The Hong Kong Polytechnic University

Department of Building Services Engineering

Integration of a Remote Source Solar Lighting System into the Architectural Design of Enclosed Lift Lobbies in High-rise Residential Buildings

IRENE WONG

A thesis submitted in partial fulfillment of the requirements for
The degree of Doctor of Philosophy

March 2012

CERTICATE OF ORIGINALITY

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__Irene Wong________________ (Name of student)

Department of Building Services Engineering

The Hong Kong Polytechnic University

Hong Kong, China

March 2012

ABSTRACT

Due to high land cost and plot ratio requirements, residential buildings are developed into high-rise central core design in which the lift lobbies are enclosed without natural lighting and the floor height of a residential building is limited to 2.8 m. In conventional remote source solar lighting system, metallic and prismatic light pipes are used as common light transfer mediums. However, the sizes of these light pipes have considerable diameters usually more than 450 mm, and require minimum 3 m headroom clearance for installation. Such headroom requirement is not feasible for the high-rise buildings in Hong Kong. This research is to develop an advanced remote source solar lighting system using side-emitting fiber optic of 10 mm in diameter to transfer natural lighting into the lift lobbies and investigate the potential and energy performance of the application to reduce energy consumption for providing illumination for the enclosed lift lobbies of high-rise buildings in Hong Kong and other countries.

Simulation and experimental study were carried to study the performance of the proposed daylighting system and analyze the factors that could affect the efficiency of the remote source solar lighting system.

As Hong Kong is a densely populated city with majority of buildings developed into high-rise buildings, the shadowing effect from neighbouring buildings was also analyzed. An installation method was proposed to solve the shadowing problem.

The remote source solar lighting system was designed to satisfy both the functional and aesthetic aspects. Design guidelines and flowchart were formulated as a design references for building professionals in applying remote source solar lighting system into high-rise buildings.

Finally, cost analysis of the remote source solar lighting system was carried out. The payback period is about 5 years. The maintenance cost and the environmental benefits offered by the proposed daylighting system were also studied. The remote source solar lighting system can reduce $6.7x\ 10^6$ kg of carbon dioxide emission in a year.

Although the side-emitting technology of fiber optic is still in a very preliminary stage of development and transmission efficiency is very low, the proposed remote source solar lighting system can still provide daylight for an average of 3 hours of 150 lx in a day. Further development in the application of RSSL is proven to be worthwhile. The research findings can provide information for further research on application of remote source solar lighting system. The application of the proposed RSSL is anticipated to be able to extend to provide illumination to interior spaces of other buildings as well when the technology becomes mature.

Keywords: remote source solar lighting system, side-emitting fiber optic, heliostat, enclosed lift lobby, high-rise residential building, central core design, shadowing effect, solar irradiance, solar altitude, solar azimuth angle

PUBLICATIONS ARISING FROM THE THESIS

Journal papers (published)

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Journal paper (submitted)

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Conference papers

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2. Wong, I. Yang, H.X. Introducing natural lighting into the enclosed lift lobbies of high-rise residential buildings by remote source lighting system.

Proceedings of International Conference of Applied Energy 2010, 21-23 April 2011, Singapore. 773-781.

3. Wong, I. Yang, H.X. Application of remote source lighting system in different layouts of enclosed lift lobbies in high-rise residential buildings of central core design. Proceedings of the 5th International Green Energy Conference 2010, 1-3 June, Waterloo, Ontario, Canada. Ref. 57CEACD3.

4. Wong, I. Yang, H.X. Integrating remote source lighting system into the enclosed lift lobbies in high-rise residential buildings of central core design. Proceedings of the First International Conference on Sustainable Urbanization 2010, 15-17 December, Hong Kong, China. 150.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

Symbols	Description
BK7	Optical glass
E_E	Transmission efficiency of an end-emitting fiber optic (%)
E_S	Transmission efficiency of a straight side-emitting fiber optic (%)
E_T	Transmission efficiency of a notched fiber optic (%)
E_{em}	Emission efficiency of a side-emitting fiber optic (%)
K	Diffuse factor (lm/W)
K_{dc}	Diffuse luminous efficacy (lm/W)
K_{bc}	Direct luminous efficacy (lm/W)
K_{gc}	Global efficacy (lm/W)

Greek symbols

θ	Incidence angle (deg)
β	Solar altitude (deg)
γ	Surface azimuth angle (deg)
η	Overall efficiency of RSSL (%)

Abbreviation

D	Light detector

EMI	Electronic and mechanical instrument
EMSD	Electrical & Mechanical Services Department
EFO	End-emitting fiber optic
FO	Fiber optic
HOS	Home Ownership Scheme
L	Length of notched fiber optic
LCP	Laser cut panel
MLP	Metallic light pipe
NFO	Notched fiber optic
NSC	Non-sequential program
PLP	Prismatic light pipe
PH	Private housing
PM	Post meridiem
PMMA	Polymethyl methacrylate
SFO	Side-emitting fiber optic
RSL	Remote source lighting system
RSSL	Remote source solar lighting system
TIR	Total internal reflection

CHAPTER 1

INTRODUCTION

1.1 Background of the research

1.1.1 Global warming

Greenhouse gases emissions cause global climate changes and chaos (Hansen, et al., 1997), and yield a steep and relentless increase in global temperature throughout the twenty-first century (Houghton, et al., 1995) with warming of 0.5 Celsius increase per century (Manabe, et al., 1965) (Charney, et al., 1979) (Hansen, et al., 2001). Carbon dioxide is the main source of greenhouse gases generated from fossil fuel consumption to produce electricity. The Kyoto Protocol in 1997 concluded that industrialized countries should aim to reduce 95% carbon dioxide emission of 1990 level by 2012 (Bolin, 1998). The increase in carbon dioxide emission in recent decades represents about half of the emissions from fossil fuels and changes in tropical landuse. Greater use of energy sources that produce little or no carbon dioxide is required to reduce the carbon dioxide emission (Hansen, et al., 2000).

Energy use in buildings accounts for nearly half of the total primary energy use in Hong Kong (Chen, et al., 2001). Increasing environmental impacts through harmful emissions and exploitation of fossil fuel resources have deeply affected the building industry to the extent that methods of low-energy construction and passive solar energy use have come to be dictated not only by public awareness, but also by global necessity (Pfeiffer, 2003). There is a growing interest to design energy conscious buildings that rely less on the depletable energy resources. A new building philosophy that optimizes solar energy uses so as to minimize the dependency on fossil fuel should be explored.

1.1.2 Central core design in highrise residential buildings

Hong Kong is characterized as a city of high-rise buildings as shown in Figure 1.1. Forty-nine of the tallest one hundred residential buildings in the world are in Hong Kong (Campbell, 2005). Approximately 80% of the 1,902 square kilometers of land in Hong Kong is mountainous (Lai, 1999). Population density was 6,500 persons per square kilometers in 2010 according to the statistic provided by the Census and Statistic Department (HKSAR, 2011). High population density and limited habitable land result in high land value. Residential premises are developed into highrise buildings to compensate the high land cost. The average property price for a common size premise between 40 to 70 m^2 was HK$ 8,627 per square meter in 1997 (Lai, 1999). The total height of a building is governed by the Plot Ratio requirement in the Building (Planning) Regulations (Building Authority, 1997). In order to build more floors within the total building height, the floor height seldom exceeds 2.8 m.

Residential buildings usually adopt a central core design in which the lift lobbies and service areas are grouped in the centre to create more peripheral areas of valuable exterior views that can be sold or leased at a higher price (Wong and Yang, 2011). These lift lobbies are enclosed without natural lighting and depend on electricity, which is generated from fossil fuels, to provide lighting. The interior of a typical lift lobby is shown in Figure1.2. Reduction in the use of electric lighting in these lift lobbies can conserve our environment. This project is to investigate the potential of applying the remote source solar lighting technology to introduce daylight into the enclosed lift lobbies. However the conventional solar light transfer mediums are mainly light pipes of sizes that require a minimum of 3m headroom clearance for installation (Yeang, 2003), which are not suitable for the major high-rise residential buildings of less than 3m headroom in Hong Kong. In this thesis a side-emitting fiber optic of smaller size is proposed to be used as an alternative light transfer medium in the enclosed lift lobbies without reducing the headroom. The application of the side-emitting fiber optic for illumination is still in an early stage of developmental. This research explores the potential for applying the side-emitting technology for fiber optic in illumination in the enclosed lift lobbies.

Fig. 1.1 Birdseye's view of Hong Kong

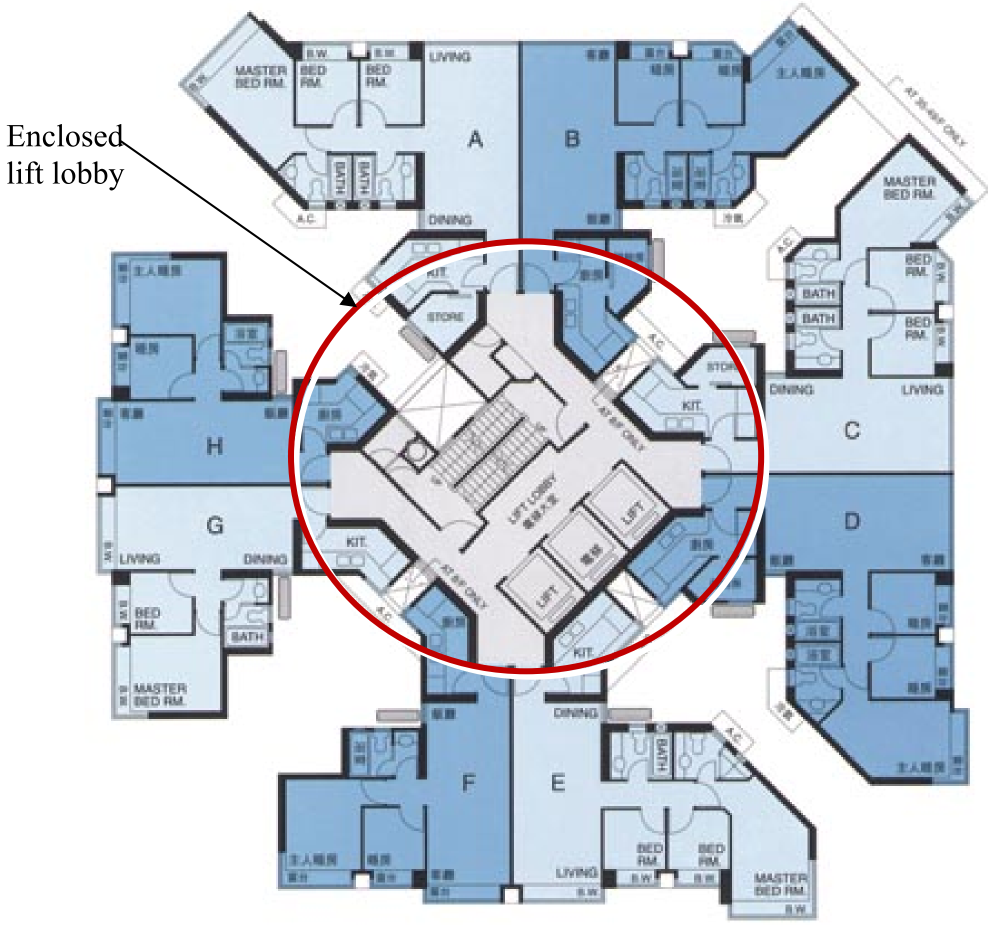

Fig. 1.2 Layout plan of a central core design high-rise building

1.2 Aims and objectives

This research aims to study the application of the side-emitting technology of fiber optic for illumination in enclosed lift lobbies and how the design can be integrated into the architectural design of the high-rise residential buildings. The application of the side-emitting fiber optic as an alternative light transfer medium can solve the limited headroom problem in the application of remote source solar lighting system to the enclosed lift lobbies in Hong Kong. Utilizing solar energy can reduce the dependency on artificial lighting, which is both costly and environmental damaging.

The development of the side-emitting property in fiber optic is still in the very preliminary stage. There are 2 types of side-emitting fiber optic, which are small diameter fiber optics of 0.1 mm to 3 mm and large core fiber of diameter up to 20mm. At present the large core fiber is mainly applied as highlights (Fig. 1.3). The small diameter side-emitting fiber optic is applied mainly in decorative lighting (Fig. 1.4). The main aim of the research is to explore the potential of applying the side-emitting fiber optic as an alternative light transfer medium in remote source solar lighting technology; and investigate the viability of further development of the technology.

In this research the main aims and objectives include:

a) To investigate the major design variables and constraints when solar energy is used for interior lighting in an enclosed lift lobby.
b) To identify the parameters that is necessary in designing the daylighting system.
c) To explore the potentials in energy conservation that can be offered by the remote source solar lighting system.
d) To develop the design guidelines and a prototype for using the remote source solar lighting system in the enclosed lift lobbies in highrise residential buildings in Hong Kong.

Fig. 1.3 Side-emitting fiber optic highlighting a swimming pool

Fig. 1.4 Small diameter side-emitting fiber optic form a chandelier

1.3 Research methodology

The following four methods are used for this research:

a) Questionnaire surveys

b) Computer simulation

c) Experimental study

d) Case study

A survey was conducted by means of structured questionnaires to explore the degree of understanding different views and extent of acceptance of a new daylighting system by both building professionals and end-users, as well as the difficulties that were expected to be encountered in the design and application process. The returned questionnaires were analyzed. From the findings, the need to develop a natural lighting system to be applied in enclosed lift lobbies was established. The survey then proceeded to the second stage.

Site visits were carried out to different residential buildings of central core design. Information of the lift lobbies were collected by recording the layout plans and taking photographs on site. Different layouts of the enclosed lift lobbies were classified. This information was then analyzed in detail to identify the potential and inherited limitations in introducing natural lighting in different types of layout. The "worst case scenario" of the lift lobby layouts with longer and winding corridors was selected for detailed study and design.

The Waterfront House in Malaysia was selected as a reference. The application of the remote source solar lighting system to the interior space of the building was studied in details. The lighting system was modified to suit the enclosed lift lobbies in the residential high-rise buildings in Hong Kong. The remote source solar lighting system was designed based on the information of the Waterfront House project.

The software package ZEMAX-EE is an optical design software package for analyzing various aspects of optical systems. The non-sequential ray tracing analysis of stray light, and physical optic beam propagation in fiber optic is used. The optics can be modeled as 3D components. From the simulations, the efficiencies of different elements and at different lengths of the remote source solar lighting system were estimated. The ZEMAX-EE was then used to analyze the performance of the proposed remote source solar lighting system for different conditions orientations. The factors such as solar azimuth angle, solar altitude and outdoor light intensity that could affect the performance of the system were analyzed.

Experiments were subsequently carried out to verify the simulation results. Part of the lift lobby was represented by a model in 1:2 scale with the remote source lighting system being installed inside. The performance of the system was monitored over the winter to summer seasons. The experimental findings were studied to understand the behavior of the remote source solar lighting system and the factors that could affect the performance of the system. From the results, design guidelines were formulated to derive an optimal model that combined both lighting and architectural design.

1.4 Organization of the thesis

The thesis is organized into 9 chapters. Chapter I introduces the research background, the aims and objectives to be achieved, the research methodology, and organization of the thesis.

Chapter 2 presents the findings of the literature review. The development and different types of the remote source solar lighting systems are studied. The different modes of light transmission, the advantages and limitations are investigated. A real case application of remote source solar lighting system and the feasibility of its application in Hong Kong are studied in details.

Chapter 3 reports the analysis of the results of the questionnaire surveys collected from buildings professional and end-users on the lift lobby types and their views regarding the application of the remote source solar lighting technology to solve the environmental problems caused by fossil fuel consumption in buildings. Site visits were carried out to different lift lobbies. The layouts of the lift lobbies were analyzed and classified into four main types.

Chapter 4 presents the feasibility study of applying remote source solar lighting system to different types of enclosed lift lobby in Hong Kong and a proposal is developed.

In Chapter 5 simulations of the proposed remote source solar lighting system at optimal and non-optimal positions are carried out to study its performances. The effects of solar altitude and solar azimuth angle on the performance of the RSSL are analyzed.

Chapter 6 presents the experimental findings on the performance of the proposed daylighting system. The factors of external light intensity, solar altitude and solar azimuth angle that can affect the performance of the system are studied and compared with the simulation results. Conclusions are drawn from the analysis.

In Chapter 7 the annual performance of the remote source solar lighting and the shadowing effects caused by the building itself, the adjacent buildings and the remote source solar lighting system itself are studied in details. The system is designed for its integration into the architectural design of the building. Design guidelines and flowchart are formulated.

In Chapter 8 an economic analysis of the proposed application is reported. The installation cost of the remote source lighting system is compared to the cost of a common conventional electrical lighting system that is installed inside the enclosed lift lobbies. The payback period is calculated.

Chapter 9 presents the conclusions with a review of the contributions, significance and limitations of this research; and recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Hong Kong is located in the sub-tropical region. The climate of the sub-tropics is clear most of the year with annual average direct sun component typically about 8 hours per day (Edmonds and Greenup, 2002). Hong Kong has the potential of utilizing daylight in buildings to save energy consumption for providing indoor lighting. However, majority of the lift lobbies in high-rise residential buildings are totally enclosed without natural lighting. The design of a daylight system design that transfers daylight into the interior of the lift lobbies can save electrical energy consumption and bring comfort to the occupants.

The purpose of this study is to develop a remote source lighting system that is able to investigate the feasibilities of applying a remote source solar lighting system in the enclosed lift lobbies of high-rise residential buildings in Hong Kong which have headroom limitation of 2.8 m. In this chapter, a literature review provides the major literature areas in: (a) development of remote source solar lighting system; (b) different types of light transmitting medium; (c) advantages; and (d) limitations of the daylighting system. Applications of remote source solar lighting system by different researchers were studied in details and their implications were analyzed.

2.2 Remote source lighting system

Provision of daylighting or mixed lighting in building construction is fundamental for the improvement of quality and comfort for the control of the cost and power consumption. Light pipes are very adaptable to this requirement (Dobrr and Achard, 2005) as shown in Figures 2.1 and 2.2.

2.2.1 Development of remote source solar lighting system

In a remote source lighting system, light can be transported from outside by collecting it and guiding it through a light guiding medium into rooms in the depth of the building (Kischkowit-Lopin, 2002). The medium is usually a light guide that brings daylight further inside buildings than the peripheral areas that are currently illuminated by artificial light (Whitehead, 1998). A remote source lighting system that directly utilizes sunlight as light source is called the remote source solar lighting system (RSSL) (Wong et al., 2011). In ancient times Egyptians designed vertical daylight shafts lined by gold leaf to bring daylight into their massive stone structures but the shafts were discarded in use due to high cost (Oliveira et al., 2000). The light transport system was further developed. Nowadays hollow light pipes and fiber optics are commonly used as a light transmission medium.

2.2.2 Different types of light transmitting materials

There are two common types of light transmitting medium as a remote source solar lighting system, i.e. the hollow light guides and solid fiber optic.

a) Hollow light guides

There are two main types of hollow light guides, which are prismatic light pipe (PLP) and metal light pipe (MLP). Light pipes are designed to collect light from both the sky and the sun (Zhang et al, 2002). Hollow light pipes can operate both in direct and diffuse daylight.

The prismatic light pipe has been developed from the first generation so-called slit light guides in the seventies and eighties to the present most promising type of hollow light guides so-called prismatic light guide (Opdal, 2006). The prismatic light pipe is a hollow tube lined with optical light film, which is a patented transparent film with a smooth surface at one side and longitudinal micro-right angled prisms of height 0.18mm at the other (Beltran and Selkowitz, 1996). Light propagates through the guide by total internal reflections (TIR) inside the prisms. Light ray that strikes the smooth surface at an incidence angle less than 27º will undergo total internal reflections. The refractive index is lower on the other side of the boundary so that no light can pass through it. All of the light is effectively reflected. Very little light is absorbed by the pipe because light travels primarily in the air space within and the efficiency has been calculated as approaching 99 % (Kneipp, 1994). In the case of a passive guidance light pipe, the prismatic film reflects completely the light rays for all angles of incidence (Dobrr and Achard, 2005).

In a diffusing light pipe, the prismatic film which acts as an extractor is translucent for some angles of incidence (a), which is complementally to the directional angle of the light beam (b), where $a + b = 90^\circ$ (Fig. 2.1). The light rays emitted under an angle (b) lower than the critical value b_{max} realize the total internal reflection on the inner surface of the prismatic FILM (Dobrr and Achard, 2005):

$$b < b_{max} = \cos^{-1} \sqrt{[4 - n^2 (2 - \sqrt{2})/ (2 + \sqrt{2})]};$$

where n is the refractive index of the prismatic film ($n = 1.5$ and $b_{max} = 27.6^\circ$ for polycarbonate prismatic film).

The fraction of the light that escapes is controlled by the width of the extractor, which changes in width along the length of the light guide allowing a portion of the light to escape with a pre-determined spatial distribution (Whitehead et al., 1999).

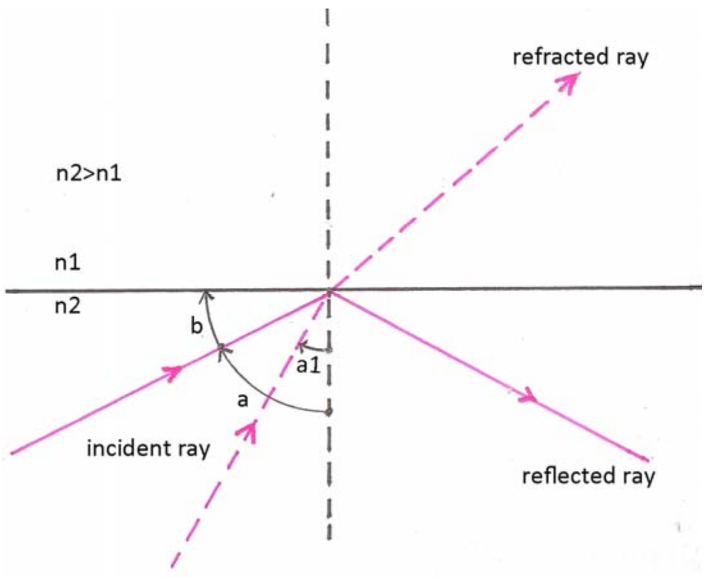

Fig. 2.1 Total internal reflection

The prismatic light pipes are manufactured in both circular and rectangular sections but circular section is more commonly in use (Fig. 2.2). The diameter of the light pipe can be up to 600mm or larger. The prismatic light pipe is suitable for large projects that cost per lumen is crucial (Knisley, 1999). The prismatic light pipe is usually side-emitting (Rosemann and Kaase, 2005).

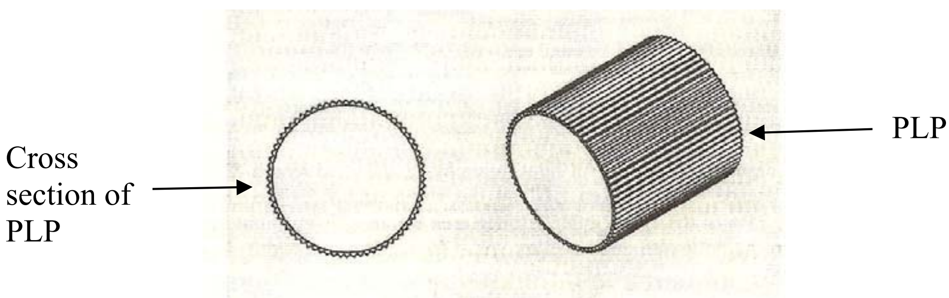

Fig. 2.2 Prismatic light pipe ((Kneipp, 1994)

The metal light pipe is made of highly reflective metal such as aluminum and transfers light by multiple specula reflections (Yeang, 1998). The system efficiency depends on the area and geometric form, reflectivity of the lining material, and directional properties of light source. Metallic reflection is inefficient, and about 5 to 20 % of the light is absorbed on each reflection (Whitehead, 1998). Well-collimated sunlight could produce an efficiency of 50 %. The metallic light pipe is usually circular in section and the length for efficient light transport is 20 to 24 m (Yeang, 1998). The metal light pipe is cheap and suitable for wider application in building design. The metal light pipe is widely used overseas due to simple manufacture process, low installation cost and ease in assembly. Special coupling can be used to change the direction of light propagation. The metal light pipe has been commonly applied in various remote source solar lighting systems. Many international companies, like Monodraught of UK, Analod of Germany, ODL of US, etc. can supply various types of the metal light pipe. An example a metal light pipe is shown in Figure 2.3.

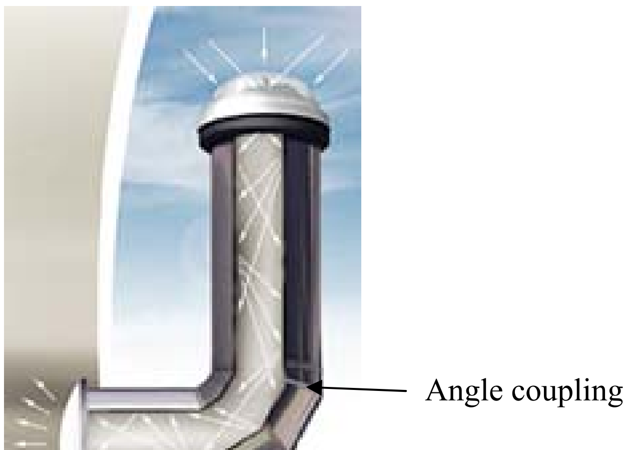

Fig. 2.3 Metal light pipe

Light pipes can operate effectively even under diffused sky conditions (Harrison et al, 1998). The performance of a long light pipe can be enhanced by adding a laser cut panel (LCP) at the input aperture to direct sunlight into a more collimated beam that travels along the light pipe (Kwok and Chung, 2008), which is illustrated in Figure 2.4. The laser cut panel can work in both clear and overcast sky condition (Fig. 2.5). A laser cut panel is formed by laser cutting an acrylic panel so as to produce an array of transparent rectangular elements which transmit and deflect incident light by refraction and total internal reflection (Oakley et al, 2002). Change in direction of light propagation in prismatic light pipe and metal light pipe require special coupling devices.

The prismatic light pipe with higher light transmission efficiency is preferable to the metal light pipe as a light guide. However both the prismatic light pipe and the metallic light pipe are not practical to be applied to the high-rise residential buildings in Hong Kong with limiting floor height of 2.8 m. Light pipe are limited in their applicability due to the pipe diameter, which can generally be more than 20 m times smaller than their length (Shao and Callows, 2003). A corridor of 12 m requires a light pipe of 600 mm in diameter. The cross sectional area of light pipes is usually 400 mm or more in diameter for efficient light transmission (Wong and Yang, 2011). The requirement of the minimum 3 m headroom for installation is not economically feasible for the high-rise residential buildings in Hong Kong.

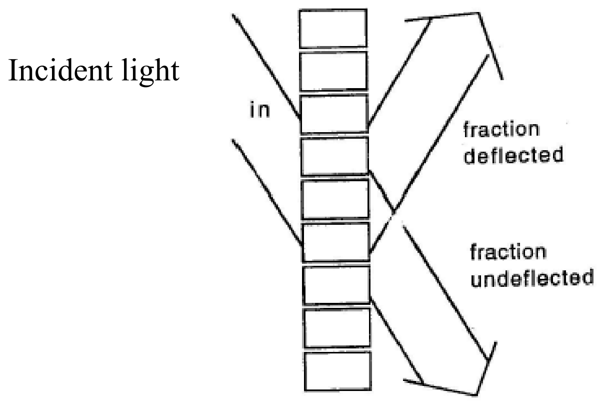

Fig. 2.4 Laser cut panel (Kwok, 2008)

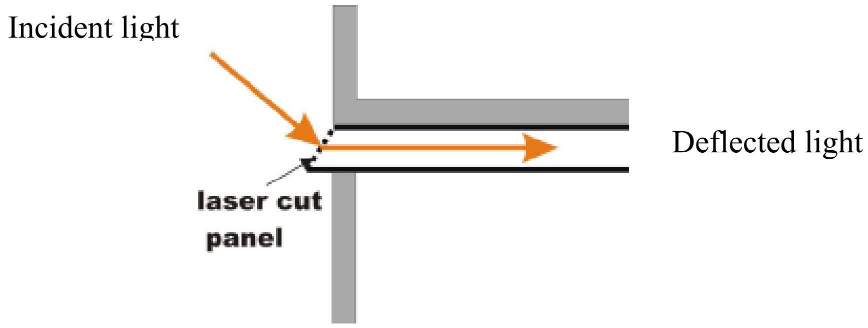

Fig. 2.5 The laser cut panel directing light into a hollow light pipe (Yeang, 2003)

b) Fiber optic

Fiber optics (FO) is mainly made of plastic or glass materials forming a solid rod as the core. The core is surrounded by a cladding material of lower refractive index. Light is kept inside the core by total internal reflections. Incident light needs to be highly concentrated before entering the fiber optic as its acceptance aperture is very small (Hansen and Edmond, 2003). Fiber optic is flexible and can be bended to change the direction of light propagation.

Comparing to plastic fiber optic, glass fiber optic is more accurate with higher efficiency in light transmission, and is more durable in resistance to ultra-violet light.

Nowadays fiber optic is commonly made from polymethyl methacrylate (PMMA), which is a more economical and lighter alternative to glass. The PMMA is lower in cost and more flexible. There are two types of fiber optic, which are end-emitting (EFO) and side-emitting (SFO). Glass fiber optic is mainly end-emitting. Plastic fiber optic can be side-emitting or end-emitting. From the information provided by the User's Guide to Fiber Optic System Design and Installation (The Fiber Optic Association), the diameter of fiber optic can range from 0.1 to 20 mm. Most of the light that enters the end-emitting fiber optic is transferred to the end and emitted as shown in Figure 2.6. The attenuation values of the end-emitting fiber optic are from 0.1 to 0.6 db m, which means light traverses for 18 to 30 m before losing half of the light intensity (Yeang, 1998). The efficiency of the end-emitting fiber optic can be up to 78 % if well-designed (Knisley, 1998).

Light transmission in the side-emitting fiber optic is basically similar to end-emitting fiber optic except that the interface between the core and cladding is made rough so that at some points the light is refracted and reflected out (Fig. 2.7). The side-emitting fiber optic can be designed so that light is emitted uniformly along the whole length. However the linear emission rate is low, which is in the range between 2 to 8 % per meter, and a large portion of the light is transmitted to the end. The side-emitting technology of fiber optic is still in a very preliminary stage of development. Further research is required before the technology can be commercialized. In this research, the side-emitting technology will be the main concern.

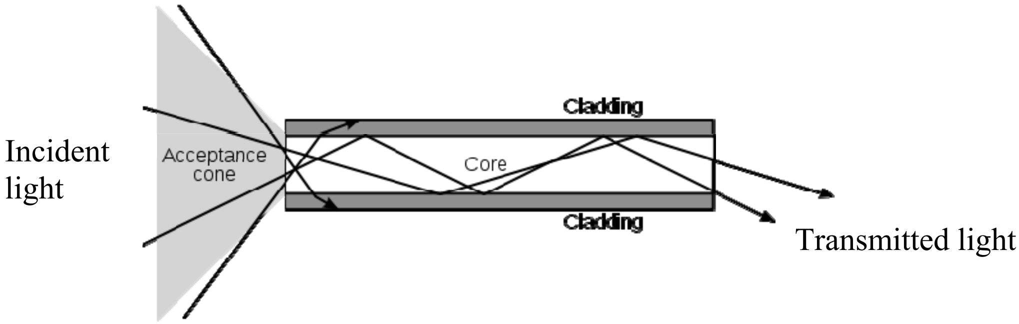

Fig. 2.6 End-emitting fiber optic (FO Assoc., 2011)

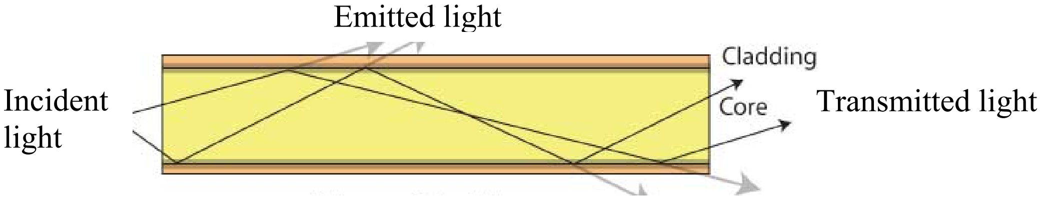

Fig. 2.7 Side-emitting fiber optic (FO Assoc., 2011)

There are three elements in a fiber optic lighting system: the illuminator, the light guide, and the fixture (Knisley, 1999). The illuminator, which is the light source, is usually a LED lamp that is installed at one end of the fiber optic. Light that is emitted from the LED lamp is transferred from one end to the other. The end-emitting fiber optic is the common light guide in light transmission. A bundle of end-emitting fiber optic is housed inside a plastic tube that serves as a cover to protect and support the fiber. Each end-emitting fiber optic is coated with a cladding that prevents light from leaking out of the fiber (Knisley, 1999). Using the sun as light source is usually applied in large scale project which uses the heliostat or parabolic mirror as light collector to concentrate the sunlight into the bundle or bundles of the fiber optic. The bundles of end-emitting fiber optic will be split up into numerous small bundles to distribute daylight into different locations in a building. Each end of the bundle will be fitted with a cover that serves as a light diffuser resembling a lamp.

At present side-emitting fiber optic has not been widely applied as an illuminator because the side-emitting technology is still in preliminary stage of development. Side-emitting fiber optic is generally used as highlights (Fig 2.8). The technology of large core side-emitting fiber optic is developing for the application in illumination. Using the large core fiber optic has the advantage of simplicity in installation that requires fewer fittings. A single large core fiber optic can be fixed along the ceiling of the lift lobby and acts as an illuminator resembling fluorescent lighting.

Side-emitting FO

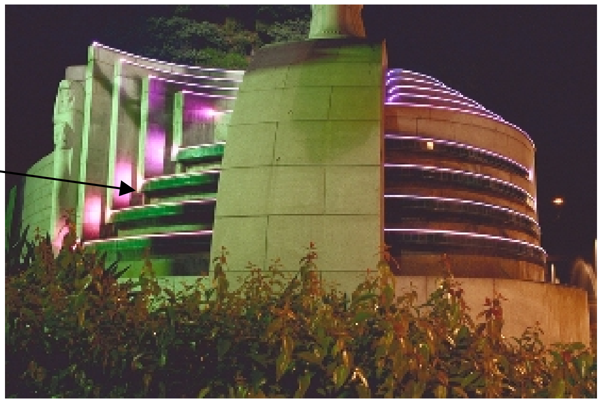

Fig. 2.8 Side-emitting fiber optic used as highlights

2.2.3 Mode of light transmission

There are two modes of light transport which are in vertical and horizontal directions. As the limiting length for efficient light transmission is 20 to 24 m (Yeang, 1998), vertical light pipes are mainly applied in low-rise buildings (Li and Shen, 2004) and widely used in North America and Australia (Elimualin, 2007). A vertical light pipe system is shown in Figure. 2.9. Light is collected on the roof by a pyramidal laser cut panel and transferred downwards along the vertical light pipe to provide natural lighting to the inner zone of a 6-storeys high office building approximating 8m high.

The extraction apertures at each floor redirect the light into the interior and illuminate an area of 12 x 12 m (Yeang, 2003). Application of vertical light pipe is not common in Hong Kong because most of the buildings are over 30 storeys.

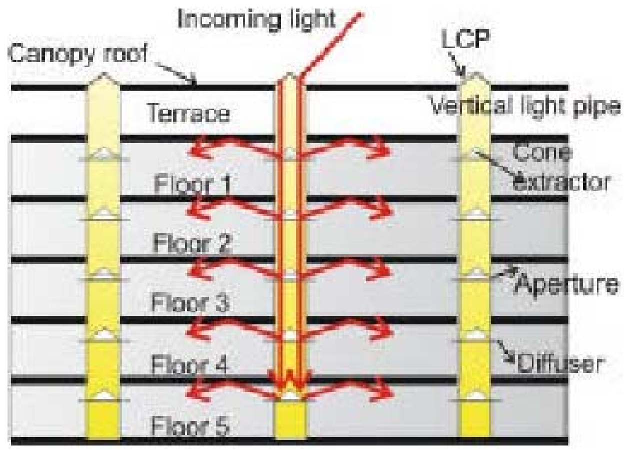

Fig. 2.9 Vertical light pipe (Yeang, 2003)

For horizontal transmission, the light pipe is installed to the ceiling in the inner zone of the building with one end extending to the exterior to collect daylight. Light is transferred along the light pipe and emitted uniformly at regular positions. Figure 2.10 shows the design of a horizontal light pipe. The laser cut panel, which acts as a sunlight collector, is installed at the aperture of the light pipe and inclines at the optimal angle in the respective geographical zone to redirect sun rays more axially along the light pipe. Extractors are installed at regular intervals in the active zone to provide natural lighting to the inner space (Yeang, 2003). As light pipe can transfer daylight into the interior space of a building up to 24 m, the horizontal light pipe is more suitable for application in high-rise buildings.

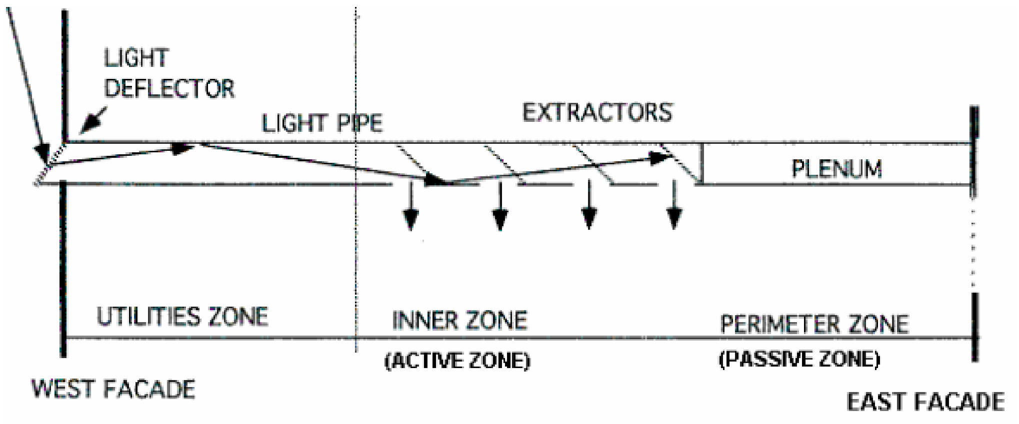

Fig. 2.10 Horizontal light pipe (Yeang, 2003)

2.2.4 Advantages of the RSSL

The application of the remote source solar lighting technology has many advantages as follows:

a) Renewable energy source

The remote source solar lighting system can transport daylight into interior for illumination. Solar energy is a renewable energy source that is free and safe to our environment.

b) Infrared and ultraviolet free lighting

The separation of the solar light source from the illuminated area and the ability to light multiple locations with one source lead to the benefits of removing infrared and harmful ultraviolet during transmission, which can also reduce the heating effect (Knisley, 1999).

c) Safety

As there are no electrical parts in the light pipes, the remote source solar light system can be used safely in wet areas such as swimming pool, and areas with explosive gases. The remote source solar lighting system has no induced electromagnetic field present and can be applied in areas with EMI sensitive electronic equipment (Knisley, 1999).

d) Reduce energy consumption

The remote source solar lighting system can provide a centralized lighting system in building replacing many electrical fixtures and cablings (Whitehead et al., 1999).

e) Elimination of glare

The transmitted light is distributed uniformly as diffused light and can eliminate the glare problem in natural light (Yang and Zhou, 2009).

f) Ease of maintenance

There is only one light source which is the sun and requires no maintenance. The other parts of the remote source solar lighting system only require regular cleaning.

g) Integrating artificial and natural lighting

The remote source solar lighting system has the potential of integrating artificial and natural light into one system increasing design freedom (Yeang, 1998).

h) Visual comfort

Natural lighting can provide visual comfort in the living environment (Ochoa and Capeluto, 2006).

Furthermore, daylight has the following benefits that are apart from energy point of view:

b) Improvement in productivity can offset the initial investment daylighting system (Leslie, 2003).

c) Natural light is associated with healthy buildings and indoor environmental quality (Hartleb and Leslie, 1991).

d) Recent research has been carried out by Rea, et al. of the Lighting Research Center in U.S. that daylight can regulate the human circadian rhythm and reduce Seasonal Affective Disorder (Rea, et. al., in press).

2.2.5 Limitations of the remote source solar lighting system

a) The efficient transmission distance

The efficient transmission distance of the prismatic light pipe, metallic light pipe and fiber topic are limiting, usually up to 20 to 24 m (Yeang, 1998). Application of the vertical remote source solar lighting system system is not feasible in highrise buildings. Installation of the horizontal RSSL system in every floor increases the installation cost.

b) Installation cost

The installation cost of the remote source solar lighting system is comparatively higher than that of conventional electrical lighting system. The prices of the fiber optic, prismatic light pipe and metallic light pipe are higher than that of fluorescent and incandescent light fittings. The cost of side-emitting fiber optic with 10.4 mm diameter is $811/m (quoted by Fiberoptics Technology Incorporation) and the unit cost of T8 florescent lamp is only $30 for the same output.

c) Change in light propagation

Change in light propagating direction for the prismatic light pipe and metallic light pipe is comparatively complicated as the they are more rigid in structure and larger in size. Special coupling devices such as flexible and miter joints are required to change light propagation direction in the metallic and prismatic light pipes, respectively (Cobb et al., 1992).

d) Installation technology

High precision in installation of fiber optic and special equipment are required in cutting and jointing fiber optic together.

e) Dust-free

Light pipes should be air-tight or routine cleaning is required. Accumulation of dust inside light pipes will decrease the transmission efficiency.

2.3 Previous researches in the application of the remote source solar lighting system

A remote source solar lighting system can collect daylight by a passive collector that involves no mechanical parts, such as a laser cut panel; or by an active collector like a heliostat that uses mechanical moving parts to track the sun. Light pipes have been commonly used in Australia, America, Canada and Britain (Zhang et al, 2002).

The European research project named ARTHELIO was conducted from 1998 to 2001 that combined utilization of daylight and artificial light by hollow light pipes. The system is now installed in the 3M European Distribution Centre in Carpiano in Italy. The main system consists of a heliostat with a duct to collect and transfer daylight; a coupling system to mix the available amount of daylight with artificial light; intelligent electronic devices to operate the heliostat and lamp; and the interface for adaptation to a building management system (Rosemann and Kaase, 2005) The system is shown in Figure 2.11. The heliostat (Fig. 2.12) collects sunlight using a Fresnel lens (3M-21X) that is operated by a motor, which rotates on a horizontal plane to track the sun at different altitudes. This is feasible because the 21X lens acceptance angle that enables the sun rays to be focused for almost every sun elevation angle. Collected sun rays are reflected by an anidolic mirror surface into the axis of a vertical duct of 0.9 m in diameter and 13 m in length. The duct is lined with 3M Visible Mirror Film of 97 % reflectivity. A diffuser (Fig. 2.13), which is located at the end of the duct, extracts daylight and lights up an area of 14 m^2. The diffuser feeds daylight into the hollow light guides lined with the 3M highly reflective film. The amount of sunlight to be delivered into the light guides is controlled by a coupling device of a rotating reflective surface at both ends of the diffuser as shown in Figure 2.14. Dimmable sulphur lamps are installed at the end of the light guides as an artificial light source. An electronic control system comprising sensors and motors controls the coupling system, which regulates the amount and incoming direction of artificial light so as to integrate with natural light according to the detected interior light intensity. The interior light intensity is maintained at 200 lx on the working plane. At night time, the rotating reflective surfaces are open and the room is illuminated by artificial light that is fed from the sulphur lamp (Mingozzi et al, 2001). The utilization of daylight helps to reduce electrical energy consumption.

The ARTHELIO basically consists of a vertical and horizontal light guides to transmit daylight. Applying the sun-tracking heliostat to the remote source solar lighting system can increase the efficiency of the system. However the size and construction of the heliostat is complicated and not economical. The application of the vertical light pipe is not suitable for the high-rise buildings in Hong Kong. Modification to the design of the heliostat is required to simplify the construction details and reduce the size before it can be applied to the high-rise buildings.

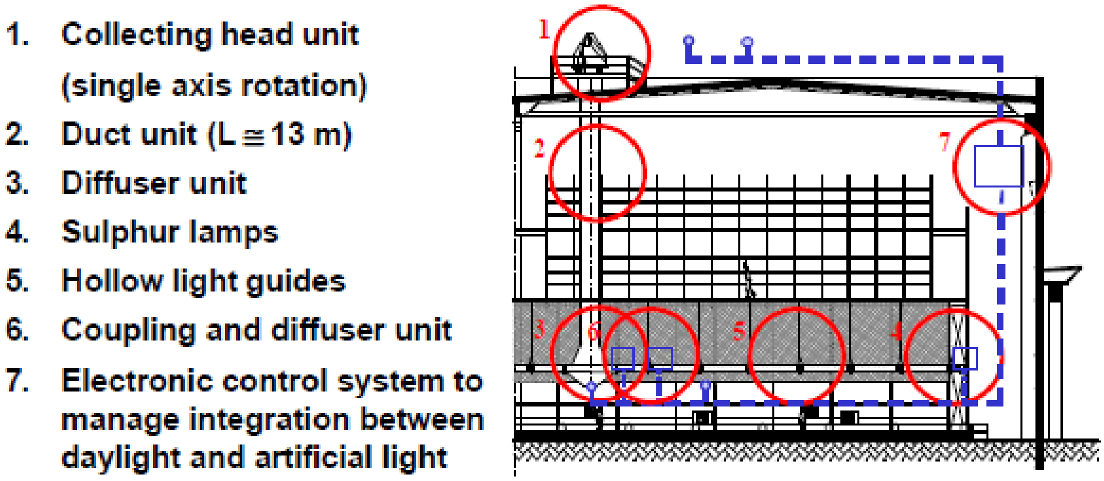

Fig. 2.11 ARTHELIO: Carpiano prototype (Mingozzi, 2001)

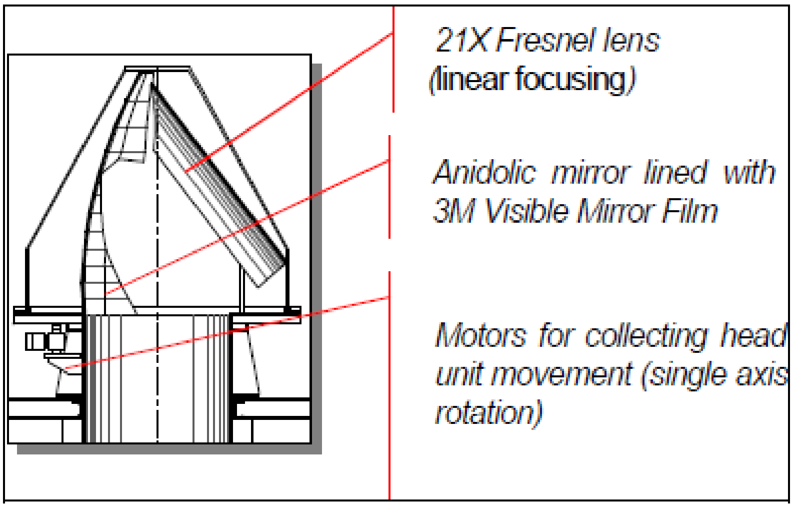

Fig. 2.12 The heliostat (Mingozzi, 2001)

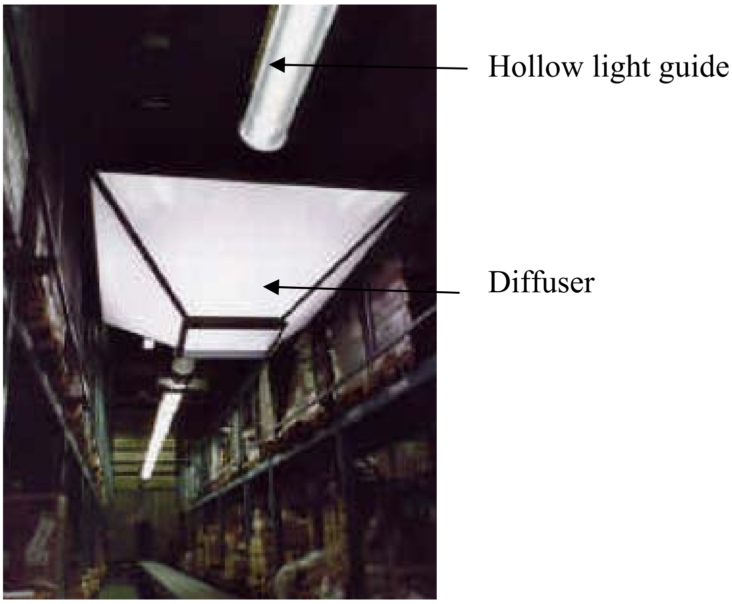

Fig. 2.13 The diffuser unit (Mingozzi, 2001)

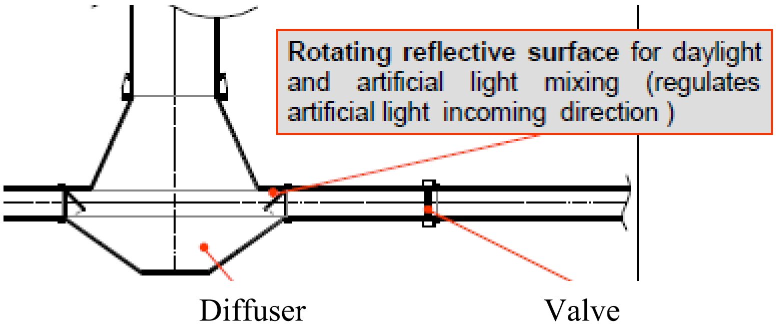

Fig. 2.14 Diffuser functional unit (Mingozzi, 2001)

Beltran et al had carried out an experiment to study the performance of a perimeter daylighting system that passively redirected sun beam by a light pipe further from the window wall in a 9.1 m deep and 6.1 m wide room (Beltran et al, 1996). The system used a spectrally selective glass to reflect and redirect daylight axially into the light pipe. The inner side of the light pipe was lined with a 95 % specular reflective film. The light pipe of 9.1 m in length and 0.6 m wide was used to illuminate the inner space from 4.6 to 9.1 m from the window wall (Fig. 2.154). The height of the light pipe was constrained to 0.6 m so that it could fit with other building services installations within the ceiling plenum. The daylighting system could achieve the work plane illuminance level consistently above 200 lx for about 7 hours per day throughout the year. The installation cost of the daylighting system is inexpensive due to the simple construction involving no mechanical parts. The application of the horizontal remote source solar lighting system in this project is suitable for the high-rise buildings as the length of the light transmission medium can be managed not exceeding the maximum length of 20 m for effective transmission of light. However the height of the light pipe will reduce the headroom of the lift lobbies in high-rise residential buildings in Hong Kong to 2.2 m which is not viable. An alternative light guide should be considered.

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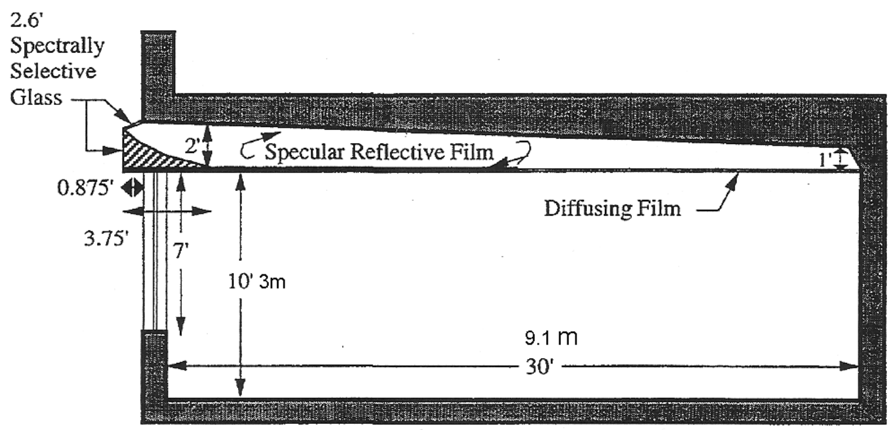


Fig. 2.15 Section of the horizontal light pipe design (Beltran et al, 1996)

A remote source solar lighting system using a simple heliostat (Fig. 2.16) as the sun tracker was installed in Austria to provide lighting to an underground room of size 7.8 x 2.4 m (Pohl and Anselm, 2001). The heliostat reflected sunlight to a redirecting mirror which reflected light to a concentrator (Fig. 2.16). The concentrator transferred sunlight into a 300 mm diameter prismatic light pipe. The light pipe acted as an illuminator. The daylighting system delivered glare-free natural light with working plane illuminance between 100 and 1200 lx under sunny conditions. The overall system efficiency is 30 % (Carter, 2004). The heliostat in this remote source solar lighting system is simpler in construction than the ARTHELIO and used as a design reference in designing sunlight collector.

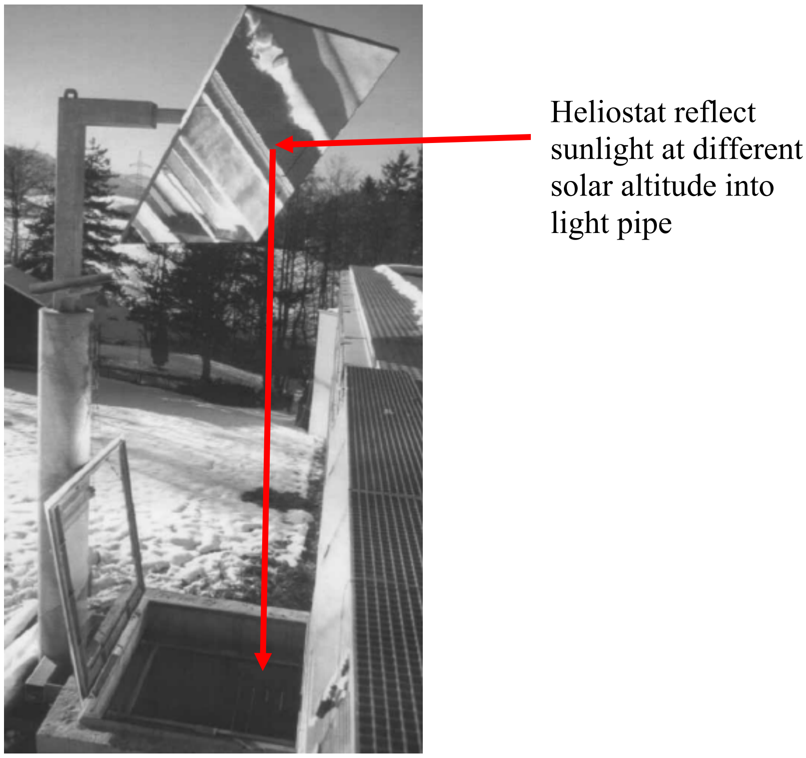


Fig. 2.16 Redirecting mirror (Carter, 2004)

Shao and Callows had carried out an experiment using optical rods in different diameters of 25 mm, 50 mm and 75 mm of lengths 500 mm, 1000 mm and 1500 mm at bending angles of 40°, 60° and 90°. The results demonstrated that light transmittance increased with the increase in diameter and decrease in length. The average light loss increased with the increase in bending angle. The surface of the light rod was polished with 5µm diamond paper (Fig. 2.17) and the finish quality was degraded using P80 sandpaper to make it side-emitting. The light rod was found to give output of up to 400 lm and calculated to be capable of spanning distance of up to 6 m despite a compact diameter of 75 mm or less (Shao and Callows, 2003). This research demonstrated the feasibility of applying side-emitting fiber optic in illumination.

Fig. 2.17 An optical rod sanded to make it side-emitting

The Oak Ridge National Laboratory developed an energy-efficient Hybrid Solar Lighting System which used the large core plastic optical fiber to directly utilized visible solar light for internal lighting. The system involved collection of direct sunlight by a 2-axis parabolic dish concentrator as the sun tracker (Fig. 2.17) (Muhs, 2000 & 2006). The 3M side-emitting rod (Fig. 2.18) utilized precision machined grooves to control light scattering more accurately along the whole length of the rod. Two assembled rods were mounted within a 4-tube florescent fixture and directly between two T8 florescent luminaries, which was used as supplementary lighting (Fig. 2.19). One collector powered about 8 florescent hybrid light fixtures, which can illuminate an approximate area of 100 m^2 (FEMP, 2011). The measured efficiency was approximately 58.4 % (Earl et al, 2003).

The use of side-emitting large core optical fiber imitates florescent luminaries and can integrate into the electrical lighting system. The application of a large core fiber optic is a viable alternative light transmission medium to be applied in the high-rise buildings in Hong Kong.

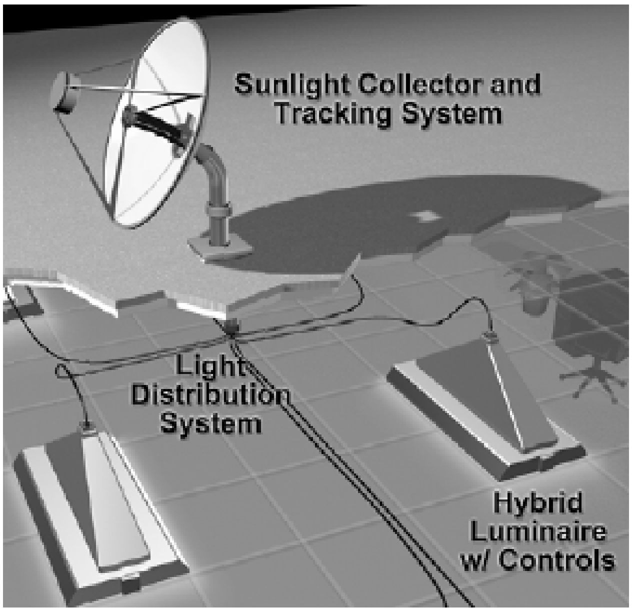


Fig. 2.18 Hybrid solar lighting system (Earl, 2003)

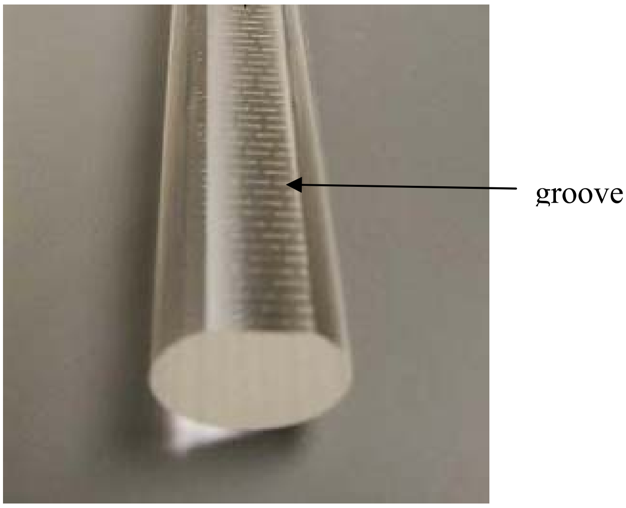


Fig. 2.19 3M side-emitting optical rod

Fig. 2.20 Hybrid luminaire with 3M optical rod

2.4 A reference study: the application of the remote source solar lighting system in the Waterfront House

The remote source solar lighting technology is not well-developed in Hong Kong as it requires minimum 3m headroom for installation. At present there are only a few experimental cases of applying the RSSL in government buildings. No comprehensive data of the RSSL are available. K. Yeang had designed a horizontal daylighting system (Fig. 2.20) that directly utilizes sunlight to illuminate the deep plan of a high-rise office building called Waterfront House in Kuala Lumpur in

Malaysia (Fig. 2.21). The system was simple in design which consisted of a laser cut panel as a passive sunlight collector and the metallic light pipes as light transmission medium. The RSSL in Waterfront House was selected as the reference study because comprehensive data of the RSSL was available.

The design parameters of Waterfront House were:

- 4.6 m floor height
- 20 m deep floor plan
- Ambient lighting level of 300 lx to be provided

The 20 m deep plan floor was not susceptible to good natural lighting. Yeang had designed a horizontal light pipe system consisted of 4 nos. of MLP per floor. Each remote source solar lighting system was composed of a laser cut panel and the metallic light pipe of 2 m wide, 0.8 m high and 20 m long. The laser cut panel was fixed at the external aperture of the metallic light pipe at an inclined angle of 55º, which is the optimal inclined angle at Malaysia (Yeang, 2003) to collect and redirect sunlight more directly along the axis of the horizontal light pipe. A light extraction system was installed to acquire uniform distribution of light across the room. 4 light extractors were installed inside the light pipe as shown in Figure 2.22. The first extractor panel was made sufficiently reflective to deflect one quarter of the light, the second deflected one third of the remaining light, the third panel deflected one half and the final extractor deflected all of the remaining light. Each horizontal MLP were able to bring in daylight to illuminate a working area of 5 to 10 m deep plan offices with illuminance level up to 300 lx without turning on electric lighting for 4 to 6 hours over the time period from 12:00 to 16:00 h (Yeang, 2003).

The optimal inclination of a laser cut panel to collect and redirect sunlight axially within a light pipe is 55° for both Kuala Lumpur and Hong Kong (Kwok, 2008). The design of the remote source solar lighting system in the Waterfront House was selected as a design reference in designing the RSSL in the enclosed lift lobbies of high-rise residential buildings in Hong Kong. Due to the floor height limitation in the residential high-rise buildings, the light transmission medium should be reduced in size in order not to reduce the headroom of the lift lobbies. The design of the remote source solar lighting system in Waterfront House needs to be modified for the application in the enclosed lift lobbies of Hong Kong

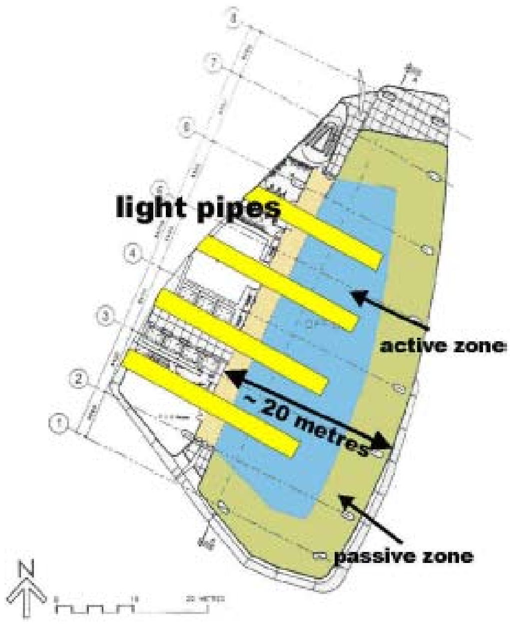


Fig. 2.21 The horizontal light pipe system in Waterfront House

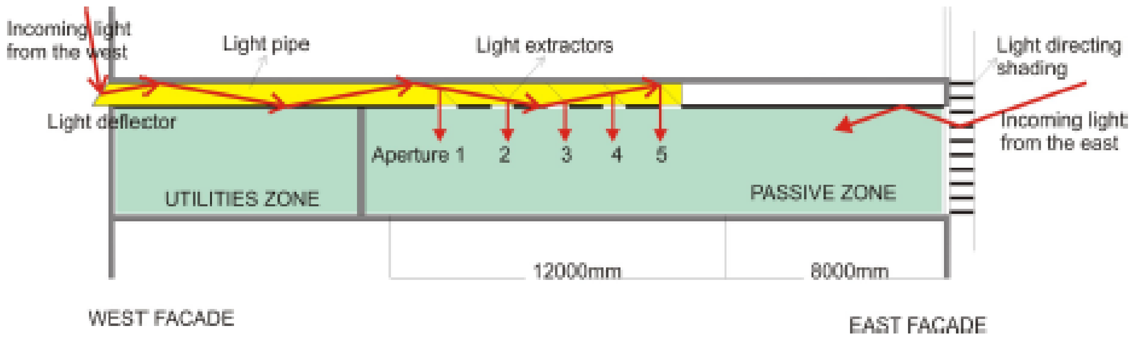


Fig. 2.22 Section of the RSSL in Waterfront House (Yeang, 2003)

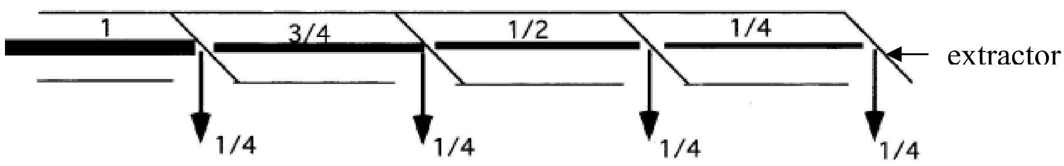


Fig. 2.23 Light extraction in the light pipe (Yeang, 2003)

2.5 Conclusions

The literature survey shows that enclosed lift lobbies are very common for high-rise residential buildings in Hong Kong and the remote source solar lighting system might be a viable alternative lighting system to bring natural light into the enclosed lift lobbies of the high-rise residential buildings in Hong Kong. The side-emitting fiber optic is a more viable light transmission medium to be applied in the lift lobbies than the prismatic and metallic light pipe as its small size will not reduce the headroom of the lift lobbies. It is also found that no such study has been done by others. It is quite necessary to develop such a solar lighting system and carry out a detail study on its potential application in high-rise residential buildings.

Solar lighting can be collected by either passive or active solar collector. The passive collector that involves no mechanical parts is simpler to be installed and inexpensive as compared to the active solar collector. The passive solar collector, the laser cut panel, will first to be considered in the preliminary design of the RSSL. There are 2 modes of light transmission which are vertical and horizontal. Vertical light pipe system is not suitable for highrise buildings as the effective transmission length of light guides is around 20 m. A horizontal light pipe system to be installed at each floor of a high-rise building is thus recommended for this project. The successful application of a horizontal RSSL in the deep plan high-rise office building in Malaysia can be used as a reference for developing the RSSL for the enclosed lift lobbies of the high-rise residential buildings in Hong Kong.

CHAPTER 3

SURVEYS ON PUBLIC VIEWS ON THE APPLICATION OF RSSL TECHNOLOGY AND THE DIFFERENT LIFT LOBBY LAYOUTS

3.1 Introduction

In order to understand the public knowledge and opinions on the application of remote source solar lighting technology, a questionnaire survey was conducted first to collect the information from both the building professionals and end-users regarding the conditions of the lift lobbies and the potential of applying the RSSL in these enclosed lift lobbies. There are two types of questionnaires. The first type was designed for the professionals working in construction industry aiming at collecting their opinions on the application of the RSSL in enclosed lift lobbies and the anticipated difficulties. The second type was designed for the end-users, which aimed to collect different views on the need of applying the RSSL in the enclosed lift lobbies. The returned questionnaires were analyzed.

Site visits were later carried out to 60 lift lobbies in high-rise residential buildings of central core design to identify different types of lift lobby layouts. The collected layout plans were analyzed, which can be classified into 4 main types. The potential of applying the RSSL in these lift lobbies was then studied. A typical lift lobby layout of the central core design with longer and winding corridors was selected as the case study for the detailed design of the RSSL.

3.2 The questionnaire survey

Interviews were carried with 20 building professionals and potential end-users to understand their expectations of a daylighting system. Two sets of questionnaires were drafted for the interviews of construction professionals and end-users. The questionnaires are attached in Appendix A. The returned questionnaires were analyzed to draw a conclusion on the degree of acceptance by the professionals and end-users; and problems that would arise in the application of the RSSL to the enclosed lift lobbies of the high-rise residential buildings in Hong Kong.

3.2.1 Views from the construction professionals

20 questionnaires were sent to construction professionals including architects, building services engineers and structural engineers. All the questionnaires were returned for analysis. The interviewees have been working in the construction industry for ten to thirty years. They agreed that energy use in building was responsible for emission of polluting gases and supported the exploration of renewable energy application in buildings. They considered architects and building services engineers as the important personnel that could play a leading role in energy conservation design. All the interviewees preferred daylight to artificial light. Over 80% of the interviewees felt more comfortable with daylight and over 70% of the interviewees believed that daylight was good for health. 75% of the interviewees regarded the remote source solar technology could be an alternative lighting system that could be applied in the enclosed lift lobbies and reduce electrical energy consumption. 70% opined that the application of the RSSL could be effective in improving the lighting situation and internal climatic condition in the lift lobbies by reducing the heating effect of electric lighting. Figure 3.1 summaries the survey results.

Regarding the obstacles that might hinder the development of the RSSL, over 83% of the interviewees believed that high installation cost was the most important obstacle. Lack of cost data, professional expertise and government support were other crucial factors. They also opined that developers might not be interesting in investing in the new technology, and difficulties would arise in the installation of the RSSL to existing buildings due to structural limitation and the required modification works. A summary of the major obstacles is shown in Figure 3.2.

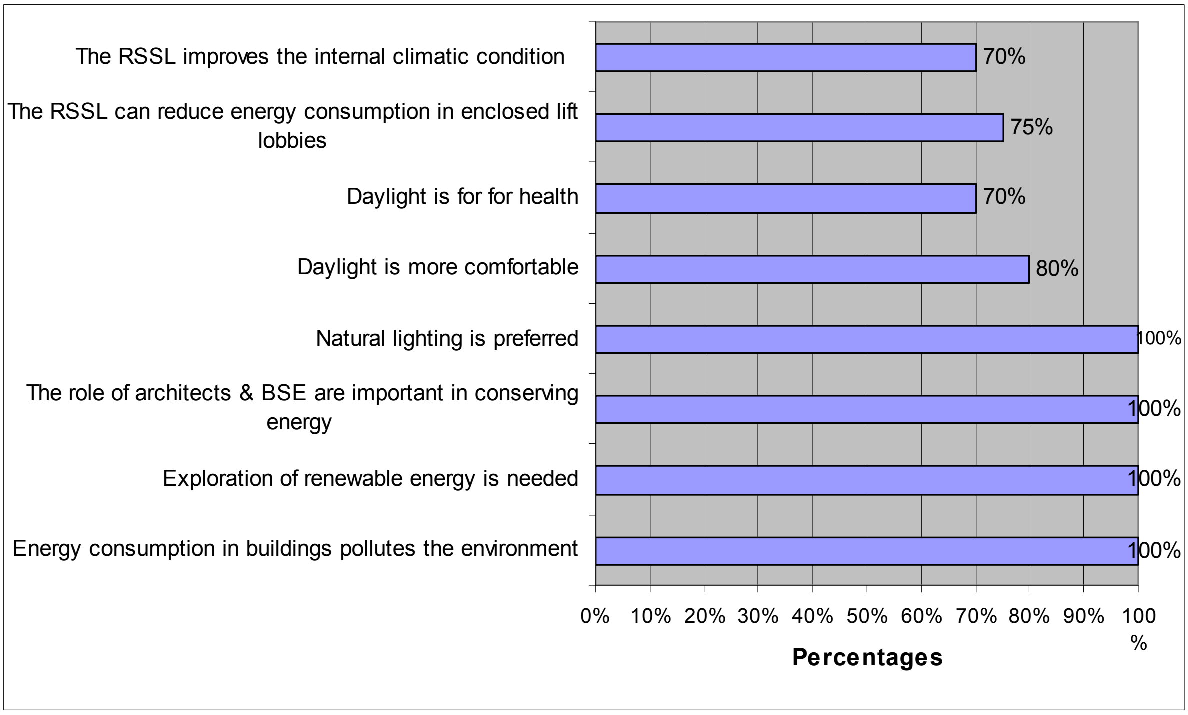


Fig. 3.1 Summary of the survey results of construction professionals

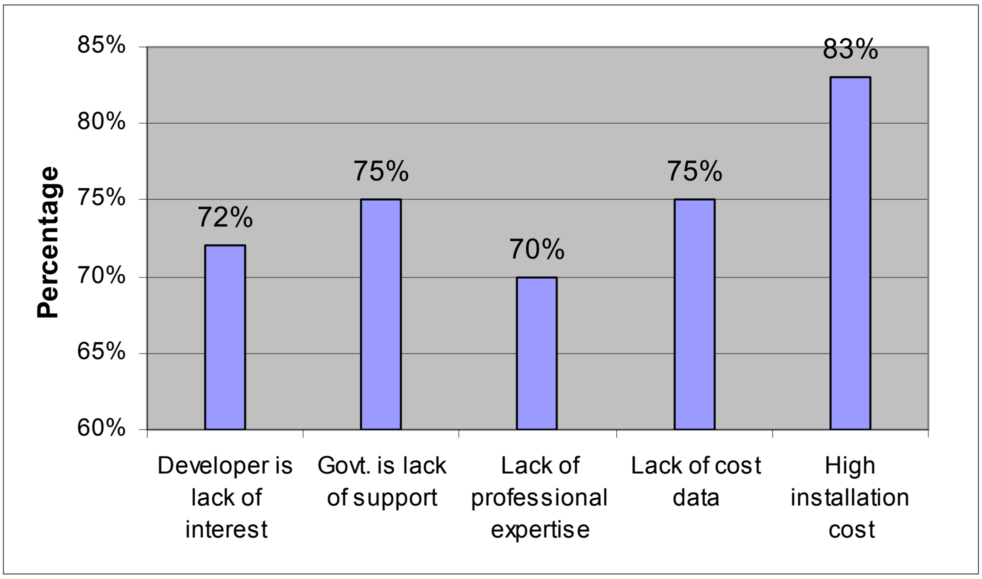


Fig. 3.2 Major obstacles in application of the RSSL

Conclusively, the professionals are aware that renewable energy source should be explored as an alternative to electrical power for illumination. Daylight is preferred to electric lighting. The RSSL requires further development to mature the technology and reduce the cost. The government is recommended to set up a funding for the research and credits should be given to developers that adopt the remote source solar lighting technology in their buildings by awarding exemption of the floor area for the installation of the RSSL in the calculation of Plot Ratio.

3.2.2 Views from end-users

400 questionnaires were distributed to end-users and 23 % was returned. More than half of the interviewees were in the age group of 25 to 35, who were mature adults. Over 90 % of the interviewees agreed that burning of fossil fuel to produce electricity polluted the environment and 80% aware that fossil fuel would be used up in the future. More than 97 % supported using less electricity and exploring renewable energy sources. All the interviewees preferred daylight to artificial light

because daylight was free of charge, good for health and comfortable. 96 % of them opined that the RSSL could reduce pollution by reducing energy use in buildings and 93 % supported the application of the RSSL in new buildings. More than 90 % opined that the government should support the development of the remote source solar lighting technology and allocate more funding for research. A summary of the survey result is presented in Figure 3.3.

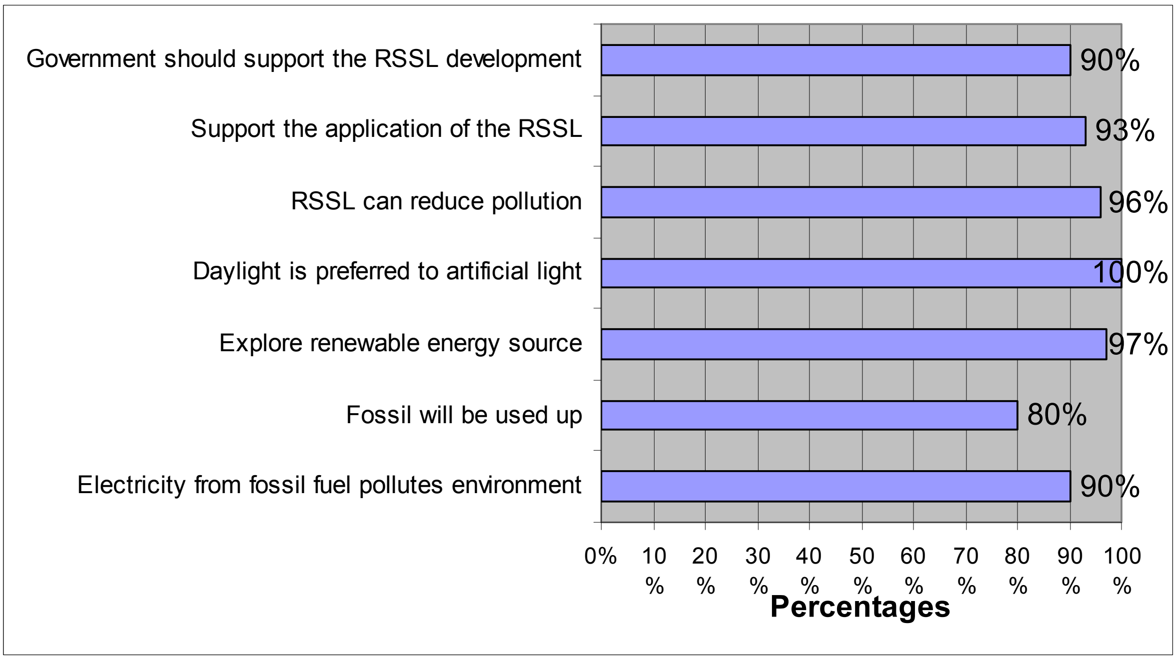


Fig. 3.3 Summary of the survey results of end-users

From the survey results, it can be concluded that the general public aware the pollution problem that arises from energy use in buildings and support the exploration of renewable energy resources to reduce the use of electrical lighting. The application of the RSSL in enclosed lift lobbies can reduce energy consumption. Government can promote the development of the new technology by allocating more research funding.

3.2.3 Conclusions

Both the building professionals and the general public welcome the idea of introducing the remote source solar lighting technology in illuminating the enclosed lift lobbies in highrise residential buildings and agree that such application can reduce the consumption of electricity in these buildings. Further research is required to mature the RSSL technology. The cost of the RSSL should be reduced for practical application. The SAR Government plays an important role in the development of the technology by allotting research funding and awarding plot ratio credits to enhance the developers' interest in adopting the RSSL in their buildings.

There are difficulties in applying the RSSL in existing buildings as structural modification may be required. The RSSL is recommended to be included in the early design stage of a new building.

3.3 Survey on different lift lobby layouts

The results of the questionnaire survey revealed that the public welcomed the introduction of the RSSL to reduce energy consumption in the lift lobbies and supported further development of the technology. A survey on the different layouts of the lift lobbies in the high-rise residential buildings in Hong Kong was carried out as well as to study the potential of applying the RSSL in these lift lobbies.

The potential of utilizing daylight for saving energy use is high in Hong Kong (T.M. Chung, 2003). The consumption of electricity by artificial lighting will be much reduced if buildings are designed to optimize daylight for interior illumination. The understanding of different layouts of the enclosed lift lobby in high-rise residential buildings is important for studying the potential of the RSSL application in these lift lobbies.

Site visits were carried out to the lift lobbies in 60 high-rise residential buildings of central core design in order to identify different types of lift lobby layout plans. The layouts were analyzed and could be classified into 4 main types. The feasibility study of applying the RSSL in these lift lobbies was studied. A typical lift lobby layout of central core design with longer and winding corridors was selected as the case study for the detail design of the RSSL.

A study was conducted to understand different layouts of the lift lobbies in the high-rise residential buildings in Hong Kong. Site visits were carried out to 60 lift lobbies of residential buildings of central core design. As required by the building regulations in the Code of Practice for The Provision of Means of Escape In Case of Fire (1996) Section 19 Lift Lobbies (Building Authority, 1996), the lift lobbies must have direct access to a staircase or link to a staircase through a common passage. The staircase should be provided with natural lighting at each floor level as required by Building (Planning) Regulations (1984), Cap. 123, Section 40 (b) (Building Authority, 1984).

All the studied lift lobbies are linked to a staircase. However, majority of the lift lobbies do not receive natural lighting because staircases must be protected by a smoke lobby as required by the Building (Planning) Regulations and The Codes of Practice for The Provision of Means of Escape In Case of Fire (1996) Section 13 Access to Staircase within a Building, 13.1 & 13.5 (b) (Building Authority. 1996).

The lift lobby layouts of residential buildings of central core design can be categorized into 4 main types:

a) Type A: Windows are provided at landings of the staircase (Fig. 3.4).

b) Type B: Windows are provided at flights of the staircase (Fig. 3.5).

c) Type C: The staircase is totally enclosed (Fig. 3.6).

d) Type D: Lift lobby or staircase adjoins a light well (Fig. 3.7).

Natural lighting is provided to the staircases of type A, B and D lift lobbies, which occupy 34 %, 20 % and 34 % of the studied residential buildings, respectively. Type C lift lobby with completely enclosed staircase occupies the remaining 12 %. Figure 3.4 shows the distribution of the 4 types of lift lobbies in the survey. 88 % of the staircases are directly accessible to natural lighting and ventilation. Type A, B and C lift lobbies are completely enclosed and require 24 hours artificial lighting. Although the lift lobby in type D is abutting against a light well, no window is usually provided in the lift lobbies to avoid the undesirable view of the light well. 78% of the studied lift lobbies do not receive natural light.

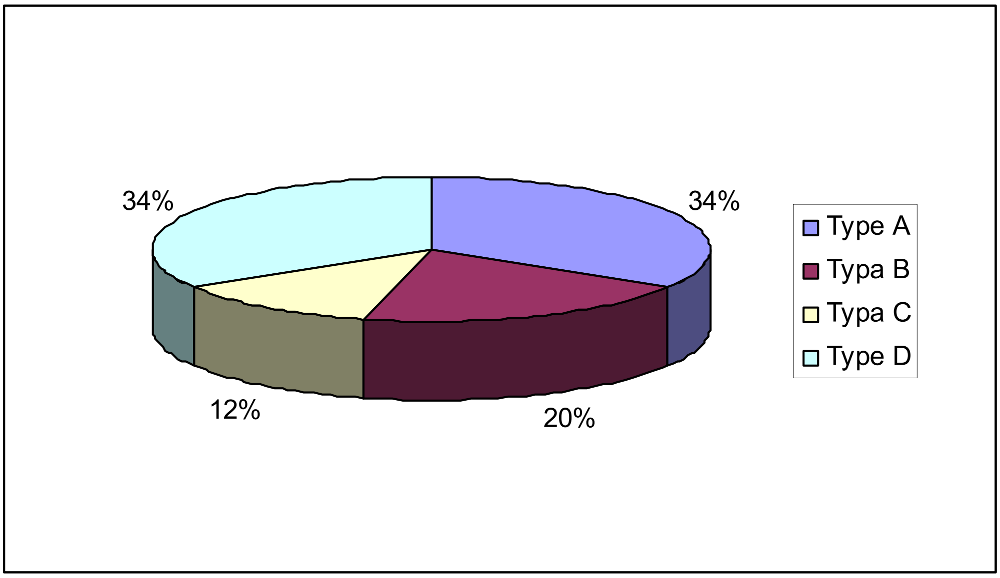


Fig. 3.4 Distribution of the 4 types of lift lobbies

The potential of applying the RSSL in these 4 types of lift lobbies were analyzed. Natural lighting could be introduced into these four types of lift lobbies by an appropriately designed RSSL. Proposed layouts of the RSSL in type A to D lift lobbies are diagrammatically represented in lines with arrows indicating the directions of daylight transfer as shown in Figures 3.5 to 3.8. However, the RSSL layout in type C lift lobby may intrude into the domestic unit, which is private property. Installation of the RSSL in type C residential buildings is not recommended; still the RSSL can be applied to more than 78% of the enclosed lift lobbies in the high-rise residential buildings in Hong Kong.

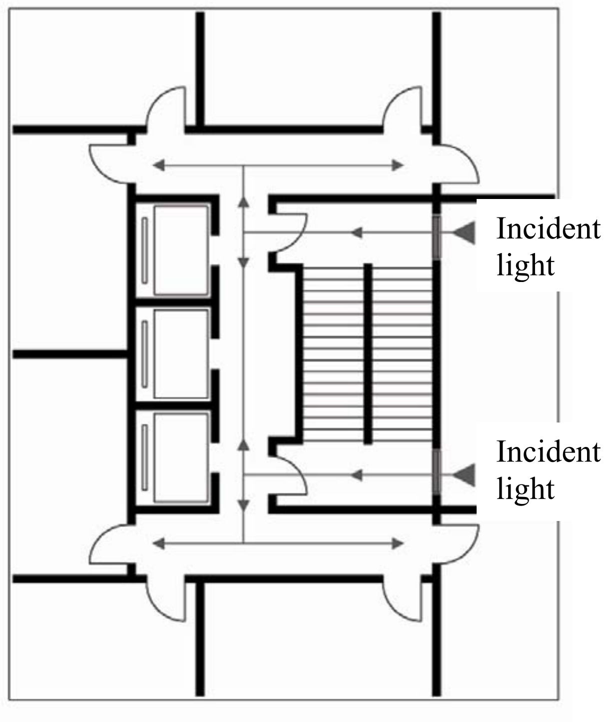


Fig. 3.5 Type A lift lobby

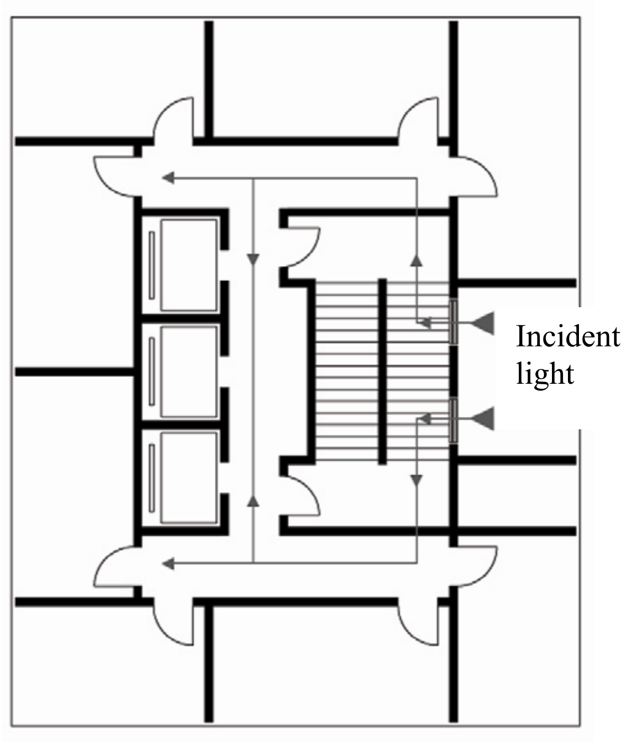


Fig. 3.6 Type B lift lobby

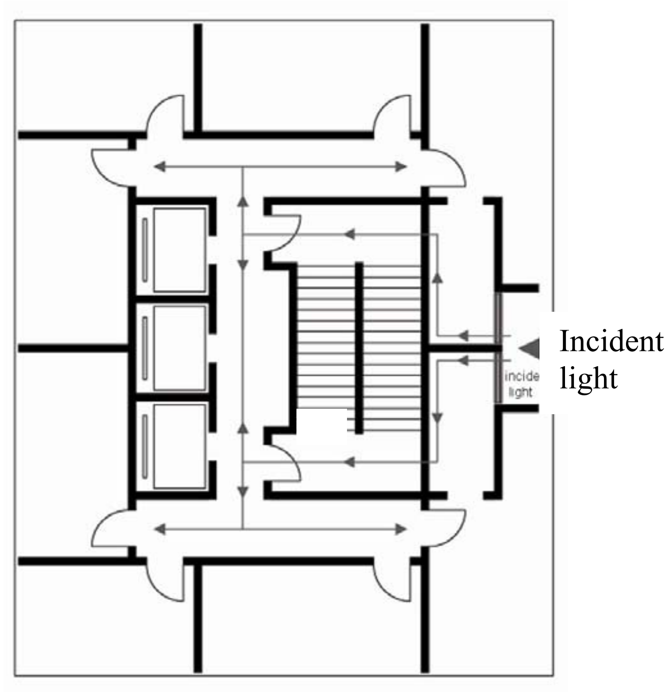


Fig. 3.7 Type C lift lobby

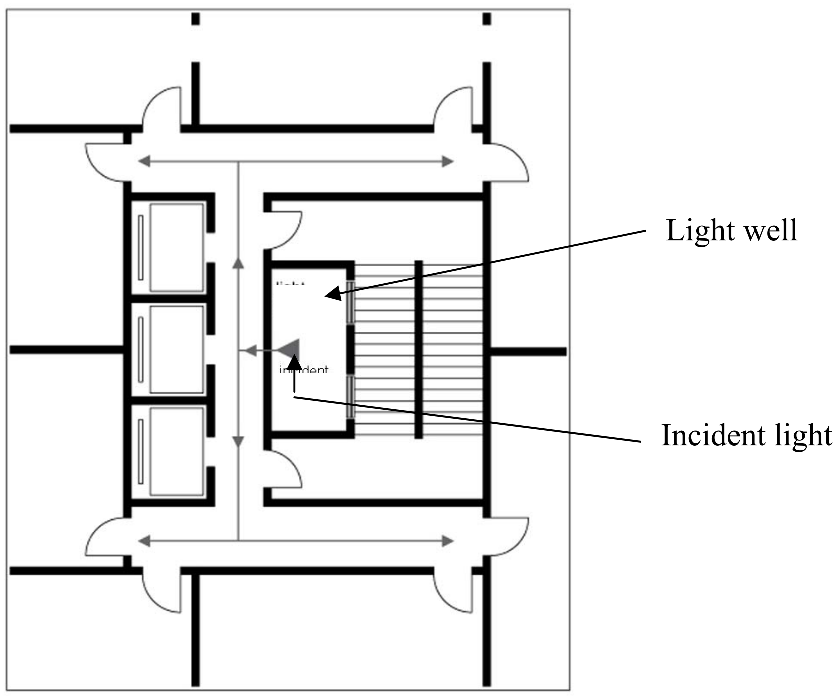


Fig. 3.8 Type D lift lobby

In order to accommodate more domestic units within one floor and maximize the peripheral views of these units, the central core develops into a diamond-pattern (Fig. 1.1), which is the typical floor plan of the high-rise residential buildings in Hong Kong. This diamond-pattern design is the modification of type A and B lift lobbies. In this design, 6 to 8 domestic units can be accommodated in one floor. The lift lobby is completely enclosed with longer and winding corridors. The RSSL layout design in this type of lift lobby is comparatively more complicated than others. This worst case scenario is selected to be the case study for the detail design of the RSSL in this thesis.

3.4 Conclusions

The questionnaire survey on the public opinions regarding the application of the remote source solar lighting technology was conducted and concluded that the exploration of the RSSL as a sustainable alternative to electric lighting inside the enclosed lift lobbies was required.

Different layouts of 60 lift lobbies in the highrise residential buildings in Hong Kong were analyzed and categorized into 4 main types. It is possible to apply the RSSL in type A, B and D lift lobbies, which amount to more than 78 % of the studied cases. The potential of applying the RSSL in the enclosed lift lobbies is high. The typical layout of the lift lobby was selected for the design of the RSSL in this thesis.

Further study on the application of the RSSL in the lift lobby layout is required. The research will then proceed to the next stage to derive a proposed design of the RSSL. This research concentrates on the development of the RSSL technology that is applied to the enclosed lift lobbies of new high-rise residential buildings in Hong Kong.

CHAPTER 4

THE DESIGN PROCESS OF THE REMOTE SOURCE SOLAR LIGHTING SYSTEM

4.1 Introduction

The Waterfront House as mentioned in section 2.4 utilizes a horizontal metallic light pipe to transfer daylight from the exterior to illuminate the 10 m deep office spaces which are originally illuminated by electric lighting. A laser cut panel was installed at the aperture of the light pipe at 55° inclination to collect daylight. As this remote source solar lighting system involves no moving parts, the installation cost is inexpensive and requires minimum maintenance. The installation cost is below HK$15000 including supplementary electrical lighting; and the system only requires routine cleaning. The horizontal light pipe system in Waterfront House is used as a design reference in this project because the optimal inclination angle of 55° is the same in Hong Kong. However, the metallic light pipe cannot be installed in the lift lobbies of 2.8 m in height as it requires a minimum of 3 m headroom clearance for installation. The design of the remote source solar lighting system in Waterfront House was modified to suit the high-rise residential buildings in Hong Kong.

4.2 The proposed system

As the studied object, the horizontal light pipe system that was designed by K. Yeang for Waterfront House was modified to solve the 3 m headroom problem for installing the RSSL. The modified RSSL as shown in Figure 4.1 composes of a laser cut panel, a 450 mm diameter and 1.5 m long metallic light pipe, 2 nos. of 5 mm thick plano-convex lenses of 225 mm in diameter and 10.4 mm diameter side-emitting fiber optic (SFO). The axes of the metallic light pipe, lenses and side-emitting fiber optic are in alignment. The laser cut panel is installed at the aperture of the metallic light pipe and inclines at 55° to collect sunlight, which is the optimal incline angle for Hong Kong (Kwok, 2008). The metallic light pipe acts as the first light transfer medium. As the acceptance aperture of fiber optics is very small, light needs to be highly concentrated before entering the fiber optic (Hansen, 2003). The plano-convex lenses are installed at the end of the metallic light pipe to converge the transmitted light into the side-emitting fiber optic, which acts as the second light transfer medium.

The metallic light pipe and the converging lenses are proposed to be installed in a service room or a reserved space, which is adjacent to the lift lobby and part of the headroom can be reduced to below 2.8 m. The side-emitting fiber optic of small diameter and the flexibility to bend around corners will be installed in the lift lobby and common corridors without reducing the headroom. An infrared (IR) filter is required to be installed before the first converging lens to remove IR light and protect the side-emitting fiber optic from overheating. The interior light intensity should be maintained at 150 lx, which is the light intensity for lift lobbies as recommended by the Chartered Institution of Building Services Engineer. Supplementary electrical lightings are required in the lift lobbies, which will be switched on automatically by a control system to maintain the interior light intensity at a minimum of 150 lx when the interior light intensity falls below this level.

Figure 4.2 shows the modified layout of the RSSL in the lift lobby. The studied lobby can be divided into 4 portions with corridors of approximately the same length. The metallic light pipes are fixed to the external wall to collect and transfer daylight into the converging lens system, which concentrates the light beam into the side-emitting fiber optic. The side-emitting fiber optic is laid along the 2 sides of the ceiling in the lift lobby. The fiber optic acts as an illuminator and emits light along the whole length. The design of the side-emitting fiber optic can integrate into the metal false ceiling as shown in Figure 4.3. Fluorescent lamps are installed along the side-emitting fiber optic and serves as supplementary lighting. Anidolic false ceiling system is designed to conceal the fluorescent lamps and side-emitting fiber optic. The ceiling panels are made of highly reflective aluminum and act as parabolic reflectors. The lower panels reflects the light that is emitted from the side-emitting fiber optic and fluorescent lamps to the upper panels which in turn reflect the light in a downward direction to illuminate the lift lobby and corridors creating a soft lighting effect.

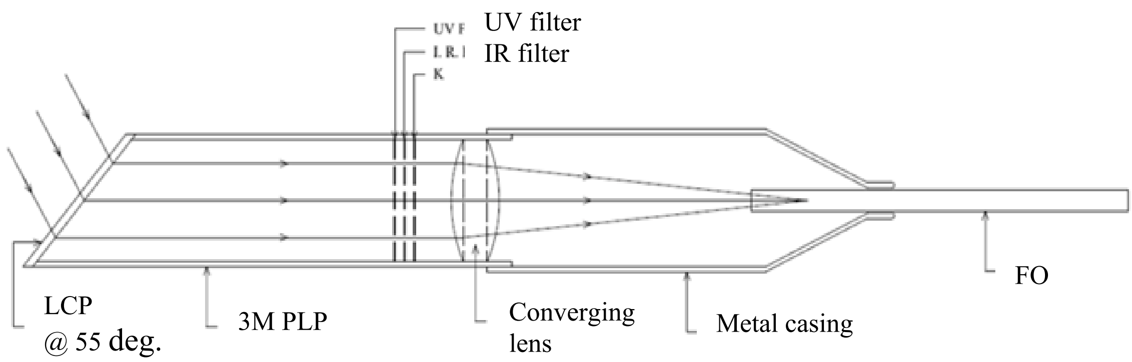


Fig. 4.1 The modified RSSL

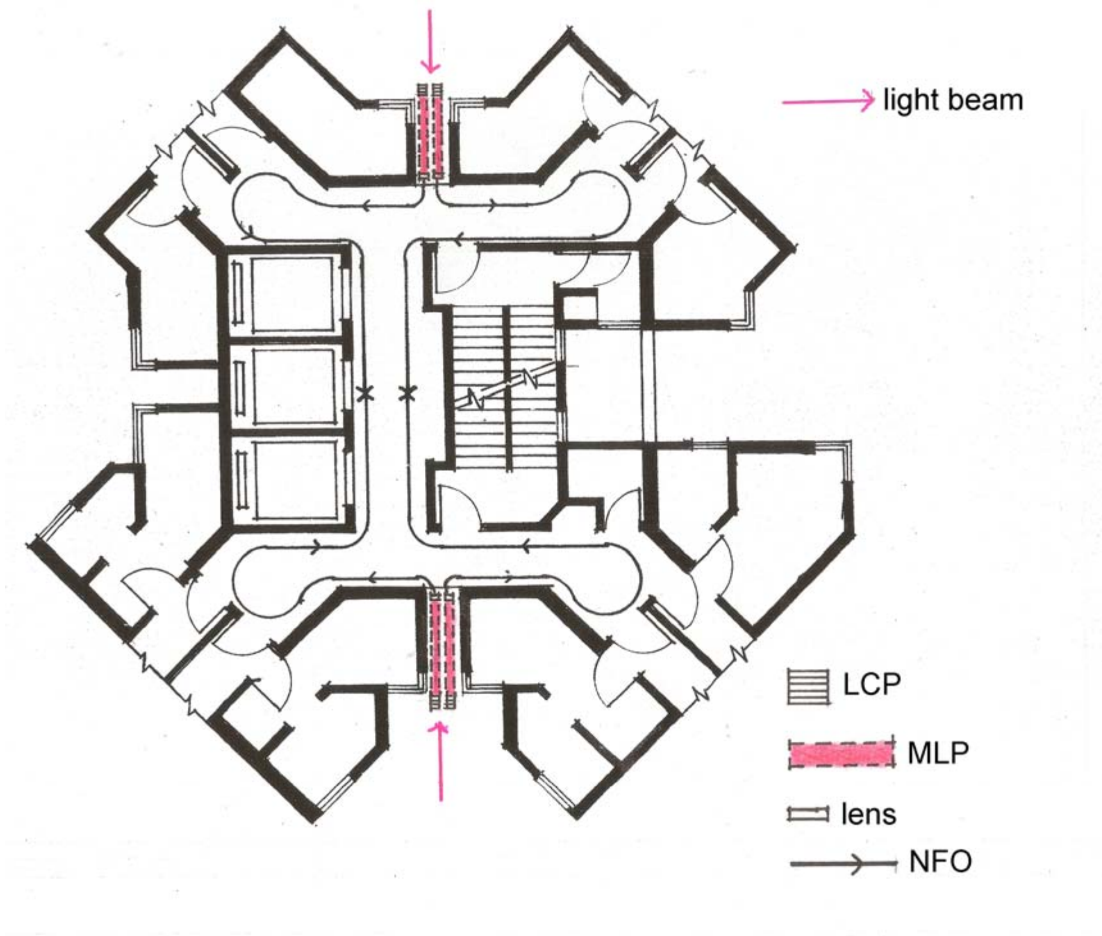


Fig. 4.2 The modified RSSL layout in the enclosed lift lobby

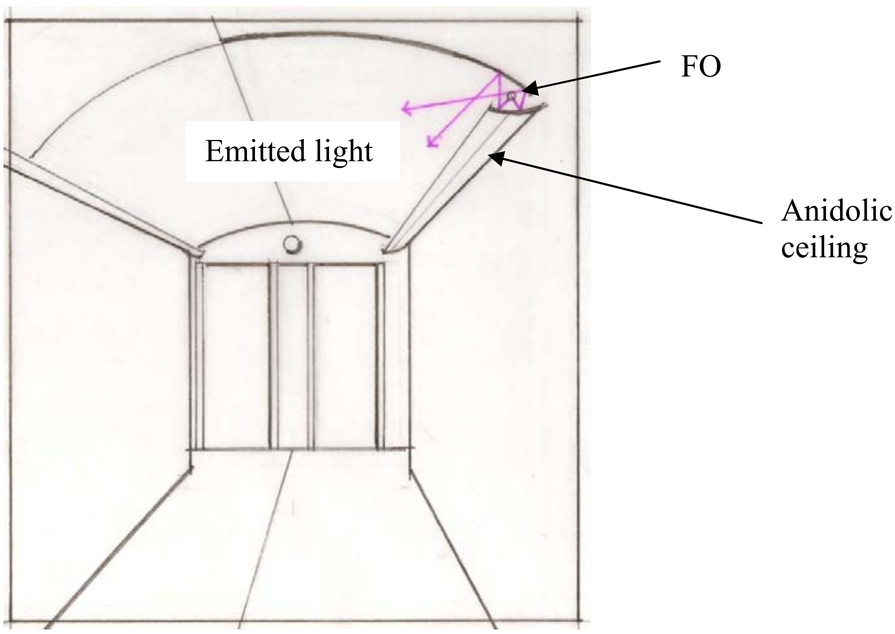


Fig. 4.3 Interior of a lift lobby

A preliminary experiment was set up to test the performance of the modified RSSL. The light beam that was collected by the laser cut panel formed a blurred light spot after passing through the lenses and could not be focused into the fiber optic at all positions of the sun. A sharper light spot began to form when the distance between the laser cut panel and the first lens was increased beyond 10 m. This distance is impractical in application. The phenomenon can be explained by the fact that light being redirected by the laser cut panel was not in a perfect collimated beam. The light beam was slightly diverging. Multiple reflections occurred inside the MLP and a blurred image was formed by the lenses. A collimated light beam started to form when the distance between the laser cut panel and first lens was approaching infinity. The performance of the laser cut panel was also affected by the angle of the incident ray (Kwok, 2008). The RSSL system required revision.

4.3 The revised RSSL

The RSSL was revised as illustrated in Fig. 4.4. The laser cut panel was replaced by a plane mirror that acts as a simple heliostat to reflect sunlight into a lens system. The lenses converged the reflected light into the side-emitting fiber optic.

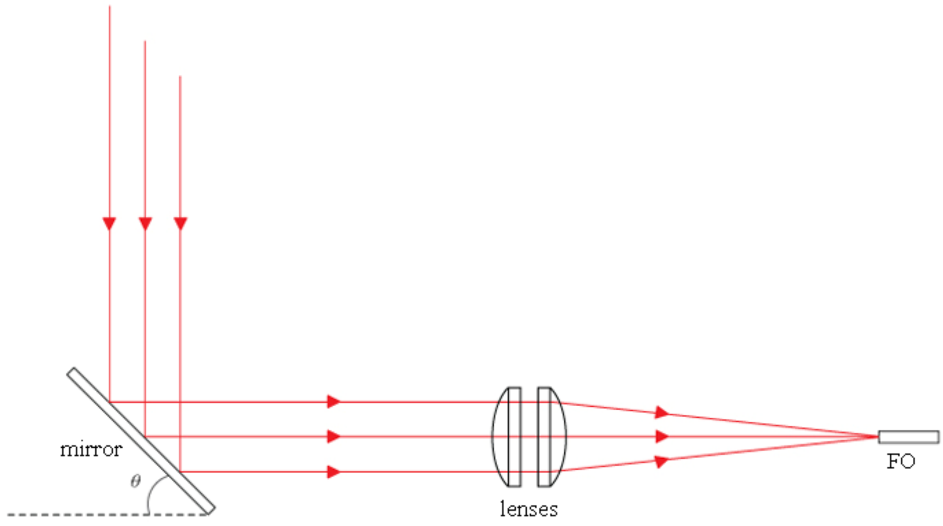


Fig. 4.4 The revised RSSL

In the revised design, the heliostat is composed of a plane mirror of size 760 x 760 mm, which acts as a solar collector. The mirror is mounted on a metal stand that is able to rotate around the horizontal and vertical axes. The rotation is controlled by an active sun tracker that senses the direct solar radiation falling on a photo-sensor as a feedback signal to ensure that the solar collector is tracking the sun all the time (Chong and Wong, 2009). The configuration in the 2-axes sun-tracking system is azimuth-elevation, which is the most popular design (Beltran et al., 2007). The tracking angle about the zenith is the solar azimuth angle (γ) and the tracking angle about the horizontal axis is the solar altitude (β) (Stine and Harrigan, 1985). The position of the mirror is adjusted in both horizontal and vertical directions (Fig. 4.5) responding to the constant changes in solar azimuth angle and solar altitude at different times and dates of a year so as to reflect the sun beam always in a direction parallel to the axis of the lenses.

Fig. 4.5 The mirror stand

From computer simulation, the configuration of a single lens was designed to be 225 mm in diameter and 70 mm thick. Such a configuration is too expensive so that two numbers of 225 mm diameter BK 7 plano-convex lenses of 5 mm thick, which is placed 70 mm apart, was designed to replace the single lens. Light transmission medium from the mirror to the lenses is not required because the mirror reflects the sun beam directly into the lens system. The reflected light is converged and concentrated into the side-emitting fiber optic.

The 10.4mm diameter large core LEF710M fiber optic (NFO), which is supplied by Fiberoptics Technology Incorporation, is selected in this experiment. The fiber optic is notched in factory at regular spacing to emit light at 6% per meter run. The upper part of the notched fiber optic is covered by a reflective jacketing that maximizes the amount of light to be emitted. Transmitted light is emitted in a divergent angle of 60° in downward direction (Fig. 4.6) and emits uniformly along the whole length.

The revised RSSL system operates in direct sunlight under clear sky condition. The notched fiber optic can be installed inside the lift lobby without reducing its floor height. Furthermore, the small diameter enables the notched fiber optic to be installed in existing buildings as well because coring a hole through a structural beam is generally viable for an opening of less than 75 mm in diameter.

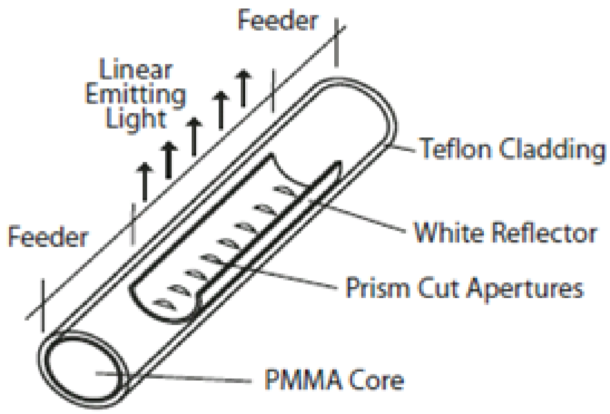


Fig. 4.6 The notched fiber optic

A RGB LED lamp of 40W is installed at the end of the notched fiber optic to act as the supplementary lighting (Fig. 4.7). The LED lamp will be instantly turned on when the light detector at the far end of the NFO detects the indoor light intensity below 150 lx. The emitted light from the LED lamp then transmits in the reverse direction inside the notched fiber optic (Fig. 4.8).

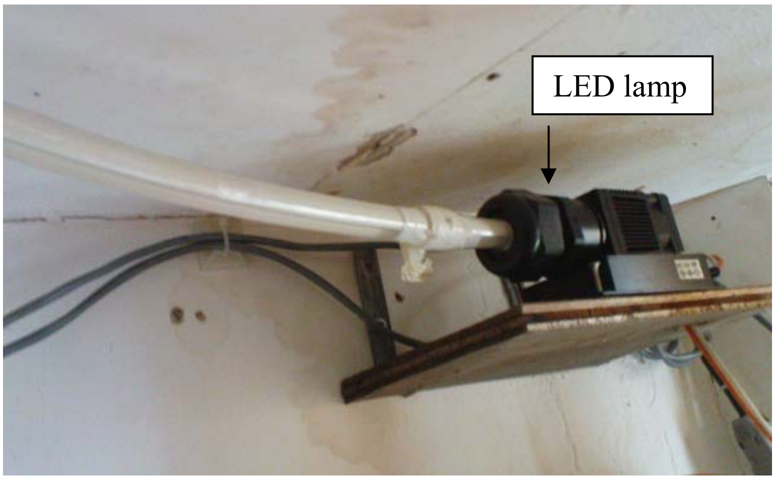


Fig. 4.7 The LED lamp at the end of the notched fiber optic

Fig. 4.8 Emitted light from the LED travels in reverse direction

As the efficient transmission length of fiber optics is limited (Yeang, 1998), the lenght of the notched fiber optic in the RSSL should be designed as short as possible. 4 nos. of RSSL with similar lengths of notched fiber optic were designed for the lift lobby as shown in Figure 4.9. The mirror is installed on the external facade to redirect sunlight into the lenses. Reflected light rays are converged by the lenses into the notched fiber optic, which is installed inside the lift lobby. The transferred light will be emitted along the fiber optic to illuminate the lift lobby. The lenses are proposed to be installed in a space that is accessible to the exterior. A minimum space of 1.2 x 1.2 m is recommended to be reserved for maintenance.

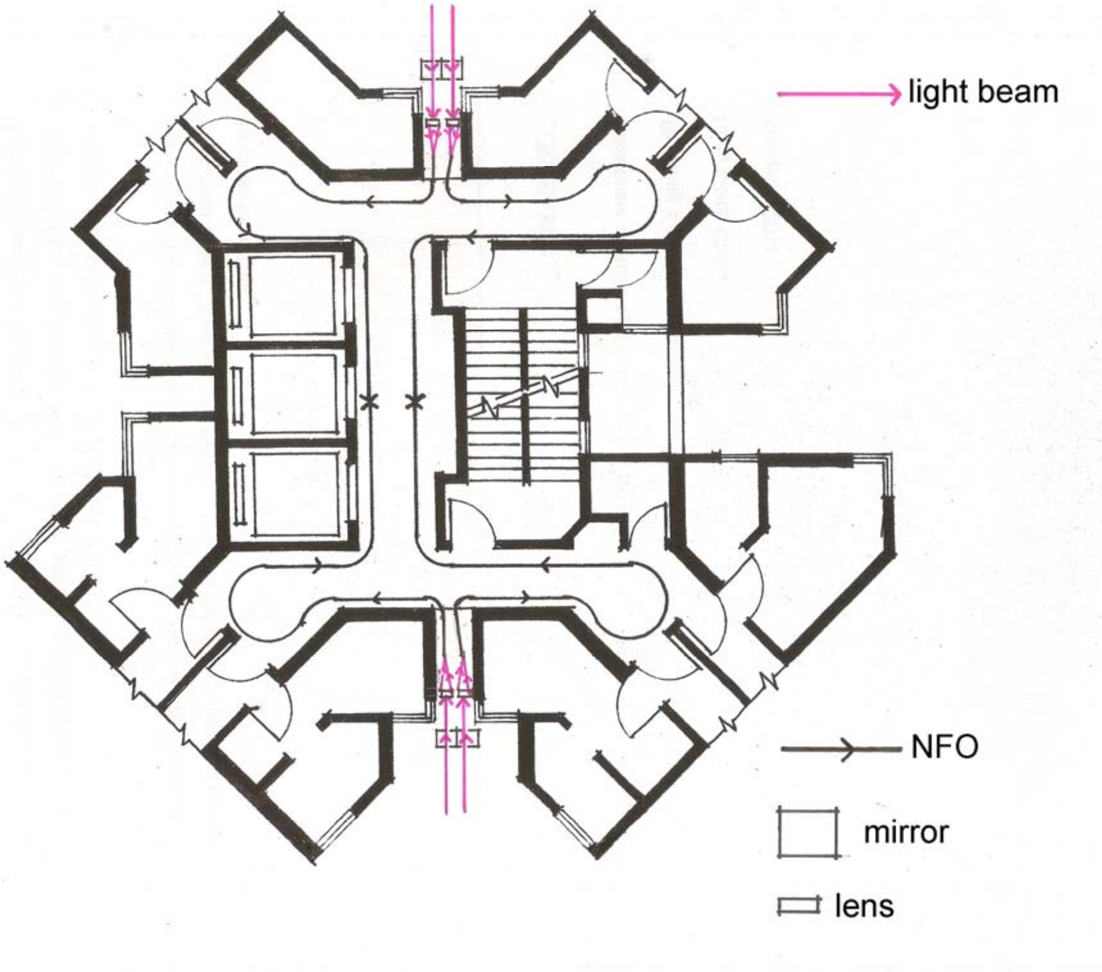


Fig. 4.9 The proposed layout of the RSSL in the lift lobby

4.4 Conclusions

In this chapter a RSSL that is suitable for the highrise residential buildings in Hong Kong was proposed. The horizontal light pipe system in the Waterfront House was chosen as a study reference. The horizontal light pipe system was modified to solve the problem of requiring 3 m headroom for installation. The metallic light pipe, which acted as the first transmission medium was proposed to be installed in a service room where part of the headroom clearance can be reduced. The notched fiber optic of 10.4 mm in diameter, which acted as a second light transmission medium, was installed inside the lift lobby to solve the headroom problem. As transmitted light is required to be highly conecntrated when entering the fiber optic of small diameter for efficient transmission, a converging lens system was designed to be installed at the end of the metallic light pipe to converge the light beam into the notched fiber optic. In a preliminary experiment, the lenses could not focus the light beam sharply into the notched fiber optic because the sunlight, which was redirected by the laser cut panel, was not in a perfect collimated beam. Multiple reflections occurred inside the metallic light pipe. The system was revised. A plane mirror replaced the laser cut panel and metallic light pipe. The mirror reflected sunlight directly into the converging lenses, which in turn concentrated the light rays into the notched fiber optic. The mirror could be adjusted in both horizontal and vertical directions to reflect the sun rays at different times and dates in a direction always parallel to the axis of the RSSL. Light was transmitted along the notched fiber optic and emitted downwards in a divergent angle of 60°. A LED lamp was connected to the end of the fiber optic, which served as a supplementary lighting. The LED would be turned on when the interior light intensity fell below 150 lx. The light that was emitted from the LED lamp travelled in the reverse direction to illuminate the lift lobby.

CHAPTER 5

SIMULATION STUDY OF THE PROPOSED RSSL

5.1 Introduction

The software ZEMAX-EE is an optical design software package for various aspects of optical systems with more advanced features like non-sequential ray tracing for analysis of stray light, and physical optic beam propagation in lenses, light pipes, and various medium. The ZEMAX-EE can trace the propagation of light through various medium where there are multiple optical paths such as mirror, lenses, light pipes and fiber optic. It can account for reflection, refraction and also the total internal reflection ray path. In non-sequential program (NSC) there is no pre-defined sequence of surfaces which the rays will hit. The ray path is solely determined by the physical properties of the optical elements and the directions of the rays. Rays may hit any part of any non-sequential object, and the same object multiple times, or not at all. Non-sequential mode is used to analyze stray light, scattering and illumination in both imaging and non-imaging systems. Light source and detector objects are set-up within the group to launch and capture rays, respectively. Rays from non-sequential sources, known as NSC rays, can be split and scattered by optical components. These rays can be diffracted at phase surfaces and objects. Detectors can be modeled as planar surfaces, curved surfaces and even 3D volumes. Non-sequential detectors support the display of a variety of data types, radiant intensity and irradiance. The optics can be modeled as 3D components. In the simulation, the efficiencies of different elements and at different locations of the RSSL can be estimated. The simulation is based on perfection of materials and the accuracy is commented by professionals to be over 90 %. At present, there is no available comprehensive optical design software in the market to analyze the side-emitting performance of fiber optic. Like most optical design software, ZEMAX-EE calculates the efficiency of end-emitting fiber optic only (Wong and Yang, 2011). The conversion of the simulated end-emitting efficiency to side-emitting efficiency of the FO will be discussed in section 5.4.

As light propagation in the RSSL is non-sequential, the non sequential program in ZEMAX-EE is used to simulate the performance of the RSSL. The 3D coordinates in the non sequential program are represented by X, Y and Z positions. The positions of the objects are entered in the X, Y or Z positions depending on which plane the object are located. The dimensions in these positions represent the lengths of the objects. The data in the 'Object Type' column represents the type of the objects. The aperture of the RSSL is set to be "0" at the X position. Sunlight, which is as 'Source Ellipse' in the 'Object Type' column enters the RSSL at -10mm in X position. Light pipes and fiber optic are represented by the 'cylinder object'. 'Detector' stands for a light detector at a specified location which can detect the amount of light at that point. The material of the object is made of is entered into the 'Material' column. For example, 'PMMA' is entered for fiber optic.

The direction of the incident light, types and configurations of each component of the RSSL were entered into the non sequential program as shown in Figure 5.1. The light beam was assumed to enter the RSSL at incidence angle of 0°. The RSSL and the light path were stimulated in a 3D model. For the sake of analysis, the solar power input was assumed to be 100 W and the numbers of rays to be analyzed was 10000 in simulation. Accuracy of the simulated results increases with the increase in the number of rays but the simulation time also increases. The general practice assumed 10000 rays to be analyzed. Fig. 5.2 shows the simulated 3D diagram of a

RSSL consisted of 2 converging lenses and a fiber optic. The overall efficiency (η) of the RSSL is the ratio of indoor light intensity to the corresponding outdoor light intensity. Detectors were located at different parts of the RSSL to detect the efficiencies at respective locations. The total power in the Detector Viewer Diagram indicates the efficiency of the system. The total power in the Detector Viewer Diagram in Figure 5.3 is 6.3321E + 001 Watts implying that the simulated efficiency of the RSSL is 63 %.

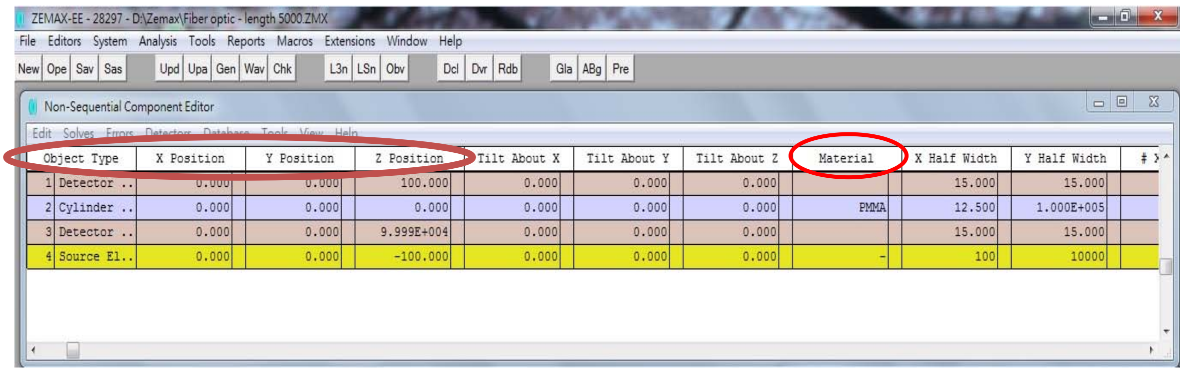


Fig. 5.1 Non-sequential program of ZEMAX-EE

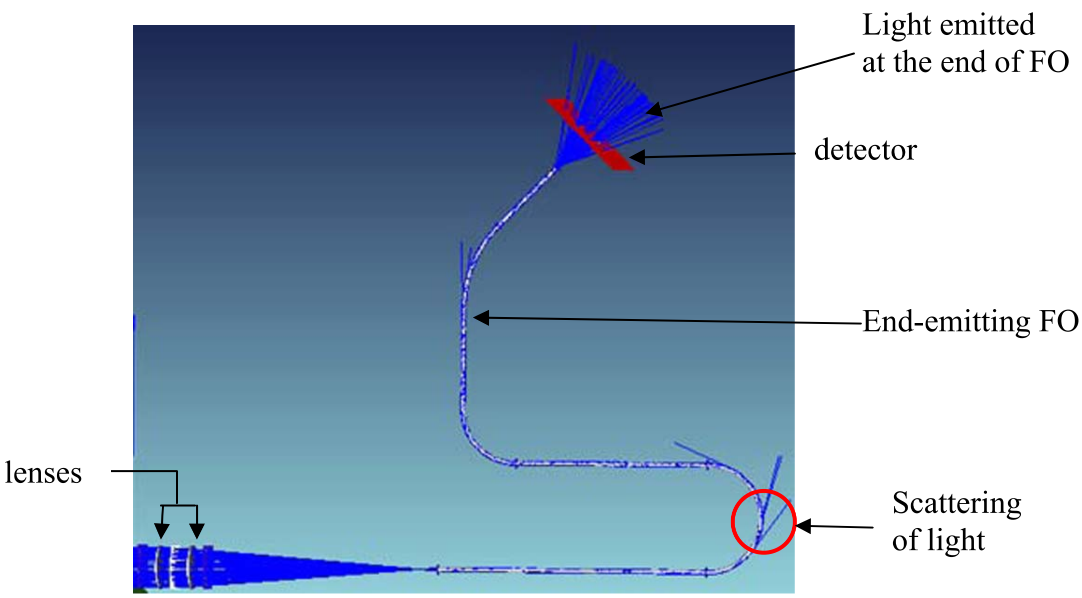


Fig. 5.2 3D diagram of a RSSL

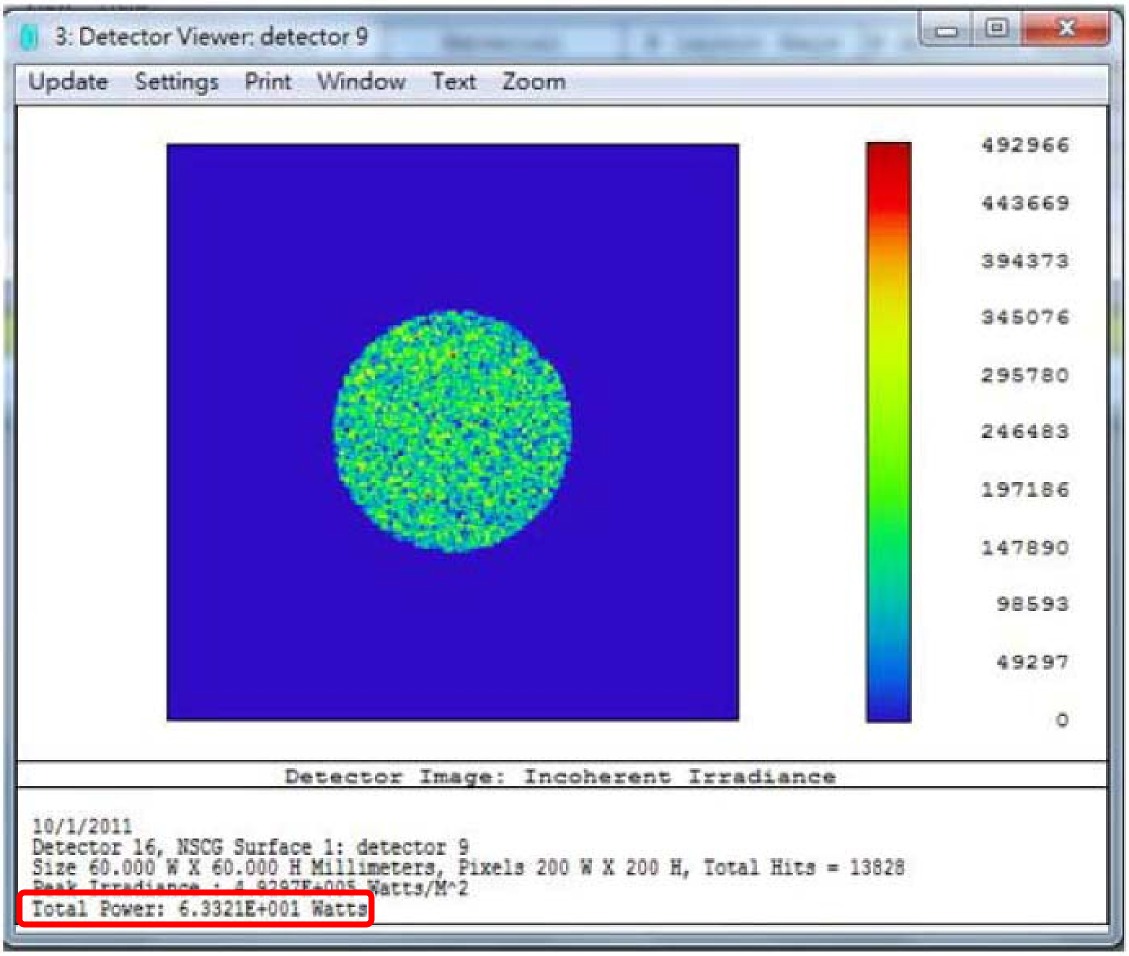


Fig. 5.3 Detector Viewer Diagram

5.2 Stage 1: simulation of the RSSL

In the 1st stage, the RSSL was assumed to be orientated to the west with mirror initially facing the east. At this location the mirror was only required to be adjusted in the vertical direction responding to the changes in solar altitude (β) at different times and dates so that the sun rays was always reflected parallel to the axis of the lenses. The position of the sun was assumed to be directly overhead at noon. The mirror was adjusted to incline 45° to reflect the light beam parallel to the axis of the lenses. The total solar power input was assumed to be 100 W. Simulations of the RSSL were carried out to study the performances of each component and analyze the factors that could affect their efficiencies. Figure 5.4 shows the simulated RSSL. 13 detectors are placed at different locations as shown. The Total Power in various Detector Viewer Diagrams record the power detected by D1 to D13.

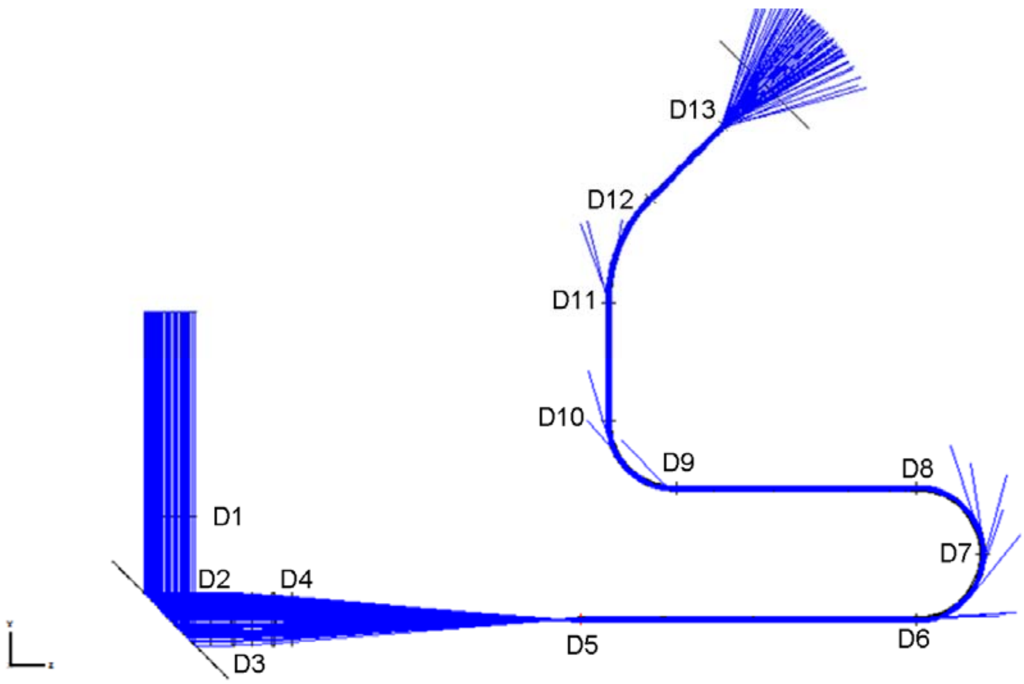


Fig. 5.4 The simulated configuration of the RSSL

Note: D1: before mirror; D2: after mirror; D3: after lens 1; D4: after lens 2; D5: just entering FO; D6: at 1.66 m of FO; D7: at 2.16 m of FO; D8: at 2.67 m of FO; D9: at 3.87 m of FO; D10: at 4.37 m of FO; D11: at 4.97 m of FO; D12: at 5.52 m of FO; D13: at 6.02 of FO.

5.2.1 Performance of the mirror

a) The effect of the solar altitude

Theoretically, the mirror inclination can be adjusted vertically from around 2.5° to 87.5° to reflect the sun rays at solar altitudes ranging between 5° to 175° as shown in Figure 5.5. The solar altitude (β) is twice the value of mirror inclination (θ) as illustrated in Figure 5.6.

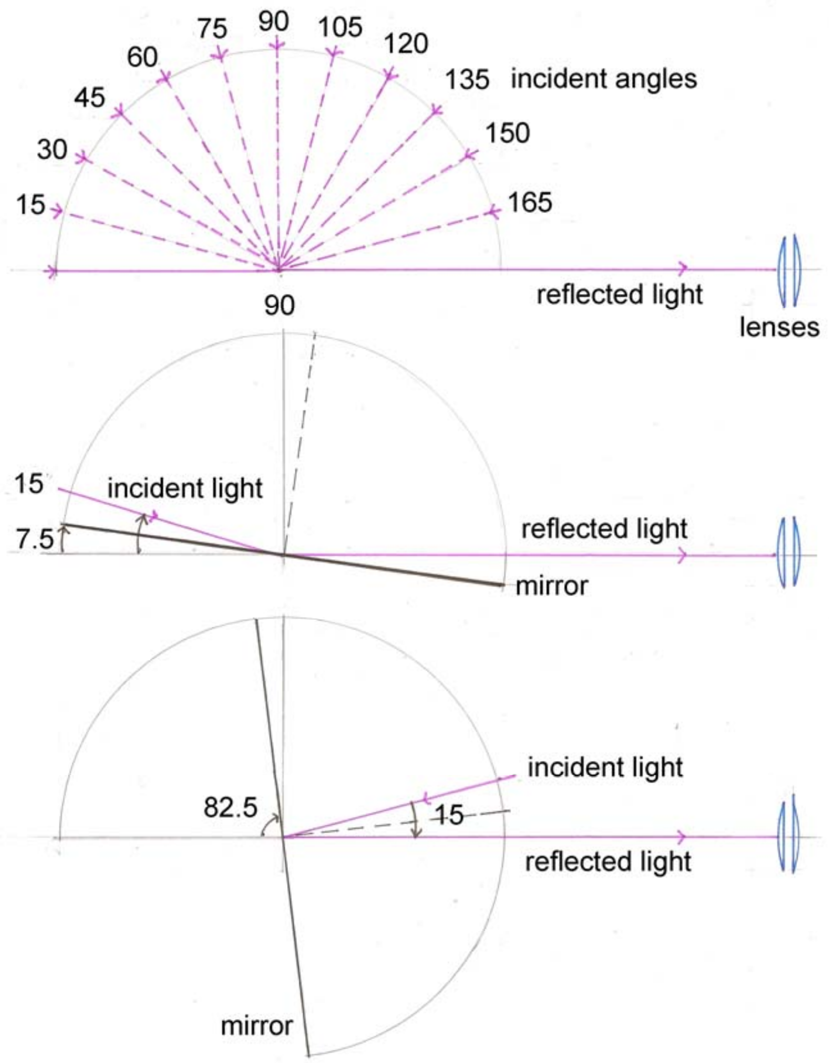


Fig. 5.5 Mirror operation at different solar altitude

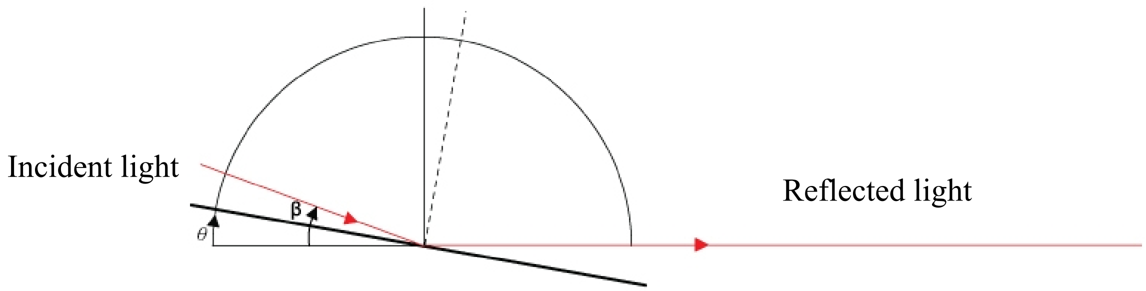


Fig. 5.6 Relationship of solar altitude with mirror inclination

As the size of the aperture is 250 mm in diameter, any dimension of the reflected light beam which is less than 250 mm may reduce the amount of reflected light entering the lenses and reduce the efficiency of the RSSL. A preliminary experiment was carried out to record the changes in solar altitude from 9:30 to 14:30 h for one week. Figure 5.7 shows the relationship between the solar altitude and time. The solar altitude increased from 60° at 9:30 h to 90° around noon and decreased to 36° at 16:30 h. The recorded inclination angles were within the range from 18° to 45°. Figure 5.8 illustrates the relationship between solar altitude and mirror inclination when the height of the reflected light beam is 250 mm. The minimum required solar altitude can be calculated as follows:

$\beta = 2 \times \theta$ (5.1)

And the height of the reflected light beam (a) is: (5.2)

$a = 760 \times \sin\theta$

Substitute 250 mm into ‘a’ in Equation (5.2),

$\sin\theta = 0.33$; $\theta = 19°$. The height of the reflected light spot will be less than 760 mm when the solar altitude is within the range of 0° and 38°. From the experimental records (Fig. 5.7), the RSSL can operate from 9:30 to 16:00 h with ‘a’ larger or equal to 250 mm. The change in solar altitude has slight effect on the efficiency of the RSSL.

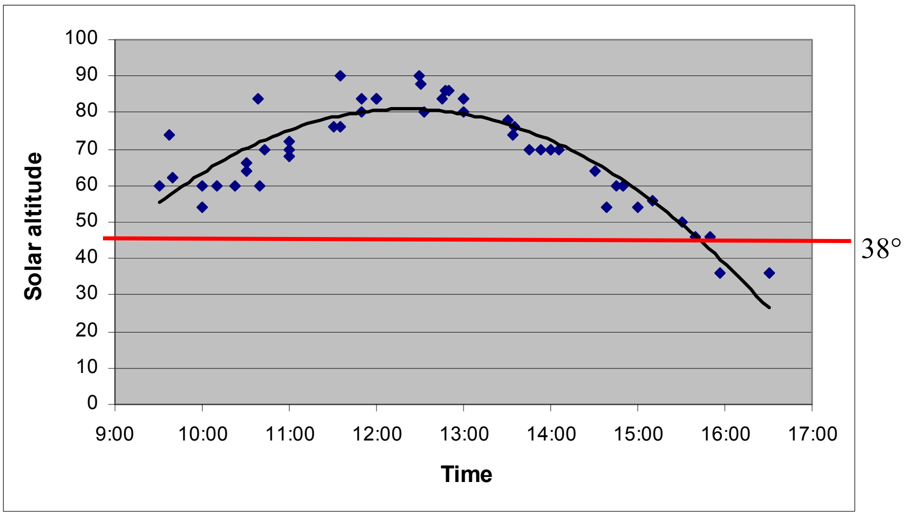


Fig. 5.7 Solar altitude vs. time

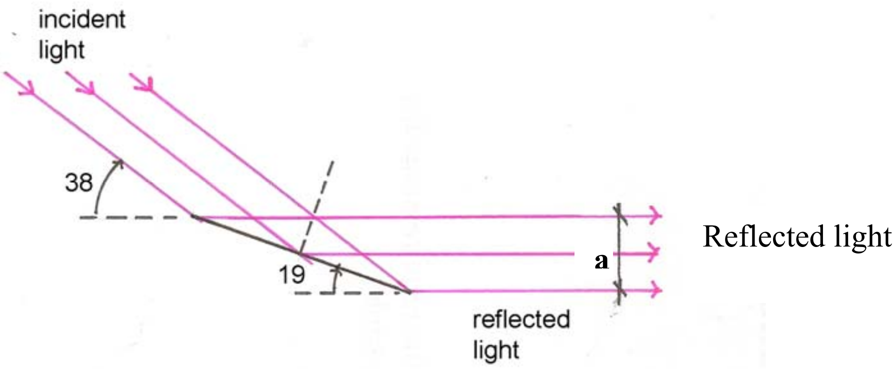


Fig. 5.8 Relationship between the solar altitude and height of the reflected image

Simulation study on the effect of the solar altitude was carried out. The performance of the mirror inclined at 10°, 45°, 65° and 80° were simulated by the non-sequential program. As the simulated results may have slight deviation, 3 simulations were carried out for each mirror inclination in order to obtain an average efficiency for the mirror at different solar altitudes. The size of the mirror was 760 x 760 mm and the detector was set to be 1.5 m from the mirror. The averaged efficiencies of the mirror were 99.8 %, 100 %, 97.7 % and 99.8 % for mirror inclination at 10°, 45°, 65° and

80°, respectively. The corresponding solar altitudes were 20°, 90°, -40° and -70°. The simulation results were tabulated in Table 5.1. The 3D diagrams and Detector Viewer Diagrams of the mirrors inclined at 10° and 65° are shown in Figures 5.9, 5.10, 5.11 and 5.12. The simulation efficiency of the mirror at 10° inclination does not agree with the expected decrease in mirror efficiency. The deviation can be explained that the mirror can concentrate and reflect most of the incident light into the RSSL. It can be concluded that the factor of solar altitude has slight effect on the mirror performance in a west-orientated RSSL. The efficiency slightly increases with the increase in solar altitude.

Table 5.1 Simulation results for mirror performance at different solar altitudes

Mirror inclination (degree)	**Solar altitude (degree)**	**Efficiencies (%)**			**Average efficiency**
		1st reading	**2nd reading**	**3rd reading**	
10	20	99.5	100	99.9	99.8
45	90	100	100	100	100
65	-40	99.5	95.6	98	97.7
80	-70	99.6	100	99.9	99.8

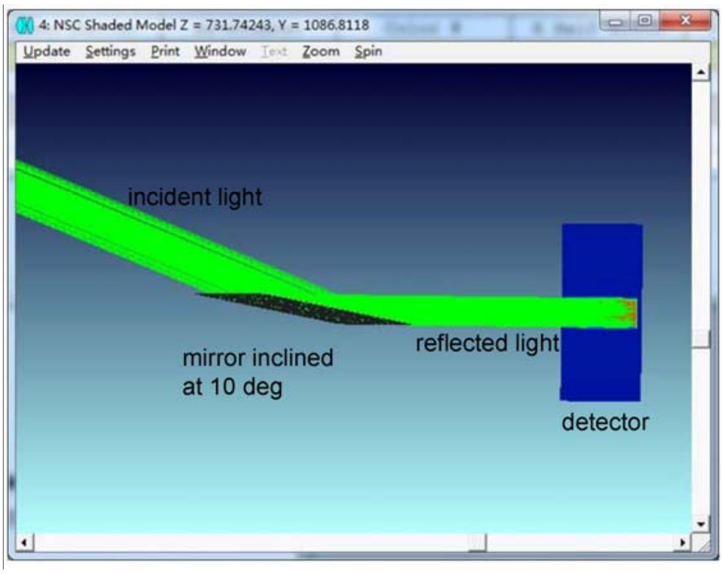


Fig. 5.9 3D diagram of mirror inclined at 10°

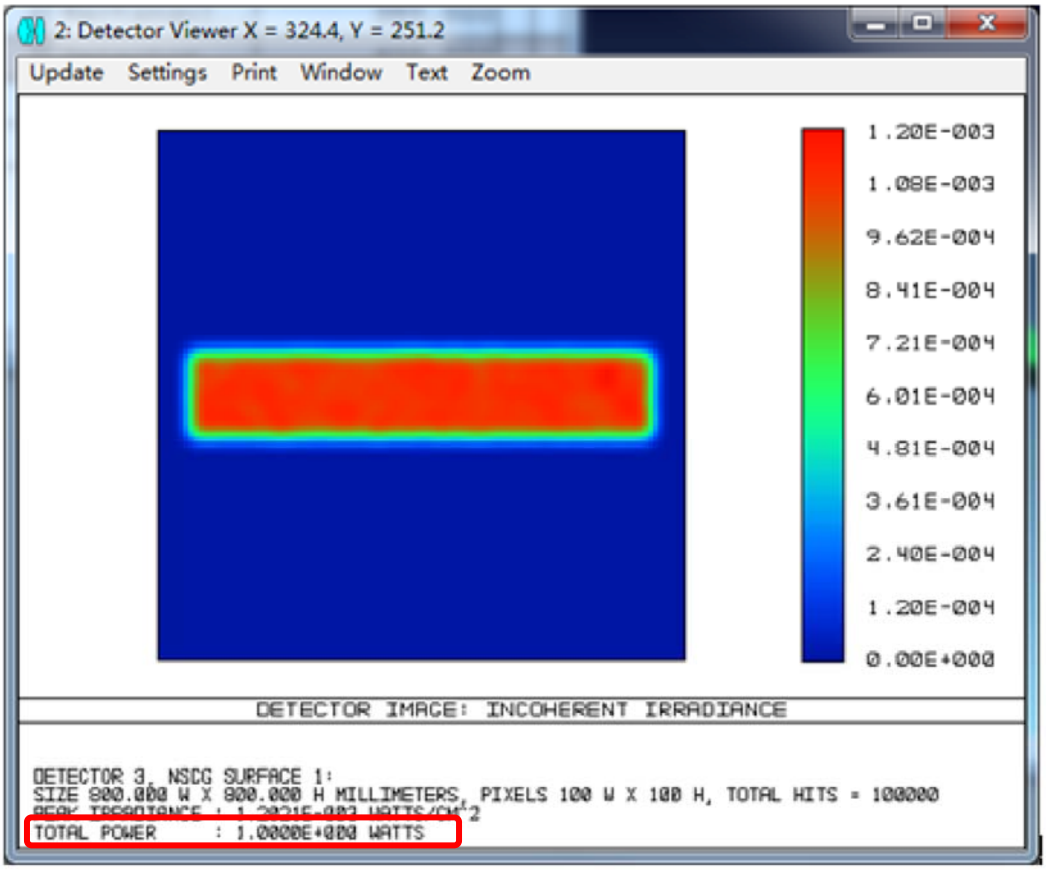


Fig. 5.10 Detector Viewer Diagram of mirror inclined at 10°

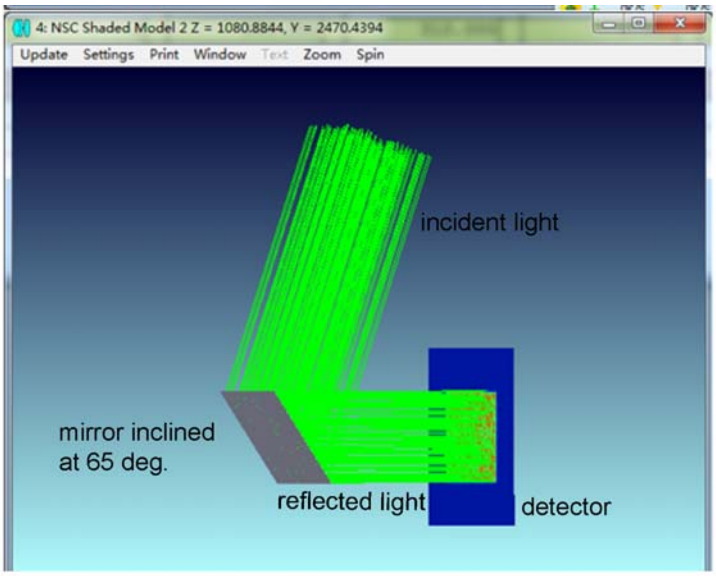


Fig. 5.11 3D diagram of mirror inclined at 65°

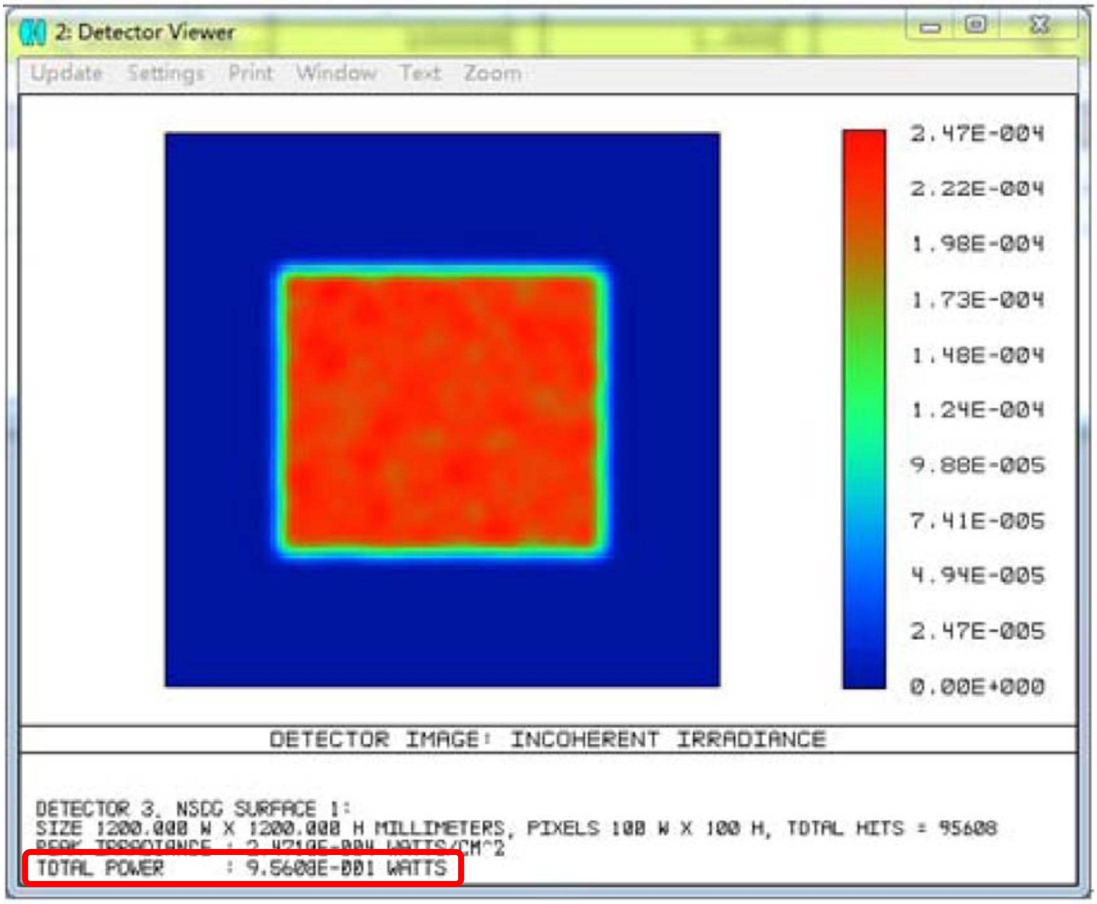


Fig. 5.12 Detector Viewer Diagram of mirror inclined at 65°

Simulation of the proposed RSSL as shown in Figure 6.4 was carried out. The mirror inclined at 45°. The solar irradiance was defined as 100W for the sake of analysis, which meant that the efficiency as recorded by D1 was 100W. The simulated results were recorded in Table 5.6. D2 was located at 10 mm from the centre of the mirror and recorded an efficiency of 99.1%. The difference as compared with the previous simulation of 100% is within 1%, which is acceptable.

In an east-orientated RSSL with mirror originally facing the west, the movement pattern of the mirror in response to changes in solar altitude is the same except in the reverse direction. The simulation results of solar altitude on the east-orientated RSSL are the same as the west-orientated RSSL. The solar altitude has slight effect on a west-orientated RSSL.

Conclusively, the effects of the solar altitude on an east-orientated and west-orientated RSSL are slight.

b) The effect of the solar azimuth angle

In the south-orientated RSSL, the mirror rotates in the horizontal plane in order to reflect the sun ray at different solar azimuth angle parallel to the axis of the RSSL. Figures 5.13, 5.14, 5.15 and 5.16 illustrate the examples of the sun ray coming from four orientations. The mirror rotates with normal from north of 10° to 90°, then retroflex to the horizontal and rotates with the normal from -80° to -10 ° responding to changes in solar azimuth angle from north of 20° to 340°, respectively. The relation between the rotation angle (r) of the mirror and the solar azimuth angle (γ) can be represented by the following equations:

$$\gamma = 2 \times r \tag{5.3}$$

The value of (r) is positive when mirror rotates in clockwise direction and negative in anti-clockwise direction. The solar azimuth angles (A) for the 4 mirror orientations are calculated from Equation 5.3.

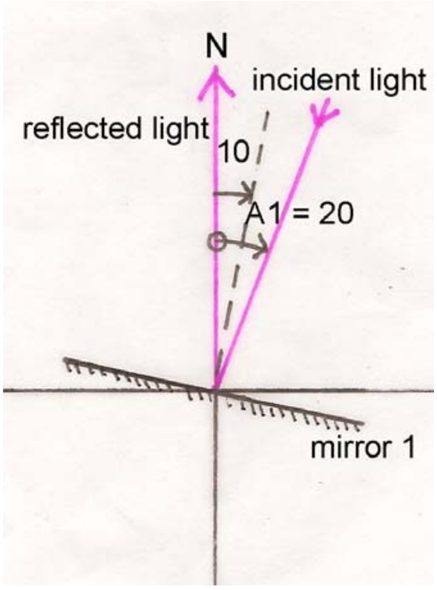


Fig. 5.13 Mirror rotation angle of 10°

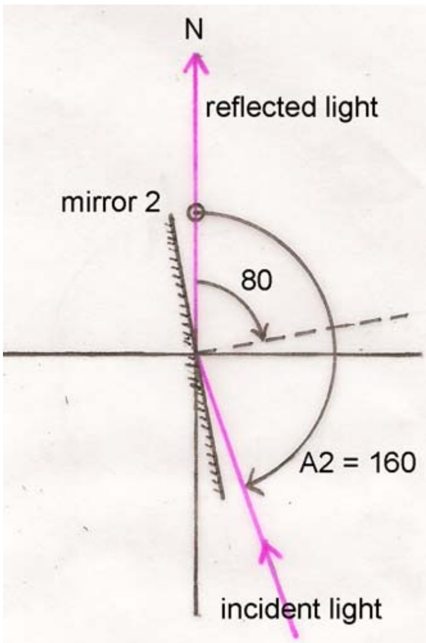


Fig. 5.14 Mirror rotation angle of 80°

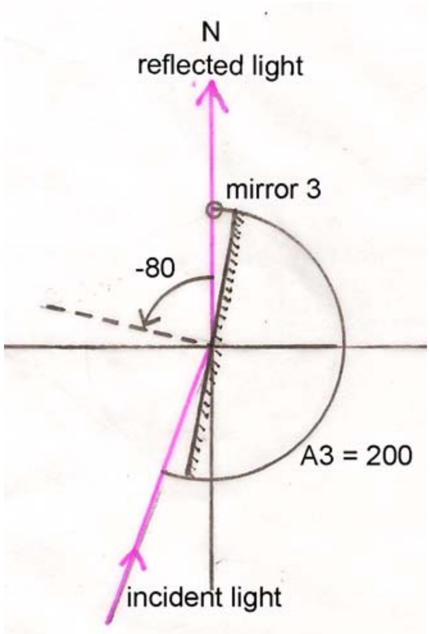


Fig. 5.15 Mirror rotation angle of -80°

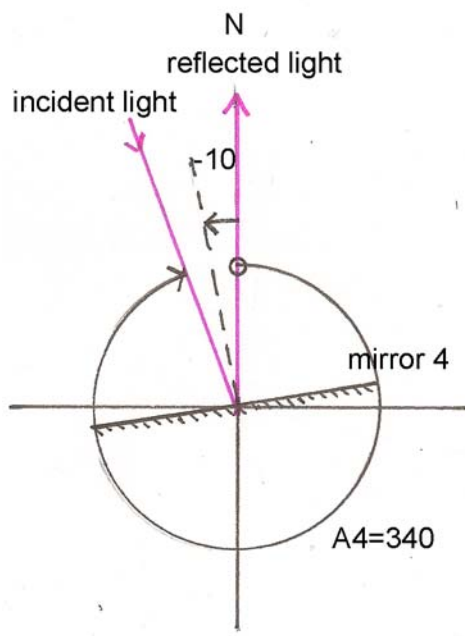


Fig. 5.16 Mirror rotation angle of -10°

In the south orientation, the RSSL can receive sunshine for most of the day. The mirror in the RSSL can reflect sun rays from all the solar azimuth angles parallel to the axis of the RSSL. Similar to the case in solar altitude, if the width of the reflected light beam is less than 250 mm, the amount of reflected light entering the lenses may be reduced and the efficiency of the RSSL reduces subsequently. With reference to Fig. 5.17, ‘b’ is the minimum widths of the reflected light beam for not reducing the efficiency of the RSSL, which is 250 mm. ‘b’ will less than 250 mm when the incidence angle is less than 38° at solar azimuth angles within the range of north of142° and 218°.

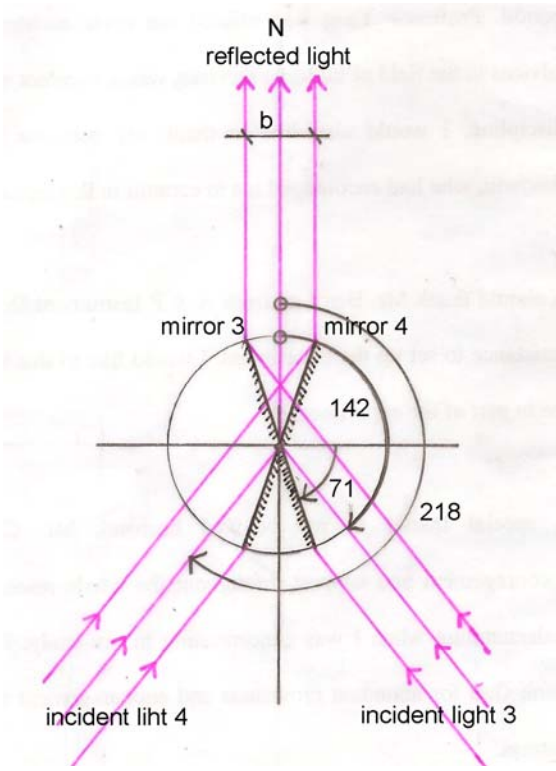


Fig. 5.17 The effect of solar azimuth angle on the S-orientated RSSL

The north orientation receives the least hours of sunshine in a day. A north-orientated RSSL is blocked by the building for most of the day, and therefore the RSSL in north orientation will not be studied

From the preliminary experiment, the changes in solar azimuth angle with time are plotted in Figure 5.18. The operating hours of the south-orientated RSSL is basically outside the period of solar azimuth angle from north of 142° to 218° when using the average solar azimuth angle-time curve. However, there may be some periods of solar azimuth angles within the range of north of 142° to 218° in spring seasons, when the solar irradiance is comparatively low resulting in the least operating hours of the RSSL. Hence, the effect of solar azimuth angle is low.

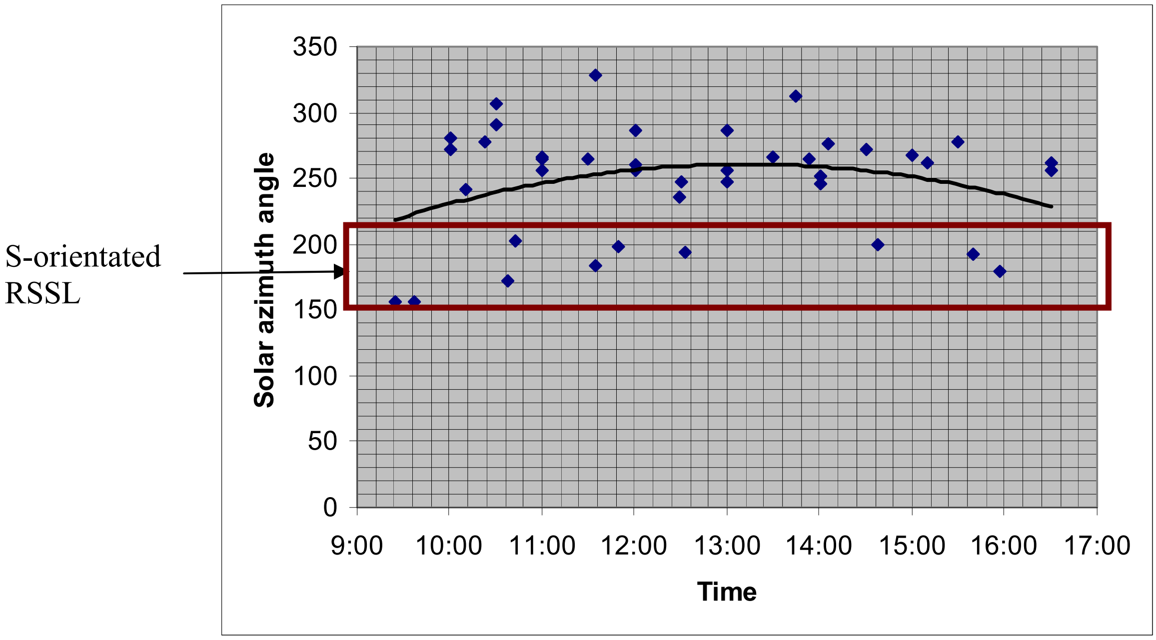


Fig. 5.18 Solar azimuth angle vs. time

The simulations of the mirror performance in a south-orientated RSSL at different solar azimuth angles were carried out. The simulation results for the efficiencies of the mirror at different solar azimuth angles are presented in Table 5.2. The efficiencies of mirror at solar azimuth angles of 290°, 250°, 0°, 180°, 70° and 110° are between 99.9 % and 100 %; and the efficiencies at 40° and 140° are 97.7 % and 96.7 %, respectively. The simulated efficiencies of the mirror also do not agree with the expected decrease in mirror efficiency when the width of the reflected light beam is less than 250 mm. The explanation is similar to the case in solar altitude that the mirror can concentrate and reflect the entire incident light intensity. It can be concluded that the factor of solar azimuth angle has slight effect on the performance of the mirror in the south-orientated RSSL.

Table 5.2 Simulation results for mirror performance at different solar azimuth angles

Turning angle of mirror (degree)	**Solar azimuth angle (degree)**	**Efficiencies (%)**			**Average efficiency**
		1st reading	**2nd reading**	**3rd reading**	
10	290	99.6	100	99.9	99.8
- 10	250	99.7	99.9	99.8	99.8
45	0	100	100	100	100
- 45	180	99.9	100	99.8	99.9
65	40	99.5	95.6	98	97.7
- 65	140	97.5	95.8	97	96.7
80	70	99.6	100	99.9	99.8
- 80	110	99.7	99.9	100	99.9

5.2.2 Performance of the lenses

The required thickness of the convex lens is calculated to be 70 mm by the non-sequential program of ZEMAX-EE. However, this thickness of the convex lens is too expensive and impractical for application. The single converging lens is replaced by 2 nos. of 5 mm thick plano-convex lens of same diameter and placed 70 mm apart. D3 and D4 record the efficiencies of 87 % and 74.7 %, respectively (Table 5.6). The overall efficiency of the lens system is around 75 %, which means 12 % of incident light is lost in the transfer of light from lens 1 to 2. For the ideal case, a single convex lens is recommended for application as far as possible.

5.2.3 Performance of the fiber optic

Simulation of a straight fiber optic ranging from 5 to 1500 m was carried out. The efficiency of the 5 m and 1500 m fiber optic was 100 % and 99.99 %, respectively. The simulation demonstrated that the length of a fiber optic has no effect on the efficiency of a straight fiber optic.

Simulation of the fiber optic at various degrees of bending and turning radius were carried out. The input solar irradiance was assumed to be 100 W. The detector which was placed after a 90° bending with 100 mm turning radius of the fiber optic recorded an efficiency of 89 % (Fig. 5.20 and Table 5.3). The simulation results of the fiber optic at various degree of bending of same turning radius and different turning radius at same degree of bending are tabulated in Table 5.3 and 5.4, respectively. The results indicate that the transmission efficiency of a fiber optic increases with the decrease in the degree of bending and increase in turning radius.

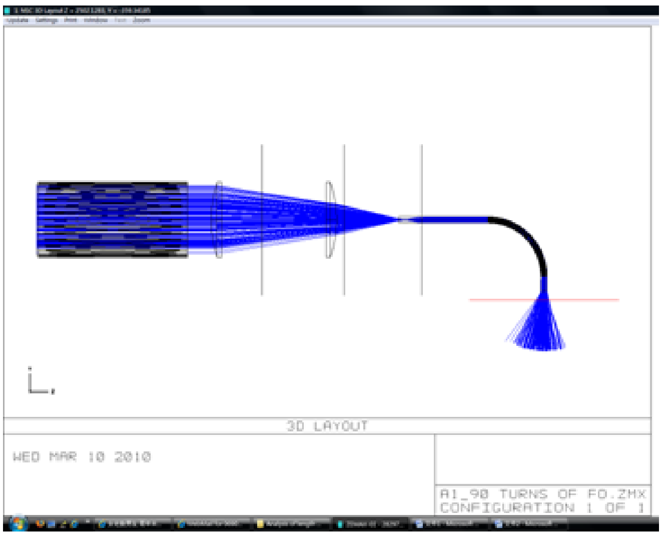


Fig. 5.19 Simulated RSSL with a 90° bending fiber optic

Table 5.3 Effects of the degree of bending on the efficiency of a fiber optic

Bending degree	Input (W) Trial 1	Output (W) Trial 1	Input (W) Trial 2	Output (W) Trial 2	Input (W) Trial 3	Output (W) Trial 3	Efficiency			
							Trial 1	Trail 2	Trail 3	Average
90°	100.21	89.221	100.23	89.299	100.21	89.114	89.03%	89.09%	88.93%	**89.02%**
80°	100.01	89.554	100.02	89.234	100.01	89.653	89.55%	89.22%	89.64%	**89.47%**
70°	99.877	89.642	99.863	89.683	99.865	89.689	89.75%	89.81%	89.81%	**89.79%**
60°	99.866	89.628	99.848	89.854	99.865	89.644	89.75%	89.99%	89.77%	**89.83%**
50°	100.03	90.238	100.01	90.034	100.05	90.24	90.21%	90.02%	90.19%	**90.14%**
40°	100.61	90.552	100.61	90.457	100.63	90.527	90.00%	89.91%	89.96%	**89.96%**
30°	100.45	91.175	100.48	91.049	100.45	91.065	90.77%	90.61%	90.66%	**90.68%**
20°	99.979	91.682	99.955	91.41	99.994	91.635	91.70%	91.45%	91.64%	**91.60%**
10°	99.926	92.485	99.928	92.49	99.932	92.475	92.55%	92.56%	92.54%	**92.55%**
0°	99.994	92.459	99.994	92.459	99.994	92.459	92.46%	92.46%	92.46%	**92.46%**

Table 5.4 Effects of the turning radius on the efficiency of a fiber optic

Degree of bending	Turning radius (mm)	Efficiencies of the fiber optic
90	375	99.0 %
90	200	98.8 %
180	375	98.5 %
180	200	98.0 %

5.2.4 The efficiency of the RSSL

For the RSSL as shown in Figure 5.4, the efficiencies which are recorded by the detectors D2 to D13 are shown in Table 5.6. As the configuration of the side-emitting fiber optic was constant, the efficiency in the RSSL depended on the efficiency of the mirror in reflecting sunlight into the RSSL. About 74 W of solar irradiance were concentrated by the lens system into the fiber optic. 68.3% of the converged light entered the fiber optic as indicated in D5. 7 % of the transmitted light was lost in the transfer process from the lenses to the fiber optic because the incident angles of the converged light beam in the outer perimeter entering the fiber were larger than the critical angle of the fiber optic. The D6 at 1.66 m of the fiber optic recorded an efficiency of 68.3 %. D8 at 2.67m and D9 at 3.87 m recorded the efficiencies of 65.4% and 65.3 %, respectively. Similarly, D10 at 4.37 m and D11 at 7.94 m recorded the same efficiency of 63.9 %. The portions of the fiber optic from D5 to D6, D8 to D9 and D10 to D11 were straight rods demonstrating that apparently no light was lost in the transmission inside a straight end-emitting fiber optic, which basically agreed with the simulated result in section 5.2.3.

1.5 % of light was lost in the transfer from D6 to D7; and 1.4 % from D7 to D8 and D9 to D10. These were the curved portions of fiber optic with 90° bending and turning radius of 375 mm. The average loss in light of a 90° bending is 1.47 %. The loss of light in the transfer from D11 to D12 was 0.7 %. The bending angle between D11 and D12 was 45° and the turning radius was also 375 mm. The simulation indicated that light was lost in the bending of the fiber optic and the efficiency decreased with the increase in the degree of bending. Scattering of light occurred at bending and resulted in loss of light (Fig. 5.2). The simulation results of different parts of the RSSL are tabulated in Table 5.3. The overall efficiency of the RSSL is 56.9 %.

5.3 Stage 2: simulation of a RSSL in SE orientation

The orientation of the RSSL was set to be S32°E. At this position, both the horizontal and vertical positions of the mirror were required to be adjusted in order to reflect the sun beam parallel to the axis of the lenses. Simulations of the performances of the RSSL were carried out for 3 different cases (Fig. 5.21 to 5.23) and the results were tabulated in Table 5.5:

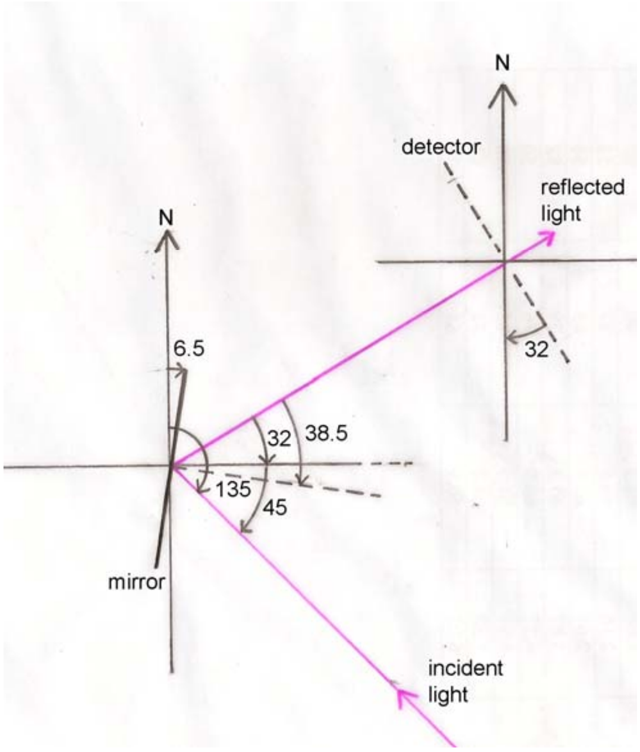


Fig. 5.20 Case 1 of solar azimuth angle N of 135°

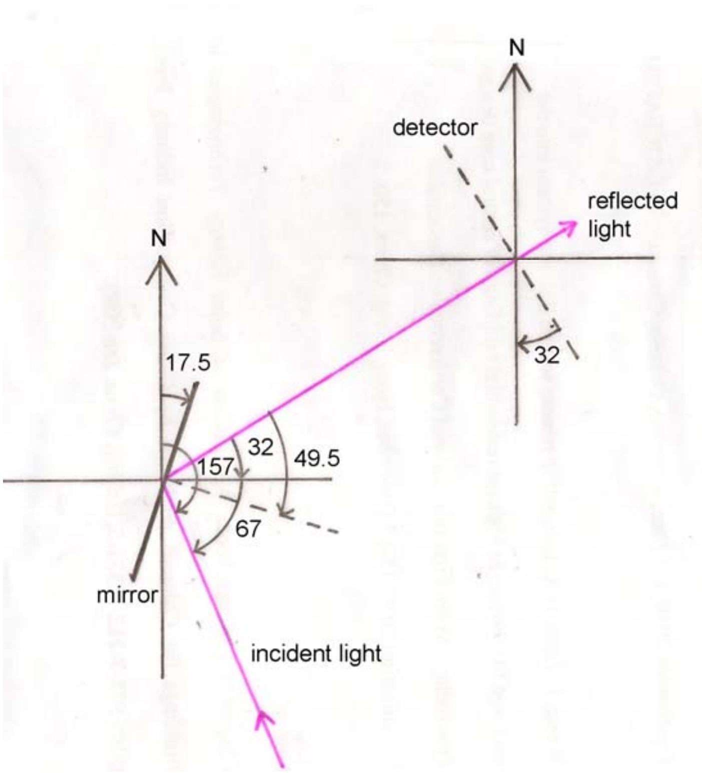


Fig. 5.21 Case 2 of solar azimuth angle N of 157°

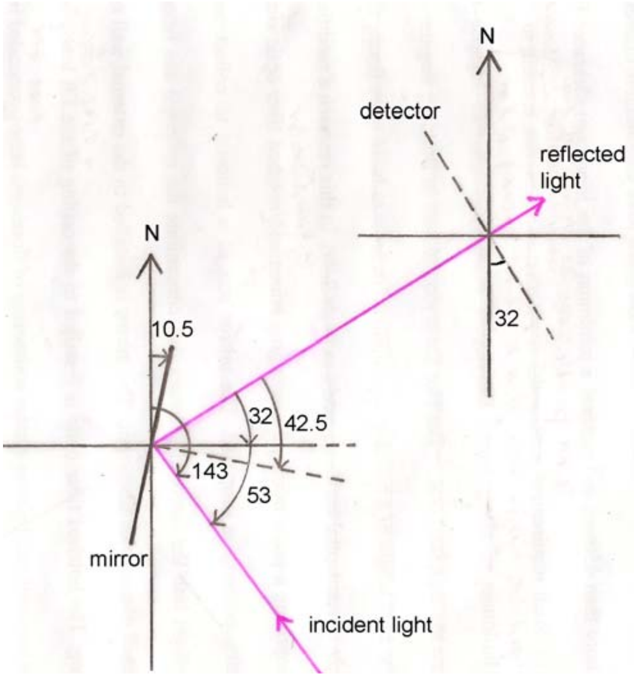


Fig. 5.22 Case 3 of solar azimuth angle N of 143°

Table 5.5 Simulation of the mirror performance under different conditions

Case	Solar azimuth angle	Solar altitude	Mirror inclination	Efficiency (%)
1	135	74	37	30.6
2	157	90	45	36.1
3	143	126	63	37.9

Comparing Case 1 to Case 2 and Case 3 to Case 1 indicate that the efficiency of the RSSL decreases with the decrease in the solar altitude. In comparing Case 1 and 2, the efficiency increases when the solar azimuth angle increases but decrease in the comparison of case 2 and 3. The 3D diagrams and the Detector Viewer Diagrams of the 3 cases are shown in Figures 5.24 to 5.29. Conclusively, the efficiency of the RSSL decreases considerably when its orientation is deviated from the east, west or south. The efficiency decreases with the decreases in solar altitude. There is no apparent relationship between the efficiency of the RSSL and solar azimuth angle. Experiments were carried out to test the validity of the simulation results.

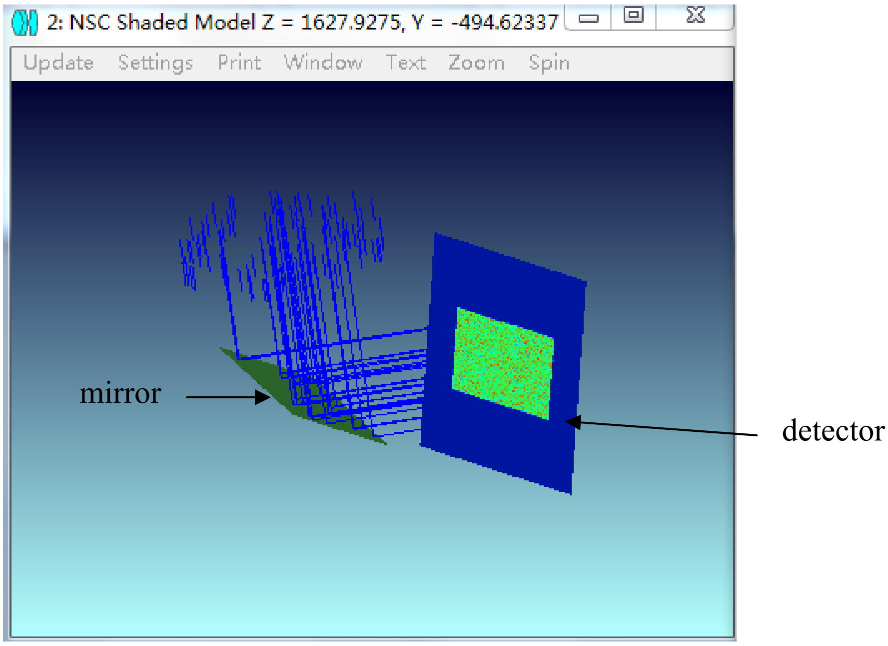


Fig. 5.23 3D diagram of Case 1

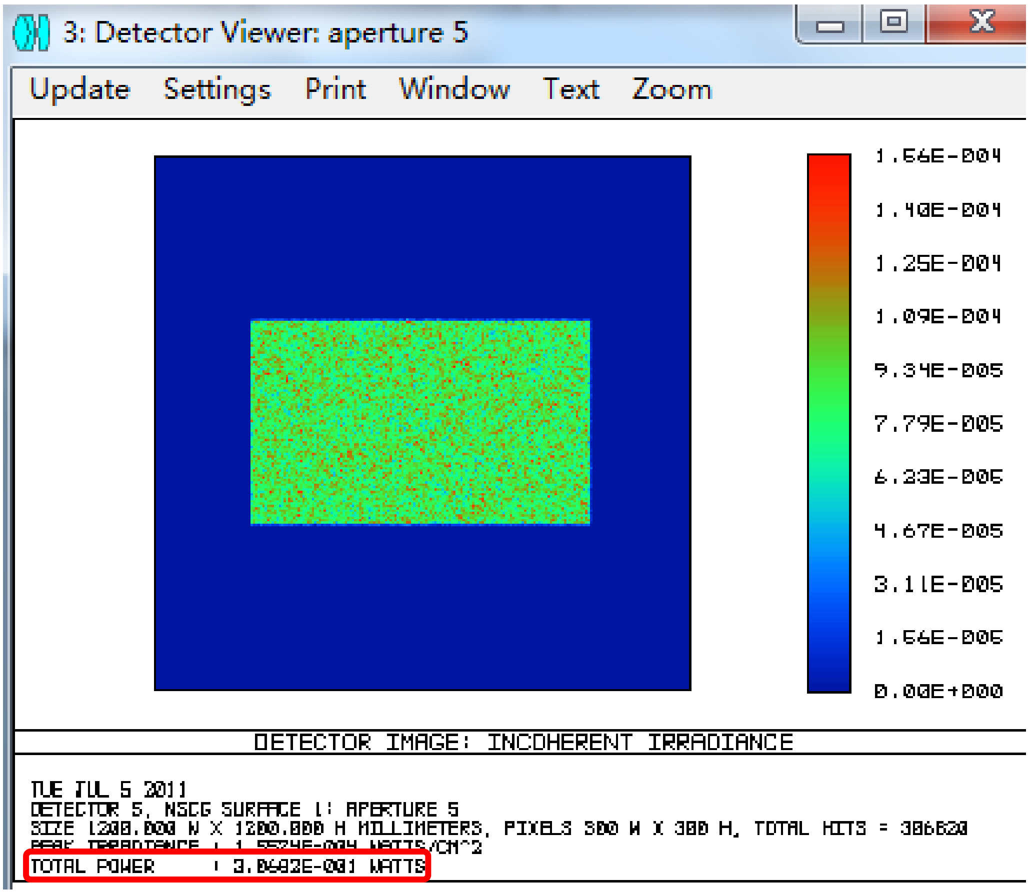


Fig. 5.24 Detector Viewer Diagram of Case 1

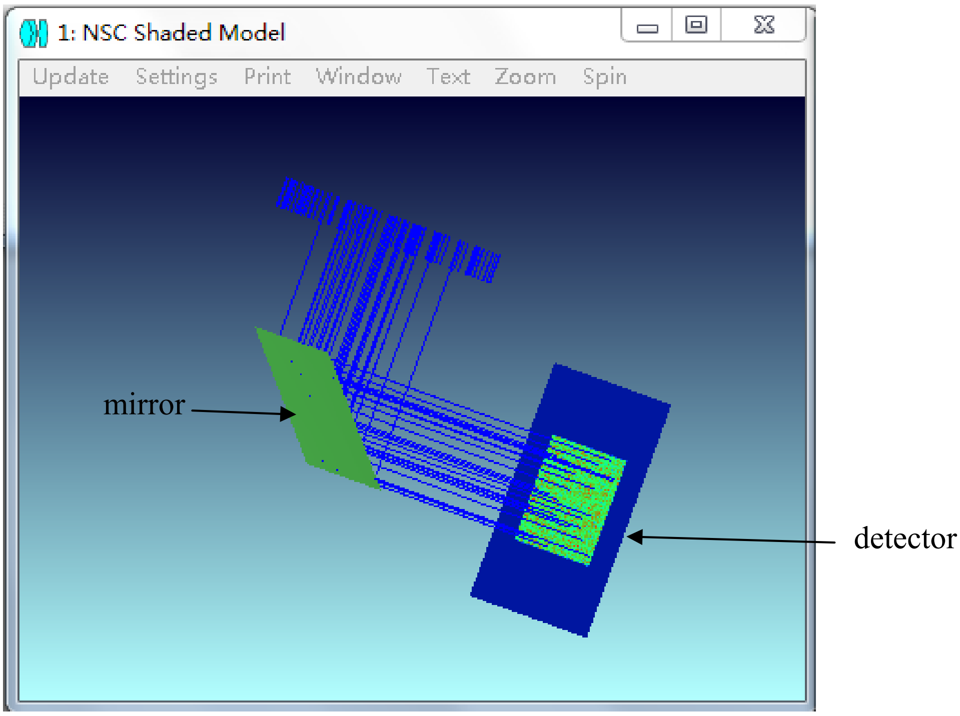


Fig. 5.25 3D diagram of Case 2

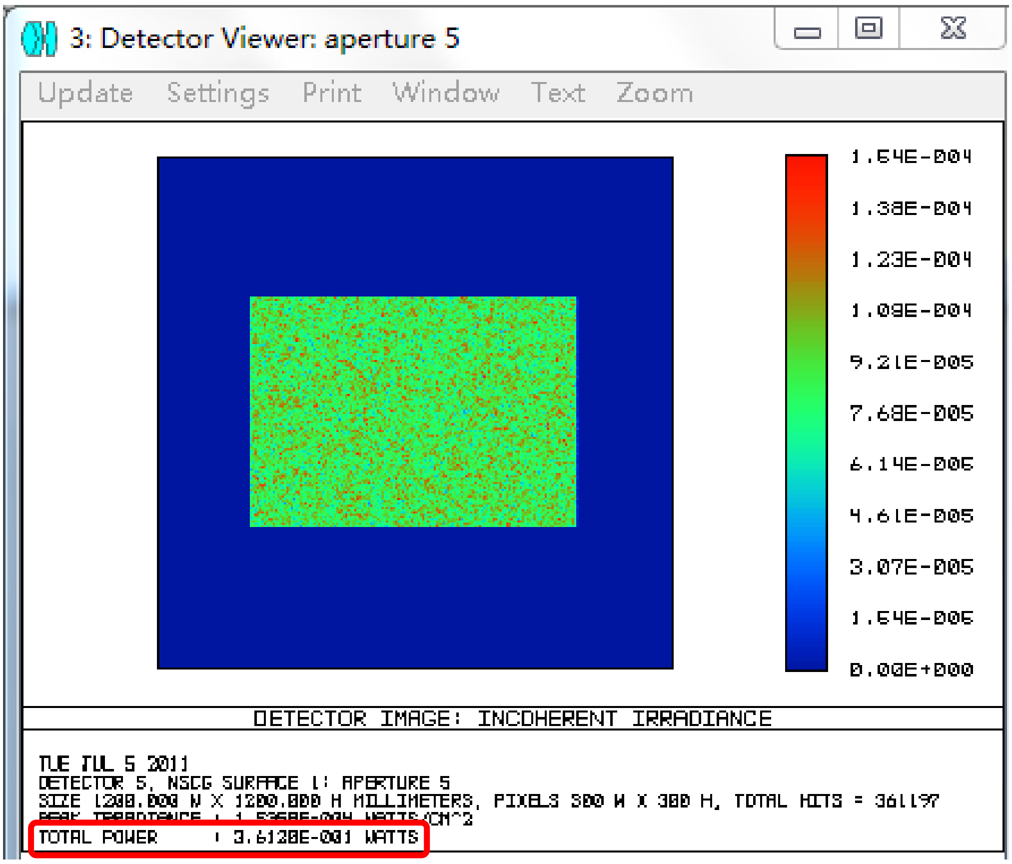


Fig. 5.26 Detector Viewer Diagram of Case 2

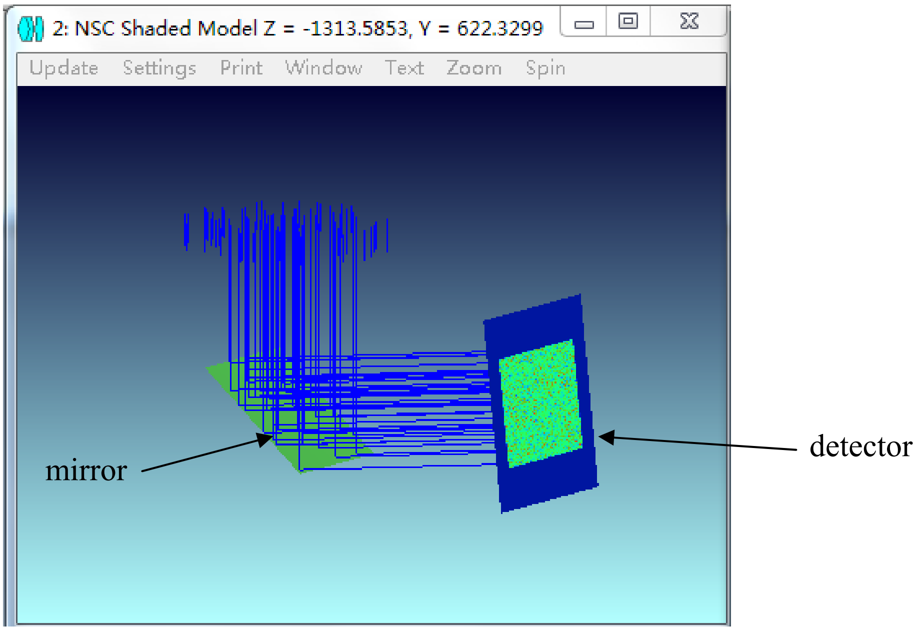


Fig. 5.27 3D diagram of Case 3

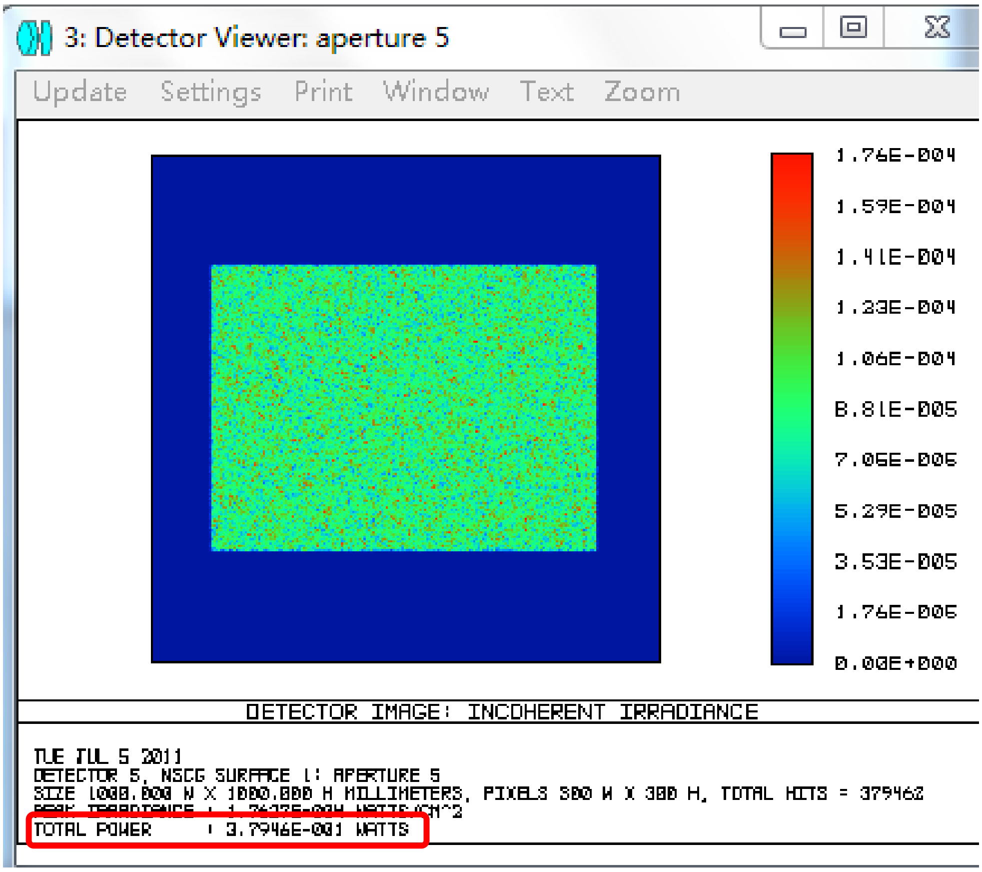


Fig. 5.28 Detector Viewer Diagram of Case 3

5.4 Conversion of the efficiencies of end-emitting to side-emitting fiber optic

At present there is no available comprehensive optical design software in the market to analyze the performance of the side-emitting fiber optic. Like most optical design software, the ZEMAX-EE calculates the efficiency of end-emitting fiber optic (E_E) only (Wong and Yang, 2011). For the side-emitting fiber optic, part of the transmitted light is emitted along the length while the remaining is transmitted towards the end. The LEF710M that is used in the RSSL is one type of side-emitting fiber optic and the linear emittance is 6 % per meter implying that $0.94^{(L)}$ of the incident light intensity at specified length (L) is transmitted along the length of the fiber optic. The transmission efficiencies (E_s) of a straight side-emitting fiber optic at various points can be defined as $94^{(L)}$ %. The simulated efficiencies of an end-emitting fiber optic at various points are tabulated in Table 5.6.

Combining the side-emitting and end-emitting properties of the fiber optic, the effective transmission efficiencies (E_T) of the notched fiber optic at D1 to D13 can be calculated from equation (1):

$$E_T\ (\%) = E_E \times E_S \qquad (5.4)$$

Table 5.6 shows $E_{E,}$ E_S and E_T at different locations of the RSSL. The overall efficiency of the RSSL of the side-emitting is calculated to be 39 %.

The emission efficiency (E_{em}) at the end of the side-emitting fiber optic would be 2% calculated as below:

$E_{em} = E_T$ x 6% (emission rate) (5.5)

Table 5.6 Transmission efficiencies at different locations of the RSSL

Detector	@ Length of FO: L (m)	Transmission Efficiency: E_E (%)	Transmission Efficiency: E_S (%)	Effective Transmission Efficiency: E_T (%)	Effective Emission Efficiency: E_T x 6%)
D1	-	100	-		
D2	-	99.1	-	-	-
D3	-	87.0	-	-	-
D4	-	74.7	-	-	-
D5	-	68.3	-	-	-
D6	1.66	68.3	90	62	3.72
D7	2.16	66.8	87	58	3.48
D8	2.67	65.4	85	55	3.3
D9	3.87	65.3	79	52	3.12
D10	4.37	63.9	76	50	3.0
D11	4.97	63.9	73	48	2.88
D12	5.52	63.2	71	45	2.7
D13	6.02	56.9	68	39	2.34

With reference to Section 5.2, the overall efficiencies of the RSSL orientated S32E at different solar azimuth angle and solar altitude were calculated and presented in Table 5.7.

Table 5.7 Changes in the efficiency of the RSSL using side-emitting fiber optic under different conditions of solar azimuth angle and solar altitude

Case	Solar azimuth angle	Solar altitude	Mirror inclination	Efficiency (%)
1	135	74	37	12
2	157	90	45	14
3	143	126	63	15

5.5 Conclusions

Simulation was carried to study the performances of mirror, converging lenses and notched fiber optic of the RSSL in different orientations. In the east and west orientations, the efficiency of the mirror is slightly affected by solar altitude and solar azimuth, which can be assumed to be negligible. There is apparently no light loss in transmission inside a straight end-emitting fiber optic. 12 % of light is lost in transmission from the first to the second lens, which are placed 70 mm apart. Although light loss can be reduced by replacing the 2 lenses by a single lens of 70 mm thick, it is not economical for application. Some light is lost in the bending of the fiber optic. Efficiency increases with the decreases in the degree of bending and increase in turning radius. The bending radius should not be smaller than 12 times the diameter of the fiber optic. The overall efficiency of the RSSL using end-emitting fiber optic is 68 %. The transmission efficiency of the RSSL with side-emitting fiber optic of 6% per meter emission rate is converted to 39%. The emission efficiency at the end of the RSSL is calculated to be 2%.

The efficiency of the mirror decreases considerably when the orientation of the RSSL changes to S32°E. The efficiency of the RSSL decreases with the decrease in solar altitude. The solar azimuth angle has no effect on the efficiency. To maximize the efficiency, the RSSL is recommended to be orientated either towards the east, west or south to eliminate the effect of the solar altitude. The numbers of the bending in the RSSL should be minimized. The radius of bending should not exceed 12 times the diameter of the notched fiber optic.

CHAPTER 6

EXPERIMENTAL STUDY OF THE PROPOSED RSSL

6.1 Introduction

An experiment was carried out subsequently to realize the proposed RSSL and compare the experimental findings and simulation results, especially on the effect of the solar altitude and solar azimuth angle. The factor of outdoor illumination was also studied. As the four numbers of RSSL proposed to be installed in the enclosed lift lobby were almost identical, only one quarter of the lift lobby was constructed in a 1:2 scale wooden structure to test the performance of the system. The wooden structure was constructed in the same orientation of the simulated RSSL, which is the S32°W.

Experiments were carried out from February to August 2011 between 09:30 h to 16:30 h. The following data were recorded for analyzing the relations and interactions between these factors; and the efficiency of the RSSL as well:

a) Solar altitude
b) Solar azimuth angle
c) Outdoor light intensity
d) Indoor light intensity

6.2 Experimental set-up

One quarter of the lift lobby was constructed in a 1:2 scale wooden structure (Fig. 6.1 and 6.2) on the roof of Block F in The Hong Kong Polytechnic University. The structure orientated S32°E. An aperture of 250 mm in diameter was formed in the external wall that faced S32°W (Fig. 6.3). A mirror of size 760 x 760 mm was mounted on a wooden stand opposite to the wooden structure. The mirror could be adjusted both in the horizontal and vertical planes (Fig. 6.4) responding to the constant changes in the solar altitude and the solar azimuth angle, respectively. Two plano-convex lenses of 225 mm in diameter and 10.4 mm diameter large core LEF710M notched fiber optic were installed inside the wooden structure. The lenses were mounted on an aluminum frame with a distance of 70 mm between them. The 6.02 m notched fiber optic was installed to the ceiling of the structure by plastic clips (Fig. 6.3). The head of the notched fiber optic was fixed in position by special coupling inside a metal cylinder (Fig. 6.5). An opening of 250 mm diameter was formed on the wall that faced the mirror to allow the reflected light to pass into the RSSL (Fig. 6.2, 6.5 and 6.6). The centre lines of the mirror, aperture, lenses and the notched fiber optic were in the same alignment.

Fig. 6.1 The model of the enclosed lift lobby

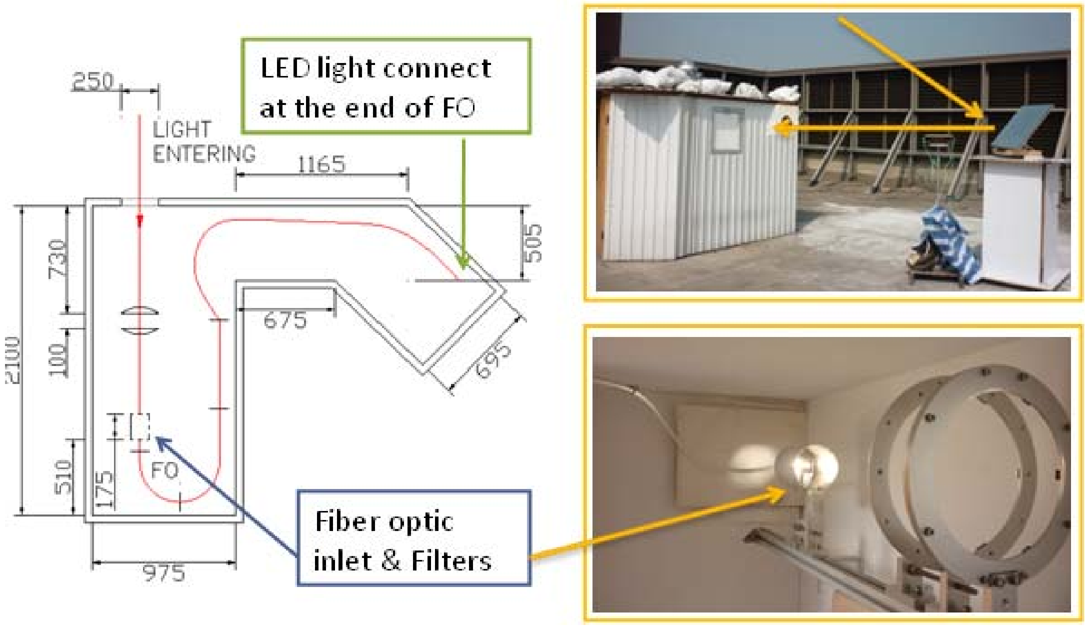


Fig. 6.2 Layout plan of the model

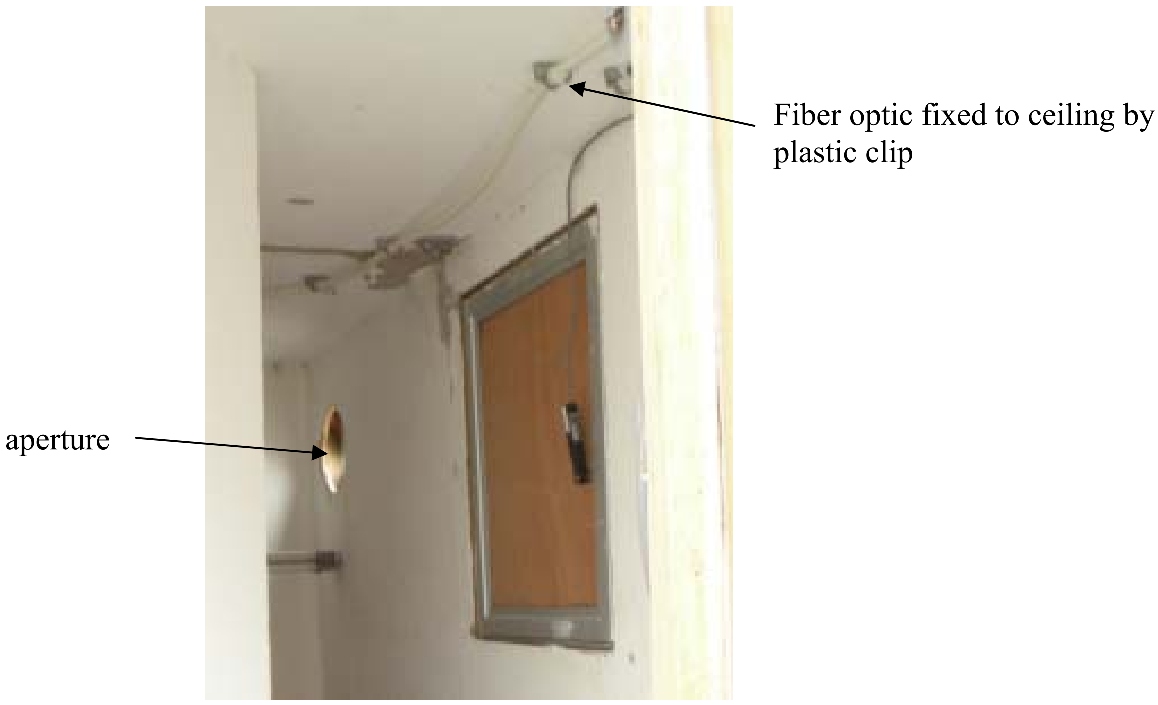


Fig. 6.3 Interior of the model

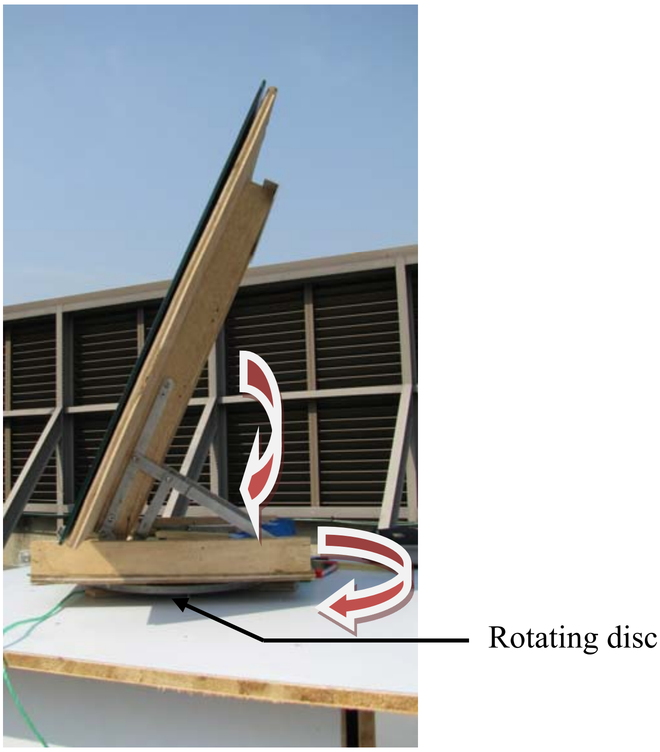


Fig. 6.4 Mirror movement

Fig. 6.5 The lenses and notched fiber optic in alignment

Sunlight was reflected by the mirror into the lens system, which converged the reflected light into the notched fiber optic. The fiber optic transmitted and emitted the light along the whole length (Fig. 6.6 and 6.7).

Fig. 6.6 Mirror reflected sunlight into the RSSL

Fig. 6.7 Light emitted along notched fiber optic

2 light sensors were installed to record the exterior and interior light intensities. One was installed on the roof of the structure (Fig. 6.8) inside a glass case to protect it from weathering. The other was installed at the far end of the RSSL (Fig. 6.9). The light sensors were connected to a data logger (Fig. 6.10) which recorded the light intensity in lux. Comparison of 50 readings of the outdoor light intensity and the light intensity as measured by the light sensor inside the glass box under clear sky condition were carried out. An average of 12% drop in light intensity was measured when light passed through the glass box. The values of outdoor intensity that were used in this thesis had accounted for the 12 % drop in light intensity.

The end of the notched fiber optic was connected to a 40W LED array lamp with output power at 700 lumen White Light (Fig. 6.2 and 6.11), which acted as a supplementary lighting. A 3rd light sensor was installed to the end of the lift lobby model (Fig. 6.12). The light sensor and LED lamp were connected to a control box that would automatically switch on the LED lamp when the light sensor detected the indoor light intensity below 150 lx (Fig. 6.11). Emitted light from LED lamp would then transferred by the notched fiber optic in the reverse direction to illuminate the lobby (Fig. 6.13).

Fig. 6.8 Outdoor light sensor

Fig. 6.9 The indoor light sensor

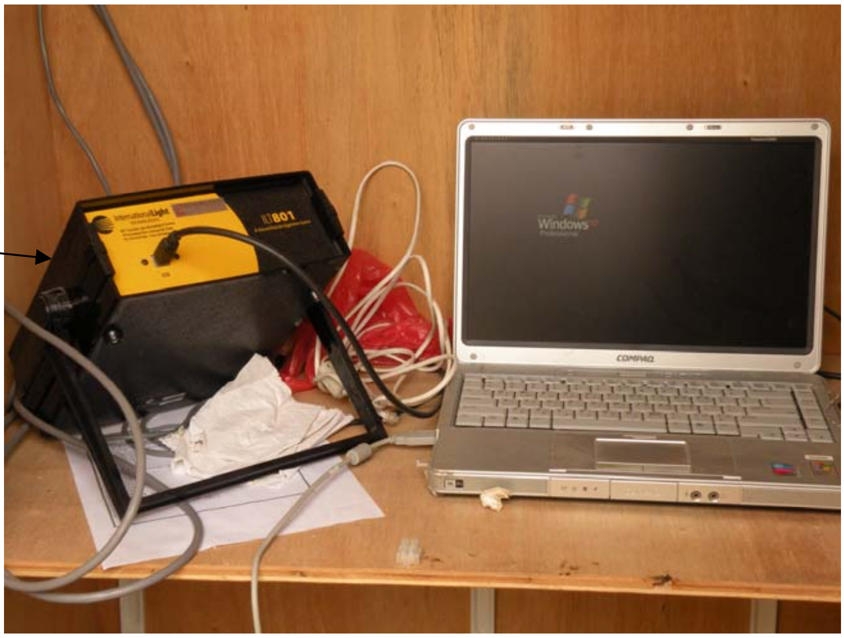


Fig. 6.10 Data logger and computer

Fig. 6.11 LED lamp and control box

Fig. 6.12 Light sensor for the supplementary lighting

Fig. 6.13 Emitted light from LED lamp travels in opposite direction

6.3 Experimental findings

The changes in indoor light intensity responding to the changes in outdoor light intensity, mirror orientations and inclinations (θ) at different times and dates were recorded. From the mirror inclination and the mirror orientations, the solar altitude and solar azimuth angle of the sun at different times and dates could be calculated.

The inclination of the mirror was measured by a protractor. The relation of the mirror inclination and the solar altitude is shown in Fig. 6.8 and can be expressed by the following equation:

$$\beta = 2 \times \theta \qquad (6.1)$$

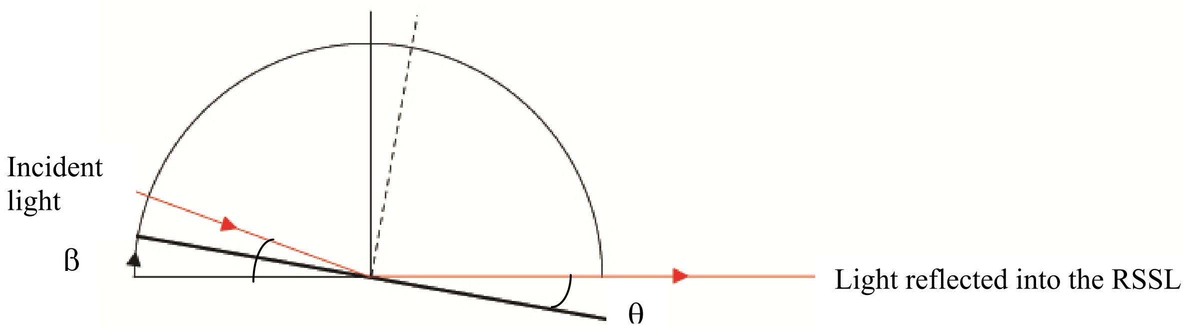


Fig. 6.14 The relation between mirror inclination and solar altitude

The outdoor light intensity was fluctuating due to the constant changes in sky condition even within a few minutes, especially in partly cloudy sky. The data was used to derive a general trend line for analysis. The collected data were plotted in graphs and used to deduce the general behavioral trends of each factor.

6.3.1 Relation of outdoor and indoor light intensities

The values of indoor and outdoor light intensity from 9:30 to 16:30 h were plotted against time in Fig. 6.15. The figure indicates a close relationship between the indoor and outdoor light intensities. Basically the indoor light intensity increases with the increase in outdoor light intensity. The peak values of outdoor and indoor light intensity occur around noon and drop to the minimum at 16:30 h.

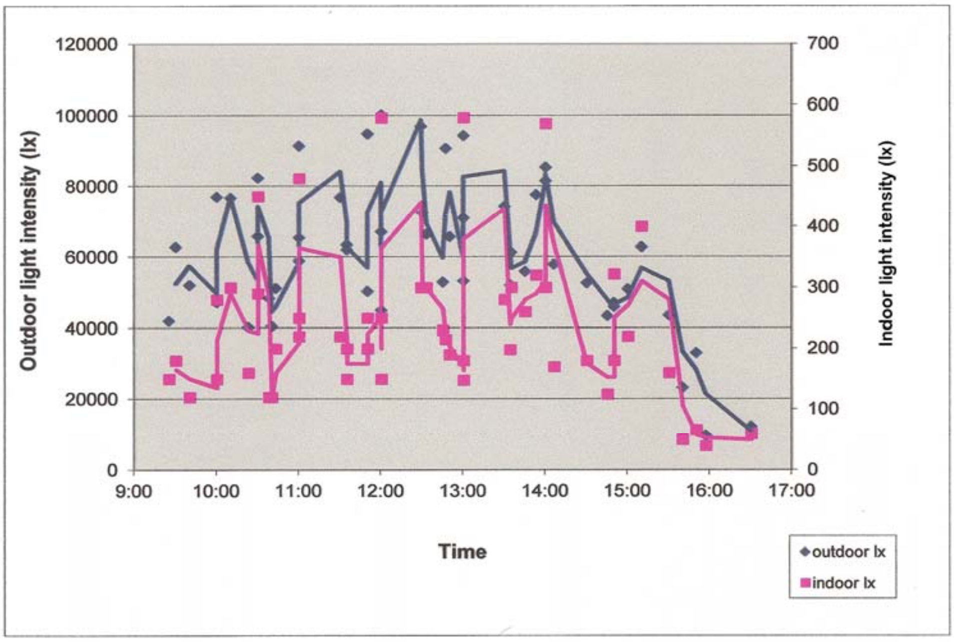


Fig. 6.15 The relations of outdoor and indoor light intensities with time

In Figure 6.16, the indoor light intensity increases exponentially with the increase in outdoor light intensity.

An average of 42500 lx is required to maintain the indoor light intensity at 150 lx. Fig. 6.17 shows the changes in outdoor and indoor light intensities with time. The outdoor light intensity can maintain an average of 6 hours of indoor light intensity above 150 lx from 9:30 to 15:30 h. About 60% of the period with outdoor light intensity above 42500 lx is in the post meridiem. In summer months from June to August, the hours of daylight intensity above 42500 lx is even longer up to an average of 10 hours.

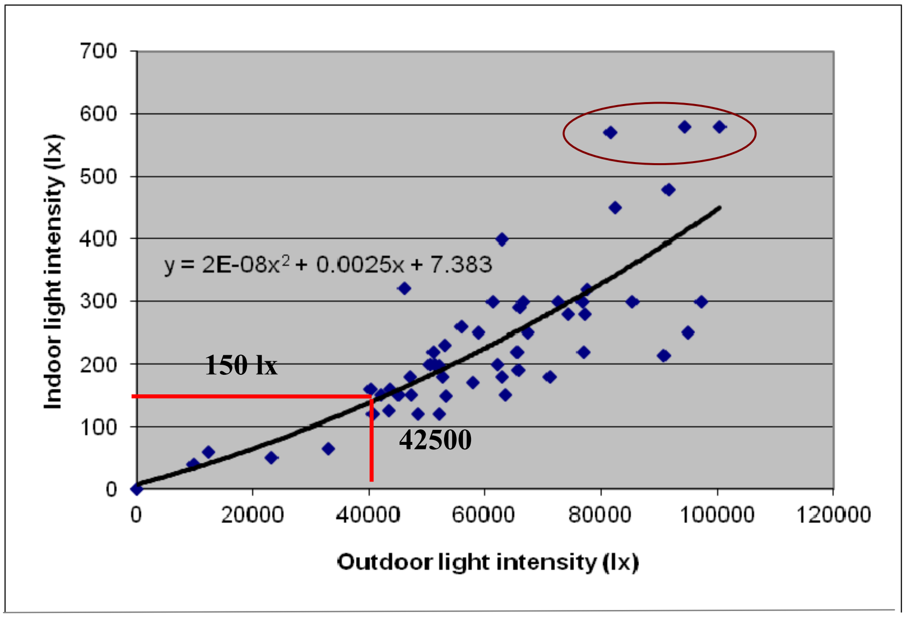


Fig. 6.16 Indoor light intensity vs. outdoor light intensity

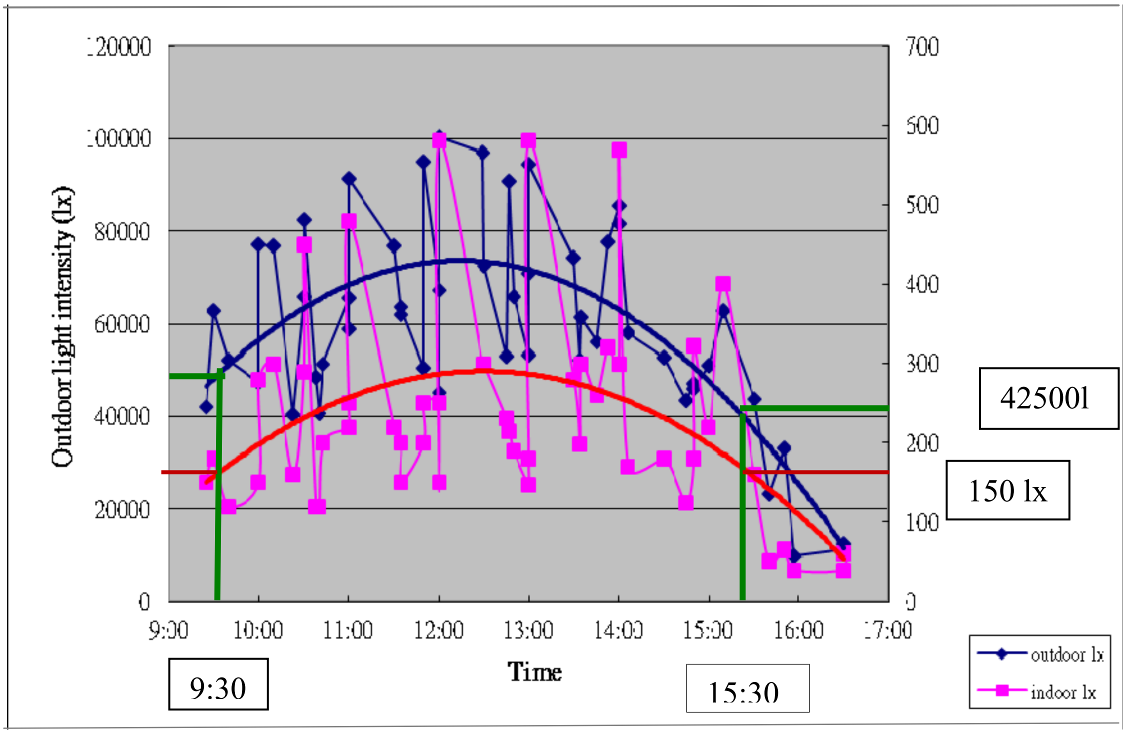


Fig. 6.17 The changes in outdoor and indoor light intensities from 9:30 to 16:30 h

The efficiency (η) of the RSSL is the ratio of indoor light intensity to the corresponding outdoor light intensity in percentage. The efficiency was plotted against outdoor light intensity in Fig. 6.18. The efficiency of the RSSL increases with the increase in outdoor light intensity and the average are within 0.3 to 0.4 %, which is far below the simulated efficiency of about 13 %. The increment in outdoor light intensity is shown in Table 6.1 and Fig. 6.19. Efficiency of the RSSL increases with the increase in outdoor light intensity. The increment is greater when the outdoor light intensity is between 10000 and 40000 lx. After 40000 lx the increase in efficiency is proportional to increase in outdoor light intensity.

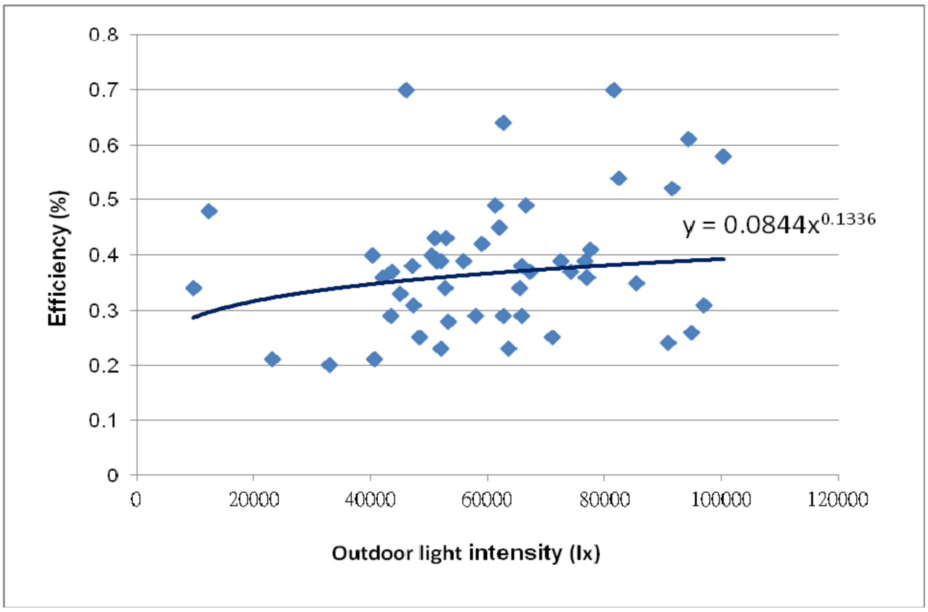


Fig. 6.18 Efficiency vs. outdoor light intensity

Table 6.1 The efficiency of the RSSL relating to outdoor light intensity

Outdoor light intensity (lx)	Efficiency (%)	Increment (%)
10000 - 20000	0.28 – 0.32	0.04
20000 - 30000	0.32 – 0.35	0.03
30000 - 40000	0.35 - 0.38	0.03
40000 - 50000	0.38 – 0.39	0.01
50000 - 60000	0.39 – 0.40	0.01
60000 - 70000	0.40 – 0.41	0.01
70000 - 80000	0.41 – 0.42	0.01
80000 - 90000	0.42 – 0.43	0.01
90000 - 100000	0.43 – 0.44	0.01

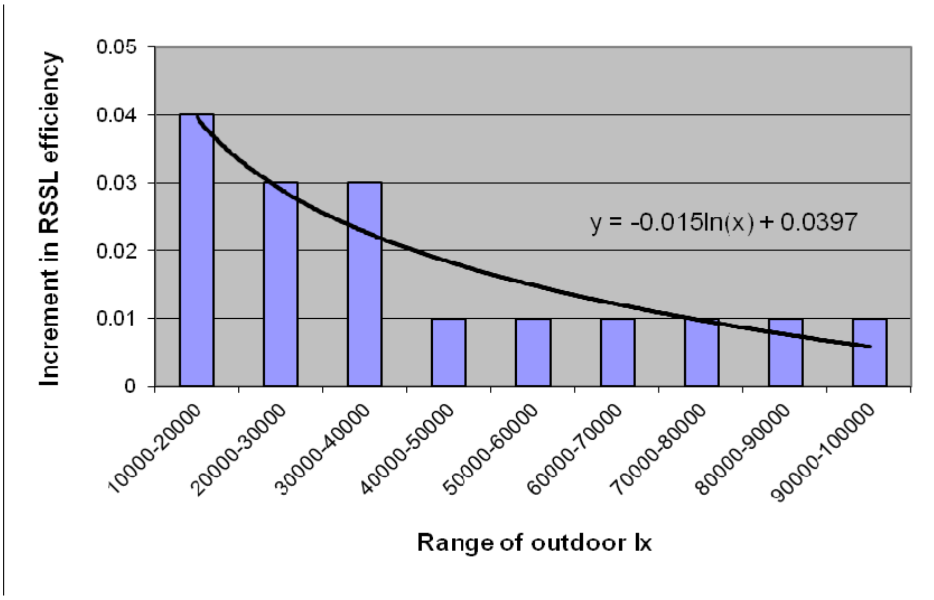


Fig. 6.19 Relation of increment in the efficiency with outdoor light intensity

6.3.2 The effect of the solar altitude

Figure 6.20 shows the changes in the efficiency of the RSSL at different solar altitude. The efficiency of the RSSL slightly increases with the increase in solar altitude, which agrees with the simulation results. When the solar altitude and efficiency of the RSSL are plotted against time in Figure 6.21, the efficiency tends to remains constant in spite of the decrease in solar altitude from 13:00 h onwards. The solar altitude increases from 55° at 9:30 h to 90° at 12:30 h and starts to decrease below 40° at 16:30 h.

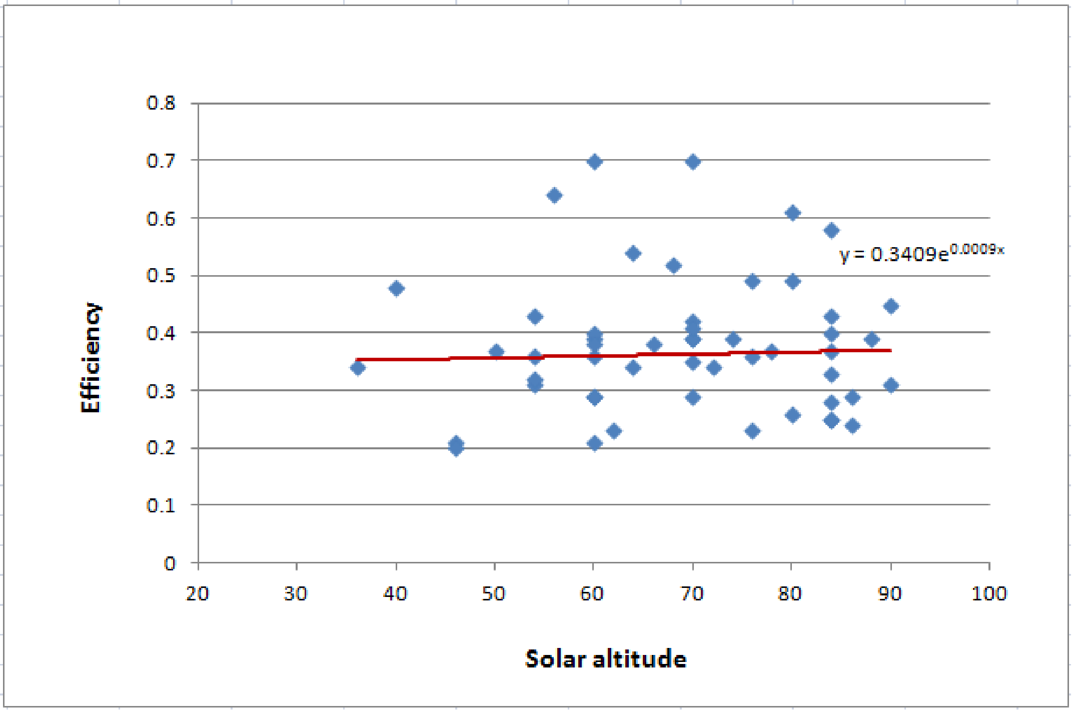


Fig. 6.20 The efficiency of the RSSL vs. the solar altitude

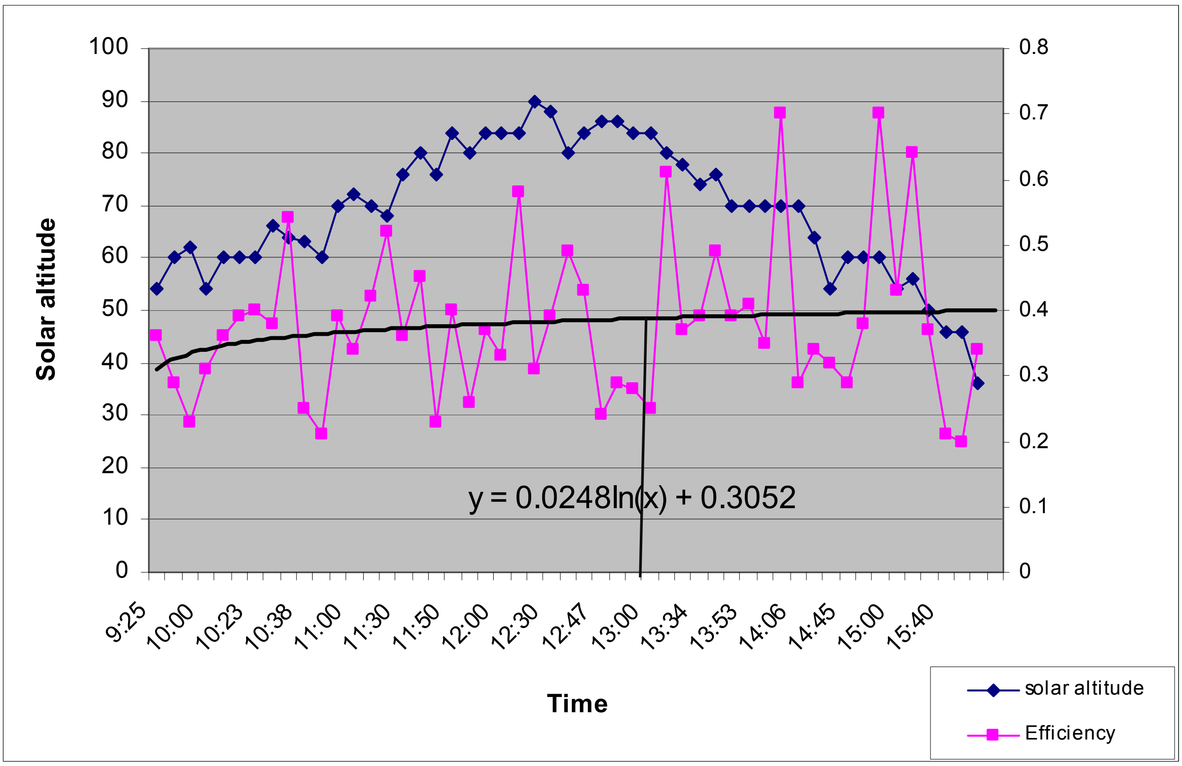


Fig. 6.21 The relation of the solar altitude and efficiency with time

6.3.3 The effect of the solar azimuth angle

Similarly the relations between the solar azimuth angle and efficiency with the time are shown in Fig. 6.22. The efficiency increases from the average minimum to maximum value of 0.3 and 0.4 %, respectively from 9:30 to 16:60 h while the solar azimuth angle is slightly decreasing. There is no strong relationship between the solar azimuth angle and the efficiency, and agrees with the simulated results.

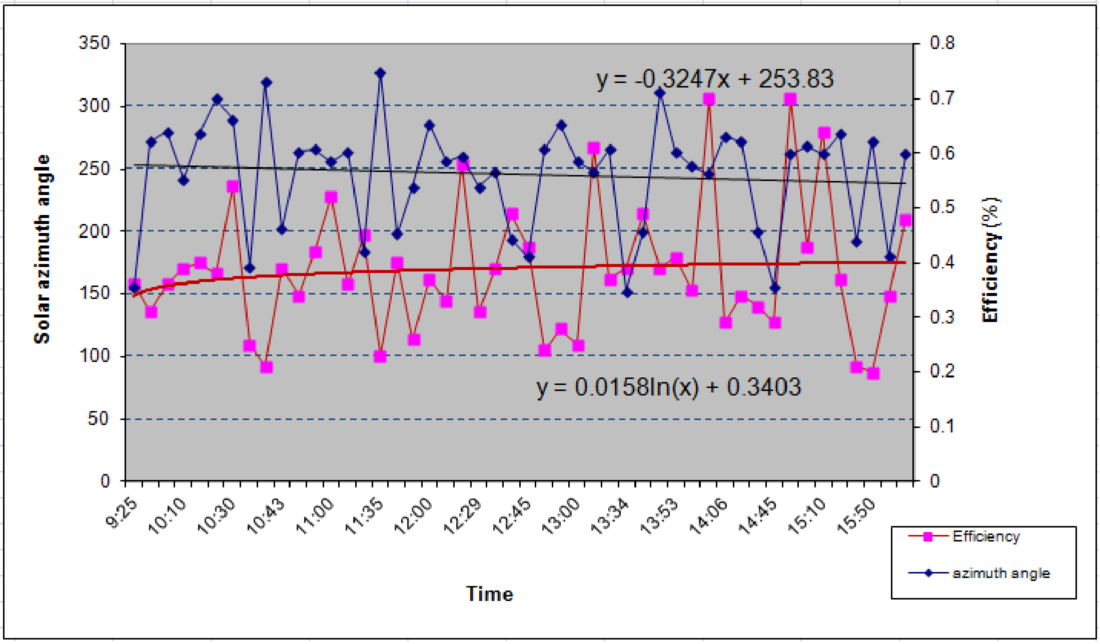


Fig. 6.22 The relation of the solar azimuth angle and efficiency with time

6.4 Data analysis

From Figure 6.15, indoor light intensity increases with the increase of outdoor light intensity. The solar energy increases from 9:30 to the peak at around noon and starts to decrease. The indoor light intensity increases when more solar energy is transferred into the RSSL resulting in more light being emitted from the notched fiber optic. From Figure 6.16 a minimum outdoor light intensity of 42500 lx is required to maintain the indoor light intensity at the recommended 150 lx. The outdoor light intensity of 42500 lx or above is a crucial requirement for the operation of the RSSL.

In Fig. 6.16, discrepancies in measurement were noted and circled in red. The discrepancies were due to the rapid changes in sky condition, which was faster than the speed of manual operation of the heliostat. The solar irradiance increases rapidly due to thinning of clouds occurred when recording the time that the reflected light beam being focused into the fiber optic. The recording frequency of the data logger was 30 per minute. There might be a few seconds in time gap between the recorded time by the user and data logger during which the solar irradiance increased sharply due to thinning of clouds.

Table 6.1 indicates that the efficiency ranges from 0.28 to 0.44 %, which is far below the simulated emission efficiency of 2 %. In the experiment, the loss of light in the process of transferring sunlight by the reflecting mirror and converging lenses into the notched fiber optic is large due to imperfection of the materials. The surface of the plane mirror is not perfectly flat and some light is lost by irregular reflections. The reflected light that enters the converging mirror is not in a perfect collimated beam. The transferred light rays are focused by the converging lenses into the notched fiber optic at different incident angles. Light rays that enter the notched fiber optic at an angle larger than its critical angle of 33° are reflected and lost resulting in a lower efficiency than the simulated result, which is based on perfection of component materials. In Figure 6.19, the rate of increase in the efficiency is greater when the outdoor light intensity is in the range between 10000 to 40000 lx. After 40000 lx, the rate of increase is constant with the increase in outdoor light intensity.

At the lower outdoor light intensity of 10000 to 40000 lx, other factors may affect the performance of the RSSL as well.

Referring back to Figure 6.17, the rate of increase in the efficiency of the RSSL is greater when the outdoor light intensity is below 40000 lx. In this period the solar altitude is also increasing, which agrees with the simulated results. After 13:00 h, the solar altitude starts to decrease and the rate of increase in efficiency becomes steady. The efficiency increases solely with the increase in outdoor light intensity. The solar irradiance becomes the dominant factor when outdoor light intensity is above 40000 lx. This finding indicates that the outdoor light intensity becomes the dominant factor affecting the efficiency of the RSSL at outdoor light intensity above 40000 lx. The intenseness of solar irradiance overrides the effect of the solar altitude. The simulation did not take into consideration the factor of solar irradiance.

Figure 6.22 indicates a weak relationship between the solar azimuth angle and time. The solar azimuth angle has negligible effect on the efficiency of the RSSL, which agrees with the simulated results. The solar irradiance is still the dominant factor that can affect the efficiency.

6.5 Conclusions

The experiment was carried out from February to August 2011 in the period between 9:30 to 16:30 h covering the months of the lowest solar irradiance in spring. The lowest daily global radiation occurred in March.

Outdoor light intensity is fluctuating throughout a day due to the constant changes in sky condition especially in cloudy and partly cloudy days, which constitutes to the variations of the collected data. The data is used to derive general trends for analysis.

The experimental efficiency of the RSSL is around 0.3 to 0.4 %, which is far lower than the stimulated efficiency. The large deviation can be explained by the facts that most of the transmission losses due to imperfect materials and the factor of varying solar irradiance are not considered in the simulation. Considerable amount of light is lost in the transmission process from the mirror to the notched fiber optic. Furthermore, the light emission rate of the notched fiber optic is not constant and below the intended 6 % per meter run as the side-emitting technology in fiber optic is still immature.

The efficiency correlates strongly with outdoor light intensity and increases when the outdoor light intensity increases. The simulation results demonstrate that the efficiency of the RSSL slightly increases with the increase in solar altitude. The experimental findings indicate that the solar altitude has slight influence on the efficiency when the solar irradiance is lower with outdoor light intensity below 40000 lx. After 40000 lx, the solar irradiance becomes the only dominant factor. There is no obvious relationship between the efficiency and the solar azimuth angle, which agrees with the simulation results. As an outdoor light intensity of 42500 lx is required to maintain the indoor light intensity at 150 lx, intenseness of the solar irradiance is a crucial factor that affects the efficiency. The performance of the RSSL can be deduced from the magnitude of the solar irradiance and the duration of outdoor light intensity that is above 42500 lx.

CHAPTER 7

ANNUAL PERFORMANCE CALCULATION OF THE RSSL AND ARCHITECTURAL INTEGRATION

7.1 Introduction

In this chapter, the annual performance of the RSSL in the clear sky is analyzed. The functioning hour of the RSSL is estimated from the records of solar irradiance at different hours and months from 2004 to 2007 that are issued by the Hong Kong Observatory.

The shadowing effects caused by the building itself and neighbouring buildings as well as within the RSSL are studied in detail. The performances of the RSSL at 2 orientations were studied. The RSSL on south orientation has longer operation period. The RSSL that orientates to the west is the most economical design at the present stage of development. The performances of these two designs were analyzed and compared.

The RSSL layout is designed to integrate into the architectural design of the lift lobby and the external facade.

7.2 Analysis on the annual performance of the RSSL

To properly design buildings with satisfactory daylight environment, an accurate indoor daylight prediction is necessary (Cheung, 2008). In the calculation of daylight availability and lighting energy use in buildings, the luminous efficacy enables daylight data to be generated from the more widely measured solar radiation data (Lam and Li, 1996). Global radiation has direct and diffuse components, and can be regarded as a combination of direct luminous efficacy (K_{bc}) and diffuse luminous efficacy (K_{dc}). The values for global efficacy (K_{gc},), K_{bc} and K_{dc} in lm/W. K_{gc} can be written as (Lam and Li, 1996):

$$K_{gc} = K_{bc} (1 - K) + K_{dc}K \qquad (7.1)$$

The diffuse fraction (K) is the ratio of the diffuse to global solar irradiance in lm/W. As the RSSL only operates under clear sky, only K_{bc} is considered. For clear sky, K_{bc} dominates as K is very small (Lam and Li, 1996). K_{bc} increases with the increase in solar altitude (β) and can be calculated from the following equation (Chung, 1992):

$$K_{bc} = 48.5+1.67\beta- 0.0098\beta^2 \qquad (7.2)$$

Section 6.3.1 illustrates a minimum outdoor light intensity of 42500 lx is required to maintain the indoor light intensity at 150 lx. From Fig. 7.1 the lowest solar altitude is 36°, which means that K_{bc} at solar altitude of 36° is the lowest in a day. Solar altitude of 36° is selected to estimate the minimum global solar irradiance that is required to maintain an indoor light intensity at 150 lx. K_{bc} is calculated to be 96 lm/W from Equation (7.2). The required minimum solar irradiance is estimated to be 443 W/m^2 by dividing the required outdoor light intensity of 42500 lx by the direct luminous efficacy.

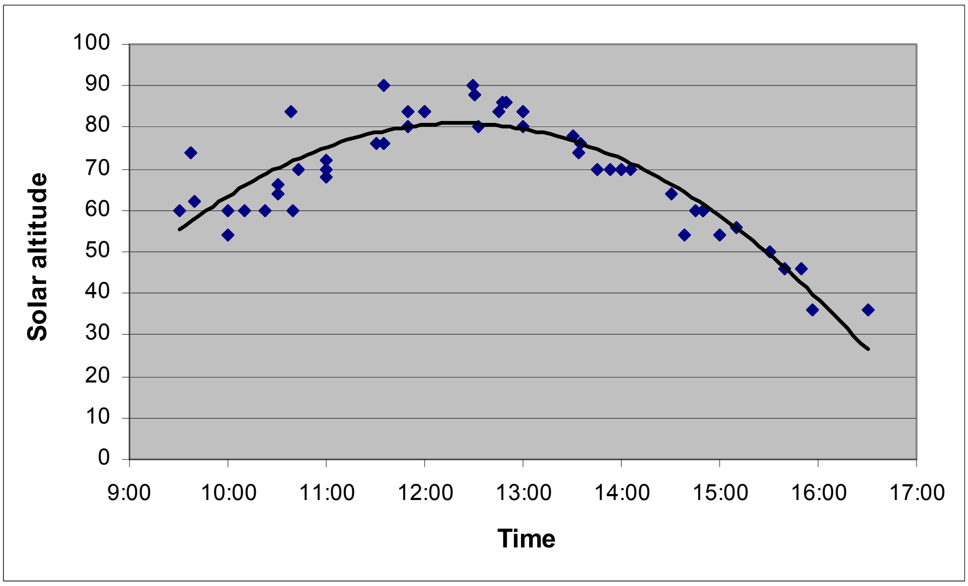


Fig. 7.1 Solar altitude vs. time

The latest available comprehensive records of solar irradiance at different hours and months issued by the Hong Kong Observatory from 2004 to 2007 in Figures 7.2 to 7.5 are used to assess the functioning hours of the RSSL in a year. From these records, the total hours of average solar irradiance at or above 443 W/m^2 for different months in a year in the period between 9:00 to 17:00 h are summarized in Column 1 to 3 in Table 7.1. However, the total hours of average solar irradiance above 443 W/m^2 can be more as the factor of the lowest K_{bc} at the lowest solar altitude in a day is used for the calculation of solar irradiance.

The records of the total hours of solar irradiance equal or above 443 W/m^2 was compared with the records of the total hours of bright sunshine as provided by the Hong Kong Observatory in the years 2004 to 2007 in Table 7.2. From the comparison, the total hours of solar irradiance equal or above 443 W/m^2 generally do not exceed the total hours of bright sunlight within each month; and the hours of bright sunshine mostly occur in the period between 11:00 to 16:00 h. It can be assumed that the total hours of solar irradiance at or above 443 W/m^2 within the period from 9:00 to 17:00 h as shown in Table 7.1 are under clear sky condition with direct sunlight. The annual operating hour of the RSSL is 1235 hours. The RSSL can contribute about 3.4 hours of daylight in a day.

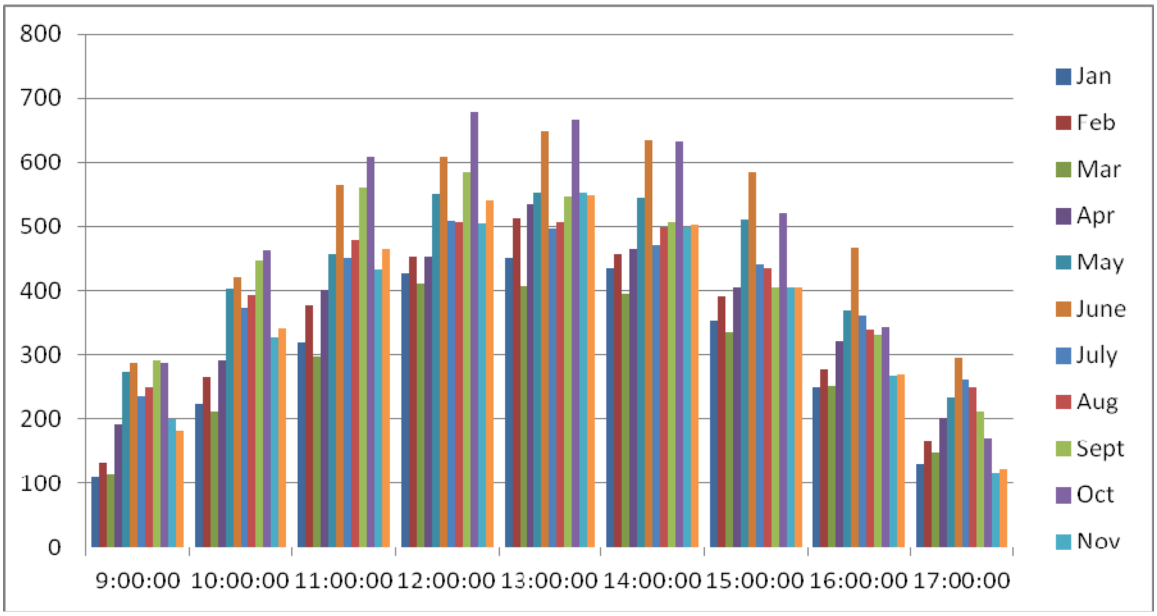


Fig. 7.2 Solar irradiance records of 2004

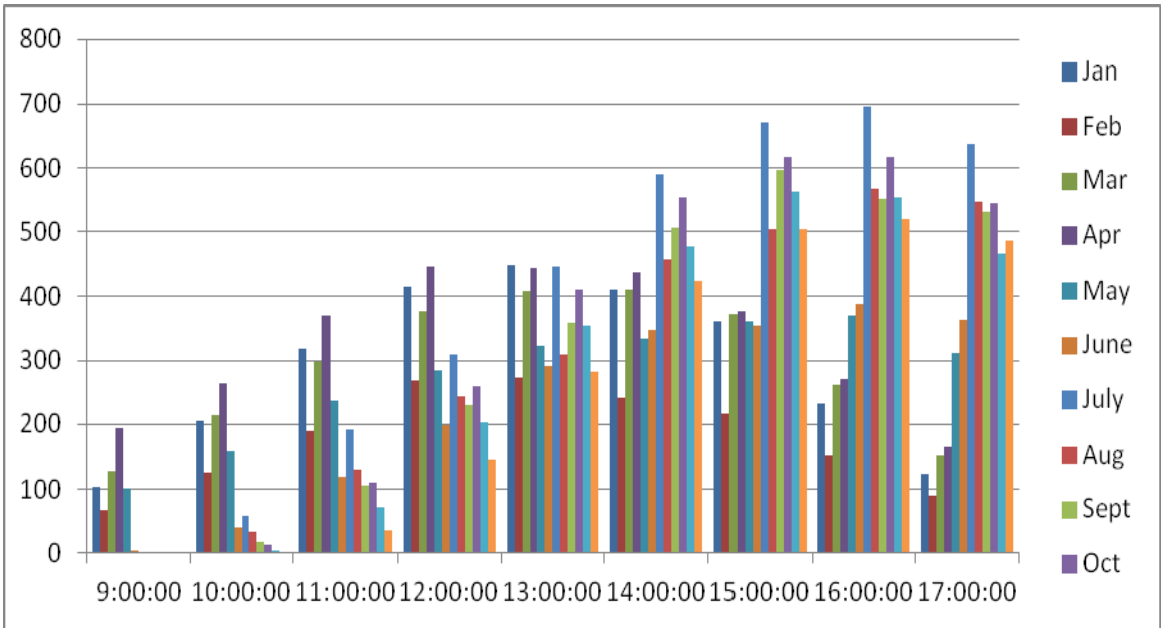


Fig. 7.3 Solar irradiance records of 2005

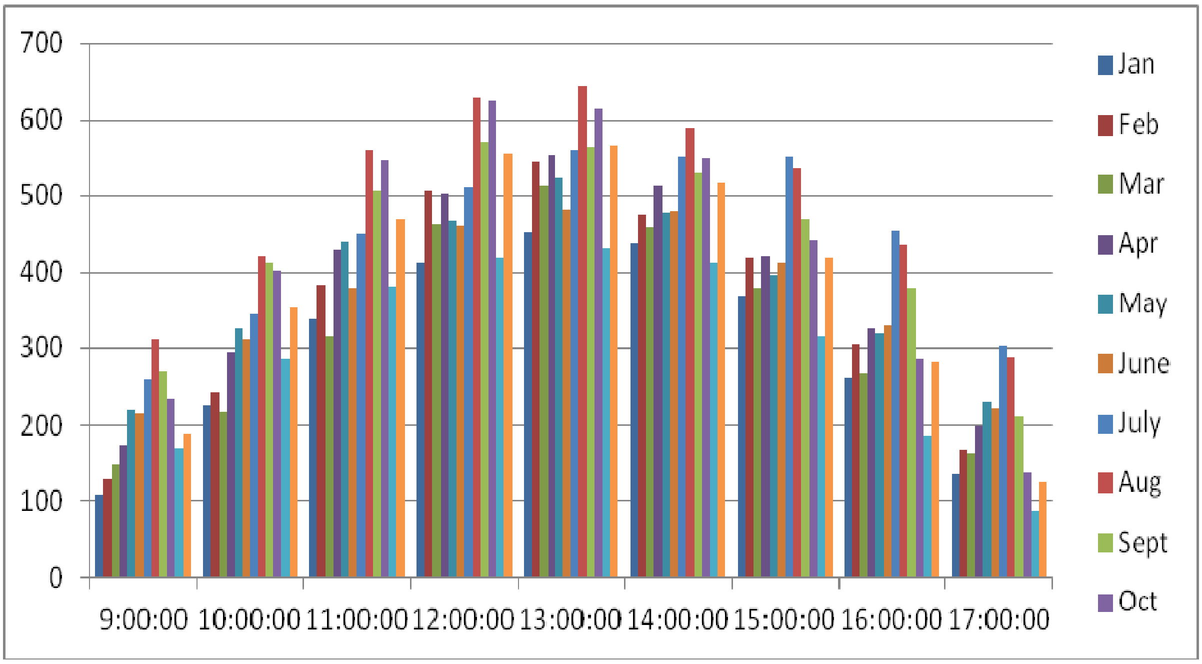


Fig. 7.4 Solar irradiance records of 2006

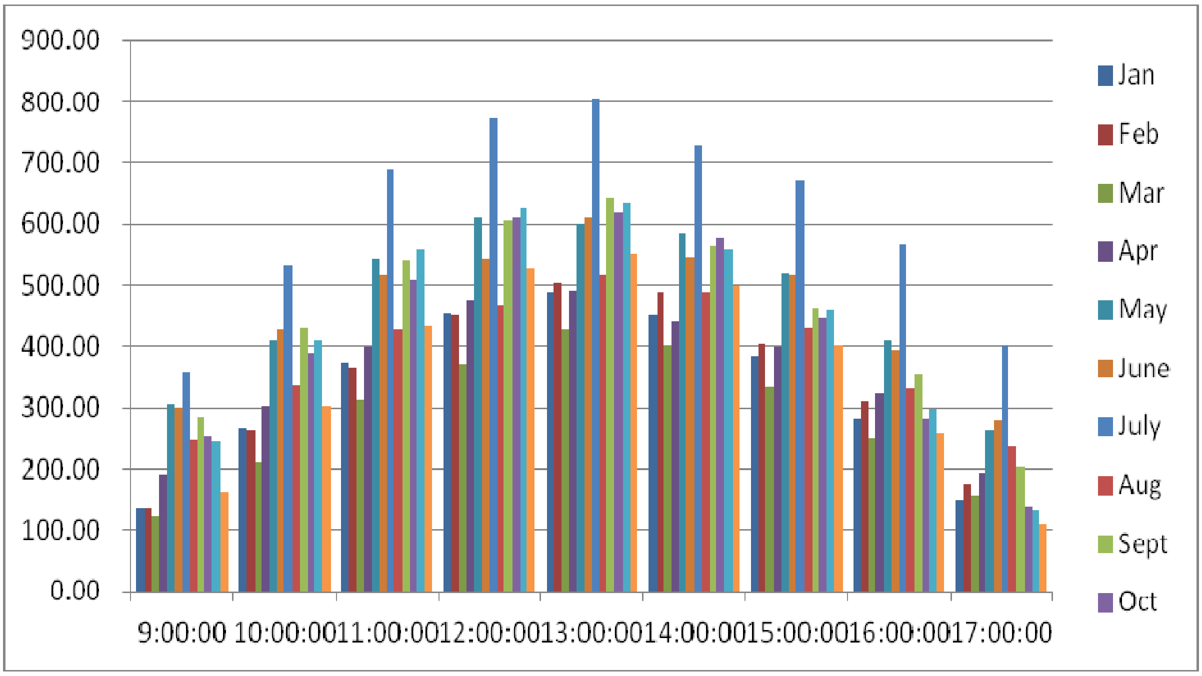


Fig. 7.5 Solar irradiance records of 2007

Table 7.1 The summary of total nos. of hours of average solar irradiance at 443 W/m^2 or above in a year

Month	**Average nos. of hours in a day**	**Total hour in a month**	**Nos. of hrs from 12:00 – 17:00**	**Total nos. of hrs from 12:00 – 17:00 in a month**
January	1.75	54.25	1.75	54.25
February	2.25	63	2.25	63
March	0.75	23.25	0.75	23.25
April	2.75	82.5	2.75	82.5
May	3.5	108.5	2.75	85.25
June	3.5	105	3	90
July	5.75	178.25	4.75	147.25
August	4	124	3.5	105.5
September	4.75	142.5	3.75	112.5
October	5	155	4	124
November	3	90	2.75	82.5
December	3.5	108.5	3	93
Total		**1234.75**		**1068.25**

Table 7.2 Records of solar irradiance and hours of bright sunshine in 2004 to 2007

	2004		**2005**		**2006**		**2007**	
	h	**h1**	**h**	**h1**	**h**	**h1**	**h**	**h1**
Jan	31	152.4	31	141.7	62	152.4	93	152.4
Feb	84	97.7	0	97.7	84	97.7	84	97.7
Mar	0	96.4	0	96.4	93	96.4	0	96.4
Apr	90	108.9	60	108.9	90	108.9	90	108.9
May	155	153.8	0	153.8	124	153.8	155	153.8
June	180	161.5	0	161.1	90	161.1	150	161.7
July	155	231.1	155	231.7	186	231.1	217	231.1
Aug	124	207	124	207	155	207	93	207
Sept	150	181.7	120	181.7	150	181.7	150	187.1
Oct	186	195	155	195	124	195	155	195
Nov	90	181.5	120	181.5	0	181.5	150	181.5
Dec	124	181.5	93	181.5	124	181.5	93	181.5
Total	1369	1948.5	858	1938	1282	1948.1	1430	1954.1

<u>Note</u>:
h = Nos. of hrs with solar irradiance ≧ 443 W/m^2
h1 = total hrs of bright sunshine

7.3 Shadowing effects

There are 2 types of shadowing effects, which are caused by the neighbouring buildings and building itself as well as within the RSSL.

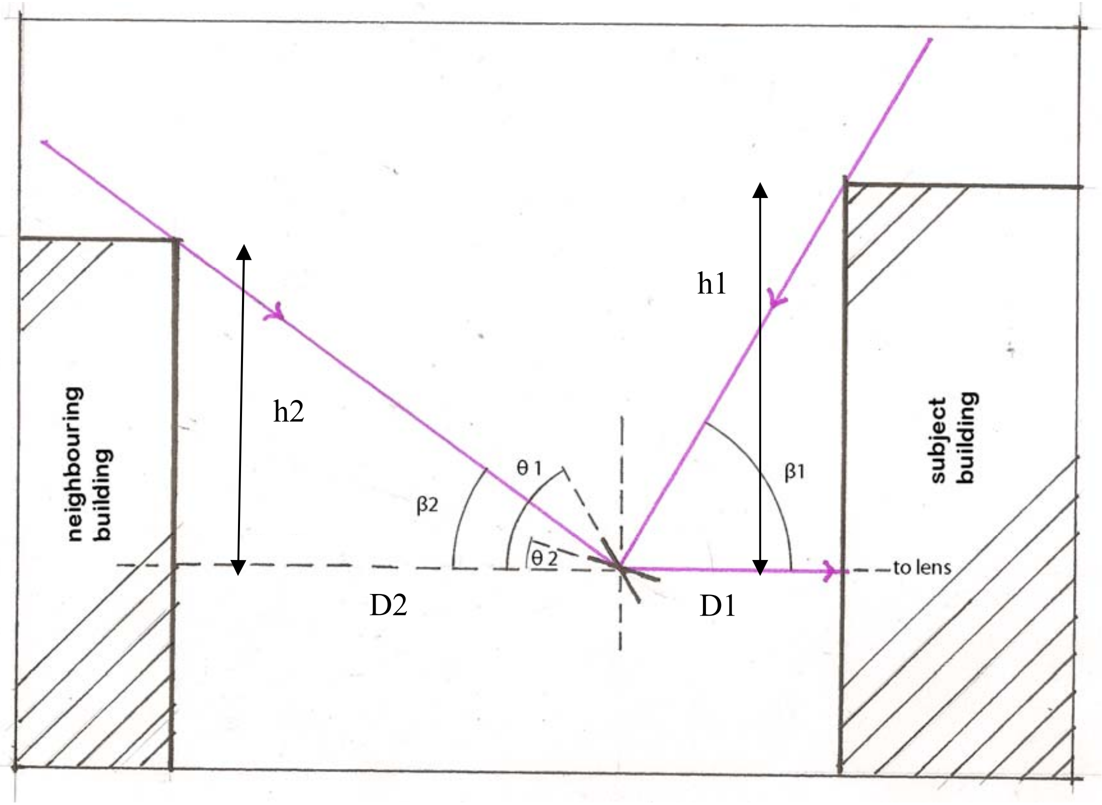
7.3.1 Shadowing effect caused by buildings

Hong Kong is a densely populated city with majority of residential buildings developed into high-rise style of over 30 storeys. Such developments may result in a large degree of shading effect from nearby buildings and the effect can be significant (Li and Wong, 2007). With reference to Figure 7.6, the angles of obstruction (β) can be calculated from Equation 7.1:

$$\tan \beta = h / D; \qquad (7.3)$$

where h is the distance measured from the top of the building to the RSSL and D is the distance between the RSSL and the external wall. The angle of obstruction equals to the solar altitude at the time concerned.

Figure 7.7 shows the relationship of indoor light intensity and the recorded mirror inclination (θ) responding to the changes in solar altitude with time. The data is obtained in the months from February to August 2011. The RSSL can generally provide 150 lx from around 10:00 to 16:30 h. The solar altitude is twice the value of the mirror inclination, which changes from 60° at 10:00 h to 36° at 16:30 h, respectively. The angles of obstruction should not be smaller than 36° or 60° for obstructions on the west or the east side of the mirror, respectively.



Fig, 7.6 Shadowing effect from buildings

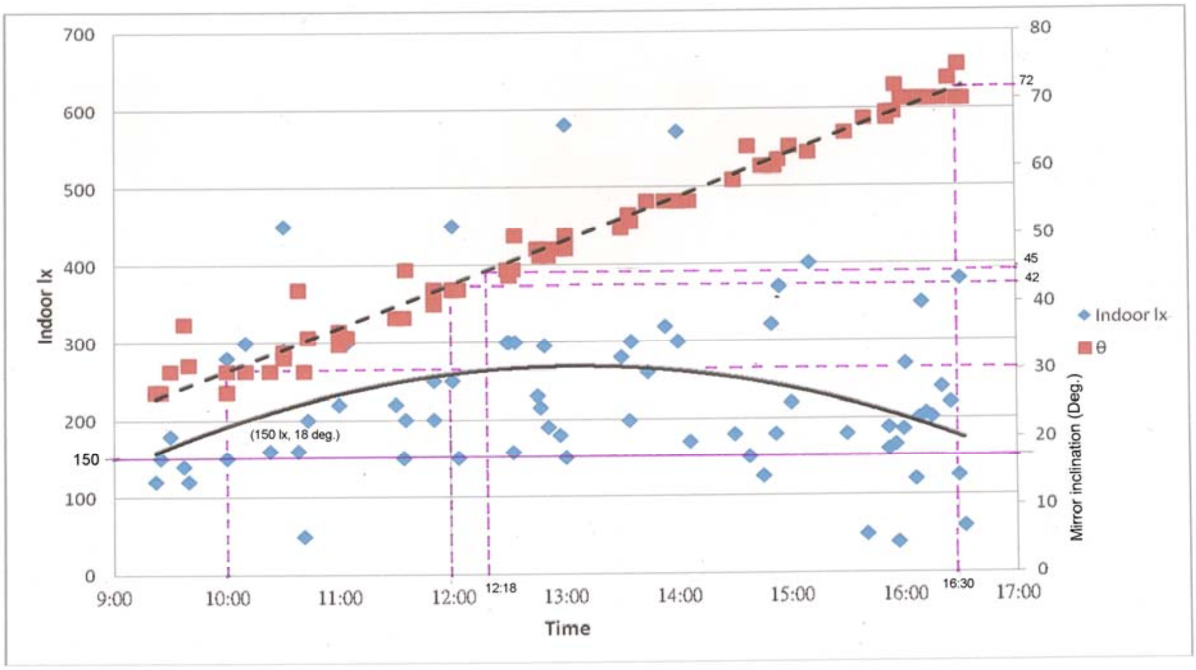


Fig. 7.7 Relations of indoor light intensity and mirror inclination with time

a) RSSL facing south

The daily average daily sunshine hours in Hong Kong is 5.28 hours. The optimal orientation of the RSSL is facing the south. At this orientation, the RSSL can receive sunshine for most of the daytime. Referring to column 1, 2 and 3 in Table 7.1, theoretically the RSSL can displace approximately 1235 hours of electric lighting in a year, which is equivalent to an average of 3.4 hours in a day. Assuming that solar energy can provide 8 hours of natural light to a lift lobby with window from 9:00 to 17:00 h without turning on electric lighting, the application of the RSSL to the enclosed lift lobby can save approximately 42.5 % of electricity in providing electrical lighting in daytime to the lift lobby.

In the south orientation, the position of mirror is required to be adjusted in the horizontal and vertical planes at the same time responding to the changes in the sun path. The mirror should be mounted on a stand that is free to rotate about the zenith-axis and the axis parallel to the surface of the earth (Fig. 7.8) (Chong and Wong, 2009). The movement is controlled by an active sun tracker. The operation of the RSSL involves a powerful motor that can rotate the mirror in 2 axes. The installation method of the RSSL is more complicated in design.

At the south orientation, the design of the RSSL needs to consider mainly the shadowing effect caused by adjacent buildings. With reference to Fig. 7.7 the solar altitude of 60° is the lowest at 10:00 h. (The solar altitude at 9:30 h is not considered because the solar irradiance at this time is usually below 443 W/m^2). The angle of obstruction formed by any neighbouring building should be not smaller than 60° for the maximum operating hours.

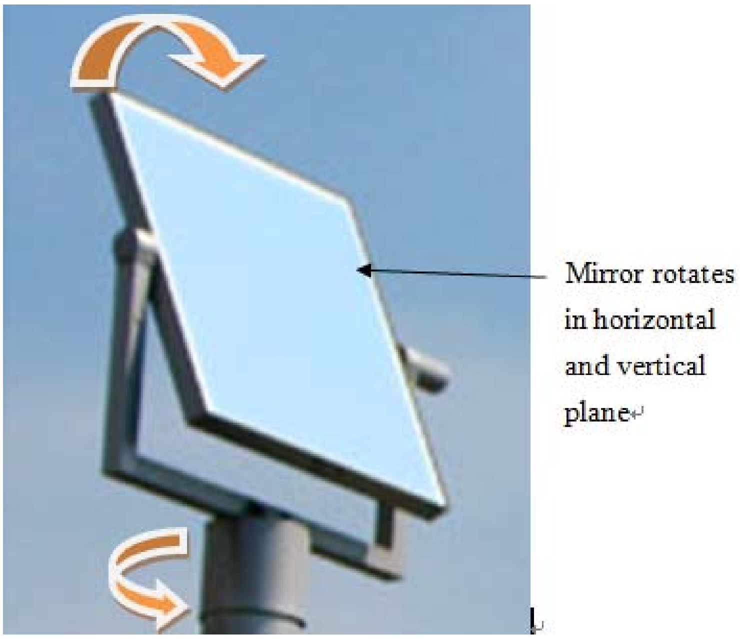


Fig. 7.8 The 2-axis heliostat

b) RSSL in other orientations

For the RSSL facing east or west, the position of the mirror is required to be adjusted in the vertical plane only. The RSSL design is required to consider the shadowing effects in the direction from the east to the west. Referring to Figure 7.7, the period of outdoor illumination above 42500 lx are mainly within 10:00 to 16:30 h. The mirror inclination in this period changes from 30° to 72°, which means that the RSSL mainly operates between solar altitudes from 60° to 144°. Fig. 7.9 illustrates the shadow-free zone for a west-orientated RSSL. The angles of obstructions cannot be smaller than 60° and 36° as shown in Figure 7.9. The RSSL can operate from around 10:00 to 16:30 h provided that no building will cast a shadow within the shadow-free zone. The sun tracker in a west or east-orientated RSSL is only required to track the sun at the varying solar altitudes. The mirror is required to rotate in the vertical plane only to track the sun at the varying altitudes. The mirror movement is simple and can be controlled by a simple motor. The RSSL installation is simpler than a south-orientated RSSL. The east-orientated RSSL operates in the same principles as the west-orientated RSSL except the mirror moves in the reverse direction, which means that the angles of obstructions are 60° and 36° for neighbouring and its own buildings, respectively.

In the lower floor of a high-rise building, the RSSL that is installed on the external facade can only receive direct sunlight from half of the sky hemisphere. The incident sunlight is blocked by the building itself even though there is no neighbouring building. Therefore the 12:00 h is used as the demarcation time for designing the orientation of the RSSL. In Figure 7.2 the post meridiem period from 12:00 to 16:30 h occupies 69 % of the period between 10:00 to 16:30 h with the outdoor light intensity generally above 42500 lx. The RSSL is recommended to be installed on the western facade of a building with the mirror facing the east for longer operation time; and the neighbouring building should not form an angle of obstruction smaller than 36°.

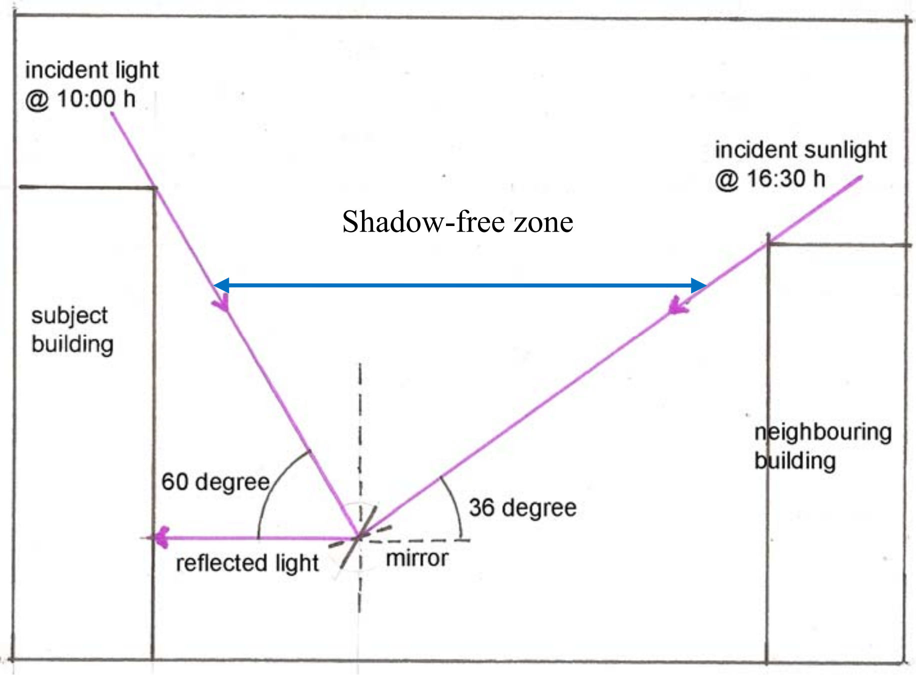


Fig. 7.9 The west-orientated RSSL

With reference to Column 1, 4 & 5 in Table 7.1, the RSSL that orientates to the west can still displace 1068 hours of electric lighting in a year, which is equivalent to an average of 3 hours in a day. The application of RSSL to enclosed lift lobby can save approximately 37.5 % of electricity consumed by illumination in daytime.

7.3.2 Shadowing effect within RSSL

As the mode of light transmission is horizontal, one RSSL is installed in every floor. The mirror of the RSSL is supported by a metal frame, which is installed to the external wall. The mirror above and the members of the framework can cast a shadow on the mirror.

a) Shadowing effect caused by mirror above

The mirror in the upper floor may cast a shadow to the mirrors in the floors below. Part of the sunlight will be blocked. A detail study on the operation of the RSSL at different times was carried out to understand the shadowing effect due to the changes in mirror inclination responding to the sun path in a day.

Theoretically, a horizontal RSSL can operate from 10:00 to 16:30 h with no obstruction. It was assumed that the dimension of the mirror is 760 x 760 mm and the floor height of the building is 2.8 m. Figure 7.10 illustrates the operation of the mirror. The inclination of the mirror is adjusted responding to the change in solar altitude. The upper mirror should be designed that it will not cast any image on the mirror below within the operating period of the RSSL. Let A be the inclination of the upper mirror that allow the incident ray to pass without casting a shadow on the lower mirror in a west-orientated RSSL. A can be calculated from the following equations:

$\tan 2A = 2 \tan A / 1 - \tan A^2$ (7.4)

$\tan A = a / b$; 'a' and 'b' are the 2 legs of the right-angled triangle formed by the mirror (7.5)

$\tan 2A = (2a + H) / 2b$; H = 2800 mm, which is the floor height (7.6)

Hence:

$2ab^2 = 2800b^2 - 2a^3 - 2800a^2$ (7.7)

$4a^2 + 4b^2 = 760^2$ (7.8)

Therefore:

$b^2 = (760^2 - 4a^2) / 4$ (7.9)

Substitute Eqt. (8) into (6):

$5600a^2 + 760^2 \text{ x } a/2 - 760^2 \text{ x } 700 = 0$

$a = 269.4$

sin A = 2a / 760

A = 45.16° ; which means the solar altitude is about 90° that occurs around 12:00 h. In this situation, the upper mirror will cast a shadow on part of the lower mirror and efficiency of the RSSL will be reduced. A must be smaller than 45° to avoid the shadowing effect. H should be larger than 2.8 m in order that the upper mirror will not cast a shadow on the mirror below. To solve this problem, 2 adjoining locations are reserved for the RSSL installation at each floor. The RSSL will be installed at each location on alternate floors (Fig. 7.11). H is now changed to 5.6 m, and A becomes 44.96° , which is below 45° . From 12:18 h onwards, θ decreases from 45° to 18° at 16:30 h. Doubling H to 5.6 m enables the RSSL to operate for a longer period.

An external metal frame is designed to support the mirrors. The minimum grid dimensions of the framework are 0.8 m wide and 5.6 m high.

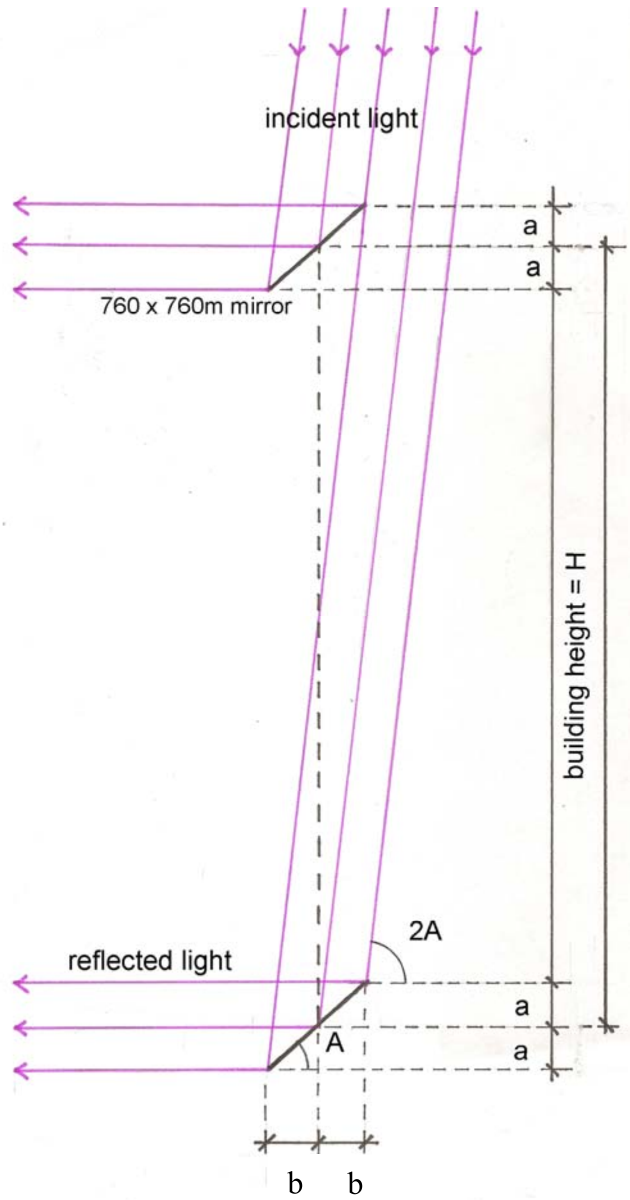


Fig. 7.10 Operation of the mirror from 12:00 to 14:30 h

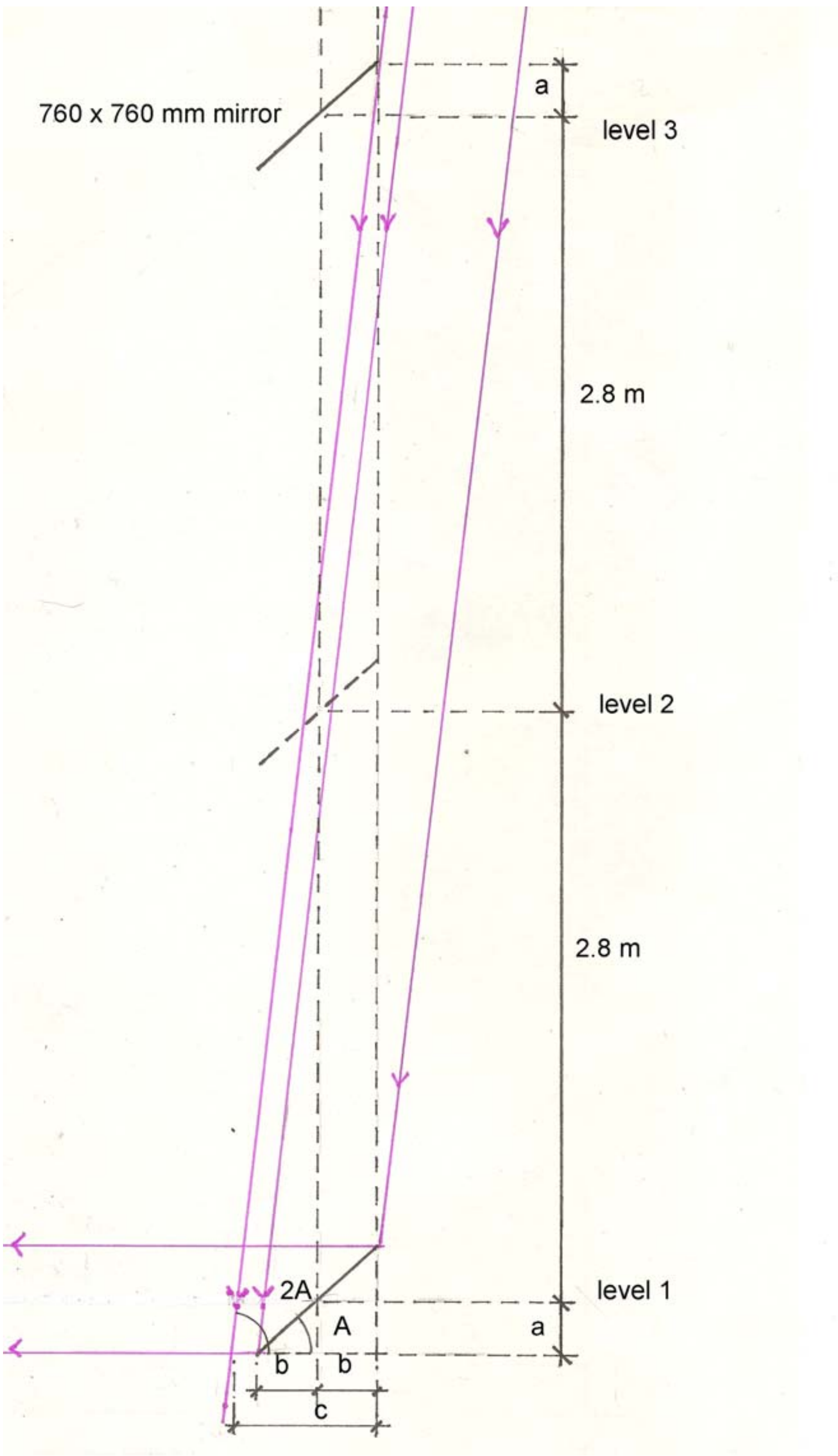


Fig. 7.11 Shadowing effect within RSSL

b) Shadowing effect caused by vertical member of the supporting frame

Figure 7.12 shows the average trend of solar azimuth angle from 9:30 to 16:30 h within the year 2011. The values of the solar azimuth angle are mainly within the range from 170° to 280°. In a south-orientated RSSL, we need to consider the shadowing effects casted by the mirror above as well as the vertical member of the metal frame to allow the RSSL to operate efficiently from 10:00 to 16:30 h without obstruction. The mirror will rotate to reflect the sunlight at different solar azimuth angles to enter the RSSL in the north direction so that the reflected light is always parallel to the axis of the lenses (Fig. 7.13). In order not to reduce the efficiency of the RSSL, no vertical member of the supporting frame should cast a shadow on the mirror. D is the distance between the vertical member of the support frame and the centre of the mirror. D will be infinitive when the solar azimuth angle is 270°. Part of the sun rays will be blocked by the vertical member of the supporting frame and reduce the efficiency.

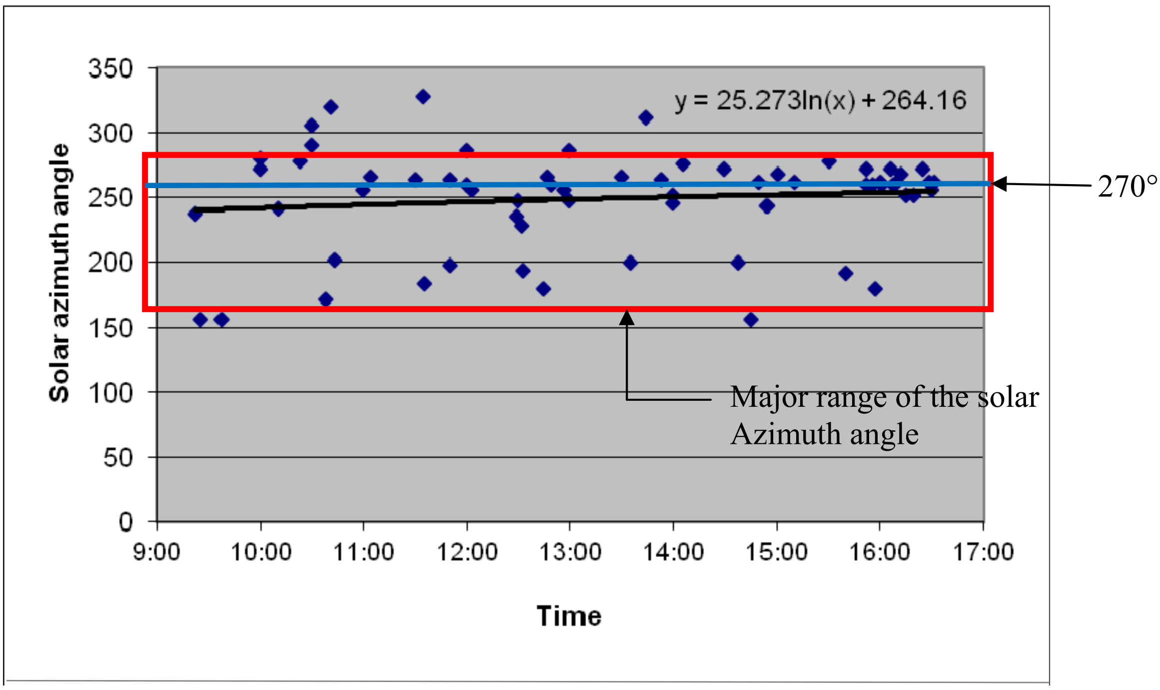


Fig. 7.12 The change of solar azimuth angle with time in 2011

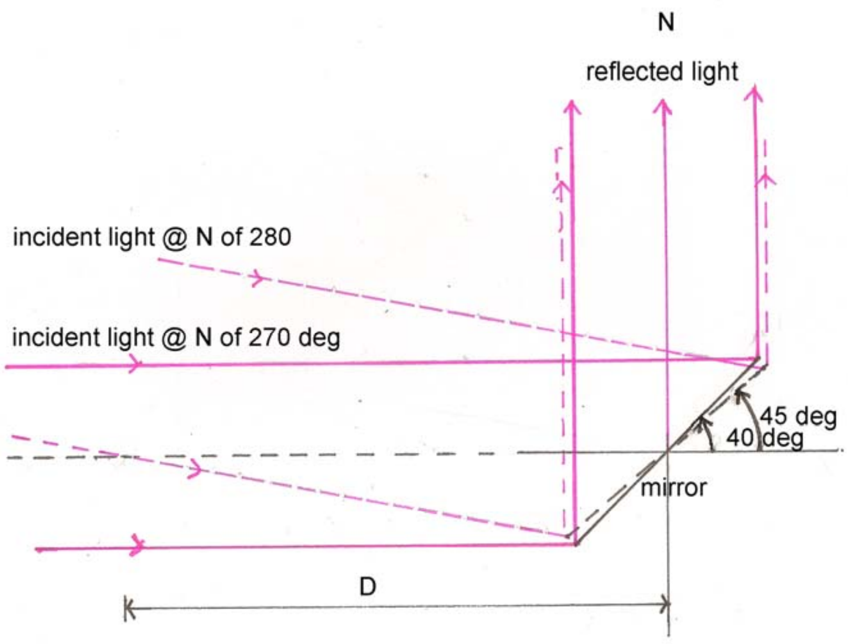


Fig. 7.13 Shadowing effect by vertical member of the metal frame

7.4 Architectural design of the RSSL

For practical and aesthetic purposes, the RSSL design should integrate into the facade and the interior design of the lift lobby.

The design concept of "Forms follows Function" is a design principle that was developed in the 20th century which has influenced Modern Architecture. In this concept, the design of a building or an object should be primarily based on and derived from its functional use. The American pioneer architect, Louis Sullivan, wrote in the "Form follows Function":

> "It is the prevailing law of all things organic and inorganic,
> Of all things physical and metaphysical,
> Of all things human and all things super-human,
> Of all true manifestations of the head,

Of the heart, of the soul,

That the life is recognizable in its expression,

That form ever follows function. This is the law.”

7.4.1 Integration into the external facade

The mirror in the RSSL acts as a heliostat, which rotates around the horizontal and vertical axis to reflect sunlight into the RSSL. Supporting bases are required at each floor to fix the mirrors to the external wall. Combining the functional movement of the mirror and conceptual design of the supporting frame evolves the design of the metal supporting frame as shown in Figure 7.14.

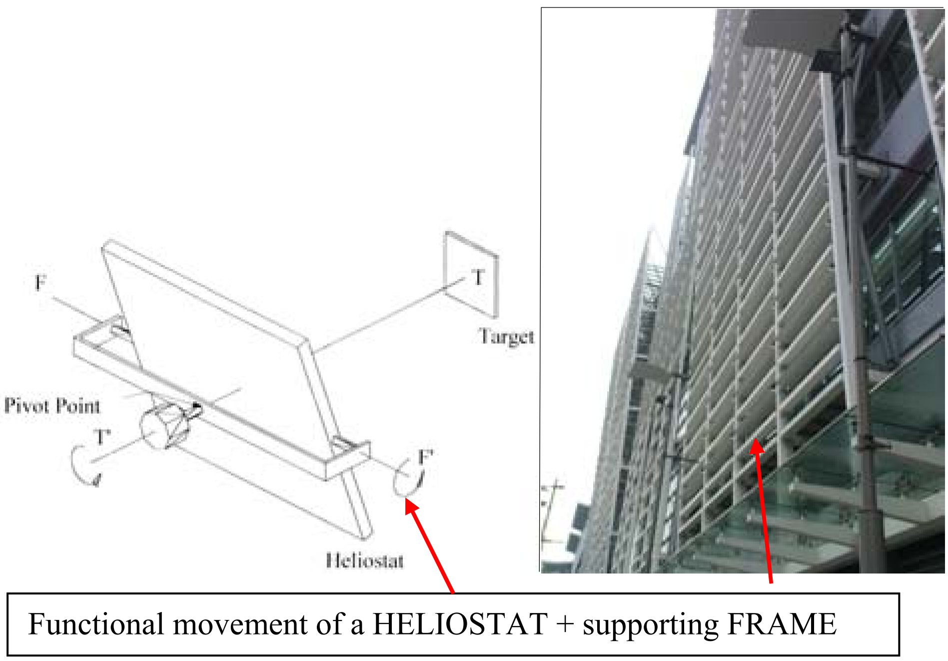


Fig. 7.14 Design concept of the external metal frame

a) West-orientated RSSL

In a west-orientated RSSL, the mirror is only required to rotate in the vertical plane. The mirror is supported by a horizontal hinge that can rotate around the horizontal axis. The mirrors are installed at alternate positions to increase the distance between the upper and lower mirrors to 5.6 m. The supporting framework is designed in grid dimensions of 0.8 m wide and 5.6 m high (Fig. 7.15). The metal frame can be designed as an architectural feature, which is anodized in either striking colors to be an eye-catching element or in similar color tone with the building as a harmonized feature (Fig. 7.16). The shape of the metal frame can be modified as shown in Figure 7.17 to allow the mirrors always facing the east even though the external wall is not orientated to the west. The principle of shadow-free zone should be applied in the design.

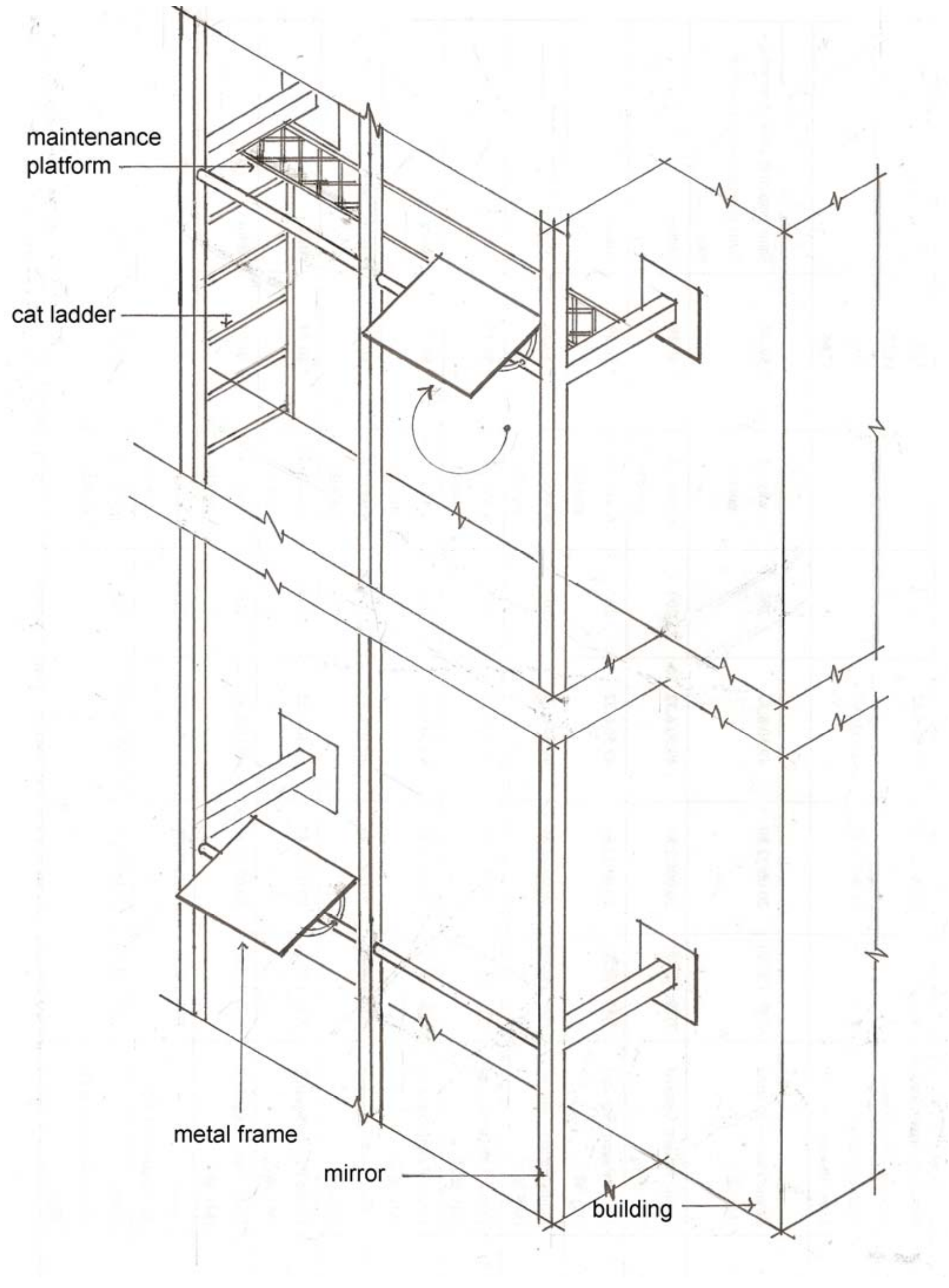


Fig. 7.15 The external metal frame

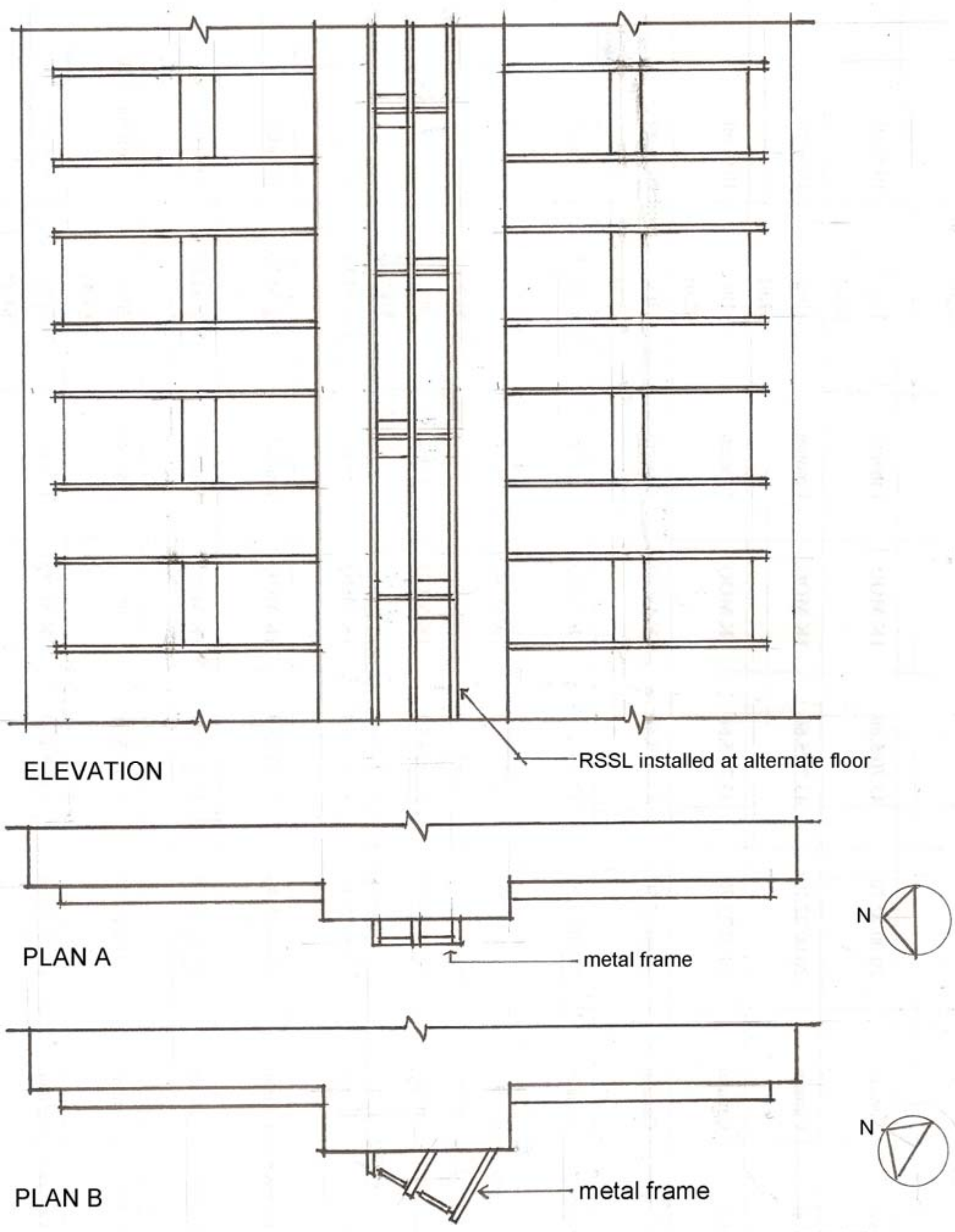


Fig. 7.16 Integration of supporting frame into the facade design

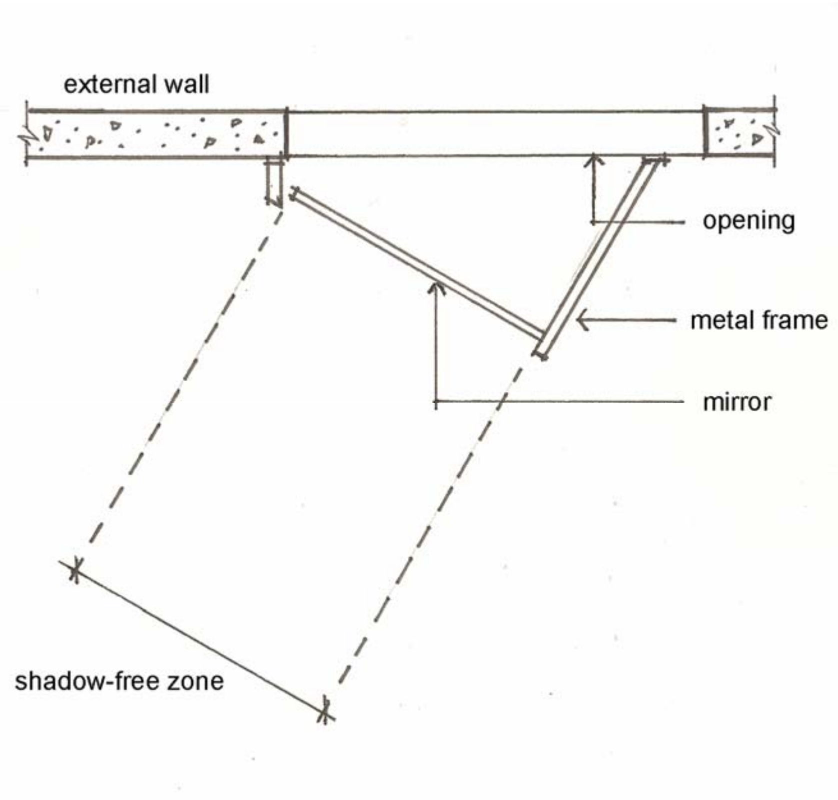


Fig. 7.17 Modified external metal frame

b) South-orientated RSSL

In a south-orientated RSSL, the mirror has to rotate in both the horizontal and vertical plane. The design of the mirror stand is more complicated than the west-orientated RSSL. The construction design of the mirror stand is shown in Figure 7.18. The mirror is mounted on a U-shaped metal stand by a horizontal hinge which can adjust the mirror inclination. The metal stand is fixed to a circular metal base that can rotate horizontally. To counteract the weight of the mirror and the stand, the diameter of the metal base is recommended to be larger than the 760 mm width of the mirror. These elements form a 2-axes heliostat. Due to the considerable size of the metal base, the simple metal frame as shown in Figure 7.15 is not suitable. A cantilever beam of width about 760 mm is designed to support the heliostat. The cantilever beam is tied to the external wall by 2 steel wires to resist the lateral wind load. The heavy duty supporting members will increase the installation cost of the RSSL and will be discussed in Chapter 8. Furthermore, the cantilever beam will also cast a shadow on the mirror below and the distance between the upper and lower mirrors will be greater than 5.6 m. The bulky structural framework is difficult to integrate into the architectural design of the facade and affect the aesthetic appearance of the building.

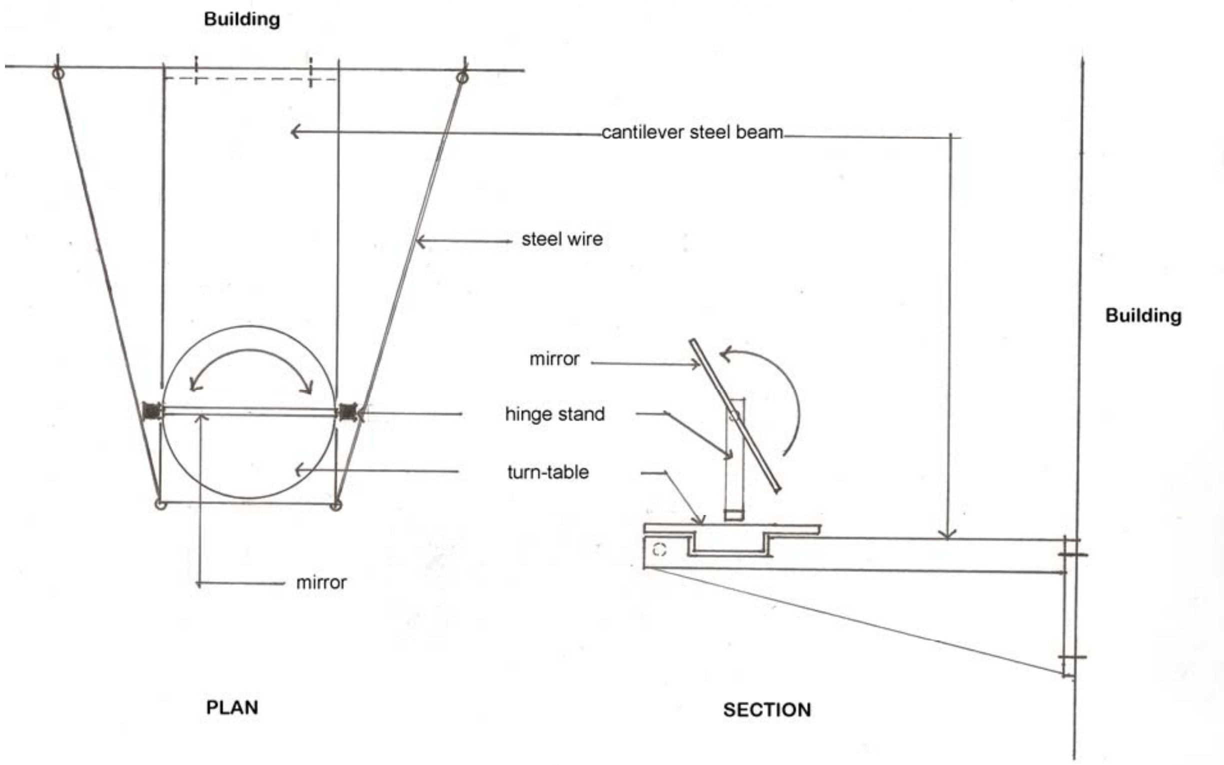


Fig. 7.18 The structural support of the mirror in the S-orientated RSSL

7.4.2 Integration into the lift lobby design

In the popular design of the conventional lighting system of an enclosed lift lobby, a series of florescent lamps joining together are installed along the 2 sides of the ceiling. False ceiling in usually installed to conceal the lighting fixtures. In the RSSL, the notched fiber optic acts as an illuminator and replaces the florescent lamps. As fiber comes in a continuous bundle, the alignment problem of the florescent lamps is solved. False ceiling is not required to conceal the notched fiber optic as in the case of florescent lamps. Anidolic reflecting ceiling panels are not required because notched fiber optic emits light downwards in a 60° cone. Light intensity is measured at eye-level of 1.5m high. The measured light intensity at 0.2 m from the margins of the emitted light zone drops to 50 % of the light intensity at the center. One notched fiber optic can illuminate an area of 1 x L m where L is the length of the fiber optic. In a corridor of 2 m wide, 2 numgers of notched fiber optic are required as shown in Figure 7.19.

Installation device is required to fix notched fiber optic to the ceiling. A fiberglass casing is designed to house the fiber optic, which also serves as a fixing device. A slit is formed along the metal casing to discharge the light being emitted from the notched finer optic. The casings run along the lobby and corridors and act as an illuminator and decorative element (Fig. 7.20). A space of 1.2 x 1.2 m^2 with an external wall preferably facing west is recommended to be reserved to house the lenses; or the lenses can also share the space of any service room that is accessible to the exterior. An aperture of 225 mm is formed on the external wall for light transmission.

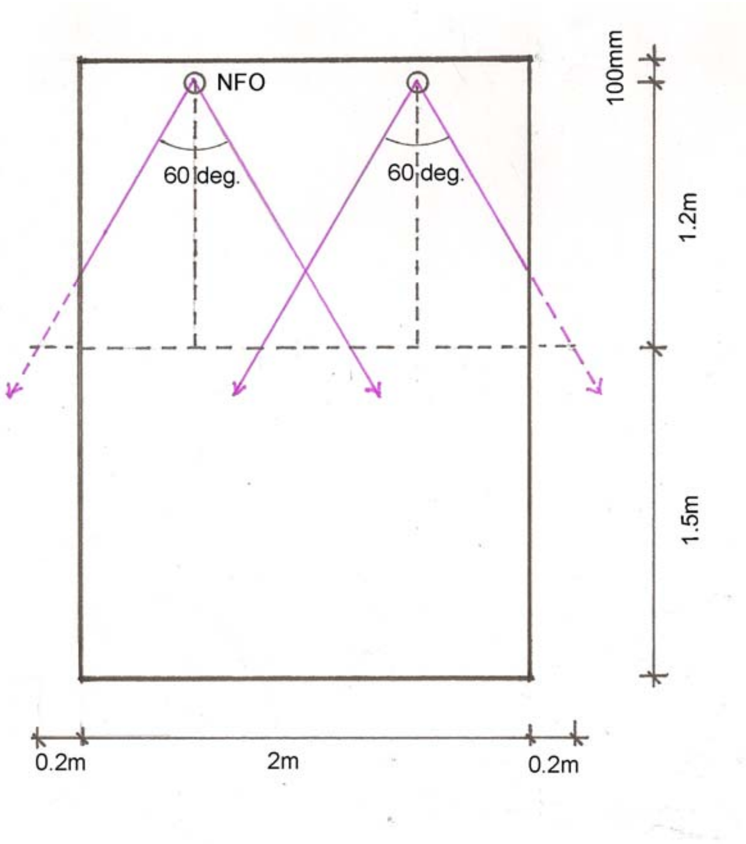


Fig. 7.19 Installation of notched fiber optic inside lift lobby

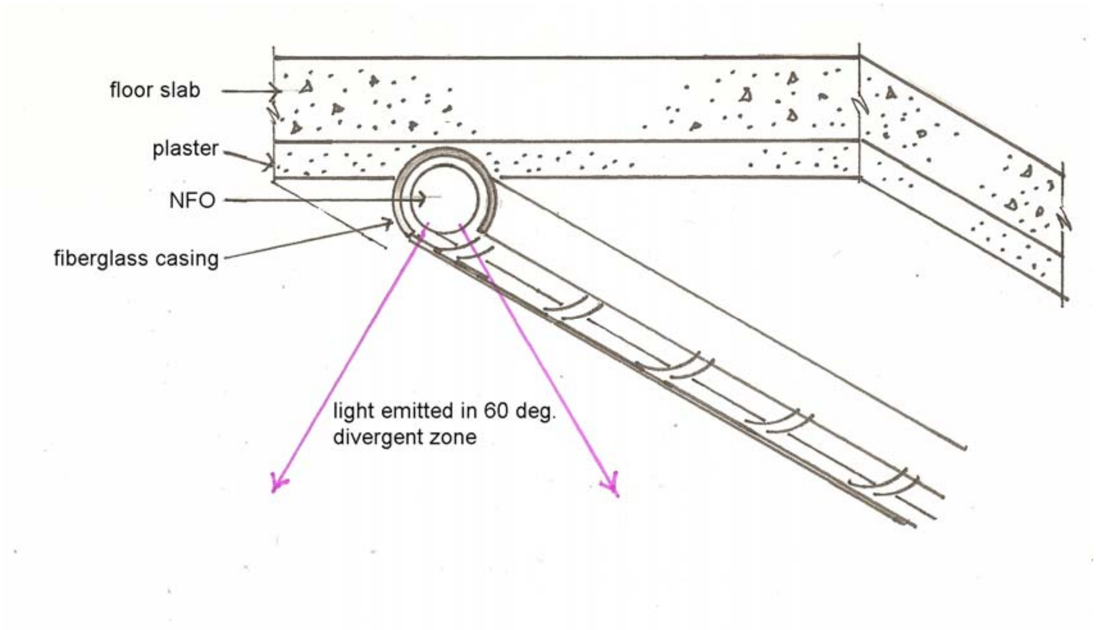


Fig. 7.20 Notched fiber optic as illuminator inside lift lobby

7.4.3 Maintenance

The life expectancy of a high quality waterproof mirror is over 5 years; and over 10 years for the lens and notched fiber optic. Replacement is not frequent. Routine maintenance such as cleaning the surfaces of the mirrors and lenses once a month is recommended as accumulation of dirt can reduce the efficiencies of these components. The moving parts of the heliostat require regular lubrication at monthly intervals.

Maintenance platforms and cat ladders should be installed to the metal framework of the west-orientated RSSL as shown in Figure 7.15. The platforms are fixed to the inner side of the metal frame right below the mirrors to avoid blocking the reflected sun rays. Structural inspection is recommended to be carried annually.

Installation of a maintenance platform to the supporting frame of a south-orientated RSSL will cast a shadow on the mirrors. For safety reason, a gondola will be required for carrying out the maintenance works and annual structural inspection of the RSSL, which is uneconomical.

7.5 Design guidelines

As analyzed in section 7.2 and 7.3, the operating hours of a south-orientated and a west-orientated RSSL is 3.4 and 3 hours and save 42.5% and 37.5% of electricity consumption per day, respectively. To reach a balance between the maximum operating hours of the two RSSL and the complication in installation, the west-orientated RSSL is preferred. The choice is also supported by the cost analysis which will be discussed in Chapter 8.

A Design Guidelines was formulated to be used as a design reference for building professionals in designing the RSSL as illustrated by Figure 7.21. The steps are listed as below:

Step 1:

In designing a RSSL, the abundance of solar energy is a crucial factor. The average hours of solar irradiance that is 443 W /m^2 or above is recommended not to be less than 3 hours in a day.

Step 2:

There shall be no buildings in the environment that will cast a shadow within the shadow-free zone as mentioned in Section 7.3.

Step 3:

When the above two factors are satisfied, allocate a space of 1.2 x 1.2 m^2 with an external wall orientating to the west for the installation of the lenses. The installation space should be as close to the lift lobby as possible.

Step 4:

The metal supporting frame for the mirror should be installed on the west facade as far as possible. The metal frame can be installed to the north-west or south-west facade if the west facade is blocked by buildings or other obstructions. Modification to the design of the metal frame is required to allow the mirrors facing the east.

Step 5:

The shadowing effect within the RSSL should be analyzed in details before designing the metal framework. The mirror should not cast a shadow on the mirror below. The principles in the designing the RSSL to eliminate shadowing effect within the RSSL as mentioned in Section 7.3.2 a) should be considered. The metal framework is divided into grid size of 0.8 m wide and 5.6 m high for the buildings of 2.8 m storey height.

Step 6:

The layout of the enclosed lift lobby should be studied in detail to determine the numbers of RSSL to be installed. The travelling distance of the fiber optic is recommended not to be more than 15 m.

Step 7:

Both the design of the external metal frame and the RSSL layout should be able to integrate into the architectural design of the building and the interior design of the lift lobby.

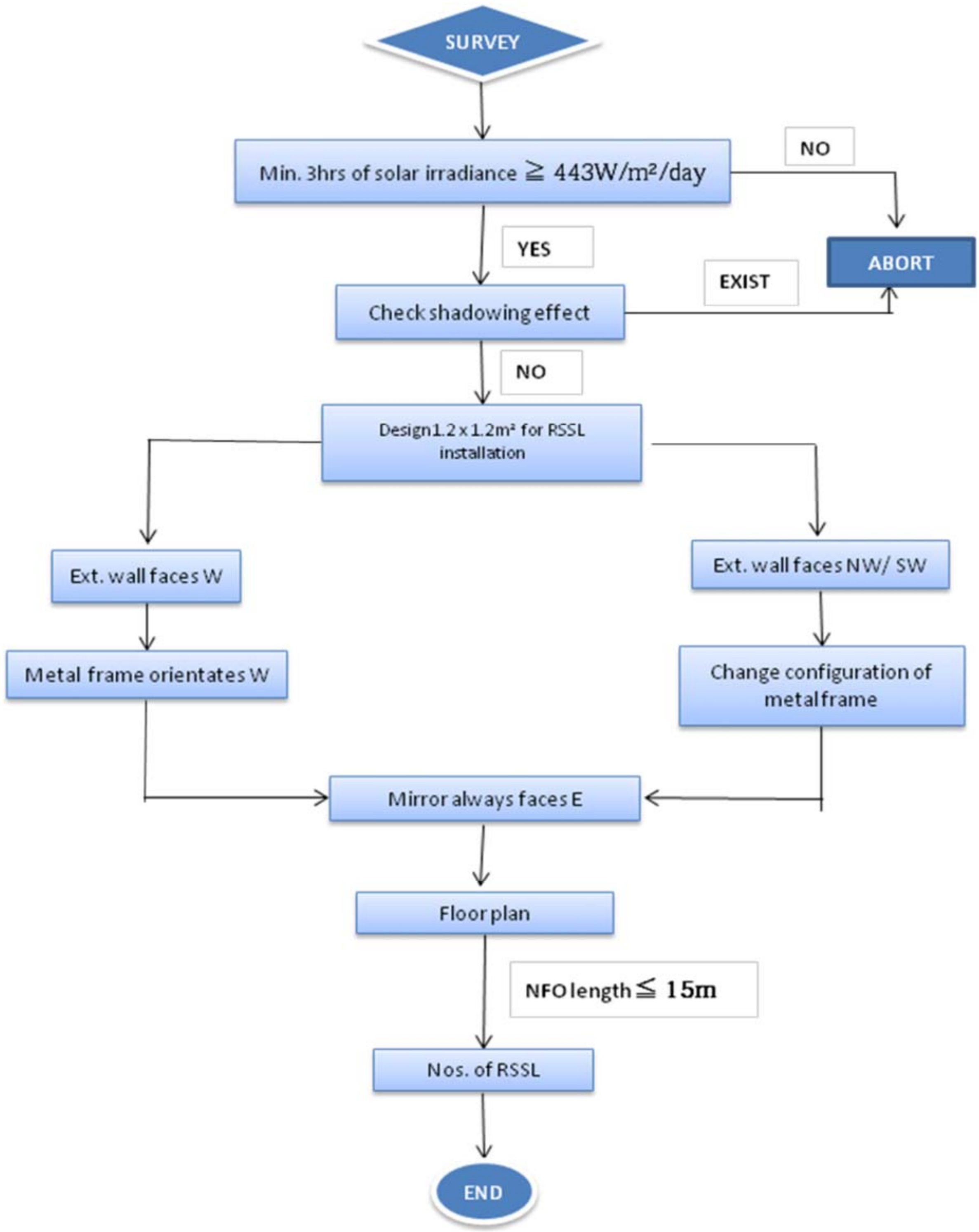


Fig. 7.21 Design flow chart of a RSSL

7.6 Conclusions

The availability of daylight in Hong Kong is high. A study has been carried out on the performance of the RSSL at different times and dates and deduced the required sky conditions for operation in this chapter. The average daily operating hours of a RSSL orientating to the south, which can receive daylight for most of the daytime, is estimated to be 3.4 hours from the records of solar irradiance at different hours and months issued by the Hong Kong Observatory from 2004 to 2007.

As Hong Kong is crowded with highrise buildings, the shadowing effect is critical to the operation of a RSSL. The design of the RSSL should avoid the shadowing effects caused by the building itself and neighbouring buildings as well as within the RSSL. The optimal orientation of the RSSL is facing the south. The mirror acts as a 2-axes sun-tracking heliostat in azimuth-elevation configuration. However the structural supporting elements for the mirror are heavy and complicated in construction resulting in higher installation cost. Modifying the orientation of the RSSL to the west reduces the average daily operating hours to 3 hours. In this orientation, the mirror is required only to track the sun along the solar altitude. The structural supporting members are lighter and simpler in construction, thus reducing the installation cost. Balancing between the operating hours and the installation cost, a west-orientated RSSL is preferred. Detail design of is carried out to integrate the RSSL into the architectural design of the building for functional and aesthetical purposes. The design of the RSSL should also facilitate routine maintenance. A design flowchart is formulated.

CHAPTER 8

ECONOMICAL ANALYSIS OF THE PROPOSED RSSL

8.1 Introduction

The installation cost of the RSSL in south and west orientation is compared with the cost of a conventional electrical lighting system which is commonly applied in the enclosed lift lobbies.

In this chapter, a new approach to calculate the payback period is introduced. The extra cost of the RSSL over the installation cost of the conventional electrical lighting system is used for calculating the payback period.

The environmental benefits that the RSSL can achieve are also studied. A balance between extra installation cost of the RSSL and environmental benefits should be considered.

8.2 Cost analysis of the RSSL

The cost estimations are based on the assumptions below:

- Nos. of buildings storey: 35
- Floor height: 2.8 m
- Width of lift lobby: 2 m
- Width of common corridor: 1.5 m
- Length of the RSSL: 12 m
- Lighting design pattern: 2 rows of lightings are installed along the ceiling of the lift lobby and corridor

8.2.1 The installation cost of the conventional lighting system

The configuration of the lift lobby is entered into the Dialux lighting design software to simulate the lighting layout. Three 32W T8 RE80 florescent lamps (T8) of 20000 life rating hours are required to be installed at the 3 sections of the lift lobby as shown in Fig. 8.1. Practically such lighting installation is good enough to provide adequate illumination to the lift lobby. However, in designing the interior lighting of a lift lobby, both the lighting requirement and aesthetic aspect should be considered. Florescent lamps are designed aligning in butt joints to provide uniform lighting along the false ceiling. There are 2 rows of florescent lamps installed along the 2 sides of the lift lobby ceiling. False ceiling is generally provided in the lift lobbies to conceal the fluorescent lamps as shown in Figure 8.2. The total length of the lift lobby and corridors is approximately 12 m. 40 numbers of 600 mm long T8 are required in the design. The unit cost of the T8 is $30 and the cost of the false ceiling including materials and installation is around $6500. The total installation cost for such a conventional lighting system using florescent lamps is around $7700 per floor.

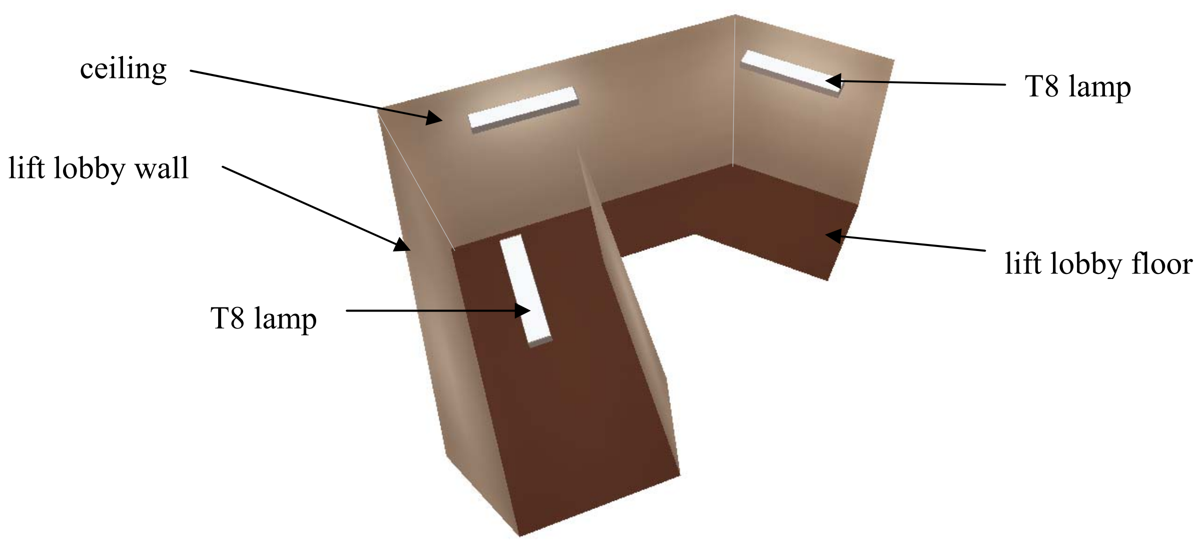


Fig. 8.1 Simulated lighting layout in the lift lobby

Fig. 8.2 Interior of an enclosed lift lobby

8.2.2 The installation cost of the RSSL

Based on the length of the lift lobby and corridors, two RSSL are required per floor. The 2 numbers of notched fiber optic replace the T8 florescent lamps. The installation costs of south-orientated and west-orientated RSSL were studied and compared. Each RSSL consists of the components as listed in Table 8.1. The installation cost including materials and workmanship of the south-orientated and west-orientated RSSL are estimated to be $45190 and $41160, respectively per floor, which are very expensive. The most expensive item is the notched fiber optic because the side-emitting technology in fiber optic is still in a preliminary stage of development and not yet matures for mass production. Further research is required before the notched fiber optic can be commercialized. With reference to the 50% reduction in the 2011 price of photovoltaic panels as compared to 2010, the manufacturer of Fiberoptics Technology Incorporation expects the price of notched fiber optic can be reduced by more than 50% when the technology becomes mature and in mass production. The installation cost of the external metal frame in the south-orientated RSSL is more expensive than the west-orientated RSSL because the structural components are larger and heavy duty. One sun-tracker is installed on the roof and connected to a computer, which controls the movements of all mirrors to track the sun in azimuth-elevation and/ or solar elevation mode based on the data input from the sun-tracker. The prices of other components can also be reduced by 50% in mass production. The price of the south-orientated and west-orientated RSSL per floor in mass production will be reduced to $20647 and $18617, respectively.

Table 8.1 Cost breakdown of the RSSL per floor

Component	**Dimensions**	**Materials**	**Cost ($)**		**Mass production cost ($)**	
			S-orientated	W-orientated	S-orientated	W-orientated
Mirror (x 2)	760 x 760mm	Plane mirror	100/pc Tot. 200	100/pc Tot. 200	50/pc Tot. 100	50/pc Tot. 100
IR filter	50 x 50mm	KG.1 glass	1500/pc Tot. 3000	1500/pc Tot. 3000	750/pc Tot. 1500	750/pc Tot. 1500
Converging lens (x 2)	225mm dia.	BK7	@ 3000/pc Tot. 6000	@ 3000/pc Tot. 6000	1500/pc Tot. 3000	1500/pc Tot. 3000
NFO (12x 2m)	10.4mm dia.	PMMA	@811/m Tot. 19464	@811/m Tot. 19464	@300/m Tot. 7200	@300/m Tot. 7200
Light sensor & control box	-	-	5000	5000	2500	2500
RGB LED lamp	-	-	1068	1068	639	639
Internal supporting frame	-	Aluminum	1000	1000	750	750
External supporting frame	-	Steel w/ anodized coating	9000	5000	4500	2500
		Sub-total	**44732**	**40732**	**20189**	**18189**
Sun tracker			11000 (total) 314/ fl.	9000 (total) 257/ fl.	314/ fl.	257/ fl
Computer control system			6000 (total) 171/ fl.	6000 (total) 171/ fl.	171/ fl.	171/ fl.
		Sub-total	**458**	**428**	**458**	**428**
		TOTAL	**45190**	**41160**	**20647**	**18617**

8.2.3 Payback period

With reference to Section 7.2, the south-orientated and west-orientated RSSL can replace 1235 and 1068 hours of electric lighting, respectively which are provided by 40 nos. of 32W T8 lamp per annum. The reductions in annual power consumption amount to the saving of $2371 and $2051 for south-orientated and west-orientated RSSL, respectively based on the charge of approximately $1.5/kWh by the Hong Kong Electric Co. Ltd. The payback periods are about 19 and 20 years for the original installation cost of RSSL facing south and west, respectively. The payback period will be reduced to 8.7 and 9 years for RSSL orientating to the south and west, respectively in mass production

A new approach is proposed to calculate the payback period based on the extra cost required to replace the conventional lighting system by the RSSL. The cost of the conventional lighting system is deducted from the cost of the RSSL. The extra installation costs of installing the south-orientated and west-orientated RSSL are $12947 and $10917, respectively using the mass production price. The payback period is subsequently reduced to about 5.5 and 5.3 years, respectively. Moreover, the present increasing trend in electricity tariff will reduce the payback period.

From the above study, the difference in payback period between a south-orientated and west-orientated RSSL in mass production by simply comparing the installation costs is only about 3 and half months. When deducting the installation cost of the conventional lighting system, the west-orientated RSSL has a shorter payback period by 2 and half months than the south-orientated RSSL. In considering the factors of complicated installation method of the external metal frame, the maintenance costs which will be discussed in section 8.2.4 and aesthetic appearance of the external facade, the west-orientated RSSL is preferred at this stage. When the side-emitting technology of fiber optic becomes mature and the light emittance efficiency is higher, which can allow the RSSL to operate for longer hours, further research is recommended to investigate the performance and design of the RSSL in south orientation to justify the installation.

8.2.4 Comparison of the maintenance cost of the RSSL to the T8 lighting system

Both the conventional lighting system and the RSSL require maintenance. A comparison of the annual maintenance cost between the conventional lighting system and the RSSL is estimated based on a 10 years period

In the conventional lighting system, the T8 lamp has an average life span of 20000 hrs which means that the 4.3 replacements are required within 10 years. Assuming that the false ceiling is required to be re-painted every 2 years and the re-painting cost is $ 3000, the annual maintenance of the lighting system is estimated to be $2016 as below:

Annual maintenance cost = $ [(30 x 40 x 4.3) + (3000 x 5)]/ 10 = $2016

In the west-orientated RSSL, the notched fiber optic can last for about 20 years, and can be regarded as maintenance free. The lift span of the mirror is about 5 years which means that 1 replacement is required within 10 years. The lift span of the LED lamp is 50000 hrs that is 5.7 years. The life span of the sun tracker can be more than

10 years with proper maintenance. If the moving parts are routinely lubricated, the replacement frequency of the parts can be reduced. The computer system requires little maintenance and can be assumed negligible. Assuming the annual maintenance cost of the sun tracker is 5% of the total cost of the system and the fee for structural inspection is $3000 per annum, the annual maintenance cost of the RSSL is estimated to be $3387 as shown below:

Annual maintenance cost of RSSL

= $[(50 x 2) + (639 x 5.7)]/ 10 + (257 x 5%) + $3000 = $3387

Although the annual running cost of the RSSL is more expensive than the conventional lighting system by $ 1371, the environmental benefit that the RSSL can offer should be considered.

8.2.5 Environmental benefits

There are 4 main types of residential buildings, which are (a) public housings, (b) home ownership scheme (HOS), (c) private housing sector (PH); and (d) villas and bungalows without lift lobbies. Natural lighting is usually provided to the lift lobbies in public housings, and villas and bungalows have no lift lobbies. Therefore only types (b) and (c) are considered in the study. According to Table 8.1 and 8.2, the average annual electrical energy consumption for lighting in the HOS and PH from 2004 to 2007 is 756 and 2,193 TJ, which is equivalent to 210 x 10^6 and 610 x 10^6 KWh, respectively (Electrical and Mechanical Services Department, 2010), amounting to 8.5 % of the average annual energy consumption in these 2 types of buildings.

Table 8.2 Energy consumption in the HOS (EMSC, 2010)

Year	Cooking	Space conditioning	Hot water	Lighting	Refrigeration	Others	Total
1998	1083	1601	1263	536	536	1029	6049
1999	1134	1469	1439	634	571	1022	6069
2000	1268	1708	1754	789	644	1047	7207
2001	1651	2150	2140	952	834	1398	9125
2002	1731	2095	2097	893	835	1448	9100
2003	1828	2153	2097	882	882	1584	9409
2004	1856	2066	1978	814	870	1622	9206
2005	1914	2075	1916	784	897	1738	9324
2006	1878	1998	1779	725	886	1789	9054
2007	1945	2014	1745	700	915	1929	9247
2008	2150	2057	1845	684	956	2110	9793

Unit in Terajoule

Table 8.3 Energy consumption in the private housings (EMSC, 2010)

Year	Cooking	Space conditioning	Hot water	Lighting	Refrigeration	Others	Total
1998	4312	6314	4330	1966	2115	3843	22880
1999	4456	5505	4430	2228	2155	3622	22395
2000	4655	5774	4508	2513	2205	33163	22967
2001	4545	5615	4428	2385	2239	3405	22617
2002	4953	5699	4615	2361	2373	3655	23656
2003	4965	5774	4722	2334	2509	3921	24225
2004	5126	5698	4765	2245	2583	4100	24518
2005	5405	5938	4993	2280	2808	4533	12958
2006	5086	5742	4863	2148	2830	4654	25296
2007	5144	5769	4886	2100	2962	4968	25831
2008	5212	5632	4935	1994	3009	5157	25940

Unit in Terajoule

In good approximation, the average annual electricity use may be assumed to be proportional to the floor area; and discussion with a number of property-management companies and property-owners associations have indicated that communal areas usually account for an average of 15 % of the total residential electricity use (Lam, 1996), which means that the remaining 85% is consumed by domestic units. Communal area includes lift lobbies, service rooms, clubhouses and car parks. Based on this assumption, a rough estimation of the required annual electric energy consumption by lighting in the enclosed lift lobbies of the HOS and private housings was conducted. A study was carried out on the different lift lobby layouts of 60 % of the HOS and 100 private housing estates.

Over 80 % of the studied the HOS require 24 hours electric lighting to illuminate the lift lobbies. For the sake of rough estimation on the annual energy consumption in lift lobbies, all the HOS are assumed to require 24 hours electric lighting in the lift lobbies. In HOS the percentage of usable floor areas, which is the area of domestic units to total building areas, is usually 75% of the building area. The average annual electrical energy consumption by lighting in the domestic units of the HOS from 2004 to 2007 is 75 % of 210 x 10^6 kWh, which is 157.5 x 10^6 kWh. From the study, the proportion of the average areas of lift lobbies to the domestic units is around 18%. As the average annual electricity use is assumed to be proportional to the floor area, the annual electrical energy consumption by lighting in the lift lobbies is 28.4 x 10^6 kWh.

Over 98 % of the studied lift lobbies in the private housings are enclosed without windows. It is also assumed that all the lift lobbies in the private housings require 24 hours electric lighting. The proportion of the average areas of the lift lobbies to the domestic units is estimated to be 7.5 %. Similarly, the average annual electricity use in lighting by the lift lobbies in the private housings from 2004 to 2007 is 38.9 x 10^6 kWh.

The total annual energy consumption by electric lightings in lift lobbies of the HOS and private housings is 67.3 x 10^6 kWh. From Table 7.1, the RSSL can replace 1068 hours of electric lighting, which is 12 % of 8760 hours of electric lighting in a year. The RSSL can replace 12 % of the total annual consumption by electric lightings in the lift lobbies of HOS and private housings, which is 8.08 x 10^6 kWh. According to the CLP Group 2009 Sustainability Report, the estimated amount of carbon dioxide emitted from the generation of electricity is 0.83 kg/kWh of electric power. The RSSL can reduce 6.7x 10^6 kg of carbon dioxide emission in a year.

With reference to the report published by U.S. Department of Agriculture in 1999, one medium size deciduous mature tree will fix an average of 133.1 kg of carbon dioxide in a year. Mature tree is defined as a tree of 36 to 40 years and Bauhinia Blakeanna is a common example of deciduous tree in Hong Kong. The installation of the RSSL in the enclosed lift lobbies of highrise residential buildings in Hong Kong can save the planting of 50338 trees in sequestrating the carbon dioxide produced from the electrical lighting system in these lift lobbies.

8.3 Conclusions

Applying the proposed RSSL to the enclosed lift lobby can replace 40 nos. of T8 florescent lamps. The installation costs of a south-orientated and west-orientated are \$45190 and \$41160, respectively. The installation cost of the conventional electric lighting system is \$7700. However the installation cost of these two RSSL can be considerately reduced to \$20647 and \$18617 in wide application. The payback period of the south-orientated and west-orientated RSSL application is calculated to be 5.5 and 5.3 years when the extra installation cost of the RSSL over the conventional electrical lighting system is used in calculation. Comparing the west-orientated to south-orientated RSSL, the west-orientated RSSL has the advantages of simplicity in structural design and installation, an aesthetic appearance and ease of maintenance. The west-orientated RSSL is recommended to be applied at the present stage.

Although the annual maintenance cost of the west-orientated RSSL is $ 1371 more than the conventional lighting system, a balance between extra maintenance cost of the RSSL and environmental benefits should be considered in parallel. The installation of the RSSL in the enclosed lift lobbies in both the private housing and HOS can reduce 6.7 x 10^6 kg of carbon dioxide emission in a year; and save the planting of 50338 nos. of tree in sequestrating the carbon dioxide produced by the electrical lighting system of these enclosed lift lobbies. The side-emitting technology of fiber optic is worth to be developed.

CHAPTER 9

CONCLUSIONS

AND

RECOMMENDATIONS FOR FUTURE WORK

9.1 Introduction

In this chapter the objectives of the research are reviewed and a conclusion is presented. The contribution and significance of the research is assessed, limitations are indicated and recommendations for future works are proposed.

9.2 Review of the objectives

As addressed in Chapter 1, the aims of the research is to study the potential of applying the side-emitting technology of fiber optic for illumination in the enclosed lift lobbies and how the design can be integrated into the architectural design of the building. The 4 objectives that are defined to fulfill the aims are: (1) to investigate the major design variables and constraints that can utilize solar energy for interior lighting in an enclosed lift lobby, (2) to identify the parameters that are necessary in designing daylighting system, (3) to explore the potential in energy conservation that can be offered by the RSSL and (4) to develop design guidelines and model in the application of the RSSL in the enclosed lift lobbies of high-rise residential buildings in Hong Kong.

Objective 1 is addressed in Chapters 3. The different layouts of enclosed lift lobbies are studied and classified. The potential and limitations in applying the RSSL are investigated and drawn to the conclusion that the application of the RSSL in the enclosed lift lobbies is viable. A novel RSSL comprising a mirror, 2 converging lenses and the notched fiber optic of side-emitting property is proposed in this thesis.

Objective 2 is studied in Chapters 4, 5, 6 and 7. Simulation and experiment were carried out to analyze the performance of the RSSL and identify the factors that can affect the performance of the system. The criteria for designing a RSSL are identified. Chapters 5 and 6 address the effects of the sun path at different times and dates on the performance of the RSSL. An outdoor light intensity of 42500 lx is the minimum requirement to maintain indoor light intensity at 150 lx. Study on the shadowing effect on the RSSL performance is carried out in Section 7.3. The parameters for designing such a RSSL are identified.

Objective 3 is discussed in detail in Chapter 8. The energy use pattern in Home Ownership Scheme and private housings are analyzed in details. The application of the RSSL in the lift lobbies of these buildings can replace 8.08 x 10^6 kWh in a year.

Objective 4 is addressed in Chapter 7. From the analysis of the availability of sunlight and the shadowing effects caused by buildings and within the RSSL, the RSSL is recommended to orientate to the west. A design flowchart is developed as a reference for architects and building services engineers in designing a RSSL. A model RSSL is also developed.

9.3 Conclusions

Global warming is a main issue of the environmental problems. Energy use in building accounts for nearly 50 % of the energy use in Hong Kong (Chen, et al., 2001). There are 2 main types of residential building in Hong Kong, which are Home Ownership Scheme and private housings. More than 90 % of the lift lobbies in these 2 types of buildings are enclosed without natural lighting and require 24 hours of electrical lighting. This thesis proposed a Remote Source Solar Lighting system (RSSL) in these lift lobbies which can save approximately 38 % of electricity consumption for illuminating these lift lobbies in daytime.

The RSSL comprises of a mirror as heliostat to reflect sunlight, 2 converging lenses that concentrate the reflected light into the notched fiber optic of side-emitting property which acts as an illuminator in the lift lobbies. The small diameter of the notched fiber optic can solve the problem of requiring 3 m headroom for installing light pipes in the high-rise residential buildings of limiting 2.8 m floor height in Hong Kong.

Performance simulation of the RSSL was carried out to study the performance of the natural lighting system, the effects of solar altitude and the solar azimuth angle on the efficiency of the system. Experiment was carried out to validate the simulated results. The solar altitude has slight effect on the efficiency at low solar irradiance. There is no obvious relationship between the efficiency and the solar azimuth angle. When outdoor light intensity is greater than 40000 lx, the intenseness of solar irradiation overrides the effect of the solar altitude and solar azimuth angle.

The overall efficiency of the system is much lowered than the simulated efficiency by more than 90 %, which can be explained by the imperfect materials of the components and immature side-emitting technology in fiber optics at the present. The rate of emission is lower than the expected 6 % per meter run and may not be consistent. In spite of the low efficiency, the RSSL can still replace 1068 hours of electrical lighting in a year. Further research on the side-emitting properties of fiber optic is proved to be worthwhile.

Shadowing effects caused by the building itself and neighbouring buildings as well as by the mirror components within the RSSL are studied. The optimal orientation of the RSSL is the south to allow the daylighting system to receive an average of 5.28 hours sunlight for most of the day and displace 3.4 hours of electric lighting. However the south-orientated RSSL has the disadvantages of complication in installation and a higher installation cost. Although the west-orientated RSSL can receive daylight in only half of the hemisphere from noon to 16:30 h, it still can displace 3 hours of electric lighting. Two separate RSSLs are proposed to be installed at alternative floors to eliminate the shadowing effect within the RSSL. The system is designed to integrate into the architectural design of the lift lobby and external facade in both functional and aesthetic purposes.

Cost analysis was carried out as well. The payback period at the present stage is 9 years if mass production of the systems can be realized and the payback period is expected to be reduced to 6 years if the cost of the replaced conventional electric lighting system is deducted from the installation cost of the RSSL.

At present the efficiency of the notched fiber optic is very low, which is around 0.3 %. A minimum 443 W/m^2 of solar irradiance is required to keep the indoor light intensity at 150 lx. The average operating hours of the south-orientated RSSL and west-orientated RSSL is 3.4 and 3 hours, respectively. The reductions in annual power consumption amount to the saving of $2371 and $2051 for south-orientated and west-orientated RSSL, respectively. However, in a south-orientated RSSL, the mirror is required to be adjusted in both the vertical and horizontal planes to track the sun at different solar altitudes and solar azimuth angles, which involves a more complicated structural support to allow the mirror to rotate around the two axes. The installation of the mirror in a west-orientated RSSL is much simpler because the mirror only moves in the vertical plane to track the sun at different solar altitudes. The installation cost of the south-orientated RSSL is 11% higher than the west-orientated RSSL. After deducting the cost of the conventional lighting system from the costs of the RSSL, the payback period of the south-orientated and west-orientated RSSL is 5.5 years and 5.3 years, respectively. It is not economical to install a south-orientated RSSL at the present stage. When the side-emitting technology can be improved to increase the efficiency of the fiber optic, the required minimum solar irradiance to maintain the indoor light intensity at 150 lx will be reduced and the operating hour of the RSSL will be longer. The design of the south-orientated RSSL is worthwhile to be developed when the extra energy saving in a south-orientated RSSL can compensate the extra installation cost.

The environmental benefits that the RSSL can achieve should also be considered. The RSSL can reduce a total of 6.7×10^6 kg of carbon dioxide emission in a year if all enclosed lift lobbies in high-rise residential buildings are installed with the RSSL.

When the side-emitting technology in fiber optics becomes mature and can be commercialized, the RSSL technology can be introduced for wider application to illuminate the inner zones of offices and commercial buildings as well.

A design guideline has been developed in this paper based on the research outputs, which can be used by local industries and developers.

9.4 Contribution and significance of this research

This research investigated the potential of applying the RSSL technology using side-emitting fiber optic to reduce the consumption of electricity for providing illumination in the enclosed lift lobbies of high-rise residential buildings. Installation of conventional RSSL using light pipes as light transfer medium, which requires a minimum floor clearance of 3 m, is not feasible in the major high-rise buildings of 2.8 m floor height in Hong Kong. The proposed RSSL using the 0.4 mm diameter notched fiber optic can solve the limited headroom problem. The small diameter of the notched fiber optic can be installed in the lift lobby without reducing the headroom.

The research significantly improves our knowledge on the behavior of a RSSL and performances of the different components of plane mirror, converging lens and side-emitting fiber optic at different times and dates and under different solar irradiance. The findings from the study on shadowing effect are crucial to the design of a successful RSSL in the densely populated city like Hong Kong with majority of buildings developed into high-rise style.

The research also lays down design guidelines and flowchart for building designers to be used as a reference.

9.5 Limitation of this research

There are three main limitations for this research. Firstly, the mirror that acts as a heliostat is controlled manually instead of by an automatic sun tracker due to limited resources. There are slight deviations or discrepancies in the measurements as the changes in sky conditions are sometimes faster than the speed of manual operation. The experimental readings were taken at one hour interval from 9:30 to 16:30 h for an average of 4 days in a week from February to August in 2011. The records show a general trend of the RSSL behavior responding to different sky conditions, changes in sun path, availability of solar irradiance in different seasons.

Due to time limitation, the findings of the research is confined to 3 seasons only, which spread from winter to summer in 2011. The findings can be more comprehensive if the time span of the experiment can be extended to 1 or more years.

The efficiency of the notched fiber optic is less than 1% as the side-emitting technology in FO is still in a very preliminary stage of development. The side-emitting fiber optic is mainly used as highlight. There are hardly available research findings on the application of side-emitting fiber optic to provide lighting for reference. Further research is required to explore the potential of side-emitting technology in illumination.

9.6 Recommendations for future works

This research basically establishes the potential of applying the side-emitting technology of fiber optic in the transfer of daylight for indoor illumination. Further research is required to improve the side-emitting efficiency of fiber optic before the product can be commercialized.

The research only concentrates on the application of the RSSL in the enclosed lift lobbies of high-rise residential buildings. Based on the findings of the study, further research can be conducted to extend the application of the RSSL to provide daylight to the inner zone of office building, commercial centers, institutional and other buildings where natural lighting is not available.

APPENDICES

Appendix A

Questionnaires

Questionnaire For Construction Professionals

Background of the research

In the central core design of highrise buildings, artificial lighting has to be switched on 24 hours imposing a continuously financial burden to owners and causing irreversible detrimental effect to our environment. The heat generated by artificial lighting increases the cooling load particularly in commercial buildings where air-conditioning is switched on during office hours.

Remote source lighting is a technique that can transport daylight from the exterior to illuminate the inner space which lacks natural lighting by optical instrument called "Light Guide" Light guide is a solid fiber optic or a hollow pipe that can transport daylight from a remote area e.g. exterior or roof to a destined area for illumination.

SECTION 1. Professional History

1. Which sector of construction industry you belong to?

☐Architect
☐Building Services Engineer
☐Structural Engineer

2. How many years of experience have you had in construction industry?

☐1-10
☐11-20
☐21-30
☐Over 30

56

SECTION 2. Energy Conservation

Instruction:

In answering question 4 to 5, please indicate the importance level by ranking 1-5. The importance is scaled as follows:

5 – extremely importance 4 – importance
3 – neutral 2 – unimportance
1 – little importance

1. Do you agree that building energy use is responsible for the emission of polluting gases?
☐Yes or ☐No
2. Do you support energy conservation by reducing the use of electricity?
☐Yes or ☐No
3. Do you support the exploration of other source of renewable energy?
☐Yes or ☐No
4. How do you rank the importance of the pledge to reduce environmental pollution?

5. Please indicate the importance of the following plays in reducing building energy consumption.
   a) Developer: install renewable energy system in new buildings
   5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐
   b) Architect: design renewable energy system in new buildings
   5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐
   c) Building Services Engineers: renewable energy system in new buildings
   5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐
   d) Supplier: promote products of renewable energy
   5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐
   e) End-user: support the use of renewable energy
   5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐
   f) Government: support the use of renewable energy
   5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐

6. Which mode of illumination do you prefer?
☐Daylight (please go to Q.7)
☐Artificial light (please give reasons: ________________________________)

7. Please give the reasons for your preference. (You can choose more than 1)

☐ Renewable energy	☐ Sustainable design	☐ Good for health	☐ Feel comfortable

SECTION 3. Application of Remote Source Lighting System in lift lobbies.

Instruction:

In answering question 1 to 4, please indicate the effectiveness by ranking 1-5. The importance is scaled as follows:

5 – extremely effective 4 – effective
3 – neutral 2 –not so effective
1 – ineffective

1. How would you rank the effectiveness of Remote Source Lighting system can improve the lighting situation of the enclosed light lobbies?

57

5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐

2. How would you rank the effectiveness of the Remote Source Lighting System can improve the internal climatic condition of the enclosed lift lobbies?

   5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐

3. How would you rank the effectiveness of the Remote Source Lighting System can reduce building energy consumption in highrise *COMMERCIAL* buildings?

   5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐

4. How would you rank the effectiveness of the Remote Source Lighting System can reduce building energy consumption in highrise *RESIDENTIAL* buildings?

   5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐

5. Please rank the importance of the following obstacles to install a Remote Source Lighting system to lift lobbies of a *NEW* highrise development. (Ranking 1 to 5, 5 being the most important obstacles and 1 being the least)

   a) Client: lack of interest 5 ☐ 4☐ 3☐ 2☐ 1 ☐
   b) Architect: lack of initiative 5 ☐ 4☐ 3☐ 2☐ 1 ☐
   c) Building Services Engineer: lack of initiative 5 ☐ 4☐ 3☐ 2☐ 1 ☐
   d) Manufacturer & supplier: lack of interest 5 ☐ 4☐ 3☐ 2☐ 1 ☐
   e) Government: lack of promotion and support 5 ☐ 4☐ 3☐ 2☐ 1 ☐
   f) Lack of expertise knowledge 5 ☐ 4☐ 3☐ 2☐ 1 ☐
   g) Lack of cost data 5 ☐ 4☐ 3☐ 2☐ 1 ☐
   h) Extra installation cost 5 ☐ 4☐ 3☐ 2☐ 1 ☐

6. Please rank the importance of the following obstacles to install a Remote Source Lighting system to lift lobbies of an *EXISTING* highrise building. (Ranking 1 to 5, 5 being the most important obstacles and 1 being the least)

   e) Lack of support and common understanding among owners to conserve energy
      5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐
   f) Extra cost to be paid by owners for installation
      5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐
   g) Inconvenience caused to owners/ tenants by construction work during installation
      5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐
   h) Manufacturer & supplier: lack of interest
      5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐
   i) Government: lack of promotion and support
      5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐
   j) Lack of expertise knowledge
      5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐
   k) Lack of cost data
      5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐
   l) Extra installation cost
      5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐

m) Limitations of existing structure: modification is required
5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐

7. Will you recommend the application of Remote Source Lighting system in the enclosed lift lobbies to your client?
☐Yes
☐No (Reasons: ____)

Thank you.

Potential of Introducing Natural Lighting into the Enclosed Lift Lobbies of Highrise Buildings by Remote Source Lighting System

The captioned project is conducted by a group of research student of the Department of Building and Real Estate of The Hong Kong Polytechnic University. The project studies the potential of introducing daylight into the enclosed lift lobbies of highrise residential and commercial buildings to replace the artificial lighting as far as possible during daytime.

The enclosed questionnaire is a part of the research to understand the public concern on energy conservation and their acceptance of using renewable energy. The findings of the questionnaire aims to study the general awareness on energy conservation and the public view on utilizing daylight in the lift lobbies of highrise buildings. Your view is very important to the fulfillment of our study.

We would be much obliged if you could spend 5-10 minutes of your valuable time to complete and return the questionnaire by email or post. Should you have any queries, please contact Ms. Irene Wong at 9028 or 0690

We promise that all data will be kept strictly confidential and used solely for academic research purposes.

Thank you for your kind assistance.

Yours sincerely,

Irene Wong
PhD Candidate of The HK Polytechnic University

Tel: 9028
Fax: 2336 9994

Enclosures: Questionnaire

If you want to get a report of the analysis result of this questionnaire survey, please write down your corresponding information in the following blanks.
Also, we promise that the information will be solely used for the purpose of sending the report.
We research team thank you again for your kind participants.

Name: ______________________
Email: ______________________
Corresponding address:
____

59

Questionnaire For End-User

Background of the research

In the central core design of highrise buildings, artificial lighting has to be switched on 24 hours imposing a continuously financial burden to owners and causing irreversible detrimental effect to our environment. The heat generated by artificial lighting increases the cooling load particularly in commercial buildings where air-conditioning is switched on during office hours.

Remote source lighting is a technique that can transport daylight from the exterior to illuminate the inner space which lacks natural lighting by optical instrument called "Light Guide" Light guide is a solid fiber optic or a hollow pipe that can transport daylight from a remote area e.g. exterior or roof to a destined area for illumination.

SECTION 1. Personal Details

1. What is your age group?

☐15-25
☐26-35
☐36-45
☐above 45

2. Are you working? (Yes, please go to Q.3)

☐Yes
☐No

3. Which working sector do you belong to?

☐Student
☐Education
☐Construction
☐Medical
☐Financial
☐Food and beverage
☐Retails
☐Social services
☐Public services
☐Others (please specify:________________________)

60

SECTION 2. General View on Pollution & Energy Conservation

1. Do you think our environment is polluted? (Yes, please go to Q.2)
   ☐Yes or ☐No

2. How do you rank the degree of our environmental pollution? (Ranking 1-5, 1 being the least)
   5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐

3. Do you know that electricity generated by burning of fossil fuel pollutes our environment?
   ☐Yes or ☐No

4. Do you know that fossil fuel is a depletable source of energy?
   ☐Yes or ☐No

5. Do you support energy conservation by reducing the use of electricity?
   ☐Yes or ☐No

6. Do you support the exploration of other source of renewable energy?
   ☐Yes or ☐No

SECTION 3. Remote Source Lighting System – to introduce daylight into enclosed lift lobbies

1. Which modes of illumination do you prefer?
   ☐Daylight (please go to Q.2)
   ☐Artificial light (please give reasons: ______________________________)

2. Please choose the reasons for choosing daylight, you can choose more than 1.
   ☐Free of charge
   ☐Good for health
   ☐Feel comfortable

3. Do you think Remote Source Lighting System can help to reduce pollution and conserve energy?
   ☐Yes
   ☐No (pls give reasons: ______________________________________)

61

4. Please choose and rank the following factors that you consider is an obstacle to apply remote source lighting system in the lift lobbies of EXISTING highrise buildings? (You can choose more than 1. Ranking 1-5, 1 being the least)
   a) Lack of support and common understanding among owners to conserve energy
      5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐
   b) Poor knowledge on the remote source lighting system
      5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐
   c) Extra cost to be paid by owners for installation
      5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐
   d) Inconvenience caused by construction work during installation
      5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐
   e) Lack of professional expertise
      5 ☐ 4 ☐ 3 ☐ 2 ☐ 1 ☐

5. Will you consider installing a remote source lighting system to your building if the technical issues can be solved?
   ☐Yes or ☐No

6. What is the acceptable pay-back period for the installation of the remote source lighting system to you? (Pay-back period is the number of years that the saving in electrical cost for artificial lighting can off-set the installation cost of the remote source lighting system)
   ☐5-7
   ☐8-10
   ☐11-12

7. Do you welcome the installation of remote source lighting system to be incorporated into the lift lobbies of FUTURE highrise buildings?
   ☐Yes or ☐No

8. Do you think the government should promote the development of remote source lighting technology?
   ☐Yes or ☐No

9. Do you think the government should support the development of remote source lighting technology by allotting research fundings?
   ☐Yes or ☐No

Thank you.

62

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