Using Tubular Daylighting Systems to Improve Illuminance Level in Double Loaded Corridors in Educational Buildings

Ahmed Freewan

Jordan University of Science and Technology (JUST), Irbid, Jordan.
E-Mail: ahmedfreewan@hotmail.com

ABSTRACT

Double loaded corridors in educational buildings generally experience a low daylight level, as they do not have enough direct contact with the outdoor environment. The task light level in those corridors is lower than that in reading or office spaces. Double loaded corridors normally depend on artificial light. On the other hand, double loaded corridors need to be lit all the day during the occupation period as one can not specify when different users could use it.

This research explores the possibility of using tubular light systems in addition to some architectural solutions to provide double loaded corridors with the required daylight. The research used anidolic, light pipe and ceiling cavity systems in addition to high windows from side offices to improve daylighting in double loaded corridors. The experimental study, which has taken place at JUST, showed that anidolic systems could provide double loaded corridors with sufficient lighting levels. On the other hand, radiance simulations showed that anidolic and some other solution systems can provide corridors with sufficient daylight in lower floors, while light pipes can provide corridors with sufficient daylight in upper floors.

KEYWORDS: Anidolic systems, Illuminance level, Uniformity, Light pipes, Light shelves, Ceiling cavity.

INTRODUCTION

Energy used in buildings counts up to 50% of the energy consumptions, while light counts more than third of the energy used in buildings. Therefore, daylight in buildings could be a promising goal for minimizing the non-renewable energy used in buildings while reducing CO_2 and environmental degradation. It is well-known that buildings consume large amounts of energy for lighting and consequent space cooling (Leslie, 2003). Daylight can improve human health, mood, performance and productivity, which then improves the economic environment, not only by saving energy, but also by increasing workers' productivity (Bommel and Beld, 2004; Freewan et al., 2008; Freewan et al., 2009; Freewan, 2010; Heschong et al., 2002; Poyce et al., 2003).

Double loaded corridors are always suffering from limited direct contact with outdoor environment and daylight. Thus, direct utilizing of daylighting through direct entering devices, such as windows and clerestory, is limited. As a result, such spaces need to be lit artificially all the time during working hours even when daylight is abundant during daytime such as the case at Jordan University of Science and Technology (JUST).

JUST is located in Irbid (latitude 31.9˚ north, longitude 35.9˚ east) around 80 km to the north of

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Amman. The campus was designed by the Japanese architect Kenzo Tange. The university buildings were constructed using prefabricated concrete panels and blocks, Figure (1). The designer used a module system of 40mx40m. Offices are located on second floors, while ground and first floors are used for lecture halls and labs, respectively. The plan of the office levels, like wing A3/ level 3, is a double loaded corridor with offices at each side as seen in Figure (2). Long doubled loaded corridors existed in the university buildings especially in offices sections. The corridors are experiencing a poor daylighting environment. Therefore, they are illuminated by ceiling-mounted fluorescent luminaries. All units are kept on during building occupancy, as the only access to daylight is *via* opened office doors.

Figure (1): JUST engineering faculty buildings

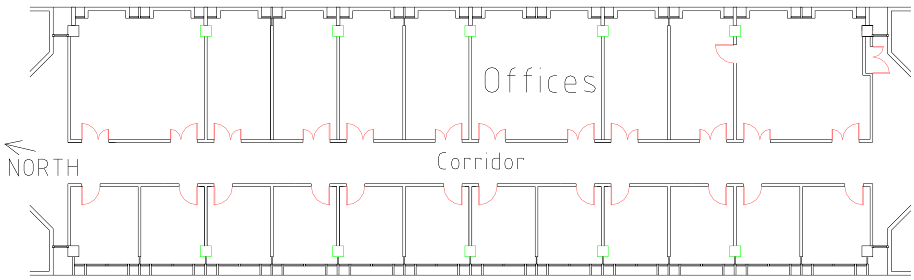

Figure (2): Double loaded corridor in offices floor at JUST (wing A3/level 3)

Double loaded corridors in educational building need lower levels of light compared to reading spaces, offices and hospital buildings. Standards like ISEE and IESNA showed that the required task light level in corridor spaces ranges from 100 to 200 Lx to be efficiently used (Ander, 1995). The purpose of this research was to explore the possibility of using tubular lighting systems to provide sufficient daylight levels and at the same time improve light environment in double loaded corridors within educational buildings.

The research investigated transferring daylighting to double loaded corridors using four daylight design choices. It explored lighting corridors by using;

1- Tubular daylighting systems like; light pipe and anidolic lighting systems.
2- High windows; windows above human level between side offices and the corridor.
3- Reflective ceiling cavity.

Tubular Daylighting Devices

Green building design is increasingly gaining awareness worldwide from legislators, building owners and designers. Therefore, the current momentum has pushed designers and researchers to create novel and reliable daylighting technologies to reduce the dependence on electric lighting while saving non-renewable energy sources. Fortunately, the emergence of optical technology has helped develop new daylight devices like tubular devices. Tubular devices could help in harnessing and distributing daylight into a building's interior spaces without direct contact with the outside. Tubular daylight devices, like light pipes and anidolic ducts, depend on capturing sunlight at the top or the side of a building, then the captured light is transferred through optical reflecting tubes to the diffuser unit in a building's interior spaces. Tubular daylighting devices help designers bring the benefits of daylight to every space in the building without difficulty. In consequence, designers find that they are no longer restricted to traditional daylighting methods.

Light Pipes

Light pipe technology is an advanced daylighting technology used to bring light to a space with no direct contact with the outside. A light pipe is a cylindrical tube connected to a collecting unit and a diffusing unit. The literature review shows that many researchers have studied light pipes. Elmualim et al. (1999) used a dichroic material to develop the light pipe's performance as an integrated system for daylighting and ventilation. The integration was based on using two concentric channels for both daylighting and natural ventilation. The inner one will guide sunlight and daylight into occupied spaces, while the outer one enables passive stack ventilation.

Oakley et al. (2000) investigated the effect of a light pipe's length, diameter, bend and shape of luminaries and space characteristics on the performance of the light pipe. Jenkins and Muneer (2003) and Jenkins et al. (2005) proposed some models to predict the performance of the light pipe. Jenkins and Muneer (2004) investigated methods used to predict the performance of light pipes. The research simulated a light pipe with a diameter of 50cm and a height of 1m with a high reflective surface of more than 90%. The light pipe has both a capture unit and a distribution unit as seen in Figure (4).

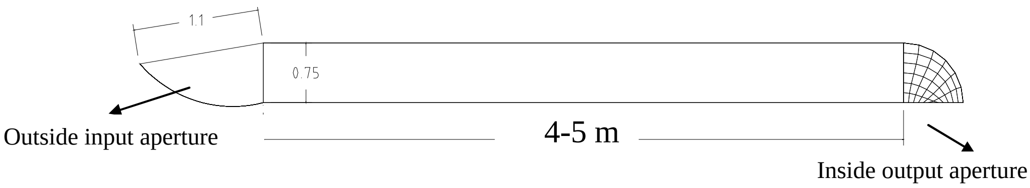

Figure (3): The tested and simulated anidolic system

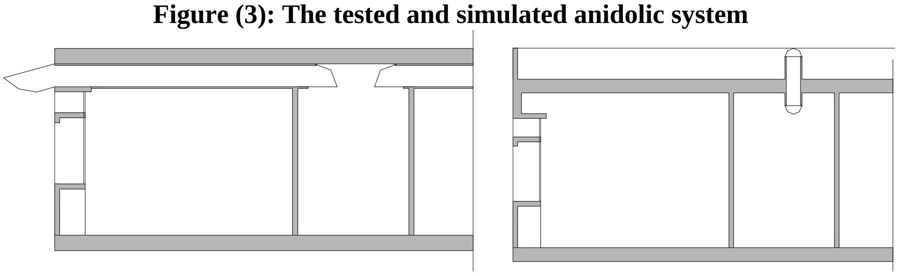

Figure (4): Anidolic (left) and light pipe (right) systems

Anidolic Systems

An anidolic system depends on non-optical materials and total reflection to collect daylight and transports it deep into a space. Scartezzini and Courret

(2002) studied the performance of three types of anidolic systems: anidolic ceiling, integrated anidolic and anidolic solar systems. They showed an overall improvement of daylight penetration and a potential for energy savings. The anidolic systems showed a good improvement in the daylight level in the back part of the tested room and improved the uniformity of distribution in highly luminous climates. Wittkopf et al. (2006) and Wittkopf (2007) studied the performance of anidolic systems in two different climates; Sheffield city in the UK with lower sun altitude and Singapore with high sun altitude. The study results showed that the anidolic system has the potential to improve daylight level and save energy in both locations.

The research used the anidolic systems from both sides of the office floor to light the corridor, Figures (3) and (4). The anidolic duct height was 75 cm, with capture and distribution units as seen in Figures (3) and (7) and a length ranging from 4 to 5 m based on the depth of the offices at both sides.

Ceiling Cavity

Side offices, at JUST, have a large glazing area as seen in Figure (6). The research studied the upper part of the window to reflect light to a ceiling cavity in order to convey light to the inner corridor. This can be done with minimum design alternation by adding an inclined reflector from the base of the upper part of the window to the ceiling cavity as seen in Figure (5). The ceiling cavity will work as a ceiling wide anidolic system.

High Level Windows from Side Offices

This option depends on using high, above human level, windows between the offices and the corridor. The windows will help convey daylight to the corridor through office spaces as the offices have a large glazing area as shown in Figures (5) and (6).

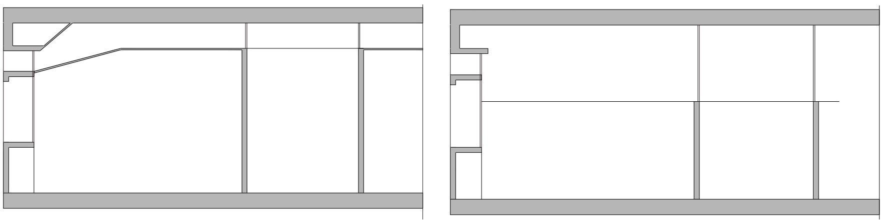

Figure (5): Ceiling cavity (left) high windows from side offices (right)

Figure (6): Office interior details (left) and window details from outside (right)

METHODOLOGY

The research was based on experimental and computer simulation models. Experiments were conducted at Jordan University of Science and Technology (JUST) under real weather conditions on a sunny day. The study included the construction of a real anidolic system and an experimental daylight chamber. The anidolic duct is of 50cm width, 50cm height and 5m length and constructed from highly reflective stainless steel sheets of more than 90% reflectance factor as seen in Figure (7).

Figure (7): The actual anidolic duct and the experimental chamber

The research also used radiance simulations to test different design choices. First, the performance of the anidolic system was examined in a room with the same dimensions and surface parameters of the room used in the experiment. The room has no openings to the outside, thus the researcher implemented the simulation to explore the effect that an anidolic systems could have on the lighting environment. In addition, more radiance simulations were performed to optimize the anidolic system’s performance by modifying its height. Secondly, the application of anidolic systems in the existing double loaded corridor at JUST was simulated and compared to the reference case of the double loaded corridor without anidolic systems. Thirdly, new simulations of double loaded corridors with a set of lightpipes were conducted to examine how light pipes could improve the lighting environment compared to anidolic systems, especially in upper floors. The research was conducted using architectural solutions to light the corridor using ceiling cavity and high windows through side offices. The windows were suggested, because the offices have large windows especially those facing west south. Therefore, it is possible to light corridors through side offices with large glazing area. The dominant sky conditions in Jordan were used as the main sky conditions for both the experiments and computer simulations. Therefore, clear sky conditions with sun were applied for simulation, and at the same time the experiments were conducted under clear sky conditions.

Radiance

Due to continual changes of quality and quantity of daylight, predicting daylight by a physical model is quite difficult and time consuming. Computer simulations have been adopted to save time and ease the changing of design options while accelerating the investigation of design options. There are two approaches which can be used for detailed estimation of the luminous environment in the interior of a building; radiosity and ray-tracing method. In the radiosity method, a given room is divided into a mesh of patches. Each patch is considered as a lambertian reflector, which means that it has a constant luminance and is independent of the viewing direction. The flux that leaves each patch is given a value. The whole process is iterative and proceeds until all the reflected flux has finally been absorbed (Tsangrassoulis et al., 1996). In ray-tracing technique, either forward or backward, rays are traced from the source or back to the source. Each ray carries a weight that is proportional to the intensity of the corresponding ray. After an intersection with a surface, new rays are generated and their weight depends on the surface reflection. A well-known tool based on the ray-tracing technique is radiance. Special extensions were developed to improve the ability of radiance in simulating devices like light pipes. It can easily deal with complex building forms and geometries and different material refelction properties like: diffuse, specular and semi-specular materials. It can also deal with transmission functions and modelling advanced lighting redirecting devices like laser-cut panels. With such exceptional flexibility, radiance is a highly capable lighting simulation program currently available (Greenup and Edmonds, 2004). Moreover, colour visual representation of a room is possible and the most important prediction of luminance values is easily done in radiance. Radiance has been validated by different researchers for a number of cases and agreed well with experimental measurements (Greenup and Edmonds, 2004; Ochoa and Capeluto, 2006).

RESULTS AND DISCUSSION

Results of Using Tubular Systems

Figure (8) shows the daylight level inside the experimental chamber as a result of using an anidolic duct. The results show that using anidolic systems with a length of more than 4m could help improve the lighting level inside the closed chamber and therefore could be used to light double loaded corridors. The results show that the minimum illuminance level with high reflective anidolic duct reaches 100 Lx, which is sufficient to maintain an acceptable task level in corridors.

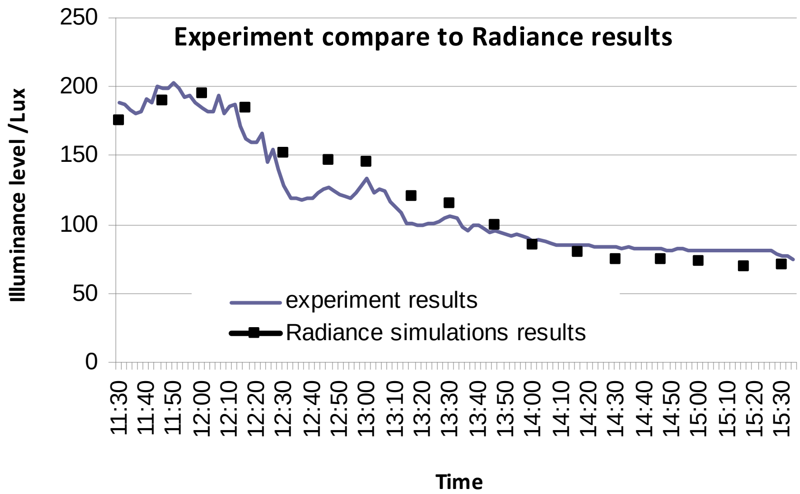

Figure (8): Experimental results compared to radiance simulation in the daylighting chamber

The discrepancy between radiance and measured data was calculated using mean bias error (MBE) and root mean square error (RMSE) (Li et al., 2004). MBE and RMSE are given as:

$$MBE = (1/N)\left[\sum \frac{i_r - i_e}{i_e}\right]$$

and

$$RMSE = \sqrt{(1/N)\left[\sum \left(\frac{i_r - i_e}{i_e}\right)^2\right]}$$

where:

i_e is the measured data from the physical model.

i_r is the reading using radiance.

N is the number of readings.

Simulation results of the experimental chamber show a good agreement with the real results with RMSE less than 10%. The setting could be used to study the suggested choices.

Figures (9) and (10) show that installing anidolic systems improves the daylight level and the appearance of the corridor. It is clear that the daylight distribution is more uniform and the corridor looks brighter, especially in the middle part, while it looks darker in the middle part in the base case without installing the anidolic system. Moreover, non-uniform distribution of lighting will increase the glare index and make the lighting environment unhealthy, creating visual problems.

Figures (9-11) show the illuminance environment in the base case at 8 am, the illuminance environment in the corridor with and anidolic system at 8 am and the illuminance environment in the corridor with light pipes at 8 am, respectively. The base case shows that the corridor lacks sufficient light and the window at the end is a source of glare. In addition, it shows the uneven distribution of light across the corridor in the base case compared to that with light pipes as seen in Figure (15). Light pipes help improve daylight quality in the corridor as seen in Figure (11). The difference in illuminance level across the corridor decreases as well as the effect of glare, improving the uniformity as seen in Figure (15).

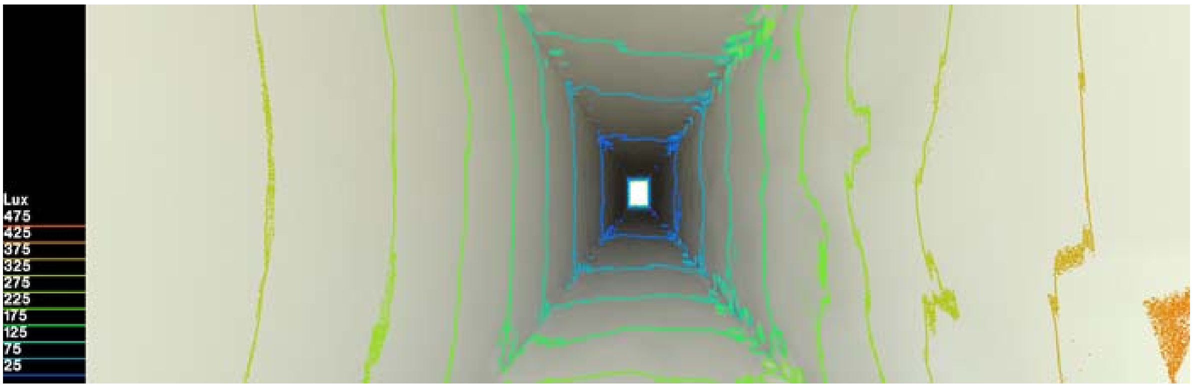

Figure (9): The illuminance environment in the base case at 8 am

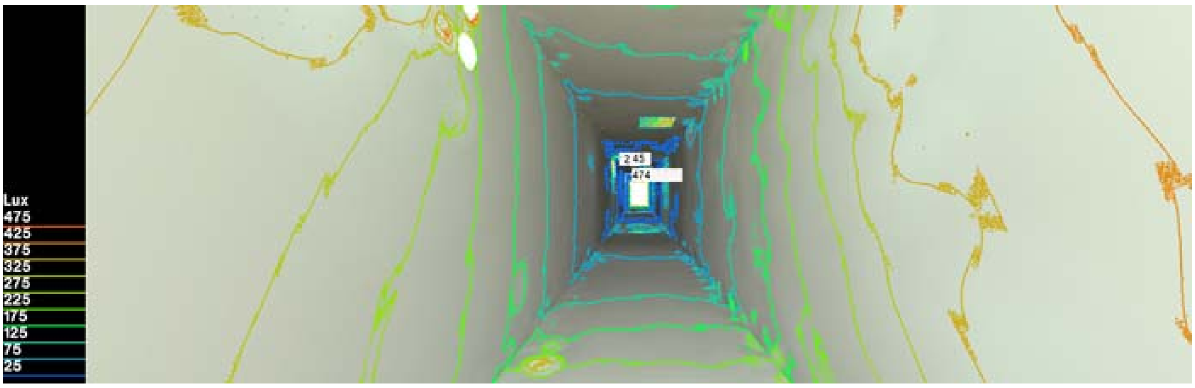

Figure (10): The illuminance environment in the corridor with an anidolic system at 8 am

Figure (11): The illuminance environment in the corridor with light pipes at 8 am

Figures (12-14) show the illuminance environment at 2 pm in the base case, in the corridor with an anidolic system and in the corridor with light pipes, respectively. The figures show that anidolic systems and light pipes helped improve daylight environment by making daylight distribution more uniform and reducing glare effect compared to the base case.

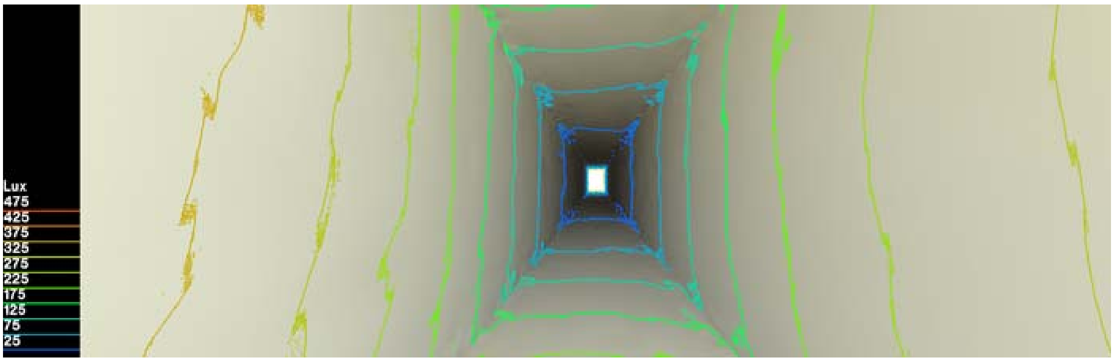

Figure (12): The illuminance environment in the base case at 2 pm

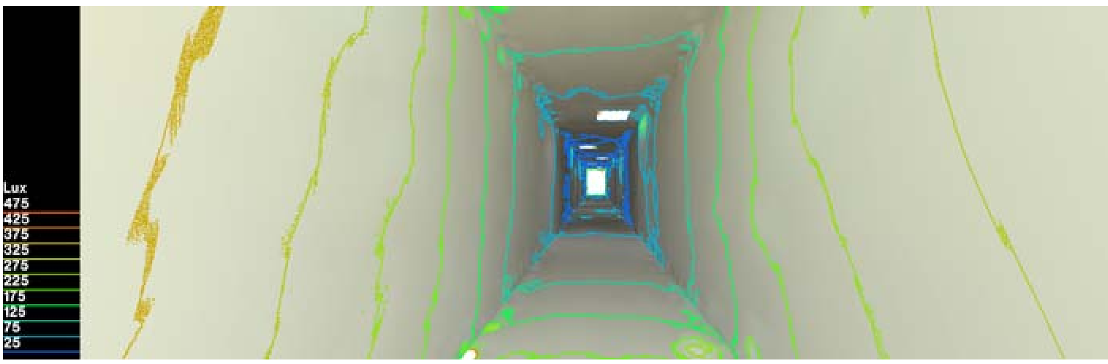

Figure (13): The illuminance environment in the corridor with an anidolic system at 2 pm

Figure (14): The illuminance environment in the corridor with light pipes at 2 pm

Horizontal working plane illuminance levels along the midline of the simulated corridor obtained from radiance simulations are shown in Figure (15). The figure shows that the anidolic systems improved daylight level along the midline by an average of more than 200%. The illuminance level in the middle of the corridor was increased from 20 Lx to around 100 Lx, while it was increased from less than 100 Lx to more than 150 Lx at both ends of the corridor. It is clear that anidolic systems could improve the lighting environment to meet the task illuminance level in corridor spaces, thus the need for artificial light could be minimized. The figure shows that the difference in the illuminance level at the midpoint and at both ends of the corridor decreased and the uniformity of daylight distribution improved.

Using light pipes, as seen in Figure (15), increased the illuminance level along the midline in the double loaded corridor in a top floor plan. Light pipes help improve daylight level along the midline to meet the task light level in corridor spaces. The illuminance level in the middle of the corridor was increased from 20 Lx to around 150 Lx. Light pipes could diminish the use of artificial light during the working hours all the day. Figures (11) and (14) show that installing light pipes improve the corridor appearance. The uniformity of daylighting distribution and the visual environment were also improved.

Both high windows from the side offices and ceiling cavity improve daylight level up to the required task level. High windows could be a right solution if the privacy of offices is maintained. The illuminance level at the midline of the corridor was increased to more than 130 Lx, which is close to the required level. The uniformity along the corridor compared to the base case. The ceiling cavity increased the illuminance level along the corridor compared to the base case and decreased the differences in the illuminance level. The ceiling cavity did not increase the illuminance level to the level achieved by the other solutions.

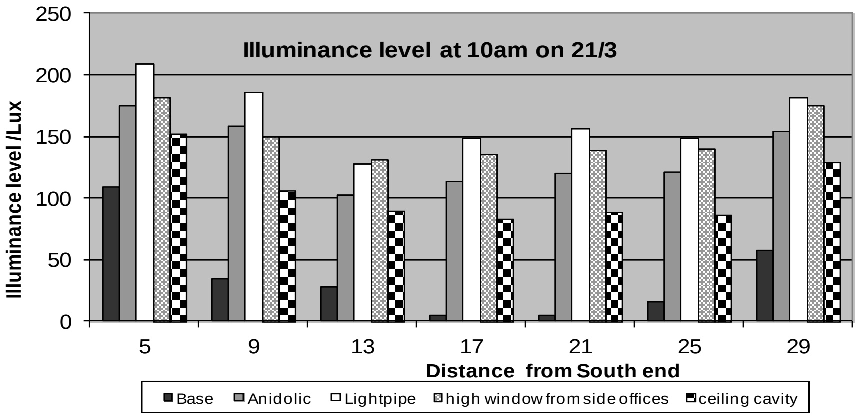

Figure (15): Illuminance level along the midline of the corridor at 10 am on 21st March

Results of Tubular Daylight Systems around the Year

Figures (16-18) show the illuminance level at the midpoint of the simulated corridor all the day in March, June and December, respectively. The midpoint was selected because it has the lowest light level in the base case. Therefore, improving the daylight level at this point means improving the daylight level along the corridor. Moreover, improving the daylight level all the time during the day in March, June and December will be a clear indicator of improving the daylight level around the year.

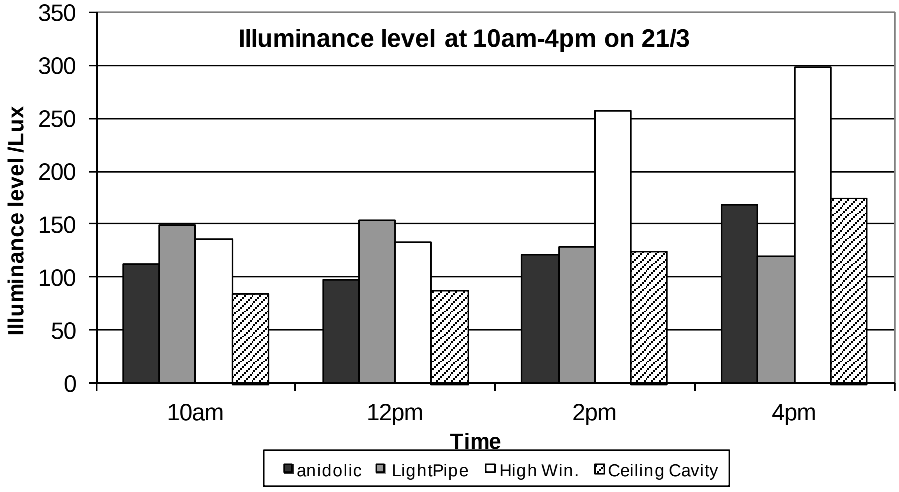

Figure (16): Illuminance level at the midpoint of the corridor in March at 10 am, 12 pm, 2 pm and 4 pm

The figures show how light pipes performed around the year. It is clear that light pipes could provide double loaded corridors with the required illuminance level. The light pipes performed well with high altitude solar angles at the noontime, especially through the period from March to October. Light pipes can provide the corridor with an illuminance level of more than 300 Lx. On the other hand, light pipes can provide the corridor with the required illuminance level up to 150 Lx in the period from November to February.

Anidolic ducts could provide double loaded corridors with the required illuminance level most of the time around the year. They provided the corridors with an illuminance level up to 200 Lx within the period from March to October, while they provided the corridors with an illuminance level up to 100 Lx in the rest of the year.

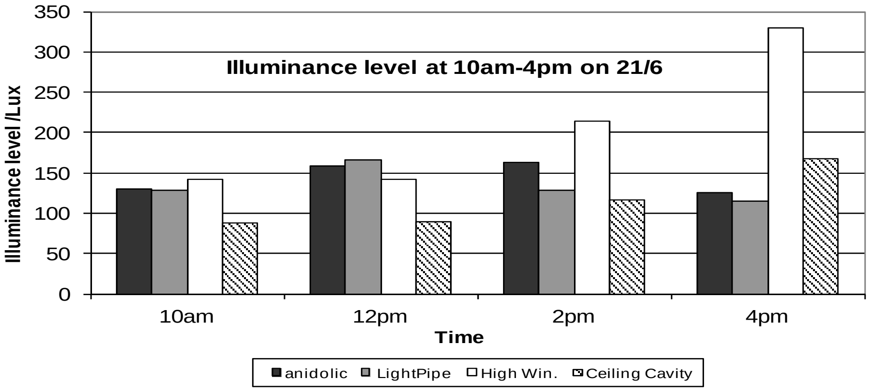

Figure (17): Illuminance level at the midpoint of the corridor in June at 10 am, 12 pm, 2 pm and 4 pm

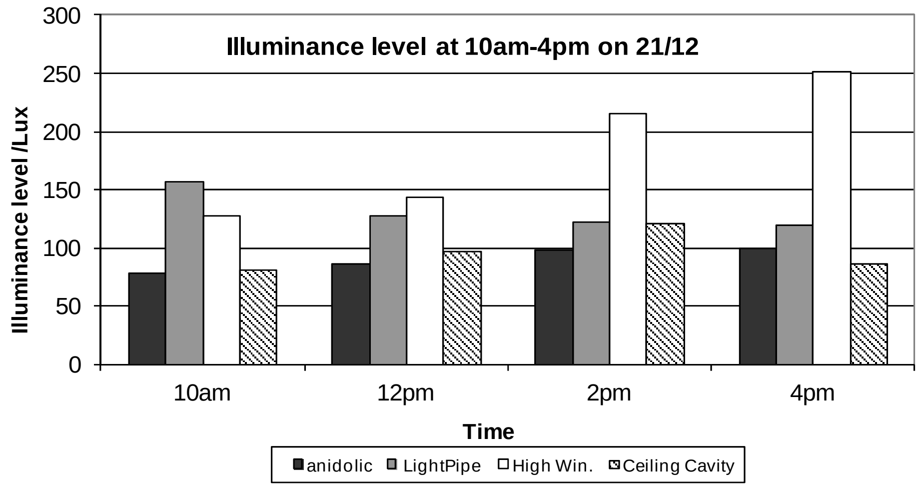

Figure (18): Illuminance level at the midpoint of the corridor in December at 10 am, 12 pm, 2 pm and 4 pm

Results of Architectural Solutions around the Year

Using ceiling cavity improves the daylight level up to the lighting standards. It could provide the corridor with the required lighting around the year. Figures (16-18) show that ceiling cavity increased the illuminance level because of the large area of the opening and diffuse unit. Ceiling cavity helps improve the visual environment in the corridors around the year and could reduce the dependence on artificial light and provide the corridors with an illuminance level up to half of the required illuminance level around the year.

High glazing panels help improve the illuminance level in the corridors, especially in the afternoon time. They could increase the illuminance level up to 150 Lx. It is clear that lighting corridors from side windows requires a large glazing area in the offices, which will create an uncomfortable environment inside the offices. Using glazing panels in the upper part of the wall between the offices and the corridor improves the illuminance environment in the corridor with minimum modifications and less cost. Around the year, as seen in Figure (16-18), this option could help provide the corridor with the required illuminance level while saving energy.

Cost and Energy Saving

JUST consumes on average about 10MWh monthly and about 120MWh yearly. Lighting classrooms, offices and corridors counts more than 70% of the energy consumption. Therefore, conveying daylight to double loaded corridors will reduce energy consumption and help improve energy performance of the whole campus.

As mentioned before, corridors were lighted using ceiling mounted fluorescent luminaries. The number of the installed fluorescent units in the tested corridor is 12 units. Each unit has 2 fluorescent tubes with power consumption of 40Wh. Therefore, the total energy consumed (EC) by lighting the corridor can be calculated as follows:

EC= Number of units (NU) x number of tubes (NT) x tube power (TP) x number of working hours (kWh).

For that reason, the total power consumed in the corridor during working hours will be around 9kW a day for a period of time from 8am to 5pm. The corridor will consume more than 2200kW yearly as for 22 days per month. The cost of the energy consumed will be more than 1100 US dollars based on energy prices in Jordan at the time of conducting the research.

The cost of the construction of a stainless steel anidolic system with a length of 5m, as the one used in the experiments, was 6000 US dollars for seven units used in the simulation, while the cost of the construction of light pipes was less than 3000 US dollars for five units used in the simulation. The payback period of anidolic systems will be less than 6 years, while for light pipes it will be less than 3 years.

CONCLUSIONS

This study explored improving daylighting environment in double loaded corridors using tubular daylight devices and some architectural solutions. These were examined using radiance simulation. Anidolic systems, light pipes, ceiling cavity and high windows from side offices were studied. The results were compared to the base case; double loaded corridors without daylighting devices. Anidolic systems improved the illuminance level to meet the task level for corridor spaces, thus reducing the usage of artificial light in more than two thirds of the corridor length at JUST. Anidolic systems depend on side openings and can be used in multi–stories. Light pipes can significantly improve the illuminance level along the corridor and therefore diminish the dependence on artificial light. Light pipes depend on roof openings and can therefore only be used on top floors. Ceiling cavity could help improve the lighting environment inside double loaded corridors, especially openings facing the sun. Ceiling cavity will not provide the corridors all the time with the required illuminance level, especially with a low reflective material, but it could provide the required illuminance level if a high reflective material with high cost is used. High windows could work in regions with dominant overcast sky conditions as the office could have large windows. Offices, in JUST, experienced poor daylight environment due to high illuminance level and glare, which push users to use curtains to overcome such problems. Also, using high windows could provide corridors with a low level of daylight if windows in the offices were designed for real requirement conditions.

Using tubular lighting systems will help improve visual comfort in corridors due to natural light and distribution to a large area. They also help save energy and could be an attractive way to reduce energy consumption in educational buildings in general. Large energy saving using tubular lighting systems will have a positive impact on the environment as a result of reducing CO_2 emission.

Acknowledgement

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