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A Daylight Calculation Method for a Louver System Under the Uniform Sky Condition

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Abstract

The configuration factors in the flux transfer method are applied to calculate daylight factors reaching a station point. To analyze the window equipped with a louver system, geometrical correlation is used for the length shielded by the louver. The space in front of a window is assumed to be an imaginary outdoor space for calculating the luminance of the louver system. The data calculated from this study are compared with SUPERLITE simulation data and the scale model data. Scale model data are collected on the roof of the Engineering building at Korea University in Seoul under the uniform sky condition.

Keywords : daylight, flux transfer method, luminance, horizontal louver, vertical louver, SUPERLITE

1. INTRODUCTION

Generally, various types of louver systems have been used to windows to control sun and daylight. Louver types can be classified into the vertical slat-type and the horizontal slat-type. In a vertical window, the horizontal type louver works well to the south and the vertical type louver can be effectively used to control low angle sunlight in the east and west. Until now, several calculation methods for louver systems have been developed for lighting energy calculations.

However, simplified calculation procedures for use by architects have not yet been provided. Even the well-known program such as Superlite developed at Lawrence Berkeley Lab. cannot simulate louvers easily. In this study, a daylight calculation method for horizontal and vertical louvers under the uniform sky condition is developed.

The simplified program developed in this study can be used easily in the early design stage.

2. THE FLUX TRANSFER METHOD

The flux transfer method[1] can be used to decide the flux transfer as a configuration factor from a luminance source surface to a small target plane or the flux transfer as a form factor from a luminance source to a second lambertian source. The configuration factor C is the ratio of the illuminance at a small target plane to the luminous existence of a luminance surface. For a parallel surface, the configuration factor C_h is defined as :

$$C_h(x,y,z) = \frac{1}{2\pi}\left(\frac{x}{\sqrt{x^2+z^2}}\tan^{-1}\frac{y}{\sqrt{x^2+z^2}} + \frac{y}{\sqrt{y^2+z^2}}\tan^{-1}\frac{x}{\sqrt{y^2+z^2}}\right) \quad \text{(Eq. 1)}$$

If the target plane is normal to the source surface, the configuration factor C_v is defined as follows.

$$C_v(x,y,z) = \frac{1}{2\pi}\left(\tan^{-1}\frac{x}{z} - \frac{z}{\sqrt{y^2+z^2}}\tan^{-1}\frac{x}{\sqrt{y^2+z^2}}\right) \quad \text{(Eq. 2)}$$

In the above equations, x and y describe the source, and z describes the distance from the surface to the target plane.

3. CALCULATION METHOD

When a window is equipped with a louver system, the total daylight factors(DF) to a work plane are comprised of the sky component from the sky, the reflected component from the louvers and the internally reflected component between the inside wall surfaces. In this study, calculation procedures are developed for the direct components such as the sky component and the reflected component from the louvers. For the calculation of the internally reflected component between the inside wall surfaces, a general calculation procedure such as the split flux principle[2] can be applied.

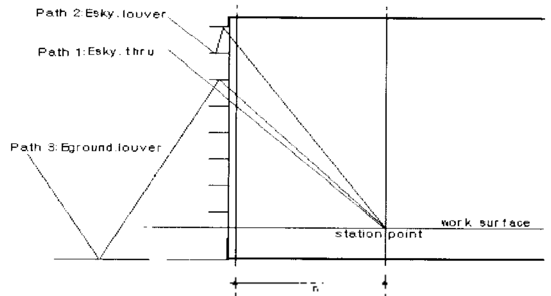


Figure1. Courses of light in a horizontal louver system

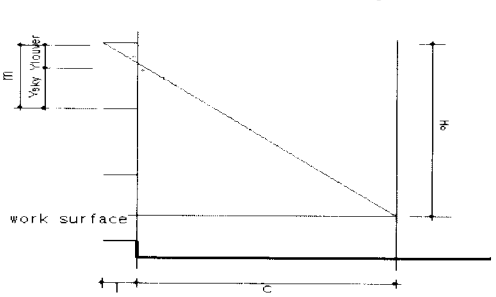


Figure2. Calculations of Y_{sky} and Y_{louver}

3.1. Horizontal Louver System

The direct components through a window are the sky component and the reflected component from the louver. The luminance of louvers is decided by the sky luminance (cd/m^2) and by the reflected luminance (cd/m^2) from the ground. Courses of light reaching the station point can be analyzed as three ways. (Fig. 1,Fig. 2)

Path 1) $E_{sky,thru}$; Illuminance (lm/m2) from the sky.

Path 2) $E_{sky,louver}$; Illuminance (lm/m2) that is reflected off the top of a blade first and then reflected off the underside of a blade.

Path 3) $E_{ground,louver}$; Illuminance (lm/m2) that is reflected off the ground first and then reflected off the underside of a blade.

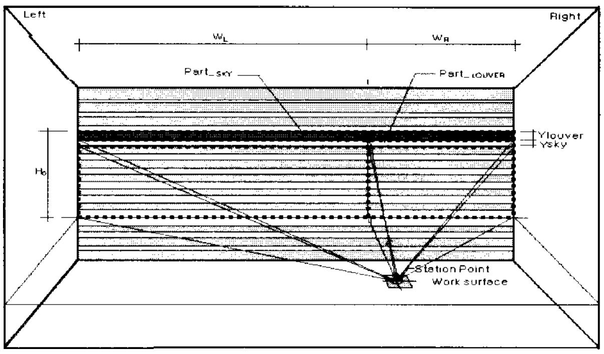


Figure3. Interior perspective of a horizontal louver system

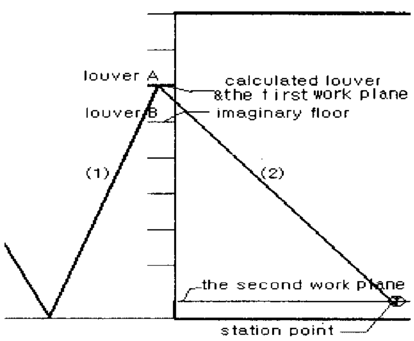


Figure4. Section of a horizontal louver system

The illuminance below the station point is not considered in this study. The calculation process for a louver system is as follows. To calculate the illuminance reaching a station point, a window is divided into several pieces by louvers, and each piece can be divided into two portions

$$\frac{Y_{louver}}{l} = \frac{H_0 - Y_{louver}}{c}, \quad Y_{louver} = \frac{l \times H_0}{c + l} \quad \text{(Eq. 3)}$$

$$Y_{sky} = m - Y_{louver} = m - \frac{l \times H_0}{c + l} \quad \text{(Eq. 4)}$$

($Part_{sky}$ and $Part_{louver}$) again. The sky can be seen through the small portion of the sky ($Part_{sky}$), and the underside of the louver can be seen through the other small portion of the louver ($Part_{louver}$)(Fig.3, Fig. 4). Vertical lengths of the two portions are dependent upon the distance from the louver to the station point (C), and the height from the work plane to the calculated louver (H_0). Y_{sky} and Y_{louver} are used to express vertical lengths of the above two portions. Y_{sky} means the vertical length of $Part_{sky}$, and Y_{louver} means the vertical length of the louver surface ($Part_{louver}$) seen from the station point. Y_{sky} and Y_{louver} can be calculated using geometrical correlation. Y_{louver} and Y_{sky} is:

Term l and m represent the protruding length of the blade and the spacing of the blade, respectively(Fig. 2).

To calculate the illuminance arriving at a station point (E_P), each portion in a window is considered as a light source. Y_{sky} and Y_{louver} become the height of the light sources, and the total width of the windows become the width of the light sources in the flux transfer equation. The term W_R and W_L represent the horizontal distance from the station point to the right and left ends of the window, respectively. The illuminance (E_{sky}) reaching the station point from the sky ($Part_{sky}$) is (Fig. 3):

$$E_{sky} = L_{window} \times C_v(W_R, H_0 - Y_{louver}, C) + C_v(W_L, H_0 - Y_{louver}, C) - C_v(W_R, H_0 - Y_{louver} - Y_{sky}, C) - C_v(W_L, H_0 - Y_{louver} - Y_{sky}, C)) \quad \text{(Eq. 5)}$$

In the above equation, L_{window} represents the luminance of the window and can be calculated as:

$$L_{window} = \text{luminance of the sky } (cd/m^2) \times \text{transmittance of window.} \quad \text{(Eq. 6)}$$

L_{louver} represents the luminance of the blade. The illuminance (E_{louver}) reaching a station point from the louver ($Part_{louver}$) is:

$$E_{louver} = L_{louver} \times C_v(W_R, H_0, C) + C_v(W_L, H_0, C) - C_v(W_R, H_0 - Y_{louver}, C) - C_v(W_L, H_0 - Y_{louver}, C)). \quad \text{(Eq. 7)}$$

The illuminance(E_P) arriving at a station point is :

$$E_P = \sum E_{sky} + \sum E_{louver} \quad \text{(Eq. 8)}$$

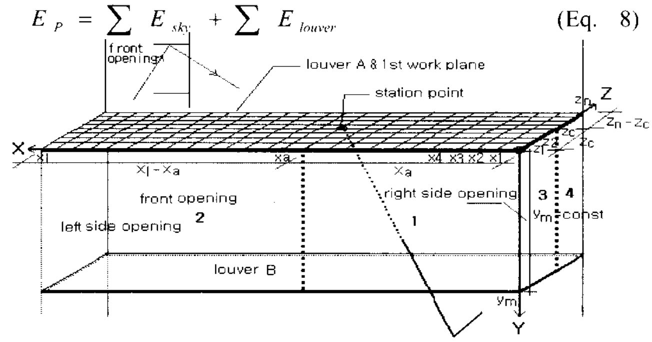


Figure5. Light component reflecting off the Ground

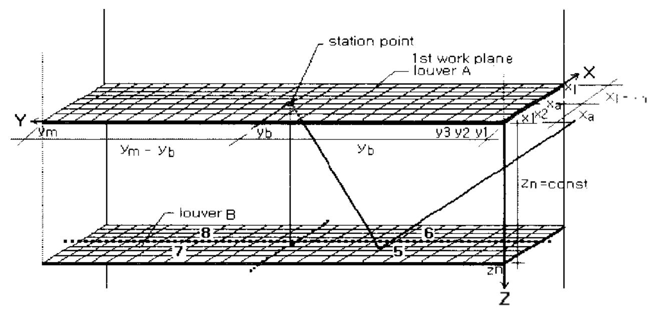


Figure6. Light component reflecting off the louver

3.1.1. Luminance calculation for a horizontal louver system

The luminance of a horizontal louver (L_{louver}) that can be seen from a station point in a room is affected by physical conditions surrounding the window exterior. The outside louver space is assumed to be an imaginary outdoor space[5] composed of the top and the underside of the blade.

To simulate these external louver systems, two louvers facing each other are assumed to be a ceiling and a floor in an imaginary space. The top of the louver B is assumed to be the floor and the underside of louver A is assumed to be the ceiling, and also the first work plane in an imaginary outdoor space (Fig. 4). The three sides (front, left & right side), except the blade surfaces, are open spaces in an imaginary outdoor space. In this imaginary space, luminance ratios[4] are used to represent daylight performance. The luminance ratio, represented L_d / L_u, is the ratio between the average luminance of the underside of the blade (L_d) and the luminance of the sky (L_u). Light courses reaching the 1st work plane in the imaginary outdoor space can be classified into two ways. These are the light reflected off the ground and the light reflected off the top surface of the louver B.

As seen in Fig. 5 and Fig. 6, the total luminance ratio can be calculated by summing up each luminance ratio (L_d/L_u) through the three side openings. $L_{fr\text{-}ground}$, and $L_{si\text{-}ground}$ are the luminance ratios (L_d/L_u) through the front opening and that through the two side openings. The total luminance ratio is thus:

$$L_d/L_u = L_{fr\text{-}ground} \cdot 2\,L_{si\text{-}ground} + L_{louver} \cdot \qquad \text{(Eq. 9)}$$

For the calculation process, a corner of the work surface is established as a coordinate axis. The luminance ratio through the front opening is: (Fig. 5)

$$L_{fr\text{-}ground} = L_{sky} \times LF \times GF \times \sum_{c=1}^{n} \sum_{a=1}^{l} (C_1(x_a, y_m, z_c)$$
$$+ C_1(x_l - x_a, y_m, z_c)) / (l \times n) / L_{SKY} \qquad \text{(Eq. 10)}$$

L_{sky} is the luminance of the uniform sky. GF and LF are the ground reflectance and the louver reflectance. X_l ,Y_m and Z_n are the distances of the louver in the X,Y,Z directions. The term l, m and n are shown in Fig.5 and Fig.6.

The luminance ratio through the two side openings is: (Fig. 6)

$$L_{si\text{-}ground} = L_{sky} \times LF \times GF \times \sum_{c=1}^{n} \sum_{a=1}^{l} (C_1(z_c, y_m, x_a)$$
$$+ C_1(z_n - z_c, y_m, x_a)) / (l \times n) / L_{SKY} \qquad \text{(Eq. 11)}$$

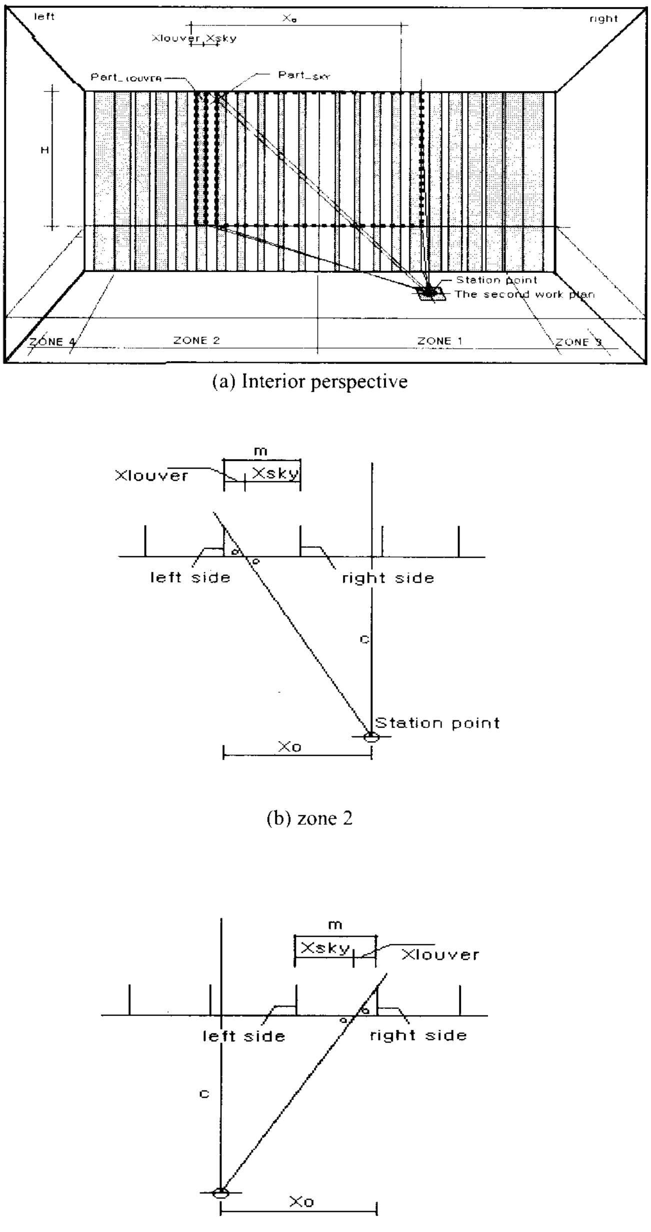
The following Eq.12 calculates the luminance ratio reflected off the upper surface of the lower louver (L_{louver}) (Fig. 6).

$$L_{louver} = (L_{fr\text{-}ground} + 2L_{si\text{-}ground}) / GF \times LF \times \sum_{b=1}^{m} \sum_{a=1}^{l} (C_h(x_a, y_b, z_n)$$
$$+ C_h(x_l - x_a, y_b, z_n) + C_h(x_a, y_m - y_b, z_n)$$
$$+ C_h(x_l - x_a, y_m - y_b, z_n)) / (l \times m) / L_{SKY} \qquad \text{(Eq. 12)}$$

3.2 Vertical Louver System

When vertical louvers are equipped under the uniform sky condition, daylight factors to the work plane are comprised of the sky component, the reflected component from the right side louver, and the reflected component from the left side louver. A window is divided into several pieces by louvers, and each piece can be divided into two portions again. The sky can be seen through one portion ($Part_{sky}$), and the right side or left side surface of the louver can be seen through the other portion ($Part_{louver}$). Two terms (X_{sky} and X_{louver}) are used to express these horizontal lengths of the two parts. X_{sky} represents the horizontal length of $Part_{sky}$ and X_{louver} represents the horizontal length of the louver surface ($Part_{louver}$) seen from the station point. (Fig. 7). 4 different zones[4] can be obtained in the window when vertical louvers are installed (Fig. 7-a). In the first zone, direct components from the sky and the reflected components from the right side louver may exist. In the second zone, direct components from the sky and reflected components from the left side louver may exist. In the third and fourth zones, the sky components are do not exist.

Daylight components in the vertical louver system are calculated using the similar methodology to the case of the horizontal louver system. These X_{sky} and X_{louver} are calculated using the geometrical correlation of a triangle.



(a) Interior perspective

(b) zone 2

(c) zone 1

Figure7. Interior perspective of a vertical louver system (a) and Calculation of X_{sky} and X_{louver} (b,c)

(1) X_{sky} and X_{louver} calculation in zone 1.

Zone 1 is the right side zone from a station point. In zone 1, daylight illuminances are reflected from the right side louver. As distance X_o increases, the distance of X_{louver} also increases and the distance of X_{sky} decreases in zone 1. The X_{sky} and X_{louver} values can be obtained as:

$$\frac{c}{X_0 - X_{louver}} = \frac{l}{X_{louver}}, \qquad X_{louver} = \frac{l \times X_0}{c+l} \qquad \text{(Eq. 13)}$$

$$X_{sky} = m - X_{louver} = m - \frac{l \times X_0}{c+l} \qquad \text{(Eq. 14)}$$

The terms X_0 and l are the horizontal distance from a station point to the louver and the protruding length of the louver, respectively. The terms m and c are the spacing of the vertical louver and the distance from station point to the louver, respectively(Fig. 7-c).

(2) X_{sky} and X_{louver} calculation in the zone 2.

Zone 2 is the zone from left of the reference point. In zone 2, daylight illuminances are reflected from the left louver. As distance X_o increases, the distance of X_{louver} also increases and the distance of X_{sky} decreases. Eq.13 and Eq.14 can be used for X_{louver} and X_{sky} calculation (Fig. 7-b).

(3) X_{sky} and X_{louver} calculation in zones 3 & 4

In zones 3 & 4, sky components do not exist, and only the reflected components are available. Each portion in a window is regarded as a segment of light source to calculate the illuminance (E_P) arriving at a station point. X_{sky} and X_{louver} become widths of the light sources. The term H represents the height from a station point to the louver (Fig .7-a).

$Part_{sky}$ and $Part_{louver}$ are assumed to be the light sources. The illuminance (E_{sky}, E_{louver}) reaching the station point from the louver is (Fig. 7):

$$E_{sky}=L_{window}\times(C_v(X_o-X_{louver},H,C)-C_v(X_o-X_{louver}-X_{sky},H,C)). \qquad \text{(Eq. 15)}$$

$$E_{louver}=L_{louver}\times C_v(X_o,H,C)-C_v(X_o-X_{louver},H,C)). \qquad \text{(Eq. 16)}$$

L_{louver} is the luminance of the vertical louver, and L_{window} can be calculated by Eq. 6.

The illuminance reaching the station point(Ep) is:

$$E_P = \sum E_{sky} + \sum E_{louver} \qquad \text{(Eq. 17)}$$

3.2.1 Luminance calculation for a vertical louver system

Like the space equipped with horizontal louvers, an imaginary outdoor space composed of two walls (the right wall and the left wall), a vertical opening and a top opening is assumed. Then, either the right wall or the left wall is assigned to be the first work plane. The luminance (cd/m^2) of the louver surface (first work plane) is first calculated.

This luminance data are then converted to luminance ratios (L_d/L_u) by dividing the louver luminance data (L_d) by the exterior sky luminance (L_u). These luminous surfaces are assumed to have uniform luminance. Daylight sources coming through the first work plane to the station point can be classified into 4 components. The first component ($L_{horizon}$) is the sky component coming from the top opening, the second component ($L_{vertical}$) is the sky component coming from the imaginary vertical opening, the third component (L_{louver}) is the inter-reflected component between louvers, and the fourth component (L_{floor}) is the reflected component from the floor in the imaginary space.

$$L_d/L_u = L_{horizon}+L_{vertical}+L_{louver}+L_{floor}. \qquad \text{(Eq. 18)}$$

As seen in Fig. 8-a, the sky component ($L_{horizon}$) comes from the top opening to the first work surface. After the first work plane is divided into small square components, the luminance of each component is calculated. The average luminance ratio of the sky component ($L_{horizon}$) can be presented as follows:

GF and LF are the ground reflectance and the louver re-

$$L_{horizon} = L_{sky} \times LF \times \sum_{c=1}^{n}\sum_{a=1}^{l}(C_P(x_a, y_m, z_c) + C_P(x_l - x_a, y_m, z_c))/(l \times n)/L_{SKY} \qquad \text{(Eq. 19)}$$

flectance, and X_l, Y_m, Z_n are the distances of the louver in the X,Y,Z directions, respectively. The terms l, m and n are shown in Fig 8. Next, in calculating the second component ($L_{vertical}$), the vertical opening below a station point in the first work plane is affected by the ground reflection. The vertical opening above a station point in the first work plane is affected by the sky (Fig. 8-a). The calculation process shown in Fig. 8-a is represented in Eq.20. Another component (L_{louver}) is the inter-reflected component between louvers, and the calculation procedure for the inter-reflected component is shown in Eq. 21.

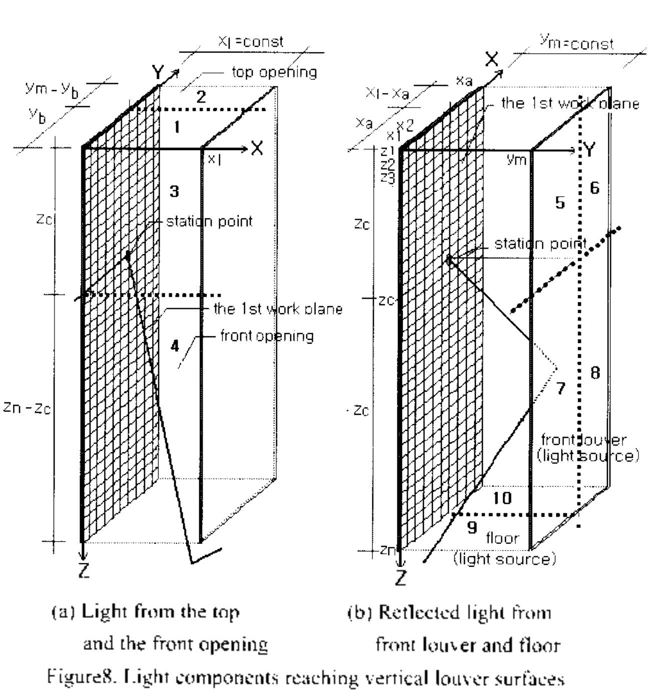
The other sources (L_{floor}) are the component reflected off the ground (imaginary floor) between louvers. These values are dependent on ground reflectance and louver reflectance.

The calculation process for the ground reflected component is shown in Eq. 22 (Fig. 8-b).

$$L_{vertical} = L_{sky} \times LF \times \sum_{c=1}^{n}\sum_{a=1}^{l}(C_P(z_c, y_m, x_a) + GF \times C_P(z_n - z_c, y_m, x_a))/(l \times n)/L_{SKY} \qquad \text{(Eq. 20)}$$

$$L_{louver} = (L_{horizon} + L_{vertical}) \times LF \times LF \times \sum_{c=1}^{n}\sum_{a=1}^{l}(C_h(x_a, z_c, y_m) + C_h(x_l - x_a, z_c, y_m) + C_h(x_a, z_n - z_c, y_m) + C_h(x_l - x_a, z_n - z_c, y_m))/(l \times n)/L_{SKY} \qquad \text{(Eq. 21)}$$

$$L_{floor} = L_{floor} \times LF \times GF \times \sum_{c=1}^{n}\sum_{a=1}^{l}(C_l(x_a, y_m, z_n - z_c) + C_l(x_l - x_a, y_m, z_n - z_c))/(l \times n)/L_{SKY} \qquad \text{(Eq. 22)}$$

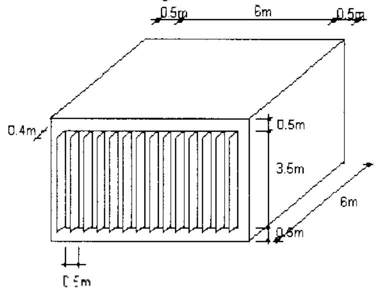


(a) Light from the top and the front opening (b) Reflected light from front louver and floor

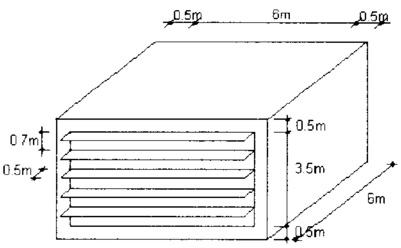
Figure8. Light components reaching vertical louver surfaces

4. EXPERIMENTAL MODEL

The calculation data using the method shown in part 3 are evaluated by comparing with the results from the Superlite simulation and the scale model testing. Original room height, width and depth are 4.5m, 7m and 6m, respectively. In front of the window (height: 3.5m, width; 6m), vertical and horizontal louvers are equipped. Louver dimensions are shown in Fig.9.



(a) horizontal louver system



(b) vertical louver system

Figure9. Configuration of the scale model

For comparison, the calculation procedures developed in this study are programmed using the visual basic language.

Then, the calculated data using the method developed in this study are compared with the Superlite data. In the Superlite simulation, a window equipped with louvers can be modeled by dividing one window into several pieces. Each piece is first simulated and then summed up to get the total values. The scale model is constructed with the scale of 1: 10. Reflectance of the louver is 60% and the ground reflectance is 30%. The scale model is tested on the outdoor roof under the uniform sky condition. The scale model data are collected on the roof of the Engineery building at Korea University in Seoul under the uniform sky condition. 24 station points are set up in a room.

In this study, the flux transfer method is applied for the luminance ratio calculation using Eq.9 and Eq.18.

Then, the calculated luminance ratios using the methodology developed in this study are compared with the data from the Superlite simulation.

5. SIMPLIFIED PROGRAM MODEL

The program used in this study is for calculating the daylight factor (DF) when horizontal or vertical louvers are equipped in front of a window.

Fig.10 shows the calculation process of this program. First, the room shape, work surface and window data are needed (Fig.11-a). If louvers are equipped in a window, louver data must be inputted (Fig. 11-b). This program calculates the total luminance ratios (%) obtained from the front opening, two side openings and louver surfaces.

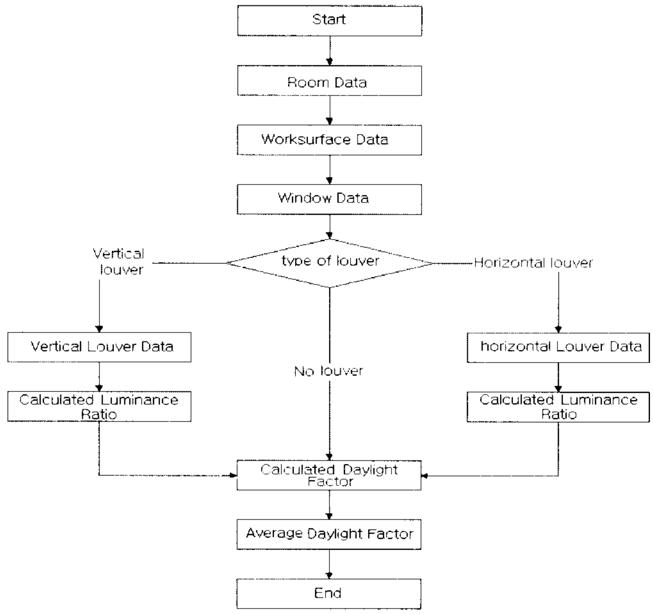
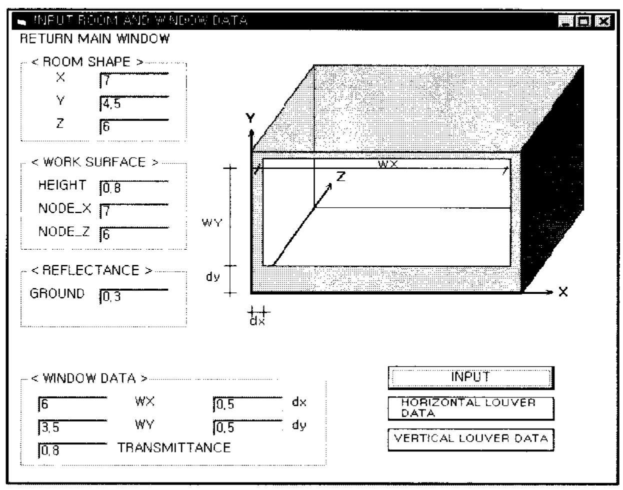
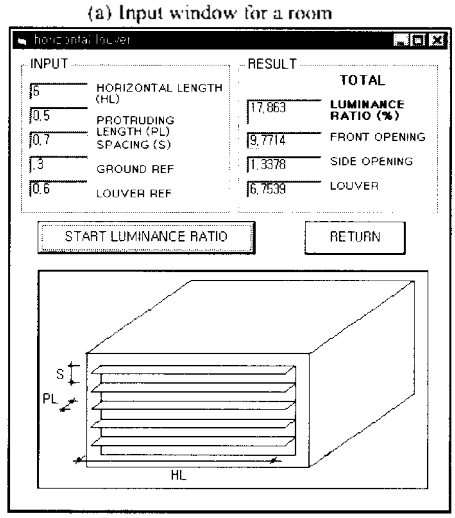


Figure10. Calculation process for horizontal and vertical louvers



(a) Input window for a room



(b)Input window for horizontal louvers

Figure11. Input windows of the calculated program

6. RESULTS & COMPARISON

Fig.12 shows the calculated luminance ratios for horizontal louvers using the method developed in this study.

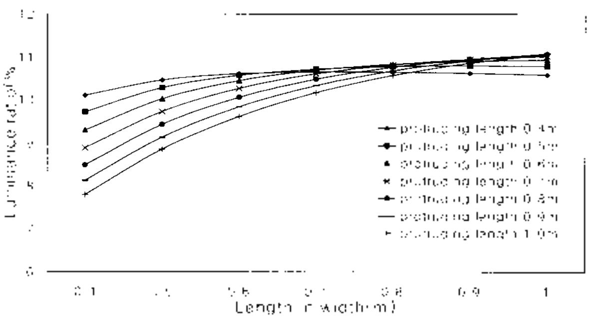


Figure12. Luminance ratios of horizontal louvers

Luminance data in the imaginary louver space are based on the average daylight factor on a louver surface. Fig.13 shows the calculated luminance ratios for vertical louvers using the method developed in this study.

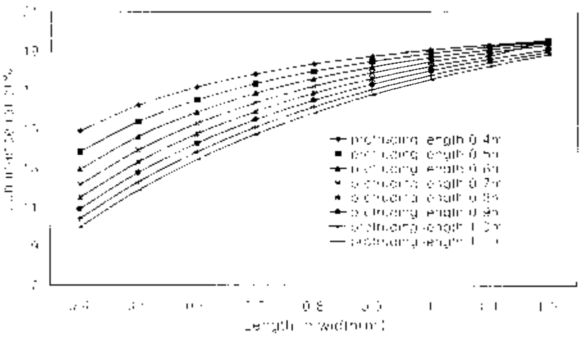


Figure13. Luminance ratios of vertical louvers

Daylight factors in a room equipped with horizontal louvers are calculated in the 24 measuring points using the method developed in this study. Then, the calculated data are compared with Superlite data and the scale model data.

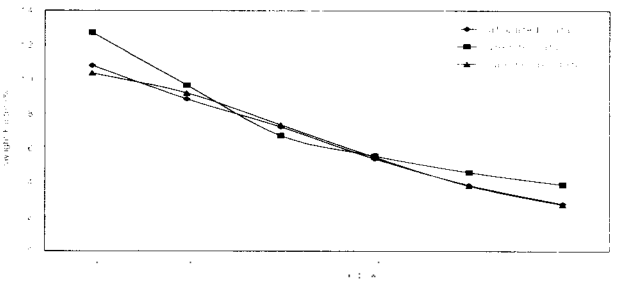
These results show that the Superlite data have higher values than those of the other two data near the window (up to 0.5m distance from the window). These three types of data are similar in the middle of the space (3.5m distance from the window), and the Superlite data are also higher than the other two data in the deep zone (3.5m distance from the window).

The relative difference between the calculated data and the scale model data is 5%. The relative difference between the calculated data and the Superlite data is 13% (Fig. 14-a).

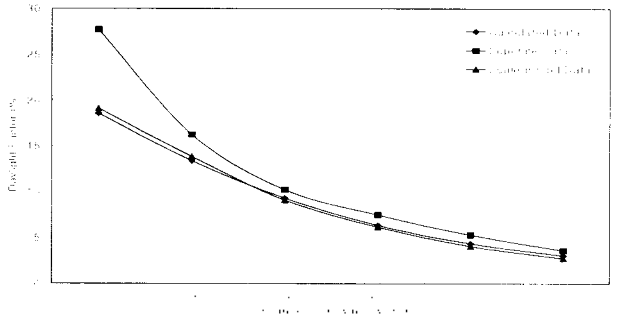
In the vertical louver condition, The calculated data, Superlite simulation data and the scale model data are compared in the 24 reference points.

Near the window (0.5m distance from the window), relatively high differences (29%) are recorded between the calculated data and the Superlite data. Three types of data are similar in the middle and the deep zone of the space.

The relative difference between the calculated data and the scale model data is 8.7%, and the relative difference between the calculated data and the Superlite data is 18%(Fig.14-b). Thus, the calculated data using the method developed in this study are similar to the scale model data.



(a) Comparison of horizontal louver data



(b) Comparison of vertical louver data

Figure14. Comparisons of horizontal and vertical louver data

7. CONCLUSION

Until now, it was not easy for an architect to predict daylight illuminance in a space equipped with louvers. In this study, a daylight calculation algorithm for louver systems is developed using the flux transfer method and geometric correlation. Data calculated using the method developed in this study is compared with Superlite data and the scale model data. In a space equipped with horizontal louvers, 5 % relative difference is recorded between the calculated data and the scale model data. In a space equipped with vertical louvers, 8.7% relative difference is recorded between the calculated data and the scale model data.

Therefore, the simplified program developed in this study can be used easily in the louver design process.

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