Time-Variable Numerical Model of Heat Transfer around Solar Shading Devices on Windows

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ABSTRACT

The establishment of heat transfer equations for windows including blinds is shown in detail as time-variable numerical models. Two types of windows—windows with inside blinds and those with middle blinds—are the subject of the establishment. Not only long-wave but short-wave radiative heat transfer is expressed by absorption factors. The equations of laminar flow of free or forced convection are used for convective heat transfer at the indoor surface of panes and slats of blinds. The predicted values of these equations and the measured values of two test houses fitted with blinds are compared to discuss the accuracy of the establishment of the heat transfer around windows. Through the comparison, we can point out that the temperature of slats of blinds and transmitted solar radiation through windows are predictable. Consequently, one can predict the solar shading effects of the blinds in the separate form of solar radiation, convection, and long-wave radiation.

INTRODUCTION

Solar heat gain through windows is the most important factor in indoor thermal performance in buildings. It is also the key factor in air-conditioning load since buildings have been air-tightened and thermally insulated. During the cooling season, solar radiation should be shut out or cut off to prevent rising energy consumption for air conditioning as much as possible with solar shading devices; venetian blinds, outside fins, installed blinds within double sashes, etc. Therefore, the validity of solar shading effects of these devices on building thermal performance is indispensable for the estimate of cooling energy consumption and the thermal environment in a building.

The solar shading effect must be a time-variable function according to the location of the sun against windows, the configuration of devices, and the situation of rooms. The accurate analysis of the solar shading effect demands that these time-variable factors should de taken into consideration. The heat transfer mechanism of the devices as well as that of the rooms should be materialized as a numerical expression employed for building thermal performance simulations (Hayashi et al. 1985; Hayashi et al. 1987).

ESTABLISHMENT OF EQUATIONS

Configuration and Definition

Two types of vertical windows are considered. One is a window fitted with inside blinds such as venetian blinds, the other is a window consisting of double sashes and blinds between them. The former is called an inside blind window and the latter is called a middle blind window. Panes of windows are transparent but the slats of blinds are opaque against solar radiation. Panes and slats are supposed to have a diffusely reflecting surface for solar radiation.

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In this paper, solar radiation and short-wave radiation have the same meaning. As for long-wave radiation, panes and slats do not transmit but reflect and emit it diffusely. The thermal capacity and resistance of panes and slats are neglected because of their thickness.

The location of the sun is defined as shown in Figure 1. Solar radiation is divided into two components—direct and diffused or scattered solar radiation. Incident solar radiation upon the window is obtained by the following equations:

$$ID_w \text{ or } ID_{mw} = IDN \cdot \cosh \cdot \cos(\alpha - O) \tag{1}$$

$$IS_w \text{ or } IS_{mw} = F_{sk} \cdot IS_{sk} + F_{gr} \cdot IS_{gr} = F_{sk} \cdot IS_{sk} + F_{gr} \cdot \rho_{gr} \cdot TH \tag{2}$$

The slats of blinds partly or completely screen the direct solar radiation in proportion to their tilted angle, as shown in Figure 2. The ratio of the transmitted direct solar radiation to the incident one can be calculated as a bypass factor conducted by the geometric relation between the slats and the pane.

$$BFD = (P - |W|)/P, \quad \text{if} \quad BFD \leqq 0 \quad \text{then} \quad BFD = 0 \tag{3}$$

$$W = S\left[(\sin\theta + \cos\theta \cdot \sinh / \{\cosh \cdot \cos(\alpha - O)\}\right] \tag{4}$$

If the value of W is negative, the direct solar radiation is incident upon surface ④.

Usually, the lateral length of slats is much longer than the longitudinal length and the vertical distance between slats. Therefore, the effects of inter-reflection, inter-emission, and absorption among slats and panes can be considered in an enclosed two-dimensional space, as shown in Figure 2. When inside blind windows are the subject, surface ① means the pane, and surfaces ② and ④ denote the slats. In the case of middle blind windows, naturally, surface ③ is the inside pane. The absorption factor proposed by Gebhart(1959) is applied and transformed to establish equations of radiative heat exchange around windows and blinds (see Appendix A). If inside blind windows are supposed, the surface ③ shown in Figure 2 is not a real surface but an imaginary plane. In this case, the emissivity and solar absorptivity of surface ③ is assumed to be 1. This assumption means that all the radiation across section ③ is absorbed there. This is equivalent to no affection of the existence of surface ③ on radiative heat exchange between the pane and the slats. Shape factors, necessary for the calculation of absorption factors, among the surfaces can be easily obtained by cross string formulas because of the two-dimensional space.

Radiative Heat Transfer

The net long-wave radiation at the pane of an inside blind window is given using absorption factors mentioned before:

$$\begin{aligned} NL_g = {} & \varepsilon_g(F_{gr} \cdot \sigma \cdot T_o^4 + F_{sk} \cdot AH) - \varepsilon_g \cdot T_g^4 + \varepsilon_b \cdot \sigma \cdot T_b^4 \, (\beta_{2,1} + \beta_{4,1}) \, S/P \\ & + \sigma \cdot T_r^4 \cdot \beta_{3,1} - \varepsilon_g \cdot \sigma \cdot T_g^4 \, (1 - \beta_{1,1}) \end{aligned} \tag{5}$$

The sum of the first term and the second one on the left-hand side in Equation 5 is the net long-wave radiation at the outdoor surface of the pane. Here, the ground surface is supposed to be a black body and its temperature is the same as the outdoor air temperature. The sum of the rest, on the other hand, denotes the net long-wave radiation at the indoor surface of the pane; the third term is the absorbed amount of long-wave radiation emitted from the slats; the fourth is that from the room surface; and the fifth is the net amount from the pane itself. The laws of reciprocity and energy conservation transform Equation 5 and lead the following equation:

$$\begin{aligned} NL_g = {} & \varepsilon_g \cdot \sigma (T_o^4 - T_g^4) + F_{sk} \cdot \varepsilon_g \, (AH - \sigma \cdot T_o^4) \\ & + \varepsilon_g \cdot \sigma (T_b^4 - T_g^4)(\beta_{1,2} + \beta_{1,4}) + \varepsilon_g \cdot \sigma (T_r^4 - T_g^4) \end{aligned} \tag{6}$$

In the same manner, the net long-wave radiation at the slats is obtained by:

$$NL_b = \varepsilon_b \cdot \sigma (T_r^4 - T_b^4)(\beta_{2,3} + \beta_{4,3}) + \varepsilon_b \cdot \sigma (T_g^4 - T_b^4)(\beta_{2,1} + \beta_{4,1}) \tag{7}$$

The net long-wave radiation of a middle blind window is also established using the long-wave

$$CV_g = \alpha c_{g,out}\ (T_o - T_g) + \alpha c_{g,in}\ (T_a - T_g) \tag{18}$$

The convective heat flux at the slats of the window is regarded as:

$$CV_b = 2\cdot \alpha c_b\ (T_a - T_b) \tag{19}$$

where the slats are supposed to be in a forced convection field caused by the temperature difference between the air in the vicinity of the window and the indoor air. (See Appendix C for the convective heat transfer coefficient [Holman 1988, Eq. 5-44].) In that case, airflow velocity through the slats is given as:

$$v = f\ \{2\cdot g\cdot Z\ (G_i - G_a)/G_a\}^{1/2} \tag{20}$$

where the height, Z, is a half vertical length of the window. Since the specific gravity of the air depends on its temperature, and since the airflow velocity is connected with the difference of the specific gravities between the two kinds of air, the heat budget equation of the air in the vicinity of the window is needed to obtain its temperature and airflow velocity.

$$\alpha c_{g,in}\ (T_g - T_a) + 2\cdot \alpha c_b\ (T_b - T_a)\ S/P + 3600\cdot v\cdot C_a\cdot G_a\ (T_i - T_a) = 0 \tag{21}$$

At a middle blind window, the following equations are given for the convective heat flux as:

$$CV_{og} = \alpha c_{og,out}\ (T_o - T_{og}) + \alpha c_{og,in}\ (T_{ma} - T_{og}) \tag{22}$$

$$CV_{mb} = 2\cdot \alpha c_{mb}\ (T_{ma} - T_{mb}) \tag{23}$$

$$CV_{ig} = \alpha c_{ig,out}\ (T_{ma} - T_{ig}) + \alpha c_{ig,in}\ (T_i - T_{ig}) \tag{24}$$

where the convective heat transfer coefficients at the following surfaces (except the outdoor surface of the outside pane) are calculated as free convection of laminar flow along a flat plate: both sides of the inside pane, the indoor side of the outside pane, and both sides of the slats. (See Appendix B for details.) The heat budget equation of the air in the space between double sashes is given considering the air leakage through the cracks of sashes caused by stack effect as:

$$\alpha c_{og,in}\ (T_{og} - T_{ma}) + 2\cdot \alpha c_{mb}\ (T_{mb} - T_{ma})\ S/P$$
$$+ L\ \{2\cdot g\cdot Z\ (G_o - G_{ma})/G_{ma}\}^{2/3}\ C_{ma}\cdot G_{ma}\ (T_o - T_{ma}) = 0 \tag{25}$$

Heat transfer around windows can be established to solve the heat balance equations of the pane and slats combining the heat budget equation of the air, shown as Equations 21 and 25. As to the heat balance equation, the summation of NL, NS, and CV should be 0. Since these equations are nonlinear, convergent reiteration procedures are required for their simultaneous solution.

EXPERIMENTS

Three experimental houses, identical in structure and finishes, have been built for the experiments. They are in a row from south to north. The southern house had double-sash window, normal glass panes 0.12 in (3 mm) thick, and middle blinds between them. Outside blinds were fitted on the window of the second house, but were omitted from the analysis in this paper. The northern house had the window, a normal pane 0.20 in (5 mm) thick, where inside blinds were installed. Each window faces south. The inside blinds and the middle blinds had the same configuration; their longitudinal length, S, was 0.59 in (15 mm), their vertical distance between slats, P, was 0.47 in (12 mm), and their solar absorptivity was 0.48. The transmitted solar radiation was measured by a photocell pyranometer.

A black-and-white pyranometer has been installed on the roof of the southern experimental house to measure global solar radiation. On the southern wall of the same house, a photocell pyranometer has been fitted to measure the solar radiation incident upon windows. Wind velocity, wind direction, outdoor air temperature, and atmospheric radiation were measured in the neighborhood of the houses. In each house, surface temperatures and air temperatures were measured by thermocouple. The indoor surface temperature, T_r, found in the equations was the average value of the ceiling, the floor, and the walls. The measurement of temperature and radiation was carried out at 10-minute intervals.

absorption factors as:

$$NL_{og} = \varepsilon_{og}\cdot\sigma(T_o^4 - T_{og}^4) + F_{sk}\cdot\varepsilon_{og}(AH - \sigma\cdot T_o^4)$$
$$+ \varepsilon_{og}\cdot\sigma(T_{mb}^4 - T_{og}^4)(\beta_{1,2} + \beta_{1,4}) + \varepsilon_{og}\cdot\sigma(T_{ig}^4 - T_{og}^4)\beta_{1,3} \quad (8)$$

$$NL_{mb} = \varepsilon_{mb}\cdot\sigma(T_{og}^4 - T_{mb}^4)(\beta_{2,1} + \beta_{4,1}) + \varepsilon_{mb}\cdot\sigma(T_{ig}^4 - T_{mb}^4)(\beta_{2,3} + \beta_{4,3}) \quad (9)$$

$$NL_{ig} = \varepsilon_{ig}\cdot\sigma(T_{og}^4 - T_{ig}^4)\beta_{3,1} + \varepsilon_{ig}\cdot\sigma(T_{mb}^4 - T_{ig}^4)(\beta_{3,2} + \beta_{3,4})$$
$$+ \varepsilon_{ig}\cdot\sigma(T_r^4 - T_{ig}^4) \quad (10)$$

Net short-wave radiation at an inside blind window is given as:

$$NS_g = ID\,\{a_{g,d} + \tau_{g,d}(1 - BFD)\rho_b\cdot\gamma_{2,1}\} + IS\,(a_{g,s} + \tau_{g,s}\cdot\gamma_{1,1}) \quad (11)$$

$$NS_b = ID\cdot\tau_{g,d}(1 - BFD)\,\{a_b + \rho_b(\gamma_{2,2} + \gamma_{2,4})\}\,P/S$$
$$+ IS\cdot\tau_{g,s}(\gamma_{1,2} + \gamma_{1,4})\,P/S \quad (12)$$

In Equations 11 and 12, the optical characteristics of the glass pane for direct solar radiation and that for diffused radiation are regarded to be different. These characteristics are also distinguished as to the thickness of the pane. The transmitted solar radiation, including direct and diffused solar radiation, through the window is obtained by:

$$TS_w = ID\cdot\tau_{g,d}\{BFD + (1 - BFD)\rho_b\cdot\gamma_{2,3}\} + IS\cdot\tau_{g,s}\cdot\gamma_{2,3} \quad (13)$$

At a middle blind window, its net short-wave radiation is regarded as:

$$NS_{og} = ID\,[a_{og,d} + \tau_{og,d}(1 - BFD)\rho_b\cdot\gamma_{2,1} + BFD\cdot\rho_{ig,d}\cdot\gamma_{3,1}\}\,]$$
$$+ IS\,(a_{og,s} + \tau_{og,s}\cdot\gamma_{1,1}) \quad (14)$$

$$NS_{mb} = ID\cdot\tau_{og,d}\,[(1 - BFD)\,\{a_b + \rho_b(\gamma_{2,2} + \gamma_{2,4})\}$$
$$+ BFD\cdot\rho_{ig,d}(\gamma_{3,2} + \beta_{3,4})]\,P/S + IS\cdot\tau_{og,s}(\gamma_{1,2} + \gamma_{1,4})\,P/S \quad (15)$$

$$NS_{ig} = ID\cdot\tau_{og,d}\,\{(1 - BFD)\rho_b\cdot\gamma_{2,3} + BFD\,(a_{ig,d} + \rho_{ig,d}\cdot\gamma_{3,3})\}$$
$$+ IS\cdot\tau_{og,s}\cdot\gamma_{1,3} \quad (16)$$

Transmitted solar radiation through the window is obtained by:

$$TS_{mw} = ID\cdot\tau_{og,d}\,\{\tau_{ig,d}\cdot\mathrm{BFD} + (1 - BFD)\rho_b(\gamma'_{2,3} - \gamma_{2,3})$$
$$+ BFD\cdot\rho_{ig,d}(\gamma'_{3,3} - \gamma_{3,3})\} + IS\cdot\tau_{og,s}(\gamma'_{1,3} - \gamma_{1,3}) \quad (17)$$

where the short-wave absorption factor, γ', is obtained regarding the solar absorptivity of surface ③, shown in Figure 2, as $1 - \rho_{ig,s}$.

Convective Heat Transfer

As a matter of fact, convective heat flux at windows is obtained to multiply a convective heat transfer coefficient and temperature difference between air and surface. In this paper, the convective heat transfer coefficient at the outdoor surface is calculated by wind velocity and wind direction using the empirical equations proposed by Ito et al. (1972).

At the pane of an inside blind window, the convective heat transfer coefficient at its indoor surface is calculated as free convection of laminar flow along a flat plate (JSME 1986). (See Appendix B for details.) The convective heat flux at the pane is given as:

ID	: direct solar radiation	, Btu/h·ft²	(W/m²)
IDN	: direct normal solar radiation	, Btu/h·ft²	(W/m²)
IS	: diffuse solar radiation	, Btu/h·ft²	(W/m²)
h	: altitude of the sun	, degrees	
L	: airflow rate for crack	, ft³/h	(m³/h)
NL	: net long-wave radiation	, Btu/h·ft²	(W/m²)
NS	: net short-wave radiation or solar heat gain	, Btu/h·ft²	(W/m²)
O	: orientation of window	, degrees	
P	: vertical distance between slats	, ft	(m)
S	: length of slats	, ft	(m)
T	: temperature	, F	(K or °C)
TH	: global solar radiation	, Btu/h·ft²	(W/m²)
v	: airflow velocity through slats of inside blinds	, ft/s	(m/s)
Z	: height	, ft	(m)
α	: azimuth of the sun	, degrees	
αc	: convective heat transfer coefficient	, Btu/h·ft²·F	(W/m²K)
β	: long-wave absorption factor		
γ	: short-wave absorption factor		
ε	: long-wave emissivity		
θ	: tilted angle of slats	, degrees	
ρ	: solar or short-wave reflectivity		
σ	: Stephan-Boltzmann constant	, Btu/h·ft²·F⁴	(W/m²·K⁴)
τ	: solar or short-wave transmissivity		

Subscripts

a	: air in the vicinity of inside blinds
b	: slats of inside blind
d	: direct solar radiation
g	: pane of inside blind window
gr	: ground
i	: indoor air
ig	: inside pane of middle blind window
in	: indoor side
ma	: air in the space between double sashes
mb	: slats of middle blind
mw	: middle blind window
o	: outdoor air
og	: outside pane of middle blind window
out	: outdoor side
r	: indoor surfaces
s	: diffused solar radiation
sk	: sky
w	: inside blind window

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DISCUSSION

The accuracy of the heat transfer modeling around windows with blinds is discussed through the comparison between the measured and predicted values of the transmitted solar radiation and the surface temperatures of the panes and the slats. Measured weather data, the indoor air temperature, and the indoor surface temperature were used as given conditions for the prediction. The main purpose of blinds is the prevention of solar radiation and the main body for the solar shading effect is the slats. From this point of view, the values of the transmitted solar radiation and those of the temperature of the slats are important.

Figure 3 shows the comparison of the window with inside blinds. The tilted angle of the slats, θ, was 30° and the experiment was carried out on December 22, in 1988, near the winter solstice. The predicted and the measured temperatures of the slats were agreed remarkably with each other. At the pane, the predicted temperature was below the measured one by 2.5~6.7 F (1.4~3.7°C). The reason for this difference seems to derive from the uncertainty of the values of the outdoor convective heat transfer coefficient. The coefficient was not measured, but was estimated by the direction and velocity of the wind. The predicted amounts of transmitted solar radiation agreed closely with the measured amounts ranging from 11 a.m. to 2 p.m, when the altitude of the sun was relatively high, but deviated from each other according to the decrease in the altitude. The measured amount was larger than the predicted amount by 21 % at 10 a.m. The incident solar radiation used for the calculation was measured at the southern experimental house. However, the inside blinds were fitted at the window of the northern experimental house. Judging from this point of view, one may point out that the incident solar radiation should also be measured at the northern experimental house.

Figure 4 shows the results of the middle blind when the tilted angle of the slats was 60°. The measured and the predicted temperature of the slats agreed within 4 F (2.2°C). The temperatures of the inside pane also agreed at the same level. Nevertheless, the predicted temperature of the outside pane was higher than the measured temperature especially in the morning. The predicted amount of the transmitted solar radiation agreed well with the measured amount.

From these results, we can conclude that the temperature of the slats and transmitted solar radiation through windows are predictable by the equations we proposed. By these equations, the phenomenon—the absorbed solar radiation at the slats and panes is converted into long-wave radiation and the convective heat flux—can be cleared. As for the temperature of the pane, we may need a more accurate procedure to estimate the convective heat transfer coefficient of the outdoor surface. However, this estimation is the problem not only of heat transfer around windows but of the thermal performance of buildings. The measurements mentioned above were conducted in December, at the sun's lowest altitude of the year. Therefore, the measurements high altitude season were also going to be carried out in the summer of 1989. At that time, slats of different lengths will be used to reconfirm the accuracy of the established equations.

CONCLUSIONS

Two types of windows with blinds—inside blind windows and middle blind windows—are the subject of the modeling of heat transfer. Radiative heat transfer was established by the absorption factors, and convective heat transfer was done by the equations of laminar flow in free or forced convection. The accuracy of the establishment was discussed through the comparison with the measurements of the experimental houses. The temperature of the slats of the blinds and the transmitted solar radiation through windows were predicted precisely. The phenomena of the conversion of absorbed solar radiation at the slats and panes into long-wave radiation and the convective heat flux can be cleared by the equations we propose.

NOMENCLATURE

AH	: atmospheric radiation	, Btu/h·ft^2	(W/m^2)
a	: solar or short-wave absorptivity		
BFD	: bypass factor of transmitted direct solar radiation		
C	: specific heat	, Btu/lb·F	(kJ/kg·K)
CV	: convective heat flux	, Btu/h·ft^2	(W/m^2)
F	: shape factor		
f	: flow coefficient, 0.8 in this paper		
G	: specific gravity	, lb/ft^3	(kg/m^3)
g	: gravity	, ft/s^2	(m/s^2)

APPENDIXES

Appendix A

The absorption factor, $\beta_{i,j}$, which denotes the ratio of the finally absorbed long-wave radiation at the surface j to the emitted one from the surface i, is given as:

$$\beta_{i,j} = F_{i,j} \cdot \varepsilon_j + \sum_{k=1}^{K} F_{i,k} (1 - \varepsilon_k) \beta_{k,j} \tag{A-1}$$

where k is an arbitrary surface in the space and K is the total number of surfaces in the space. The laws of reciprocity and energy conservation exist in the relation among long-wave absorption factors.

$$\varepsilon_m \cdot A_m \cdot \beta_{m,n} = \varepsilon_n \cdot A_n \cdot \beta_{n,m} \tag{A-2}$$

$$\sum_{k=1}^{K} \beta_{k,n} = 1 \tag{A-3}$$

where A denotes the area of a surface.

Transforming long-wave absorption factors, one can obtain short-wave absorption factors. The short-wave absorption factor, $\gamma_{i,j}$, which denotes the ratio of the finally absorbed short-wave radiation at the surface j to the first reflected one from the surface i is given as:

$$\gamma_{i,j} = F_{i,j} \cdot a_j + \sum_{k=1}^{K} F_{i,k} \cdot \rho_k \cdot \gamma_{k,j} \tag{A-4}$$

The law of reciprocity exists in the relation of short-wave absorption factors. The law of energy conservation, on the other hand, does not consist of transparent surfaces.

Appendix B

In laminar flow of free convection, convective heat transfer coefficient, αc, of a flat plate is established by four kinds of non-dimensional number—the Nusselt number, Nu; the Rayleigh number, Ra; the Grashof number, Gr; and the Prandtl number, Pr.

$$\alpha c = \lambda \cdot Nu / l = \lambda \cdot C_1 . Ra^{1/4} / l = \lambda \cdot C_1 (Pr \cdot Gr)^{1/4} / l \tag{B-1}$$

where

C_1	: function of Prandtl number	$[= \{Pr/(2.4 + 4.9Pr^{1/2} + 5Pr)\}^{1/4}]$	
Gr	: Grashof number	$\{= g \cdot \sin\theta \cdot \beta \; (T_s - T_a) \; l^3 / \nu^2\}$	
l	: height of window or longitudinal length of slats	, ft	(m)
T	: temperature, T_a for the air and T_s for surface	, F	(K or °C)
β	: cubical expansion coefficient	, 1/F	(1/K)
θ	: tilted angle of slats or 90° for pane	, degrees	
λ	: thermal conductivity	, Btu/h·ft·F	(W/m·K)
ν	: kinematic viscosity	, ft^2/s	(m^2/s)

Appendix C

In laminar flow of forced convection, convective heat transfer coefficient, αc, of a flat plate is established by the Nusselt number, Nu, and the Reynolds number, Re.

$$\alpha c = \lambda \cdot Nu / l = \lambda \cdot C \cdot Re^{1/2} / l \tag{C-1}$$

where

C	: function of Prandtl number	$(= 0.332Pr^{1/3})$
Re	: Reynolds number	$(= v \cdot l / \nu)$
l	: longitudinal length of slats, ft (m)	

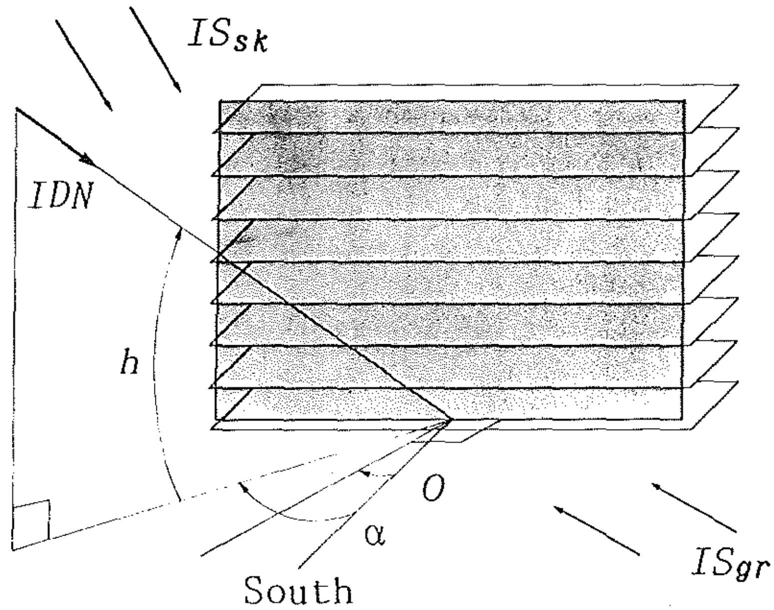

Figure 1. *Location of the sun against windows and incident solar radiation; IDN = direct normal solar radiation, IS_{sk} = diffused solar radiation from the sky, and IS_{gr} = diffused solar radiation from the ground, namely, reflected global solar radiation from the ground*

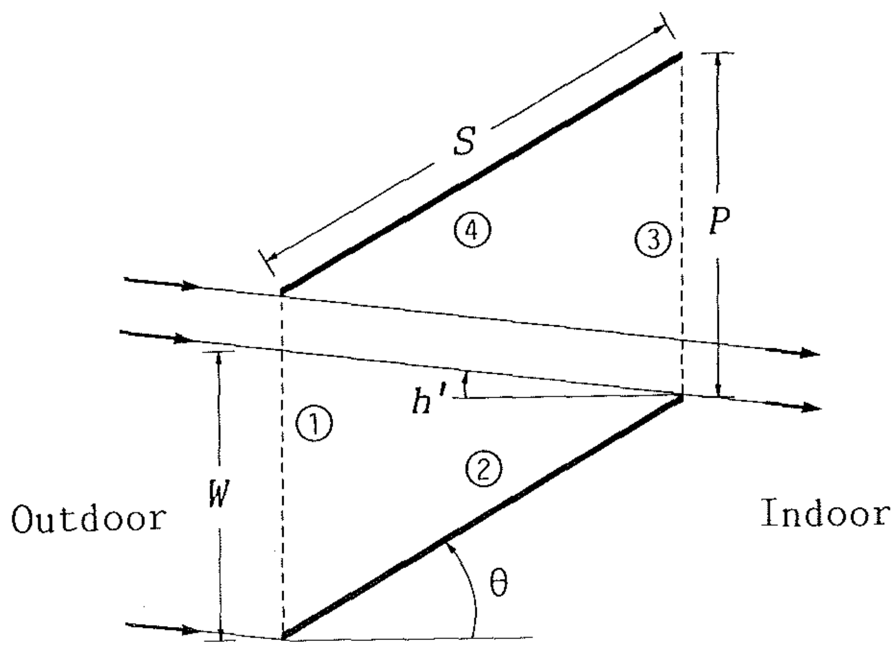

Figure 2. *Bypass factor of direct solar radiation transmitted through the slats of blinds, and two-dimensional enclosed space for calculation of radiative heat exchange*

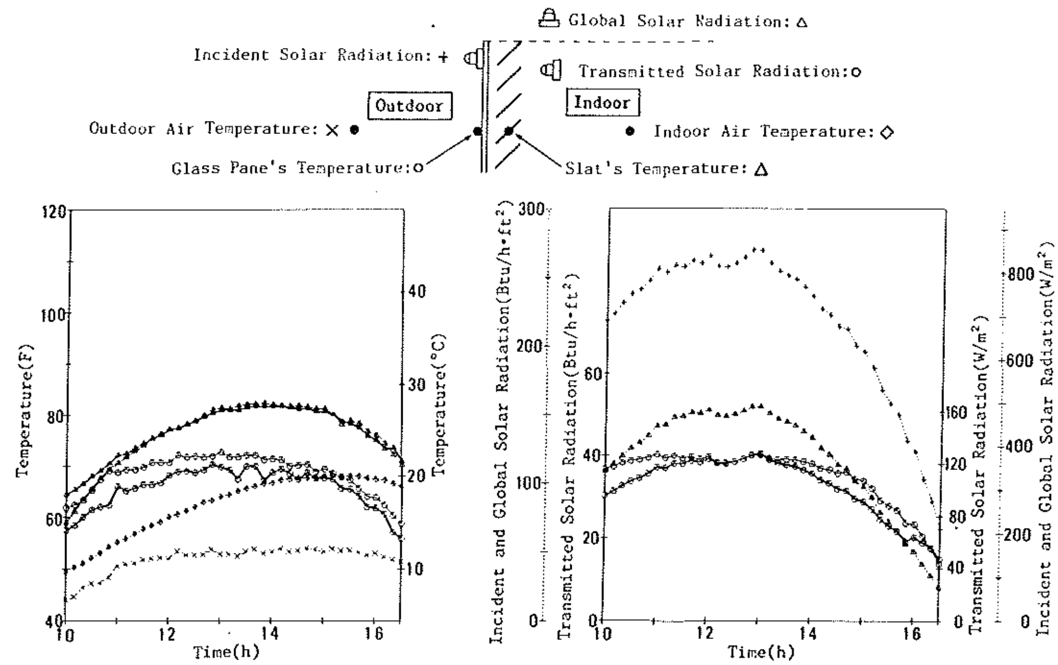

Figure 3. Comparison of measured and predicted values of an inside blind window on December 22, 1988. Tilted angle of the slats was 30°. Thick solid lines are predicted values, thin solid lines are measured values, and broken lines are measured values as given conditions for the prediction.

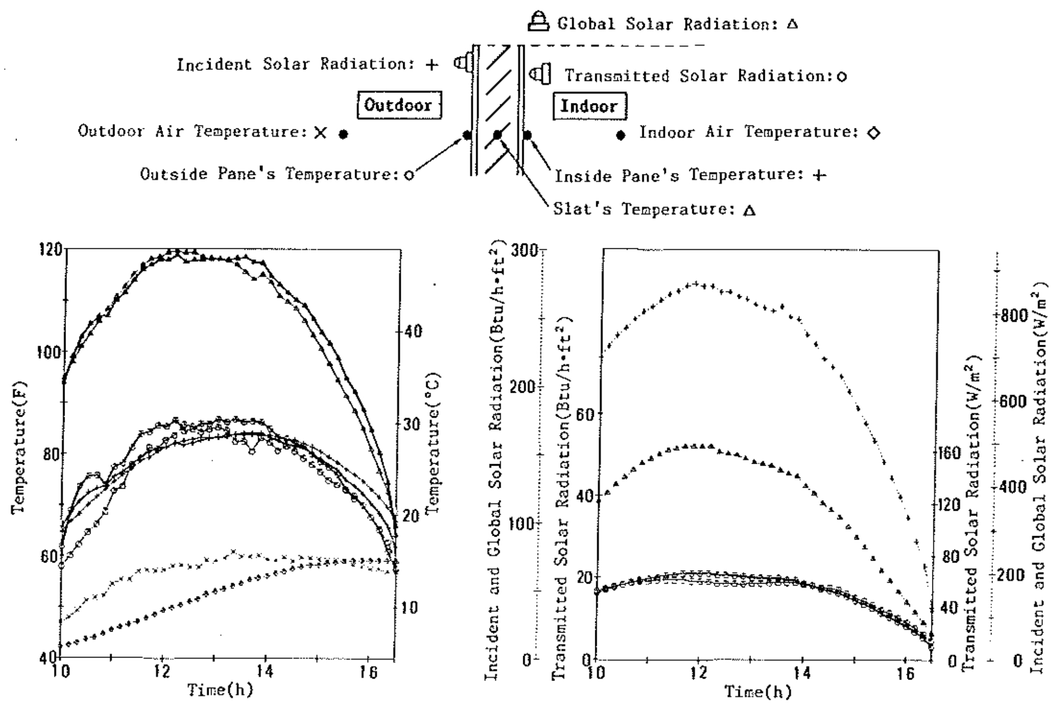

Figure 4. Comparison of measured and predicted values of a middle blind window on December 13, 1988. Tilted angle of the slats was 60°. Thick solid lines are the predicted values, thin solid lines are measured values, and broken lines are measured values as given conditions for the prediction.