T11-O-05: Sustainable technologies

# ANIDOLIC DAYLIGHTING SYSTEM: A SUSTAINABLE DAYLIGHTING TECHNOLOGY FOR HIGH-RISE AND HIGH-DENSITY RESIDENTIAL BUILDINGS

Lau S.Y. Stephen[1,*] and Baharuddin[1,2]

[1]Depertment of Architecture, The University of Hong Kong, Hong Kong SAR, China
[2]Department of Architecture, Hasanuddin University, Makassar, Indonesia

[*]Corresponding email: ssylau@gmail.com

**Keywords:** Anidolic daylighting system, Light redirection, High-rise buildings, High-density environment

## SUMMARY

This paper describes the application of advanced daylighting system to improve daylight illuminance of residential units in Hong Kong. In the high-dense environments, residential units that located at lower floor level are very difficult to get daylight because most parts of the sky are blocked by surrounding buildings. The only daylight available is coming from the zenith parts of the sky and reflected from surrounding buildings. In order to make use of this light, light redirecting device should be used. Based on the Hong Kong conditions, anidolic system has been selected. This device collects light from the zenith and redirects it to the rooms by using parabolic concentrator. The results of simulation show that a significant improvement of daylight illuminance can be achieved at lower floor level. This was indicated by the improvement of DF and DA as well as the vertical illuminance at the rear part of room.

## INTRODUCTION

### Background

Daylighting is an important strategy in architectural design. As a strategy, it aims to provide spaces with suitable lighting environments. Daylighting offers ways to save energy by reducing electrical consumption of artificial lighting, which renders it a vital component in sustainable architecture. In residential architecture in particular, daylighting is the preferred choice of the occupants, who perceive it as healthier than artificial lighting and a way of maintaining contact with the outdoor environment (Wilson and Brotas, 2001).

Even though daylight is well appreciated by Hong Kong residences, its utilisation is very marginal. The urban form which is mostly high-rise buildings located in high density situations become one of the obstacles in utilizing daylight in Hong Kong urban area. Hong Kong is the city of the world's highest average urban densities of about 6,500 persons per $km^2$ overall or a peak density of about 46,000 persons per km2. In a compact urban environment where live, work and leisure happens in a mixed and combined mode. The urban form portrays a case of urban canyon where living spaces at the lower parts of high-rise residential buildings is often disadvantaged of daylight, natural ventilation and views.

In the high-dense environments, residential units that located at lower floor level are very difficult to get daylight because most parts of the sky are blocked by surrounding buildings. The only daylight available is coming from the zenith parts of the sky and reflected from surrounding buildings. Light coming from the zenith has very little contribution to the illuminance of room that only depend on side opening. Apart from this built forms, Hong Kong sky condition has also great impact on the utilising daylight in high-rise residential buildings. Hong Kong sky is dominated by overcast (cloudy) sky. One study reported that as high as 42% of the sky condition in Hong Kong is overcast sky (Ng et al., 2007).

This paper proposed the way of improving daylight illuminance at lower floor by applying innovative technology (Ullah and Lin, 2003; Edmonds, 2005), such as light-redirecting devices. There are a number of light-redirecting devices available. However, the system that applicable for Hong Kong situation might be different to others. In Hong Kong, the available light from the sky are mostly diffuse light coming from zenith part and light reflected by surrounding buildings. In our preliminary investigation on the application of anidolic daylighting system in the heavily obstructed environments (Lau and Baharuddin, 2006), it was found that anidolic daylighting system has a potential to work well in this situation. Therefore, the present paper investigates the application of this system in more details.

**Basic Principles of Anidolic**

Non-imaging optics principles have been applied to the design of new reflectors forming daylighting systems (Courret et al., 1998; Scartezzini and Courret, 2002). These systems called anidolic systems (an: without, eidolon: image in ancient Greek). The principles of this system is based on the used of compound parabolic concentrator (CPC) to redirect lights.

The properties of anidolic system, according to Scartezzini and Courret (2002) are as follows:

a) Anidolic based on non-imaging optics (Edge-Rays principles)
b) Minimize the number of reflection, by maximising collection and distribution of daylight flux (Law of conservation "Etendue").
c) Accurate definition of admittance sector for incoming light rays (capture of diffuse daylight from sky vault)
d) High angular selectivity for exiting light rays ("Beam Projector" for diffuse daylight)

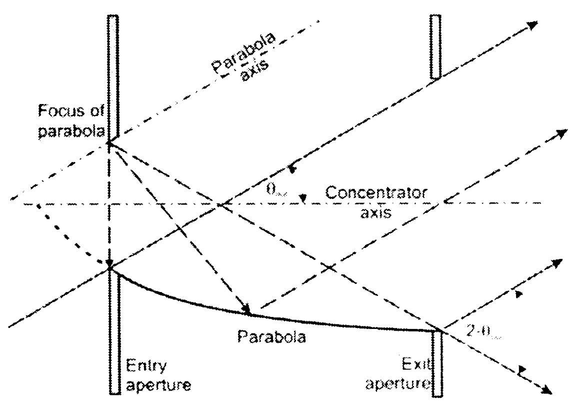


Figure 1. The basic principles of compound parabolic concentrator (CPC) based on edge-rays principles (Scartezzini and Courret, 2002)

According to Winston et al. (2005), all lights coming from the focus of parabolic will be reflected parallel with the parabolic axis (Fig. 1). By using this principle, all lights in front of the window can be redirect to the inside the room.

The research on the application of anidolic daylighting system has been carried out in several research institutes around the world (Courret et al., 1998; Molteni et al., 2001; Lau and Baharuddin, 2006; Ochoa and Capeluto, 2006; Wittkopf et al., 2006; Lau et al., 2007; Wittkopf, 2007). The main focus of these researches is the use of this non-imaging optics to increase the daylight factor in the rear zone of the deep room.

Anidolic system increased daylight factor in the back of the room and decreased DF in the front part of the room in overcast sky condition. It reduces discomfort due to glare or to improve the illuminance uniformity ratio, the upper window has to be equipped with a daylighting system. This system also improves visual comfort probability for a large part of the room (Compagnon et al., 1993). They further explain that anidolic concentrator is designed to accept all incoming light from half the sky hemisphere.

**Daylight Performance Criteria**

A daylight performance criterion is used to evaluate the performance of daylight systems which is relate to visual performance. This criterion covers daylight quantity and daylight quality aspects. Daylight quantity is an absolute numbers for measuring the penetration and the spread of daylight illuminance levels. These performance criteria commonly measure with the minimum illuminance in the working plan level at 0.85m from the floor assumed for domestic building (Wilson and Brotas, 2001). While daylight quality is a relative numbers that indicate the directionality and contrast. It is very hard to measure the quality of daylight. In the literature there are several methods available to measure this performance. Some of them are daylight uniformity and glare index.

For the purpose of this study, three performance criteria have been used. Two of them were quantitative metrics i.e. daylight factor (DF) and daylight autonomy (DA) and one was qualitative evaluation i.e. vertical illuminance distribution at the wall, especially at rear parts of the room.

DF is a common parameter to evaluate the daylight performance at a point in a building. It is defined as the ratio of the indoor illuminance at a point of interest to the outdoor horizontal illuminance under the overcast CIE sky (Hopkinson et al., 1966). The daylight factor enjoys considerable popularity since it is an intuitive quantity which can be measured and/or calculated either based on calculation tables or more refined simulation methods (Reinhart, 2006).

Based on our experience, the use of DF performance criteria alone could not satisfy the daylight requirements. Because DF does not take into account the orientation of the buildings under the assessment, since the CIE overcast sky is invariant to the building orientation and independent to the geographical location, date and time. CIE Overcast Sky is 3 times brighter than the horizon. To supplement the DF criteria, the daylight autonomy (DA) has been applied. DA at a point in a building is defined as the percentage of occupied hours per year, when the minimum illuminance level can be maintained by daylight alone. In contrast to the more commonly used daylight factor, the daylight autonomy considers all sky conditions throughout the year (Reinhart, 2006).

The minimum illuminance level corresponds to the minimum physical lighting requirement which has to be maintained at all times so that a certain task can be carried out safely and without tiring the working occupant. In this study we used the minimum illuminance of 150 lux. This minimum illuminance taken from the preferred light level at home for the people living in Hong Kong, based on the research report by Zhan qingxuan cited in Yuan (2005).

The vertical illuminance at the wall of the room is the qualitative judgment that compared the brightness and the dark part of the wall. It can be judged based on the rendering images with the false colour. The importance of vertical illuminance has been discussed by Chung (Chung, 2005). He states that design for sustainable lighting not only consider the illuminance at the horizontal work plane but should also takes into account the vertical illuminance at normal eye level of the occupants e.g. 1.2 m for normally seated occupants and 1.7 m for normally standing occupants.

## METHODOLOGIES

### Computer Simulation Method

This study was carried out using the computer simulation technique. Two lighting simulation programmes have used i.e. RADIANCE and DAYSIM. RADIANCE is a physical based, backward ray-tracing rendering tool that has been developed by Greg Ward at Lawrence Berkeley National Laboratory. RADIANCE is able to simulate internal illuminance and luminance distributions in complex building under arbitrary sky conditions (Larson and Shakespeare, 1998).

DAYSIM is a RADIANCE-based lighting simulation program that dynamically calculates the daylight performance in the interior. The calculation based on one year round. It has been used to calculate the DF and DA inside the rooms (Reinhart, 2006). DAYSIM was used to calculate the DF & DA performance of all cases, while RADIANCE was used to render the images of all cases. The simulation parameters used in RADIANCE and DAYSIM are listed in Table 1.

Table 1. RADIANCE and DAYSIM settings

| Parameter settings | RADIANCE | DAYSIM |
|---|---|---|
| -ab (ambient bounces) | 5 | 5 |
| -aa (ambient accuracy) | 0.15 | 0.2 |
| -ar (ambient resolution) | 256 | 128 |
| -ad (ambient division) | 1024 | 512 |

### Model Settings

In order to investigate the contribution of anidolic system, three cases have been simulated. The three cases include one base-case and two different scenarios. The first scenario was to put clerestory window above the bay window. The other scenario based on the anidolic system. The detail of three cases, the room and the surface reflectances can be seen in the Fig. 2(a). The room selected was a 12 m2 room that located at the lowest floor of residential buildings. The building obstruction is very high with inclined angle of 71.5$^{o}$ in front of the window to the opposite building (Fig. 2(b)).

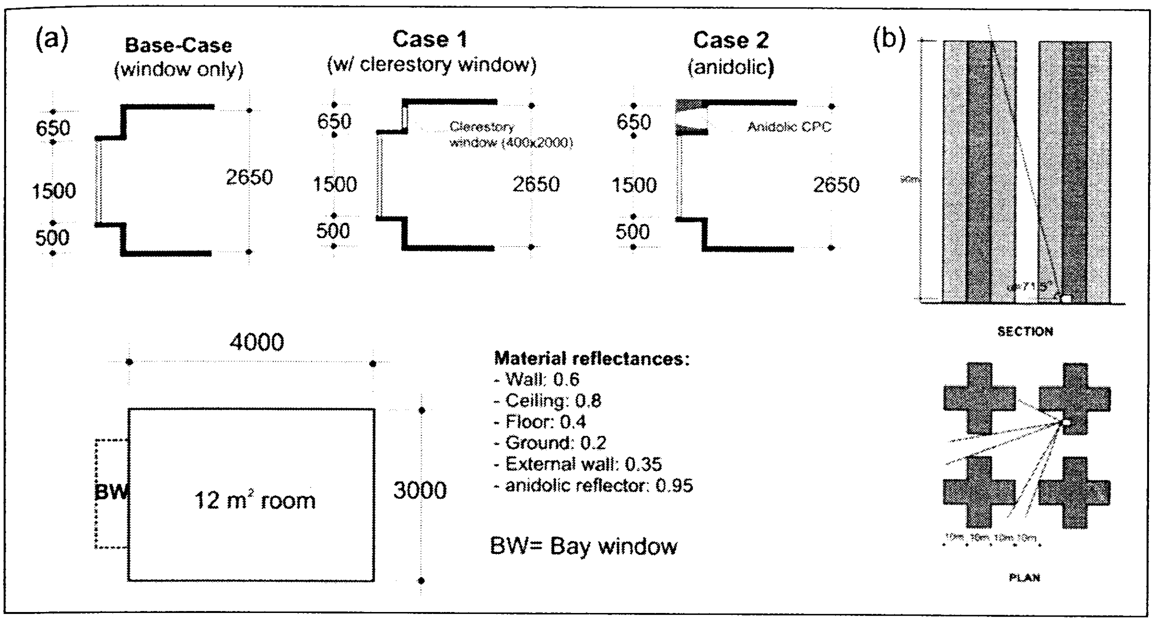


Figure 2. (a) The geometries of the three cases, plan and material reflectance of the rooms and the reflector, and (b) Plan and section of the building form & layout

## RESULTS AND DISCUSSION

The summary of DF and DA results of the Base Case and the three cases can be observed in Table 2. In the overall, among the three cases, Case 2 (anidolic) performed higher than the Case 1. The Case 2 has very big impact on the DF performance of the room. The overall improvement can as high as 63.6% and 12.1% for DF and DA, respectively, in comparison to the Base Case window.

Table 2. Summary of Daylight Factor (DF) and Daylight Autonomy (DA) performance of the three cases

| Daylight Performance | Base Case | Case 1 | Case 2 |
|---|---|---|---|
| DF (%) | | | |
| Minimum | 0.5 | 0.7 | 0.8 |
| Maximum | 2.9 | 3.6 | 4.2 |
| Average | 1.1 | 1.6 | 1.8 |
| Improvement (%) | - | 45.4 | 63.6 |
| DA (%) | | | |
| Minimum | 57.0 | 68.0 | 70.0 |
| Maximum | 86.0 | 88.0 | 4.2 |
| Average | 71.7 | 78.9 | 80.4 |
| Improvement (%) | - | 10.0 | 12.1 |

Daylight Factor distribution at the working plane level for the three cases are presented in the Fig. 3. The yellow colour shows the highest DF, while the blue one represent the lowest DF. As can be seen from the Fig.3, both Case 1 and Case 2 have higher DF distribution than the Base Case. Among the three cases, Case 2 has the highest DF distribution.

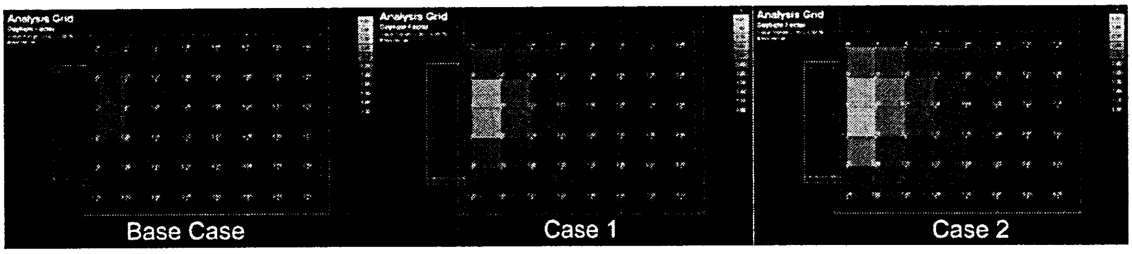


Figure 3. Daylight Factor distribution at the working plane level of the three cases.

## Daylight Factor

The comparison of DF of the six points at the centreline of the room for the all cases can be seen in Fig. 4(a). As can been from the figure, both cases (Case 1 and 2) have DF performance higher than the DF of Base Case. Among the three cases, Case 2 performed the highest DF. Therefore, Case 2 has the best DF performance.

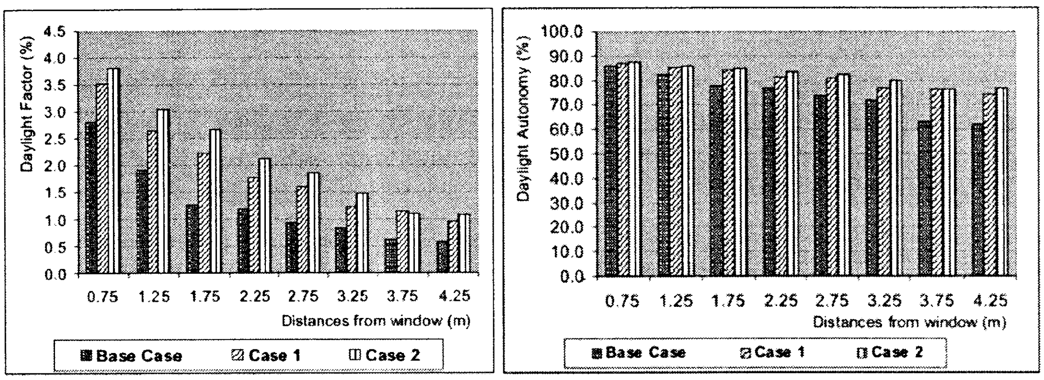


Figure 4. (a) Daylight Factor and (b) Daylight Autonomy of the three cases.

The problem of DF criteria is because it is only based on one single sky i.e. overcast sky. It does not take into account other types of skies e.g. clear sky and intermediate sky. In these types of skies, DF can be used. Therefore, using DF only represent the worst case. To supplement this performance criterion, the DA criteria has been used.

## Daylight Autonomy

As can be seen from Fig. 4(b), the anidolic system (Case 2) had improved the DA performance of the room. Their performances were better than the Base Case and Case 1. By comparing the DA in eight points at the centreline of work plane, it was found that DAs of Case 2 at seven points are higher than the two cases (Base Case and Case 1). Therefore, anidolic system in Case 2 produces the best DA performance.

## Vertical Illuminance

For residential buildings, vertical illuminance at the wall could be very important criteria. This will determine the room looked bright or gloomy. If the vertical illuminance between the walls surfaces too contrasts, then some part will look gloomy and others look bright. Fig. 5 shows that the wall in the rear part of the Base Case window looked quite dark. The addition of clerestory window above the bay window improved the vertical illuminance to some extent. The used of anidolic lighting system (Case 2) made the vertical illuminance even better.

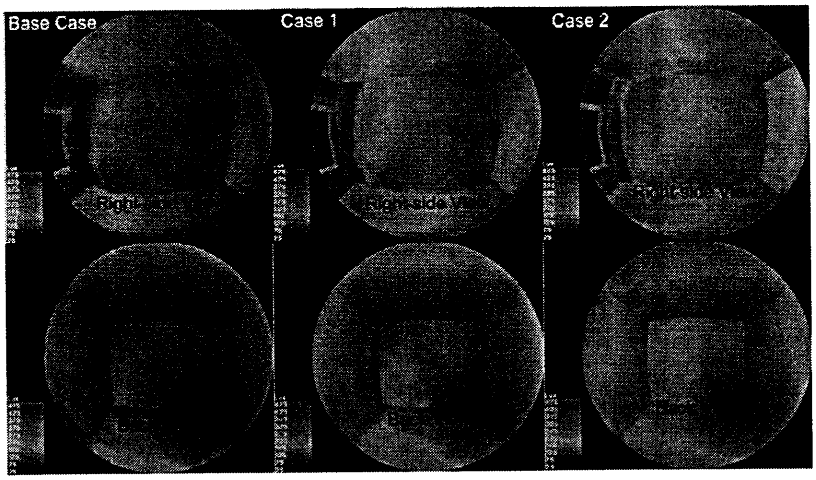


Figure 5. Vertical Daylight Illuminance at the wall of the three cases

From the three performance criteria, we found that, in the overall, Case 2 has the best performance compared to the Base Case and Case 1 (Table 3).

Table 3. Evaluation of the performance of three cases compared to the Base Case

| Performance criteria | Case 1 | Case 2 |
|---|---|---|
| Daylight Factors (DF) | √ | √√ |
| Daylight Autonomy (DA) | √ | √√ |
| Vertical Illuminance | √ | √√ |

Notes: √ = better performance than the Base Case
√ √ = the best performance

## CONCLUSIONS

This study has demonstrated the application of anidolic daylight system for improving daylight performance of high-rise residential buildings in high-density environments. It shows a significant improvement of daylight illuminance of the unit situated at the lowest floor where the obstruction is very high i.e. 71.5°. The Case 2 (anidolic) has shown to be the best performance in the overall. It improved DF by 63.6% and 12.1% DA compared to the Base Case window. It also improved the vertical illuminance at the rear wall of the room.

This study recommends that application of this system to improve daylight illuminance (DF & DA) and vertical illuminance in the rear wall for the units at lower floor level. This could be applied for the existing building as well as new buildings. The integration of this system for the existing residential buildings need further study in order to find out the practicality aspects of its application. This may includes for examples construction and cost issues.

## ACKNOWLEDGEMENT

The authors acknowledge the support of The University of Hong Kong Small Research Funding (Project Code: 200807176215) for this research.

## REFERENCES

Chung, T.M. (2005) Sustainable lighted environment: health and lifestyle. *2005 International Lighting Symposium Lifestyle Lighting in Modern Cities.* Hong Kong, CIE Hong Kong.

Compagnon, R., Scartezzini, J.-L. and Paule, B. (1993) Application of nonimaging optics to the development of new daylighting systems. *ISES World Solar Congress.* Budapest, Hungary.

Courret, G., Scartezzini, J.-L., Francioli, D., et al. (1998) Design and assessment of an anidolic light-duct. *Energy and Buildings,* **28,** 79-99.

Edmonds, I. (2005) Daylighting high-density residential buildings with light redirecting panels. *Lighting Res. Technol,* **37,** 73-87.

Hopkinson, R.G., Petherbridge, P. and Longmore, J. (1966) *Daylighting,* London, Heinemann.

Larson, G.W. and Shakespeare, R.A. (1998) *Rendering with RADIANCE: the art and science of lighting visualization,* Los Altos, CA, Morgan Kaufmann.

Lau, S.S.Y. and Baharuddin (2006) An Investigation of Innovative System for Daylight in Tall Building in the Subtropics: the Use of Computer Simulation Technique. *Proceeding of 2nd CIB International Conference on Smart and Sustainable Built Environments-SASBE2006.* Shanghai, China, CIB - SRIBS.

Lau, S.S.Y., Baharuddin and Wittkopf, S.K. (2007) The use of anidolic lighting system in improving daylight illuminance of high-rise buildings in Hong Kong. in Wittkopf, S. K. & Tan, B. K. (Eds.) *PLEA2007 - The 24th Conference on Passive and Low Energy Architecture.* Singapore, Department of Architecture National University of Singapore.

Molteni, S.C., Courret, G., Paule, B., et al. (2001) Design of anidolic zenithal lightguides for daylighting of underground spaces. *Solar Energy,* **69,** 117-129.

Ng, E., Cheng, V., Gadi, A., et al. (2007) Defining standard skies for Hong Kong. *Building and Environment,* **42,** 866-876.

Ochoa, C.E. and Capeluto, I.G. (2006) Evaluating visual comfort and performance of three natural lighting systems for deep office buildings in highly luminous climates. *Building and Environment,* **41,** 1128-1135.

Reinhart, C.F. (2006) Tutorial on the use of Daysim Simulations for sustainable design Institute for Research in Construction, National Research Council Canada. [On-line] Available: http://irc.nrc-cnrc.gc.ca/ie/lighting/daylight/daysim/docs/DaysimTutorial.pdf. Accessed: 5 December 2007.

Scartezzini, J.-L. and Courret, G. (2002) Anidolic daylighting systems. *Solar Energy,* **73,** 123–135.

Ullah, M.B. and Lin, L.W. (2003) Daylight distribution in the living rooms of four types of public housing building in Singapore. *Lighting Res. Technol,* **35,** 91-100.

Wilson, M.P. and Brotas, L. (2001) Daylight and domestic buildings. *11th National Conference on Lighting (Light 2001).* Bulgaria.

Winston, R., Miñano, J.C. and Benítez, P. (2005) Nonimaging optics Elsevier Academic Press. [On-line] Available: Accessed: 2 May 2007.

Wittkopf, S.K. (2007) Daylight performance of anidolic ceiling under different sky conditions. *Solar Energy,* **81,** 151-161.

Wittkopf, S.K., Yuniarti, E. and Soon, L.K. (2006) Prediction of energy savings with anidolic integrated ceiling across different daylight climates. *Energy and Buildings,* **38,** 1120-1129.

Yuan, Q. (2005) Chinese life with lighting. *2005 International Lighting Symposium Lifestyle Lighting in Modern Cities.* Hong Kong, CIE Hong Kong.