Technical Review

A Study on Daylight Distribution and the Associated Heat Gain of a Typical Flat in Hong Kong Commercial Buildings

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ABSTRACT

Daylight distribution and the associated heat gain of a commercial building with curtain wall façade under different degrees of obstruction are studied. A new metric ‘useful daylight illuminance’ (UDI) is applied to analyze the time varying illuminance distribution on a work plane. The solar irradiance obtained from the daylighting simulation is input to a two-node thermal model for energy simulation. The indoor air temperature profile, cooling and heating load requirement and the associated electrical energy consumption based on a typical coefficient of performance (COP) are reported.

KEYWORDS: Useful daylight illuminance, commercial buildings, radiance, daylight coefficient, daylight availability, thermal simulation

1. Introduction

Solar radiation incident on window apertures can be desirable or undesirable depending on a number of factors such as the location and the use of the building, the time and the intensity of incident radiation and whether it is direct or diffuse radiation. Passive solar heating in winter is often desirable and may contribute to the annual energy budget of the building. In summer, solar radiation penetrating through window apertures can easily become the dominant heat source in the building. This produces overheating causing thermal discomfort as well as requiring high energy consumption for cooling. Therefore, appropriate sun shading device for window apertures is necessary to reject the undesirable amount of solar radiation but letting the desirable amount of solar radiation to penetrate the aperture for daylighting purpose.

Effective use of daylight in buildings is very crucial since it gives high quality illumination with a saving of electric lighting energy. Additional benefits of daylighting include reduction of maximum electricity demand, enhancement of occupants’ health and well-being and improvement of productivity. However, many commercial buildings in Hong Kong are typically high-rise and built close to each other. This phenomenon limits the access of natural light to interior spaces.

A survey on the investigation of current solar shading design and the degree of shading due to nearby buildings was carried out on both residential and commercial buildings. Preliminary findings of the survey were presented previously1). Typical sun shading measure was identified for each type of building and the extent of the shading effect for a district due to neighboring buildings was reported. Results of commercial buildings is further explored and analyzed in the present paper.

Figure 1 Layout of the reference building (Abridged from Chan and Chow 2).

2. The reference buildings

There are two common types of commercial building constructions in Hong Kong: the traditional one with concrete frame and load-bearing external wall and the latest one with steel or concrete frame and non load-bearing external wall. Curtain walls are typical for commercial buildings since late 1970s whilst concrete wall
Structures with ceramic tile finish or stucco finish are common for traditional buildings. Chan and Chow developed a reference building based on a survey of 64 commercial buildings in Hong Kong. The reference building is a 40-storey high curtain wall construction with a square plan of 36m × 36m as shown in Figure 1. There is a core zone in the center which is used for accommodating MVAC and lift services. The interior and perimeter zones are for office use in general.

3. Simulation approach

3.1 The simulation model

A computer model which includes the reference curtain wall building and a heavily obstructed environment was set up for daylighting simulation. Four obstruction walls were erected in front of the building façade facing the four cardinal directions. The height of the obstruction walls was the same as the height of reference building so that the walls completely enclose the building perimeter mimicking a heavily obstructed environment. An office model accounting for the whole floor area of the building was set up. The reflectances of the walls, ceiling, floor, ground and building façade were set to be 0.5, 0.7, 0.3, 0.2 and 0.2, respectively. The window aperture was 1.6 m high with a sill height of 0.9 m above the floor level. A transmittance value 0.3 (0.327 transmissivity) was used to model the properties of the curtain wall glazing.

3.2 Daylighting simulation

Daylighting models of the office floor with different degrees of obstruction were generated based on the obstructed building model for internal daylight illuminance prediction. Four scenarios with obstruction angles of 0°, 25°, 50° and 75° were modeled (Figure 2) by varying the office floor height (for cases 25°, 50° and 75°) and removing external obstruction (for the case 0°). Hourly illuminance was calculated using daylight coefficients derived at grid points and the hourly sun and sky radiation which were generated using the Hong Kong test reference year (TRY) data. The daylight performance of the flat was determined in terms of a new metric called ‘useful daylight illuminance’ (UDI). This new metric was formulated using human factors data derived from published studies on occupant preferences for daylight in buildings. The sensitivity of the UDI metrics to the degree of obstruction is presented. Details of UDI are elaborated in section 4.1.

To predict the time-varying illuminances, a grid of 1000 calculation points with distance 1 m between consecutive points in both directions was put over the horizontal reference plane of height 0.8 m above the office floor. Time-varying illuminances were predicted based on the framework for climate-based analysis adopted by Nabil and Mardaljevic. Daylight coefficients for all 1000 grid points were computed first using the rigorously validated ray tracing engine – Radiance. The horizontal irradiation data in the TRY for Hong Kong were then used to determine hourly sky and sun conditions and finally generate the varying sky luminance patterns for every daylight hour in the year (i.e. when the irradiation is greater than zero). The hourly internal illuminances of the grid points were then calculated from the pre-computed daylight coefficients and the hourly sun and sky luminance distribution. The total number of illuminance values computed was: 4353 (daylight hours) × 1000 (points) × 4 (obstruction angles including 0°) = 17,412,000. These data were processed to determine the UDI metrics.

Apart from the horizontal grid, line grids of 12 calculation points were also set up on four cardinal facades for evaluating the vertical illuminance. The total number of vertical illuminance values computed was: 4353 (daylight hours) × 12 (points) × 4 (facades) × 4 (obstruction angles including 0°) = 835,776. Vertical illuminance obtained for four facades were converted to vertical irradiance, using the factor 110 lm/W, which were used as input to the thermal model.

3.3 Thermal simulation

Dynamic thermal simulation was carried out using a two-node thermal model. Since the simplified model can only handle one thermal zone at a time, a single office floor with an internal air volume of 3427 m³ and internal surface area excluding windows of 2564 m² was modeled. Typical values of the wall thermal capacity, wall thermal conductance, conductance between internal wall surfaces and indoor air; internal air thermal capacity, U-value of the external wall surface, air change rates due to ventilation and infiltration, fraction of solar energy directly absorbed in indoor air; fraction of solar energy directly absorbed in internal surfaces and internal loads were used in the thermal simulation. For each hour, the entrant solar radiation through the window aperture obtained from the dynamic daylighting simulation was used as input to the thermal model. The hourly external air temperature was obtained from the TRY climate data. The thermal simulation calculates the required cooling
and heating load for maintaining a desirable indoor air temperature. The energy required to keep a constant indoor air temperature using air-conditioning with a typical coefficient of performance (COP) and the hourly indoor air temperature assuming naturally ventilated rooms with air change rate 0.45 per hour were also obtained. Thermal simulations were then repeated with different sets of solar irradiances obtained from daylight simulation.

4. Daylighting performance

4.1 Usefull daylight illuminance (UDI)

UDI is a newly proposed index for quantifying daylit conditions in buildings. UDI is different from the traditional approaches for daylight assessment e.g., daylight factor and daylight autonomy. Daylight factor cannot account for the dynamical change under real sky conditions since it is based on a static overcast sky. Daylight autonomy which is climate-based defines a threshold illuminance to be achieved. However, it does not give credit to those daylight illuminances below the threshold (for example, 500 lux) which may still be beneficial. Nor does it account for high levels of daylight illuminance which may cause occupant discomfort. In contrast to these two indexes, UDI is defined as those illuminances that fall within the range 100-2,500 lux. When evaluating predicted time-varying illuminances on a work plane, UDI is said to occur whenever the illuminances at a calculation point fall within the range 100-2,500 lux.
Daylight illuminances in the range 100 to around 2500 lux are often perceived either as desirable or at least tolerable. For those illuminances out of this range, they are considered as either falling short (i.e., less than 100 lux) or exceeding (i.e., greater than 2500 lux). Thus, UDI scheme takes into account of not only the useful range of work plane illuminance which meets the daylight requirement but also the likelihood of excess daylight illuminance causing occupant discomfort which considers human behavior. Hence, three UDI metrics can be used to characterize the hourly varying illuminances over a full year for each calculation point. UDI in the following section were expressed as a measure of how often (e.g., percentage of the working year) a useful work plane illuminance in the range of 100-2,500 lux can be achieved for a period of a full year through climate-based analyses using real weather data (e.g., direct normal irradiance and global horizontal irradiance) from TRY. The UDI scheme was recently refined by dividing the UDI achieved range (100 to 2,500 lux) into UDI-supplementary (100 to 500 lux) and UDI-autonomous (500 to 2,500 lux). For the UDI-supplementary range, additional artificial lighting may be needed to supplement the daylight for common tasks such as reading. For the higher UDI-autonomous range, additional artificial lighting will most likely not be needed.

4.2 UDI Plots for different obstruction conditions

UDI area plots on working plane of the office under different obstruction angles (1) 0°, (2) 25°, (3) 50° and (4) 75° are presented in Figure 3. Case 1 acts as the base reference which indicates how often that the work plane illuminance over a work year fell within UDI achieved range when external obstruction does not exist. Most of the grid points acquire UDI more than 70%. Even for those points closed to the core and at southeast and southwest corner, the minimum UDI achieved is still over 60%. The drop of UDI in the southeast and southwest corner is probably due to the abundant distribution of high level of illuminance (i.e., over 2,500 lux) over the year resulted from its geometrical advantage of receiving relatively more direct sunlight coming from south and east/west sky. The interior zone in case 2 with an obstruction angle of 25° experiences a reduction in UDI achieved. Further increase in the obstruction angle, as in case 3, causes UDI achieved to decrease in the perimeter zone and dropping quickly to less than 10% in the interior zone. It is even worse for case 4, the picture seems completely dark and UDI achieved is very close to zero. Obstructed environment as in case 4 is not beneficial to daylighting application.

Figure 4 is a line plot along the middle line of north-south direction for the office floor without external obstruction. The UDI achieved range is split into UDI-supplementary and UDI-autonomous. It gives insight to the time when artificial lighting is not needed, when supplementary lighting is required, when artificial lighting needs to be fully operated, and when shading devices need to be activated.

5 Thermal performance
5.1 TRY dataset

TRY for thermal simulation is based on 1989. Wong and Ngan’s conducted a study of meteorological data for 24 years from 1967 to 1991, and concluded that the data of 1989 can be used as an example of typical weather year. For the two-node model, outdoor temperatures and solar irradiances are required for the energy simulation process. The year round outdoor air temperature and the outdoor dew point temperature from TRY 1989 was used as input. The use of outdoor solar irradiances in the model is to calculate the amount of entrant solar radiation through the window aperture. This part of work was replaced with the results obtained in daylighting simulation. Since vertical time varying illuminances were derived on the window aperture, a factor of 110 lm/W was applied to get solar irradiances.

5.2 Entrant solar radiation based on lighting simulation

Total entrant solar radiation through window apertures for four cardinal facades under different obstruction angles (0°, 25°, 50° and 75°) is plotted in Figure 5. The figure shows the hourly values when the outdoor irradiance is greater than zero. It can be seen that the amount of solar radiation passing through the window aperture becomes very limited after being blocked by the external obstruction.

5.3 Temperature profile and required cooling/heating load

The Illuminating Engineering Institute of Japan
The hourly indoor air temperature profile for a naturally ventilated office floor with air change rate 0.45 per hour is shown in Figure 6. Two extreme cases of obstruction angles 0° and 75° are plotted. Without air-conditioning, indoor temperature for both cases can be higher than 35°C during summer. Figure 7 depicts the temperature difference between two cases across office hours of the whole year. The temperature difference ranges from 0.5°C to 3°C with an average value 1.67°C.

Table 1 summarizes the monthly cooling and heating load required for the office floor with different degrees of obstruction for maintaining a desirable indoor air temperature. The set point temperatures for cooling and heating are 25°C and 20°C respectively. In general, cooling load is needed almost all of the time for the office to compensate for the heat load generated from occupants, equipment, lighting, ventilation, etc. The cooling load required for the case with heavy obstruction (i.e. obstruction angle 75°) is the least which is 20% less than the reference case without external obstruction, but the heating load demanded is higher than other cases. Since the internal environment and the occupant characteristics are the same for all cases of obstruction, the decrement in cooling load for this case is solely due to the reduction in solar irradiation available to the window aperture. The electrical energy required to keep a constant indoor air temperature using air-conditioning with a typical coefficient of performance are shown in Figure 8. COP values of 2.5 and 3 were assumed for cooling and heating respectively. The total electrical energy consumed for maintaining a set point temperature are 48622 kWh, 46,348 kWh, 42,217 kWh and 39,094 kWh for obstruction angles 0°, 25°, 50° and 75° respectively.

### Table 1 Cooling and heating (kWh) load summary

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### Conclusion

The above results show that, on the basis of energy consumed, the lowest annual load occurs for the most heavily obstructed setting. In the model this is entirely...
due to lower cooling loads, as might be expected. The overall lighting load during daytime for the scenarios was 53,464 kWh which is much greater than the difference in overall cooling load. The question then becomes: how much of the electric lighting use can be displaced by daylight?

For non-domestic buildings a number of studies have found that the switch-on probability is small for desktop illuminances above 250 lux\(^8,9\). The following can be reasonably assumed:

- The switch-on probability will be high for illuminance less than 100 lux (i.e. UDI fell-short).
- The switch-on probability will reduce from high to low as the illuminances increase from 100 to 500 lux (i.e. that covered by the UDI-supplementary range).
- There is significant variability and associated uncertainty in user switching behaviour over the illuminance range where the probability of switching on reduces from high to low.

At this stage therefore it is difficult if not impossible to predict with certainty the switching on and off of lights by occupants in office buildings. Furthermore, modern control systems that combine daylight responsive automatic control with occupant override show better promise in delivering energy savings than manual switching alone. However data on the performance of these systems is only just emerging. Perhaps the most prudent use of the current occupant switching models is to determine bounds for lighting energy usage rather than to provide single estimates (that have significant associated uncertainties).

In addition to refining the lighting control component of the simulation, the authors intend to compare predictions from the simple thermal model with those from more detailed dynamic thermal models such as EnergyPlus in another publication.

To summarize, daylighting and simple thermal simulation studies were performed for a test floor of a typical office building with curtain wall design commonly found in Hong Kong. Daylighting simulation is based on ray optics with short waves. The calculated time varying illuminances were analyzed with UDI metric. The advantages of UDI is that it informs not only on useful levels of daylight illuminance, but also on the propensity for excessive levels of daylight that are associated with occupant discomfort and unwanted solar gain. The simulated illuminances were also expressed in irradiances with a luminous efficacy of 110 lm/W which were used as an input to the two-node thermal model. The year-round temperature profile, cooling and heating load requirement and the electrical energy consumed to attain a desirable indoor temperature are derived.

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References