Analytical study of the size of solar tubes for interior spaces for Cairo, Egypt

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Abstract

Indoor thermal and visual comfort are core issues in designing sustainable buildings. Natural daylight and ventilation are proved to improve the occupants' performance and productivity levels. The buildings sector in Egypt and specifically the residential sector is responsible for 42 % of the total energy consumption. Utilizing natural daylight in buildings plays a great role in reducing the energy used for artificial lighting and especially in a country like Egypt with high solar exposure rates.

This research paper proposes an evaluation of solar tubes configurations in a space located in Cairo, Egypt (semi desert climatic zone). This evaluation is conducted using a simulation study that has been held to determine the optimum size of the solar tunnel as well as the optimum placement of them, and to optimize their performance in the case study investigated space. Twenty-four configurations of solar tunnels have been studied and twelve combinations of skylight have undergone evaluation. The analytical study provides the optimum size of the light tubes that is able to provide the highest level of daylight factor in the case study space.

The selected space is located in Cairo, Egypt in a building. The coordinates are 30.0444° N, 31.2357° E and 23m elevation above sea level. The size of the room is 4.20 m length, 3.60 m width and 3.00 m height, oriented to the north, the main feature of the room is that it has no windows in order to accurately analyze the effect of the light tubes.

The building envelope of the selected case study is as follows, the wall finishing is plaster and flooring tiles both have the following characteristics 0.90% reflectance, 0.03% rugosity and 0.0% specularity. The reference plane where the light properties have been calculated is a wooden table centered in the room, and has the following characteristics, 0.66% reflectance, 0.02% rugosity, 0.05% specularity.

Keywords:

natural light, daylight, solar tubes, visual comfort

1. Introduction

The great increase in the number of residential buildings in Egypt in the recent years explains the massive energy consumption caused by this sector. Residential sector consumes around 42% of the total energy in Egypt. One of the main contributors to this high consumption rate is artificial lighting. Providing natural lighting to spaces depend on multiple factors such as glazing type, Window to Wall ratio (WWR).

Lighting in Egypt consumes around 31% of the total energy consumption which is considered a high rate (Hanna 2013). Optimizing the use of electricity for providing the required illumination level in spaces can be achieved through multiple methods. As shown in figure 2, and according to the British Standards Institution (BSI)- 1992, Egypt has a high solar exposure

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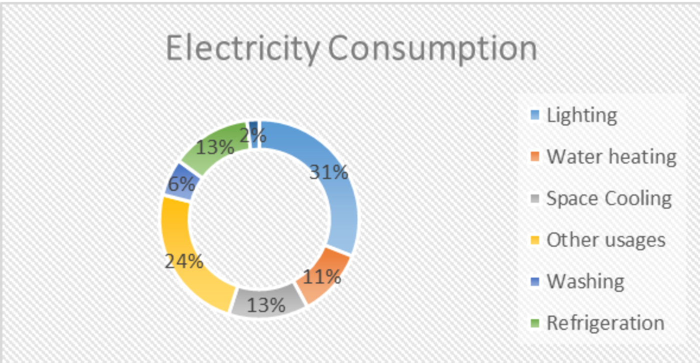
rate that varies from 5.4: 7.1 KWh/m^2/day which has a great potential concerning providing indoor daylight.



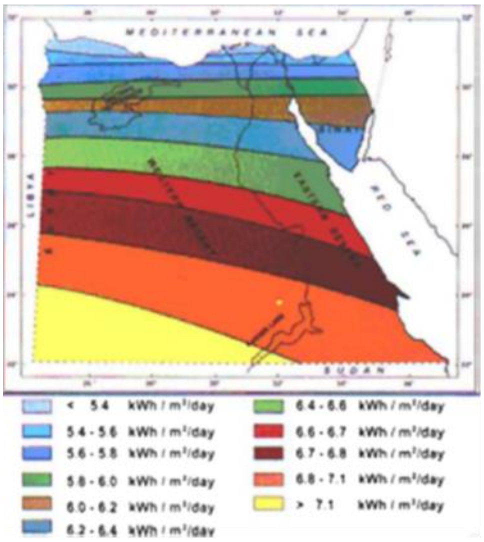


Fig. 1. Electricity consumption patterns in Egypt
Fig. 2. Daylight power intensity distribution on Egypt.

Many researches were done to analyze the performance of systems providing natural lighting by using numerical simulation studies (Pui Wah Wong, et al. 2008). By reviewing many researches that were held to improve the natural daylighting and according to Alessandra Galatioto (2016), Daylight factor is the mostly used among other indices in assessing indoor visual comfort (Galatioto , Beccali 2016). As stated by R. R. Date, et al. (2014), multiple natural daylight methods were discussed and solar tubes were the most effective. They provide consistent daylight at high quality of delivered light, they are energy efficient and affordable. Furthermore, they are easy to install and maintain (Date et al. 2014). According to M. V. Lapsa et al. (2007) Using daylight systems to provide light for interior spaces has the potential of reducing the cost and energy of heating and cooling of buildings (Lapsa et al 2007). Using daylight systems such as solar tubes and natural light in general can have a contribution in reducing energy consumption in buildings by 30% as stated by S. Dutton (2007). Solar tubes are considered an affordable system that provides daylight to deep plan spaces where there are no windows or where windows are not able of providing adequate lighting. They are able to provide adequate illuminance levels in buildings (Mohapatra et al 2020).

A study held by Ji, Simci et al in 2016 stated that multiple designers and end users do not tend to use or invest in natural light systems such as solar tubes as there are a very limited number of researches and studies about their performance and efficiency (Simci et al 2016).

2. Solar Tubes

Solar tubes, also known as tubular daylighting devices, are devices installed on building roofs that are responsible for transmitting light to some interior spaces of the building. Solar tubes transfer less heat to the interior spaces than normal skylights due to their smaller surface area. Solar tubes harvest the daylight through the dome, a roof mounted object made from acrylic or polycarbonate and is designed to have the ability blocking ultraviolet rays. The ducts are responsible for redirecting light rays into aluminum tubes system (Wanda 2006).

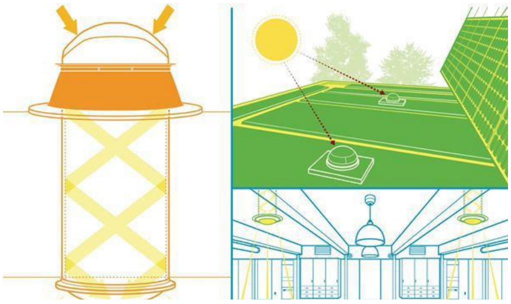


Fig. 3: Solar tubes collecting, transporting, distributing, and controlling daylight

Solar tubes were invented in 1993 and was targeting providing daylight to residential and commercial buildings as well as reducing the carbon footprint and improving sustainability. The common problems of skylights are the excessive heat gain caused by them, glare and water infiltration. The solar tubes present an advanced technology of collecting, transporting, distributing, and controlling daylight using the development of physics and material science.

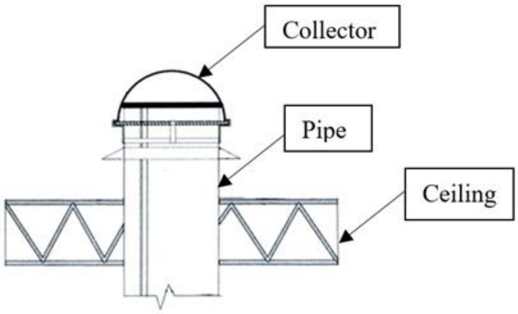
3. Case Study Methodology

This paper proposes an analytical study that aims to provide the optimum size of the light tubes that is able to provide the highest level of daylight factor in the case study space. The selected space is located in Cairo, Egypt in a building. The coordinates are 30.0444° N, 31.2357° E and 23m elevation above sea level. The size of the room is 4.20 m length, 3.60 m width and 3.00 m height, oriented to the north, the main feature of the room is that it has no windows in order to accurately analyze the effect of the light tubes.

The building envelope of the selected case study is as shown in table 1, the wall finishing is plaster and flooring tiles both have the following characteristics 0.90% reflectance, 0.03% rugosity and 0.0% specularity. The reference plane where the light properties have been calculated is a wooden table centered in the room, and has the following characteristics, 0.66% reflectance, 0.02% rugosity, 0.05% specularity.

Table 1: the case study building envelope characteristics

Elements	Material	Conductivity (W/m. K)	Specific heat (J/kg. K)	Density (Kg/m^3)
Walls	Masonry brick	0.72	835	1920
	Reinforced concrete (columns)	2.30	1000	2300
Surface Finishing	Plaster (Dense)	0.50	100	1300



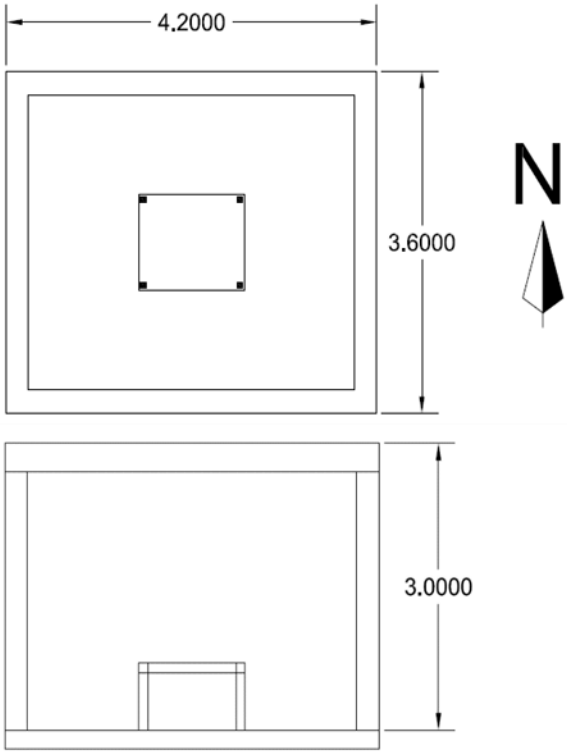


Fig. 4: light tube section
Fig. 5: case study space section

The main purpose of this research paper is to determine the natural light provided by different sizes of light tubes and skylight devices. This simulation was conducted on Daysim software, a daylight simulation plugs in on Rhino software that conducted the simulation using an energy plus weather data file assigned according to the location of the building and climatic zone of the case study, Cairo, Egypt (semi desert climate). The evaluation of the daylight factor, illuminance and luminance values were performed by the analysis of the simulation study.

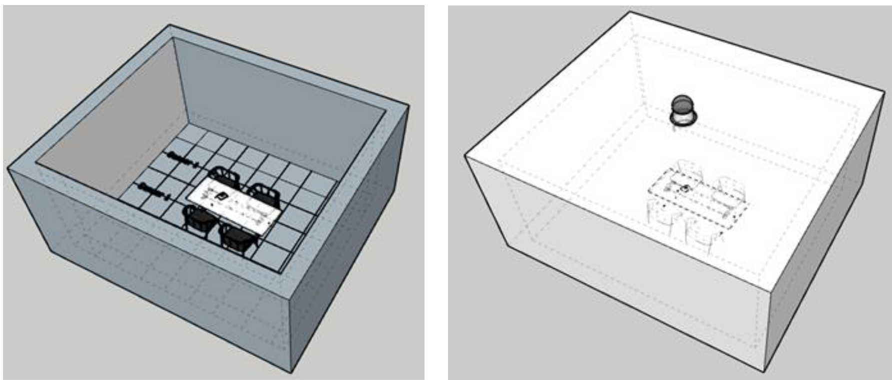


Fig. 6: Simulation model interface

The simulation study has been held as to determine the optimum size of the solar tunnel as well as the optimum placement of them as well as optimizing their performance in the case study investigated space. 24 configurations of solar tunnels have been studied and 12 combinations of skylight have undergone evaluation.
The analysis was on the following cases:

- 12 cases of 1-meter-long tunnels with (1-3-5-7-8-10-15-20-25-30-35-40 tunnels)
- 12 cases of 3 meters long tunnels with (1-3-5-7-8-10-15-20-25-30-35-40 tunnels)
- 12 cases of traditional skylights with (1-3-5-7-8-10-15-20-25-30-35-40 skylights)

The analysis included the following data for each configuration:

- Daylight factor (%)
- Daylight Autonomy (%)
- Annual Light Exposure (lx. h)
- Useful Daylight Illuminance (%)
- Continuous Daylight Autonomy (%)

As mentioned in the introduction, daylight factor and annual light exposure indices are able to provide a general overview of the contribution of daylight. Daylight autonomy utilizes the illuminance at work plane to indicate the sufficiency of daylight in a space in order to determine whether the occupant can rely solely on daylight (Reinhart et al 2006).

4. Results and discussion

The following figure (fig. 7) shows the correlation between Daylight factor and A_{RB}/A_{RG} number of corresponding solar tunnels.

A_{RB}	Total area of the skylight/tunnels openings (m^2)
A_{RG}	Floor area of considered space (m^2)

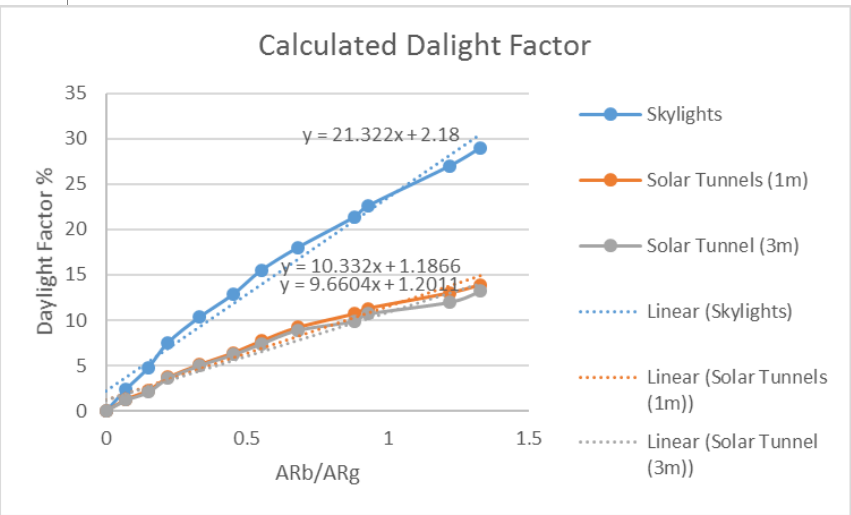


Fig. 7: Calculated Daylight factor for three typologies of systems of a number of devices

The figure clearly shows that skylights are the optimum contributors to higher daylight factor and is proportional to number of devices and the ratio of rooflight opening area and room area. Light distribution in the room area differs because not all tunnels are located on the roof in correspondance of the table, and the dayligt factor was calculated in a point of the table in the center of the room. Daylight factor correlation to A_{RB}/A_{RG} is represented to be almost linear for all the systems which highlights that Daylight factor increases in a linear way by increasing the skylights area, 1 meter tunnels and 3 meters tunnels.

In the case of the one meter long solar tunnel, six solar tunnels are required to achieve the Daylight factors (2%) according to the European Committee for Standardization (CEN 2011). Nine tunnels are required for the case of the three meters long solar tunnels. The use of skylights is always the optimum due to the calculations but is not applicabe due to architectural design constraints. Smaller number of skyights is able to provide the same Daylight factor provided by a larger number of solar tunnels. Solar tunnels have been recently provided with light diffusers that cause lower riske of indirect glare, while skylights have an issue concerning glare. The light diffusers in the solar tubes enlarge the luminous uniformity and decrease the overheating of spaces.

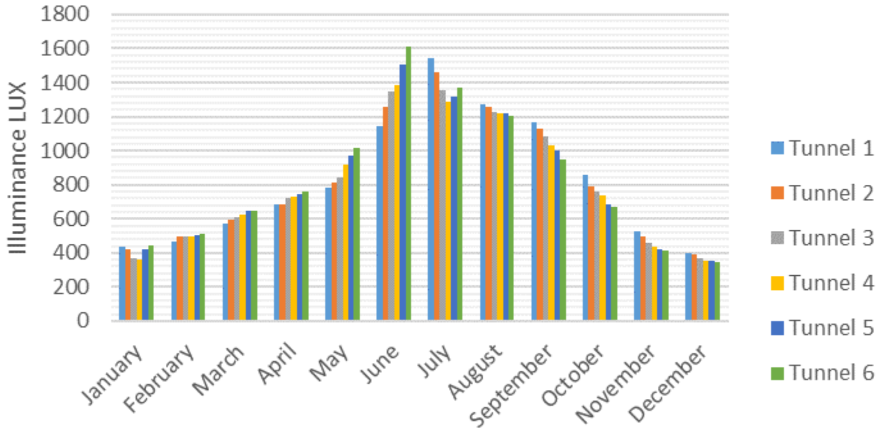


Fig. 8: Daylight Illuminance distribution over 12 months (1 meter long 6 light tubes)

This graph shows the illuminance over 12 months for six light tubes of one-meter long. The illuminance values here are calculated on the plane level on which the Daylight factor has been calculated as well. It is observed that the peak months delivering the highest illuminance values are June, July and August while the winter months deliver lower values yet we can depend on them for delivering indirect light that has no glare. The winter months with lowest delivered illuminance, didn't deliver less than 300 Lux at any of them.

5. Conclusion and Recommendation

This research paper is considered an aid for designers willing to install daylight devices in their design. Due to the lack of scientific studies on daylight performance in solar tunnels, this paper represents the performance of solar tubes in a room in Egypt as a guide. A very important thing is that oversizing the daylight devices is not recommended as it causes glare and overheating. The case study was conducted on a room located in Cairo, the capital of Egypt and can be applied to various spaces and locations as well.

As a recommendation that is sorted out of this study, solar light tubes are suitable for use in Cairo, Egypt and in this climatic zone generally due to the high solar exposure. They proved great performance but needs accurate sizing in order to achieve the required illumination level in interior spaces as well as to avoid overheating and glare.

For future research, it is recommended that further research should be done in order to spread and facilitate the use of daylight devices as it is a very efficient method specially in a country like Egypt with high solar exposure and daylight power intensity. It is also recommended that further studies consider the calculation of the achievable energy efficiency from using daylight devices instead of depending on artificial lighting sources only. Moreover, some improvements to the light path and light diffusers can be studied in order to improve the delivered illumination.

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