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DEVELOPMENT OF AN INDOOR ILLUMINANCE DISTRIBUTION SIMULATOR BY USING THE MONTE CARLO METHOD

Li Chenglin*, Mahmudul Kabir
* Graduate School of Engineering and Resource Science,
Akita University, 1-1 Tegata Gakuen Chou, Akita 010-8502, Japan

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ABSTRACT
About 20-30% of the power consumption in an office or a workshop depends on the illumination system. Hence, the use of renewable energy such as sunlight is very important in illumination system on the basis of energy saving. But the design of nature helping illumination system is not easy to plan due to its difficulty of various conditions. We have developed a simulation system by using Monte Carlo method to calculate the interior illumination distribution which can also be aided with natural light system. Our simulation method have focused well the illuminance distribution of a room for both man made light and natural light.

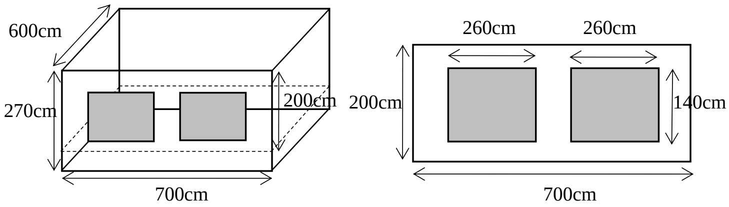
INTRODUCTION
Generally, the consumption of electric power due to illumination is 20-30% of total electric power consumption in office buildings as the illumination system runs from morning to night. Again, the illumination system also acts as a heat dissipation generator which is a heat load in the office rooms. The using of natural sunlight may pave the way to the energy saving system of the office buildings. Naturally, the light enters to the room from a window, may be counted in the illumination system. In order to plan for an illumination device, it is necessary to calculate the illumination distribution of the working surface. However, it needs quite time and manpower for measuring the illumination values of the surface and calculate the illumination distributions.

To solve this problem, several simulation methods are available in this arena. Recently, with the development of the computers, the calculation speed and performance has increased rapidly. Monte Carlo simulation method is one of them which provide the light's characteristics on the virtual screen by using the random numbers. It can imitate the illumination system in a very accurate way and easily. The main lag of this method is that it uses thousands of calculation numbers and which needs very active computation systems. A decade early, the calculation needed the help of super computers. But recent progress in hardware of the computers has paved the way of using Monte Carlo simulation method in illumination system.

In this paper, we will discuss about a simulation method for interior illumination system which is aided with natural light by using the Monte Carlo method. The calculation of the illumination distribution of a room is carried out by this simulation method and it fits the original illumination system of the room.

MATERIALS AND METHODS
Composition of Model Space
Our simulation can be suited in any office room having a window. Thus, we have chosen a general room in Akita University where the students study and perform their research works. The space model of the room can be seen in Fig.1. The length of the window of this room is 260cm×140cm, and the value of transmittance of the window are 90% and reflectance is 10%. The values of reflectance of the ceiling, inner wall and the working surface are 80%, 70%, 40% respectively [1]. The model room consists of ceiling and side wall. Illumination device are to be set up in the ceiling. Windows will be placed on the side wall. The working surface is 70cm above from the floor. The Fig.2 shows the details of the model room. A vivid narration is available for model space at previous paper [2].

We have used the illumination system of HNM4205V made by Hitachi, Japan. All the reflection of the surface is assumed and applied for the tracking of the photon flux. In order to imitate the natural light and the interior illumination i.e. fluorescent lamp, natural light are considered as point sources. The photon flux is calculated by arranging random numbers. The random numbers are generated by Visual C# programming language and the simulation is carried out by Monte Carlo method.



(a) Model space *(b) Window side*

Fig.1. Model diagram for the simulation work

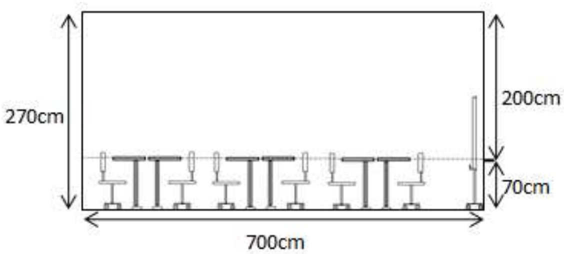


Fig.2. Working space in the model room

Calculation Methods

The calculation process by using Monte Carlo method will briefly be explained here. A point light source can release emerge but finite numbers of photon flux which carries the finite energy in it. The number of photon flux at a finite time can be calculated. The direction vector of a photon flux can be calculated by using random numbers in Monte Carlo method. Again, the diffuse reflection of the arrival point, specular reflection and absorption is also calculated from random numbers. Thus the flight trajectory for each and every photon flux is determined. Finally, the number of photon flux which can reach the working surface is calculated according to each surface element and thus the illumination distribution is calculated. The details of the simulation process are described below.

Calculation of Illuminance and flow of the program

Using Monte Carlo method in simulating illumination system, the radiation of the light source and reflection or absorption of light all are calculated by generating random numbers. The process is like below,

① The light flux radiated from a point light source is substituted by a large numbers of photon flux. The radiation of the photon flux is determined from random numbers considering the illumination system's light distributing characteristics.

② The reflection or absorption at inside a room will be determined according to the reflection or absorption properties of the interior things. The flight trajectory will be carried on for a photon flux until the photon flux will be absorbed.

③ These trajectory and calculation are carried out repeatedly and the incident photon flux for a surface element of working surface is determined. From the incident photon flux, the illumination distribution is calculated.

As the incident photon flux numbers are proportional to illuminance, the illuminance *E* [lx] for each surface element can be calculated from eq. (1).

Here,

F: the total photon flux of a point light source [lm]

k: efficiency of the illumination system [%]
N: the primary radiated photon flux from a light source
N`: the incident numbers of photon flux for each surface element
S: surface area of a surface element [m^2]
The flow chart used in this program is expressed vividly in Fig.3.

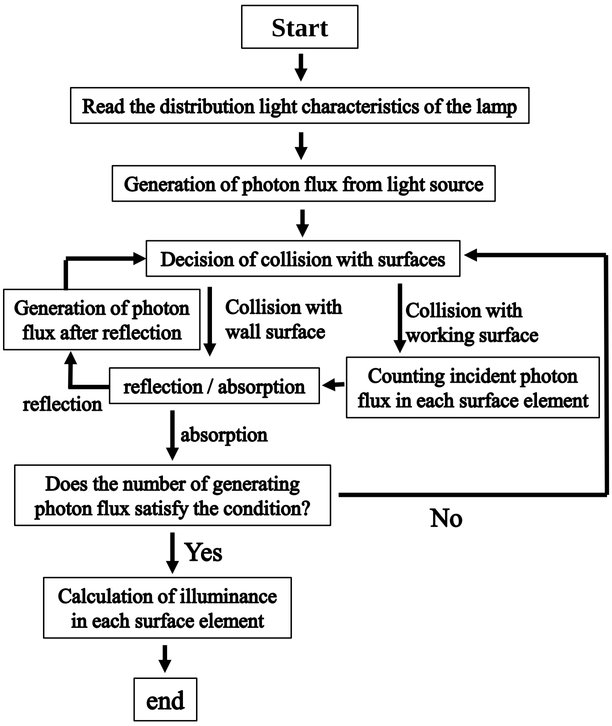


Fig.3. Calculation flow chart

Fluorescent Lamp
This paper deals with an illumination simulator that can explain the light distribution characteristics by using a point light source, line source and surface light source. We have modelled a fluorescent lamp of HNM4205V which is being used in offices, schools in large numbers. This is a buried underside open type tube light. Fig.4 shows the diagram of a straight fluorescent lamp whose length, diameter is 119.4cm and 3.2cm respectively. The total luminous flux is 6000lm of the fluorescent lamp. Again, the efficiency of the light is 80%. The calculation

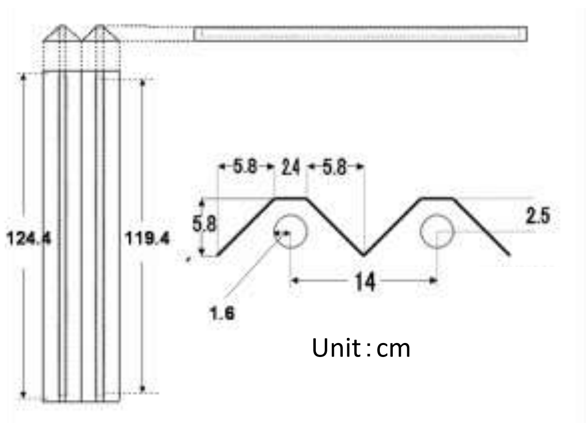


Fig.4. Shape and dimensions of the fluorescent lamp

methods for the illumination devices can be found in other papers [3], [4]. Again, the number of calculations is fixed to 20,000,000 times for each simulation.

Window

This simulator can deal with natural light which enters through the window as can be seen in Fig.5. The window that we consider for this simulation program has very good transmittance ability. And the light beam that will transmit through the window will be leaded to the ceiling and will be reflected there. As a result, the light will be simulated as a sum of point light sources as shown in Fig.6.

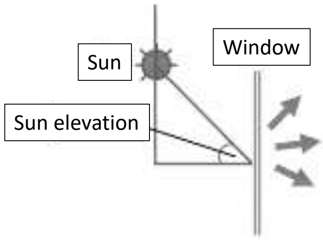
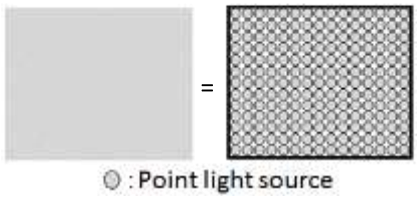


Fig.5. Relations of the light and sun elevation



(a) Window (b) Surface illuminant

Fig.6. Surface assuming as a collection of point light source

The point light sources are selected by 2 coordinates of axes Y and Z on the window surface. e.g. A point P (y, z) on the window is selected as a way, where y and z follows the boundary of $40 \leq y \leq 300$ and $-70 \leq z \leq 70$ respectively where the size of the window is 260×140 cm. The point P is selected by generating random numbers and thus the natural light that comes through window is simulated. The number of calculations is selected at 50,000,000 times for each window. This calculation number is larger than that of fluorescent lamp as it is a surface light source comparing to a point light source. Again, the angle of photon flux will be changed according to the sun light elevation angle. For a cloudy day, the light source is modelled with random numbers with diffusion light.

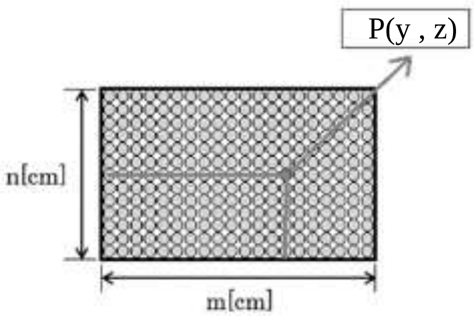


Fig.7. Determination of a photon flux point (for window)

Radiation Vector

The photon flux is calculated with vector after transforming the light into photon flux. In this research work, the point light source is assumed as equivalent diffusion point light source. The photon flux vector from the light source represents diffusion reflection and radiosity from the light source on XYZ space. The calculation method will be discussed below where V is the unit vector, θ and φ are vertical angle and azimuthal angle respectively in eq. (2), (3), (4).

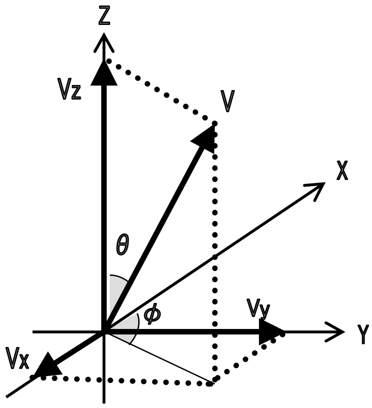


Fig.8. Vector of photon flux

The angles θ andφ are determined by uniform random numbersξin the range of 0～1 as we have assumed the light source as the radiation of Lambert-like light. Please follow the eq. (5) and (6).

The vivid descriptions of these equations are eq. (5), (6) is available in other paper [2]. However, the values of θ and φ vary with the eq. (7) and (8).

Collision with Surface and photon flux

The photon flux radiated from the light source will move straight forward in the space. The vector of this photon flux will be expressed by the vector **V**; i.e. . The trajectory of the photon flux is defined by a straight line which deals with the coordinates of the radiated axes and direction vector. The calculation process will be described below. The coordinates (X, Y, Z) of arrival point can be expressed by the coordinates of the point source (Xs, Ys, Zs) and direction vector as follows,
Here t is a parameter.
The interior surface is a plane surface and the intersection of the plane and straight lines can be decided by eq. (12).
The X, Y, Z can be decided from eq. (9), (10), (11) where a, b, c represent the normal vectors of the according planes and d is a constant number. The parameter t can be found by eq. (13).
If t=0 exists, the photon flux can arrive to the plane and make collisions with the plane. But, if t=0, then there will be no collisions with plane surface. The coordinates for the collisions will be calculated by using t in eq. (9), (10), (11).

Reflection and absorption of photon flux

When the photon flux enters in the room and collides to the room's surface plane, then it is necessary to know whether the photon flux is reflected or absorbed by the plane.

In this work, the reflection from the interior configuration plane is considered as a Lambert reflection model shown in Fig.9. Lambert reflector plane is mainly a rough plane, which acts a new point source when a photon flux collides on it. The new trajectory of the photon flux is calculated with the cosine of Lambert's law.

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The decision of reflection absorption for a photon flux will be decided by another random number Rd (0-1) with considering the reflection rate R of the planes described before in this paper.

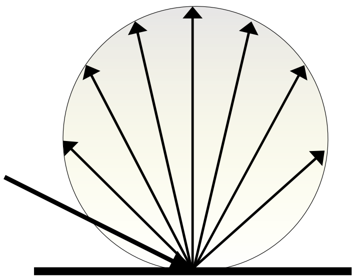


Fig.9. Diffuse-reflection

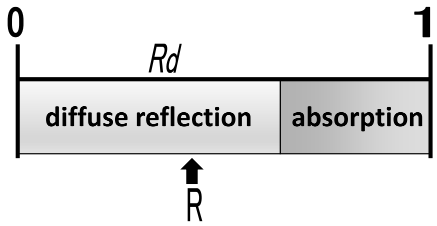
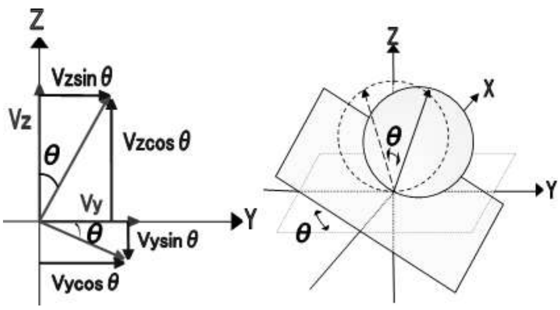


Fig.10. Reflection/absorption

Reflection Vector
The reflector flux at a reflector plane needs again a vector transformation. The transformation will use again the Lambert reflection shown in Fig.11. The transformation will be changed according to the position of the coordinates of the reflector plane and the shape.
The vector **V** (Vx, Vy, Vz) described at sections 4 and 6, is a unit vector to the surface. Therefore, this vector needs to rotate along with the X and Y axes by an angle θ inclined to the Z axis described in Lambert plane in Fig.11 (b) for vector transformation at the plane [5].



(a) 2D change *(b) 3D change*
Fig.11. Reflection vector

Here, the values of the vector transformation rotated along with the X axis will be shown below. The value of X axis will not be changed as it has rotated along with X axis. So, the values of Y and Z axis will be changed by using linear transformation with the angle θ (please see Fig.11).The transformed values are shown by eq. (14), (15), (16).

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Measurement Conditions

The reflection number of times is fixed 50 for this simulation work and when a photon flux crosses the reflection number 50, and then it is overlooked. The details of the simulation process are narrated in section 1. The results of our calculation will be compared with the measured data of illumination distribution of the room.

The office room used for the measurement is shown in Fig.12. The fluorescent lamp is in the middle of the room and it is 200cm far from the working surface. The working surface is divided into 12×14 surface elements. Each

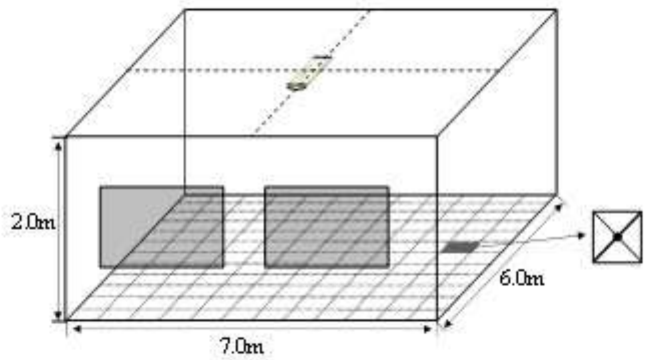


Fig.12. Model room with only one illumination device

surface element is a square of 50cm. The illuminance meter (ANA-F11, Tokyo Photoelectric Co. Ltd.) is placed on the center of a surface element while measuring the illuminance. The illuminance of the room is measured with 5 point method. The details of the measurement system can be found in other paper [6].

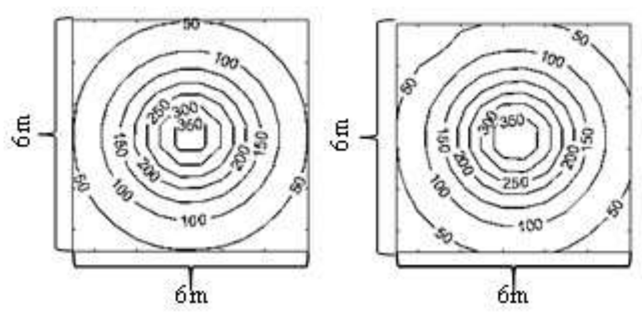
RESULTS AND DISCUSSION

In this research work, we have built models for light, window, blind's angle, sun's elevation angle etc. by using Monte Carlo method. And finally, have succeeded to make a simulator that can imitate the interior illumination distribution aided with natural sunlight at various conditions. The simulation results are compared with measured data.

Illumination system

For one fluorescent lamp, the measurement of the illuminance was carried out and the results can be seen in Fig.13 (a). The simulation results for the room of 6m×6m was calculated and the results can be seen in Fig.13 (b). Fig. 14 shows the comparison of measured data and simulation results.

It is clear from the Fig.14 that the simulation results are quite similar comparing to the measurement data. It indicates that considering a fluorescent lamp as point light source in simulation program does not affect the calculation of the illumination distribution of a room.



(a) Measured results in [lx] ***(b) Simulated results in [lx]***

Fig.13. Illuminance distribution for a model light

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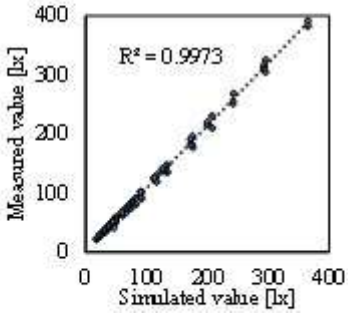
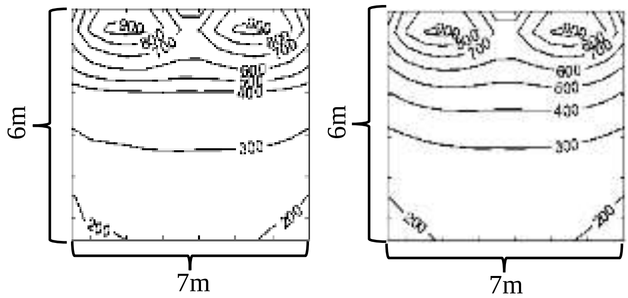


Fig.14. Correlation for the results of simulation and measurement data

Illumination system with natural light (cloudy weather)

We have also simulated the illuminance distribution by using natural light. The natural light varies with season and the time period of a day. In this paper we will introduce the simulation results without any reflector; a cloudy day. The measured data will be compared again for a cloudy day. Fig.15 (a) shows the measured data and the simulation results are shown in Fig. 15 (b). The comparison of simulation results with the measured data is shown in Fig.16. The simulation results also fit with the measured data for a cloudy weather also.

The relations of measured data and calculated data are very close and it can be seen from the correlation coefficient which is almost 1 in value. Thus it is clear that our simulation program can easily imitate any kind of simulation of illuminance system with using natural light which will pave the way to save electric power and build a sustainable life in near future.



(a) Measured results in [lx]   *(b) Simulated results in [lx]*

Fig.15. Illuminance distribution for natural light at a cloudy day

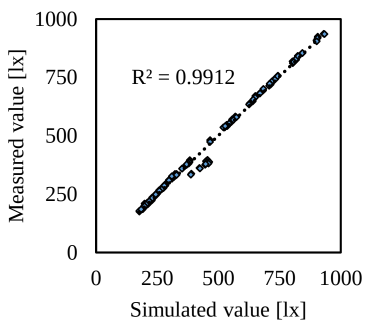


Fig.16. Correlation of results for the model room in a cloudy day

Formulae:

E=$\frac{F\times k}{N}\times N'\times\frac{1}{S}$ (1)

Vy =$sin\theta\ \cdot cos\varphi$ (2)

Vy =$sin\theta\ \cdot sin\varphi$ (3)

Vz =$cos\theta$ (4)

θ=$\frac{1}{2}cos^{-1}(1-2\xi)$ (5)

φ=$2\pi\xi$ (6)

$0\ \leq\ \theta\ <\ \pi/2$ (7)

$0\ \leq\ \varphi\ <\ 2\pi$ (8)

X=Xs+$Vx\ \cdot t$ (9)

Y=Ys+$Vy\ \cdot t$ (10)

Z=Zs+$Vz\ \cdot t$ (11)

$aX+bY+cZ=0$ (12)

t=$-\frac{aXs+bYs+cZs+d}{aVx+bVy+cVz}$ (13)

Vx'=Vx (14)

Vy'=$Vy\ \cdot cos\theta-Vz\ \cdot sin\theta$ (15)

Vz'=Vz・cosθ + Vy・sinθ (16)

CONCLUSION

In our research work, a method is introduced to calculate the illumination distribution by using Monte Carlo simulation method when the interior illumination system can be aided by natural light. The simulation results have showed very good results with the measured data for an office room with and without the natural light. Our next step will be to simulate the interior illumination system using natural light on different seasons and time periods of a day. This simulation works will pave the way for a better energy saving life.

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