Applied Energy 205 (2017) 13–22

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Balancing energy and daylighting performances for envelope design: A new index and proposition of a case study in Hong Kong

Jing Chao Xie[a], Peng Xue[a,*], Cheuk Ming Mak[b], Jia Ping Liu[a]

[a] Beijing Key Laboratory of Green Built Environment and Energy Efficient Technology, Beijing University of Technology, Beijing, China
[b] Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong, China

HIGHLIGHTS

- Daylighting and energy performances were studied simultaneously.
- Energy demands of lighting and air-conditioning systems were both included.
- Luminous comfort was quantified by Ave. DA_{300} with the range from 29.6% to 57.8%.
- Energy Daylight Rate was proposed as a simple multi-objective optimization approach.
- Optimal scenarios for all directions were tested and chosen by EDR method.

ARTICLE INFO

Keywords:
Luminous environment
Energy saving
Daylight autonomy
Energy daylight rate
Envelope design

ABSTRACT

Being healthy and energy saving have become two important principles of building development. Daylight is an influential factor with the characteristics of both photometry and radiometry. Irradiance brings solar heat gains that transfer to building cooling load, while illuminance provides a luminous environment and affects artificial lighting system at the same time. To balance the energy and daylighting performances, it is reasonable to minimize the environmental load under moderate comfort conditions. This study first quantified luminous comfort with a dynamic daylighting metric, average daylight autonomy (Ave. DA_{300}), from a questionnaire survey and simulation work. The benchmark of this metric should range from 29.6% to 57.8% for high-rise residential buildings. With this guideline, the Hong Kong public housing units is found that part of units lack of daylight due to the high building floor and density, while some units have potential to save energy by compromising daylighting performance. Therefore, a new index, energy daylight rate (EDR), is proposed to help decide the best scenario of envelope design for both daylighting and shading purposes. The results show that opening a secondary window is an efficient way to bring more light in and lengthening overhang is an efficient way to block excessive sunlight. This method and the new index are proved to have the ability to help defining proper building envelope design at the early stage.

1. Introduction

1.1. Characteristics of daylight

Light is a valuable resource as it not only brings people brightness and affects human circadian physiology [1], but also enhances people's productivity [2] and satisfaction [3]. Increased consciousness about satisfaction such as thermal comfort, acoustic comfort, as well as luminous comfort has attracted people's attention to their living conditions. Researchers have adopted innovative feature [4] and glazing [5] to create a comfort luminous environment more intentionally and efficiently. Nowadays, being livable and energy saving have become two important principles of building development. Daylight is an influential factor as the characteristics of both photometry and radiometry. Irradiance brings solar heat gains, which transfer to building cooling load, while illuminance provides a specific luminous environment and affects energy usage of lighting system at the same time. Therefore, how to balance the energy consumption and daylighting performances becomes a critical issue [6], and three important questions should be addressed first: (1) should the energy be consumed as little as possible? (2) Can the comfort level of luminous environment be quantified? (3) How to guide the energy-efficient daylighting design based on luminous comfort?

* Corresponding author at: Room 2504-1, Environment and Chemistry Building, No. 100 Pingleyuan, Chaoyang District, Beijing, China.
E-mail addresses: xiejc@bjut.edu.cn (J.C. Xie), xp@bjut.edu.cn (P. Xue), cheuk-ming.mak@polyu.edu.hk (C.M. Mak), liujiaping@bjut.edu.cn (J.P. Liu).

http://dx.doi.org/10.1016/j.apenergy.2017.07.115
Received 25 April 2017; Received in revised form 23 July 2017; Accepted 26 July 2017

1.2. Energy efficient design about daylight

Hong Kong has a fruitful daylight resource for saving artificial lighting energy as the outdoor horizontal illuminance could reach to 10,000 lux for over 80% office hours in a year [7]. Both the simulated and measured data showed the daily lighting energy savings could reach to 8 kW h for 52 m^2 in spring and summer [8]. The Electrical & Mechanical Services Department (EMSD, Hong Kong) reported that the annual lighting consumes 9% of the total electricity end-uses, which ranks the third following the space-conditioning 36% and refrigeration 13% [9]. Better utilization of daylight and better control of lighting, such as window systems [10] and dimming control [11], could generate more lighting energy savings up to 30% and 60% respectively. However, daylight also brings radiation, and solar heat gain becomes cooling load which will increase around 28% of the energy consumption for air-conditioning (AC) system unintentionally [12]. Hong Kong still suffers from an intense increasing of annual total electricity consumption with an average rate of 6.67% per year over last 40 years [13]. It is reported that an ideal envelope design could reduce 33% of annual cooling load without consideration for daylighting [14]. Therefore, in order to achieve total energy-efficient objective, cooling load and artificial lighting electricity should be considered simultaneously when optimizing envelope design related to daylight [15].

To reduce the annual energy consumption, static or dynamic façade features are often adopted for envelope design. For an individual flat, the electricity savings could decrease from 40 to 28 kW h/m^2 when the angle of obstruction varied between 25° and 30° [16]. An automated control strategy of inside slat-type blind was proposed with the considering visual comfort, and an energy saving of 24.6% could be achieved [17]. The sensitivity analysis identified window to wall ratio and slat angle as highly influencing factors for energy performances regardless of façade orientation [18]. The glazing properties [19] and climate variation [20] are also found as great issues for energy performance. A research [21] found that a minimum saving of 10% in total energy consumption could be achieved by modifying the size of the windows. Except for energy saving purpose, façade features (balconies, sunshades and reflectors) are recommended by Hong Kong government to incorporate into building development also for enhancing luminous environment of residential units. To balance the energy consumption and daylighting performances and also answer the first question, it's reasonable to minimize the environmental load under moderate comfort conditions [22].

1.3. Satisfaction with daylighting

The Director of interior lighting division of International Commission on Illumination (CIE), believes that people's subjective perception of light should be quantified by objective metrics [23]. At present, the daylighting metrics are generally divided into three categories: static metrics, glare metrics and dynamic metrics. Static metrics include illuminance, brightness, color temperature, daylighting factor, uniformity, outdoor view, etc.; glare metrics include daylight glare coefficient (DGI) and daylight glare probability (DGP). Some researchers qualified the comfort as illumination level [24] and some treat it as uniformity [25]. While, most researchers believe offering luminous comfort environment means reducing glare problem [26]. With the development of climate-based daylight modeling (CBDM) technology and the continuous improvement of computer performance, cumulative effect of daylight on indoor luminous environment are put forward, namely daylight autonomy (DA) [27], useful daylight illuminance (UDI) [28], annual light exposure (ASE) [29] and so on. A basic study lead by Reinhart and Weissman [30] found that an objective dynamic metric - spatial daylight autonomy (sDA) can accurately representative the area in which students assessed subjectively as the mean daylit area, with an error of around 7%. Based on the process of proposing dynamic metrics [31], linking with energy savings [32] and linking with subjective assessments [33], the North American Institute of Illumination (IESNA) has incorporated the dynamic metrics sDA and ASE into the latest daylighting measurement methods [34]. In 2016, the latest version of the US LEED Green Building Assessment System also includes these two metrics and legalize them as one of three standard methods of indoor lighting evaluation [35]. At the same time, the Society of Light and Lighting (SLL) is studying the feasibility of using dynamic metric as a statutory evaluation metric [36], and it can be seen that the characterization of subjective requirements with dynamic metrics has become a trend [37]. Since the dynamic metrics can only be obtained by numerical calculation, the quantitative process needs further simulation work [38].

In this study, the rest two questions above-mentioned will also be answered. A dynamic daylighting metric, average daylight autonomy (Ave. DA_{300}), will be first tested to quantify luminous comfort with the data from a questionnaire survey [39] and simulation work. The benchmark of this metric will be established for high-rise residential buildings. With this guideline, the daylighting performances of Hong Kong typical public housing units could be checked to decide whether they needs daylighting or shading. Several different scenarios will be built trying to meet the balanced daylighting and energy requirements. A new index, Energy Daylight Rate (EDR), is then proposed to help decide the best scenario of envelope design.

2. Methodology

2.1. Questionnaire survey

Hong Kong is the densest city with the highest number of high-rise buildings all over the world. However, the regulations for 'rights of light' (window to floor ratio should be more than 10%) do not ensure an acceptable daylighting in many residential building units because of the external obstruction. A questionnaire survey was conducted in a public housing estate to obtain the residents' subjective comfort feeling for the living room luminous environment. Participants chose the comfort level based on the Likert 5-point scale [40]. The type of the buildings is selected as Harmony 1 with the building plan shown in Fig. 1a. This is the most famous type of public housing, as there exists 293 the same buildings in Hong Kong. Questionnaires were coded and issued by mail, and 108 valid questionnaires were collected through collection boxes for further analysis. These coded questionnaires reveal the specific physical information, including floor level, orientation and shading devices of the living room (Fig. 1b). By searching further information from Housing Authority, each unit's external obstructions could be known based on real location and surroundings (Fig. 1c).

2.2. Simulation set-up

The building model has 40 storeys and 16 units on each floor level according to the real conditions. To investigate the individual difference among the units, a group (3 × 3) of building blocks is built, which is closed to real condition (Fig. 2a). The center block is the target building which the units are built in.

As there are 640 units in a single building block, it is essential to study the daylighting and energy performances with typical units. The typical models are built according to the characteristics of the units. Except for the orientation and floor level, the location of the neighbour rooms differs much when considering the self-shading. Therefore, the total 16 units in one certain floor is separated into two groups, namely inner ring and outer ring, and 8 units for each (Fig. 2b). The units in inner ring are more sensitive to the self-shading than the ones in outer ring. However, the distance of the buildings is also an influential factor as it affects much about the angle of obstruction. In this case, the inner and outer rings' units are modelled in the target building on 5, 15, 25 and 30 storeys facing 4 different orientations in a group of building blocks with the distance of 15 m, 25 m and 35 m for each other. In this