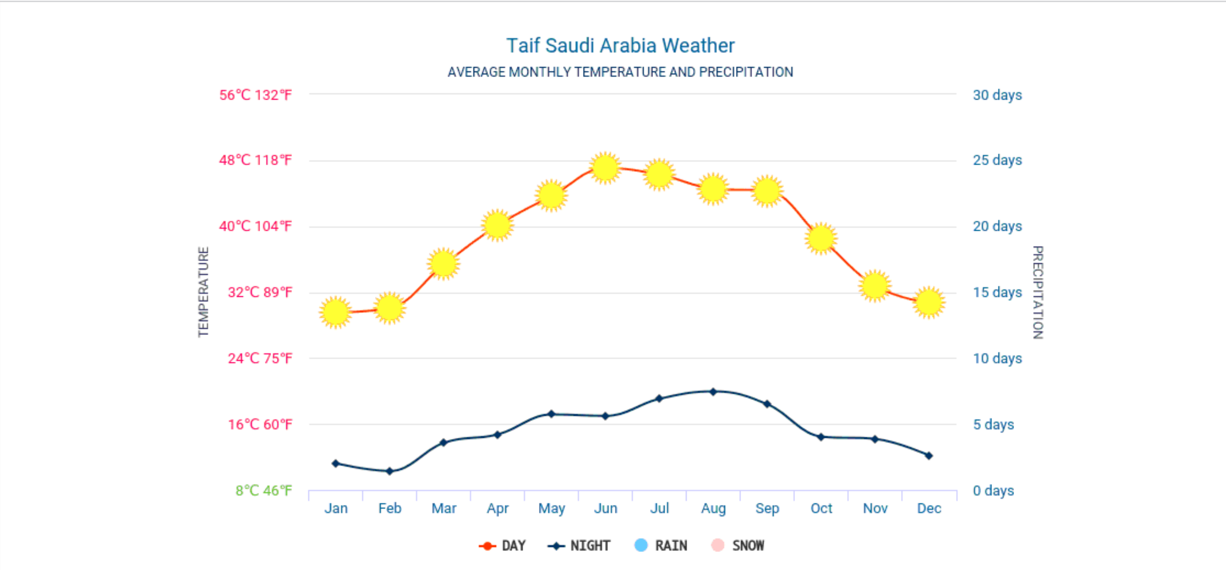


Fig. 4. *Comparison of the solar light intensity (outside) and the Solatube light intensity measured directly z = 0*

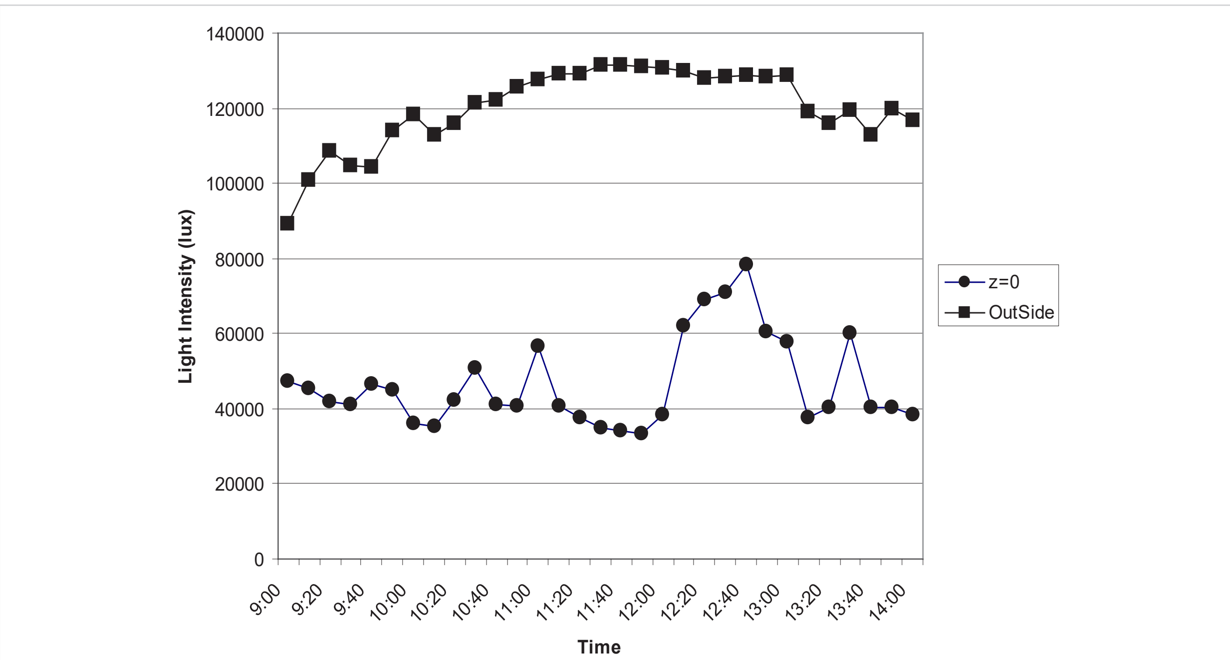


Fig. 5. *The Solatube light intensity measured at vertical distance z = 0.8 m and z = 1.0 m*

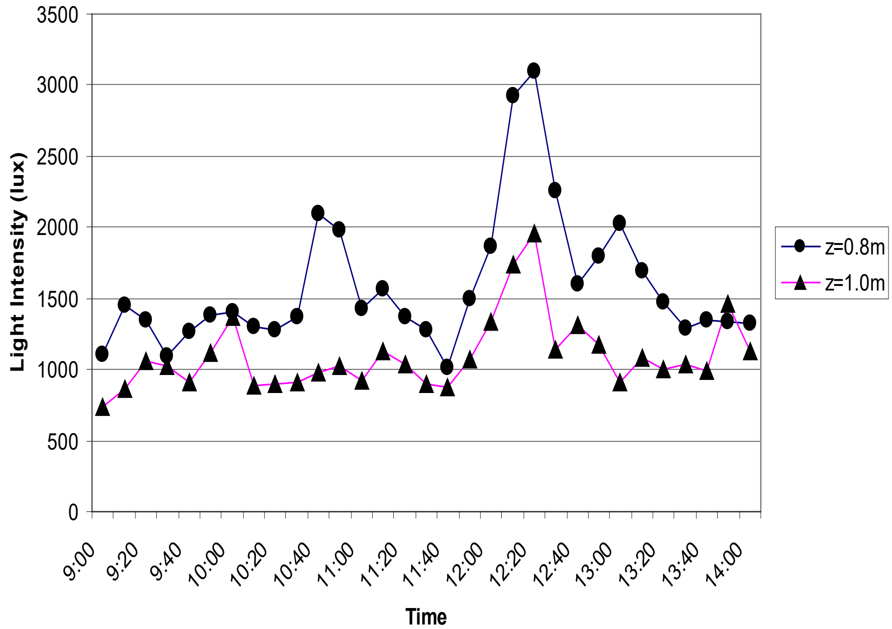


Table 2. *Comparison of Solatube system with four bulbs of standard ratings*

Bulbs/Watt/Lux	Z = 0.0	Solatube Max./Min. Z = 0.0	Z = 0.8 m	Solatube Max./Min. Z = 0.8 m	Z = 1.0 m	Solatube Max./Min. Z = 1.0 m
LED (4.5W)	50.500	78.500/30.300	304	3100/1010	186	1954/464
LED (20W)	105.300	78.500/30.300	1570	3100/1010	935	1954/464
Halogen (60W)	18.250	78.500/30.300	186	3100/1010	117	1954/464
Halogen (100W)	46.000	78.500/30.300	454	3100/1010	284	1954/464

Indeed, it is important to compare the experimental results obtained with previous investigations. However, the experiments performed were carried out according to the climate conditions of Taif city, Saudi Arabia. No previous investigations have been found regarding the same operating conditions as our experiments. In the future, the authors are planning to perform numerical simulation using numerical software such as EnergyPlus or Heligilm software, and verifications of the experimental results obtained will be performed.

Conclusions

The present paper introduces the application of the Solatube daylight system in sustainability building within the concept of smart cities technology. Experimental measurements were performed in College of Engineering, Taif University, Taif, Saudi Arabia. A test model was designed as a cubic chamber with dimensions of 1 m^3, and with a Solatube system located in the middle of the chamber surface. The Solatube 160 DS 10” in diameter and with length up to 30’ was used for the current experiments. The results showed that the Solatube system can convert about 60% of sunlight to passive light inside the test chamber. This ratio was obtained when the outside average temperature is nearly 40°C. Higher conversion ratios are expected by increasing the outside average temperature. A comparison was made with different bulbs with standard ratings in order to show the effectiveness of the Solatube system. In general, the Solatube gave high performance when compared with the standard bulbs at different vertical distances below the light source. Moreover, the economic evaluation of the Solatube project is encouraged and could be observed after a long period. This is also approved by the previous investigations mentioned in the introduction section of the current paper. According to the potential of solar energy in Saudi Arabia, the Solatube system can work efficiently for about 12 hrs per day. This means that nearly 50% of the energy cost per day can be saved. Generally, it can be concluded that the Solatube system is a promising technology that can be used in sustainability buildings within the concept of smart cities technology.

{Gurauskiene, 2006, Eco-design methodology for electrical and electronic equipment industry}

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