AN EVALUATIVE METHOD FOR HIGH-PERFORMANCE WINDOW SYSTEM AND WINDOW SIDE RADIATION ENVIRONMENT

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ABSTRACT

A study was performed on a method to evaluate performance of window system necessary to satisfactorily maintain the window side radiation environment in a glass building. On general type window using high-performance glass, air flow window and push-pull window, U-factors and SCs in various specifications were obtained from numerical calculation. Also, a simulation model for indoor radiation environment is proposed using the newly defined window thermal property values. As an evaluation index of radiation environment, "OT increase on window side" is proposed, and a window system is indicated, which is recommendable from the viewpoint of numerical analysis performed on office buildings.

INTRODUCTION

In recent years, more and more office buildings have been designed with glass structure using glass material on the entire building surface. In such buildings, there is the possibility that much energy may be consumed, or radiation environment may be aggravated on window side, and it is necessary to adopt high-performance window system. As the high-performance window system, it has been proposed, in addition to general window using high-performance glass, air flow window (AFW) and push-pull window (PPW) to pass the room air into the windows. In Japan, aggravation of radiation environment must be avoided particularly in summer season, and there are strong demands on the development of new window system, which guarantees good radiation environment on window side in summer season. In the present study, a simulation method and an evaluation method for radiation environment on window side are discussed, and the performance of various types of window systems in office building are evaluated.

GENERAL FEATURES OF WINDOW SYSTEMS

Fig. 1 shows three types of window system. In AFW, the room air is introduced between dual glass system incorporated in the blind, and all of the air from the window is basically discharged out of the building. In PPW, the room air is blown from the bottom of window into a gap between glass and blind, and it is then discharged from the upper part of the window. A certain air volume is required until the blown air flow reaches the upper part of the window.

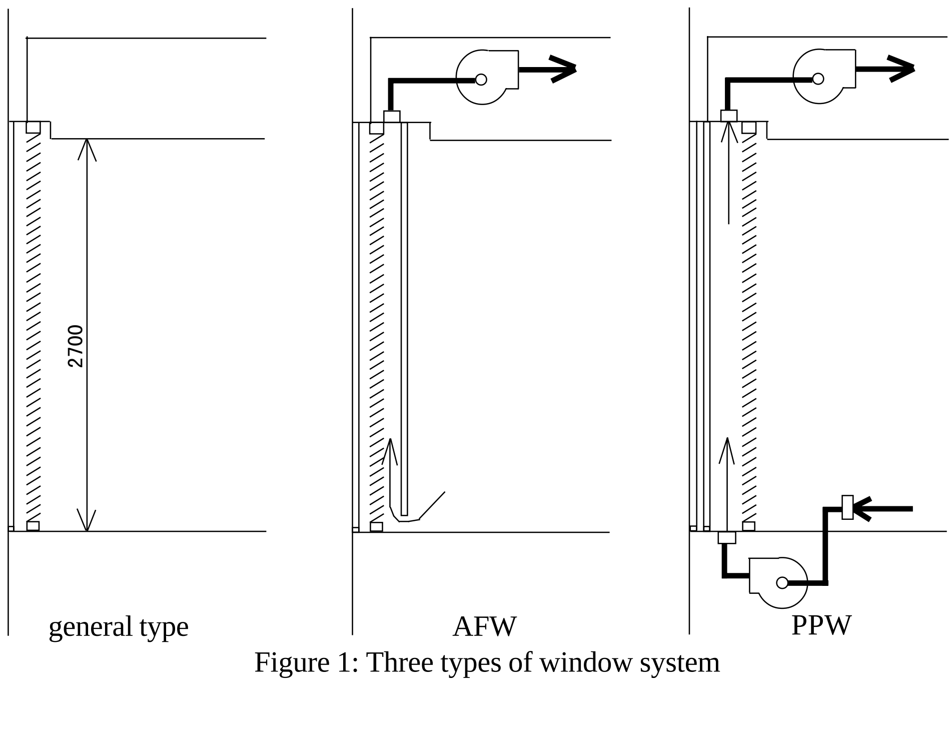

Figure 1: Three types of window system

THERMAL EQUILIBRIUM EQUATIONS OF WINDOW

First, description will be given on thermal equilibrium equation when blind is closed. Window thermal equilibrium equations of PPW are expressed by the following equations:

$$I_{a1}/h + C_{OG}(t_{Oe} - t_1) + \alpha_{CG}(t_2 - t_1) + \alpha_R(t_3 - t_1) = 0 \quad \cdots(1)$$

$$I_{a2}/h + \alpha_{CG}(t_1 - t_2) + \alpha_{CB}(t_3 - t_2) + C_P \cdot \rho\,(V_S + V_P)(t_R - t_2) = 0 \quad \cdots(2)$$

$$I_{a3}/h + \alpha_{CB}(t_2 - t_3) + \alpha_R(t_1 - t_3) + \alpha_I(OT_w - t_3) = 0 \quad \cdots(3)$$

where t_1 is glass inner surface temperature, t_2 is air layer temperature between glass and blind, and t_3 is blind temperature, all being unknown values.

In thermal equilibrium equations of general window, it is assumed that $V_P = 0$ in the above equations, and natural circulation volume of air passing through the gap of slats is used as V_S.

Thermal equilibrium equations of AFW are as given below, where t_1 is outer glass temperature, t_2 is outer air layer temperature, t_3 is blind temperature, t_4 is inner air layer temperature, and t_5 is inner glass temperature, all being unknown values.

$$I_{a1}/h + C_{OG}(t_{Oe} - t_1) + \alpha_{CG}(t_2 - t_1) + \alpha_R(t_3 - t_1) = 0 \quad \cdots(4)$$

$$I_{a2}/h + \alpha_{CG}(t_1 - t_2) + \alpha_{CB}(t_3 - t_2) + C_P \cdot \rho \cdot V_2(t_R - t_2) + C_P \cdot \rho \cdot V_{SA}(t_4 - t_2) = 0 \quad \cdots(5)$$

$$I_{a3}/h + \alpha_{CB}(t_2 - t_3) + \alpha_{CB}(t_4 - t_3) + \alpha_R(t_1 - t_3) + \alpha_R(t_5 - t_3) = 0 \quad \cdots(6)$$

$$I_{a4}/h + \alpha_{CB}(t_3 - t_4) + \alpha_{CG}(t_5 - t_4) + C_P \cdot \rho \cdot V_4(t_R - t_4) + C_P \cdot \rho \cdot V_{SA}(t_2 - t_4) = 0 \quad \cdots(7)$$

$$I_{a5}/h + \alpha_I(OT_w - t_5) + \alpha_{CG}(t_4 - t_5) + \alpha_R(t_3 - t_5) = 0 \quad \cdots(8)$$

Next, description will be given on a case where blind is opened. Thermal equilibrium equations of PPW are given as follows:

$$I_{a1}/h + C_{OG}(t_{Oe} - t_1) + \alpha_{CG}(t_2 - t_1) + \alpha_R(MRT_w - t_1) = 0 \quad \cdots(9)$$

$$I_{a2}/h + \alpha_{CG}(t_1 - t_2) + C_P \cdot \rho\,(V_P + V_S)(t_R - t_2) = 0 \quad \cdots(10)$$

where t_1 is glass inner surface temperature and t_2 is push-pull flow air temperature, both being unknown values.

In case of general window, thermal equilibrium equation having only glass inner surface temperature as unknown value is used. In case of AFW, thermal equilibrium equations having temperature values of outer glass, inner glass and air layer as unknown values are used.

BASIC THERMAL PERFORMANCE OF WINDOW

Based on the thermal equilibrium equations as described above, basic thermal performance values of window, i.e. overall coefficient of heat transfer (U-factor) and shading coefficient (SC), were obtained. In calculating SC, interreflection inside the window was calculated in detail, and absorbed solar radiation at each portion of window was obtained. **Table 1** shows standard conditions of three types of window system. In the following, standard conditions are described unless otherwise specified. U-factor and SC in various types of glass are shown in **Table 2**. General window, PPW and AFW are compared with each other under the standard conditions. In case blind is opened, U-factor shows the lowest value in PPW and about the same values in general window and AFW. SC is at the lowest in PPW and at the highest in AFW. In case blind is closed, both U-factor and SC are at the lowest in AFW and at the highest in general window. However, radiation component of SC is at the highest in AFW. Because of this, in the analysis given below, AFW is the most disadvantageous in radiation environment even though the value of SC may be low.

Fig. 2 shows the relationship between window ventilation volume V and U-factor or SC in PPW and AFW in case blind is closed. Window ventilation volume V is given as follows.
In case of PPW,

$$V = V_p + V_S \quad \cdots(11)$$

In case of AFW,

$$V = V_2 + V_4 \quad \cdots(12)$$

PPW represents an ideal condition where it is assumed that push air flow and induced air are completely exhausted from the window by pull fan. AFW gives sufficient solar radiation shielding effect

Table 1: Standard conditions of window systems

General type window
glazing: low-e glass 10 mm + air space 6 mm + clear glass 10 mm
distance between glazing and blind: 0.1m
Push-pull window
glazing: low-e glass 10 mm + air space 6 mm + clear glass 10 mm
distance between glazing and blind: 0.4m
push fan air volume Vp: 8 lit/sec m^2 pull fan air volume : 8 lit/sec m^2
induced air volume Vs: 16 lit/sec m^2 (with blind), 24 lit/sec m^2 (without blind)
Air flow window
glazing: clear glass 10 mm + ventilated air space 400 mm + clear glass 10 mm
window ventilation rate: 5 lit/sec m^2
Common conditions
window height: 2.7m, window azimuth: west
solar absorptance of blind slat: 0.5, slat angle: 45°
blind operation: if depth of sunlit floor is larger than 1.5m, blind is closed
natural circulation rate through gap of slats: 5 lit/sec m^2

Table 2: Basic Thermal properties of various window systems

U-factor: overall coefficient of heat transfer w/m^2 K
SC: shading coefficient, SCR: radiant component of SC
η_{EX}: ratio of exhaust solar radiation from window to solar radiation incident on window

type of window system	without blind			with blind		
	U-factor	SC (SCR)	η_{Ex}	U-factor	SC (SCR)	η_{EX}
(a) general typwindow						
clear single	7.1	0.91 (0.84)	—	4.9	0.53 (0.20)	—
clear double	3.8	0.75 (0.64)	—	3.1	0.53 (0.18)	—
ceramics 30% double	3.8	0.63 (0.52)	—	3.1	0.45 (0.15)	—
low-e double (standard)	2.9	0.44 (0.35)	—	2.4	0.34 (0.11)	—
low-e tinted double	2.9	0.34 (0.24)	—	2.4	0.27 (0.08)	—
(b) PPW						
clear single	6.6	0.88 (0.79)	0.03	5.5	0.54 (0.17)	0.08
clear double	3.4	0.72 (0.60)	0.04	2.9	0.51 (0.14)	0.09
ceramics 30% double	3.4	0.60 (0.48)	0.03	2.9	0.43 (0.12)	0.08
low-e double (standard)	2.5	0.41 (0.33)	0.03	2.2	0.32 (0.08)	0.06
low-e tinted double	2.5	0.31 (0.22)	0.03	2.2	0.25 (0.06)	0.05
(c) AFW						
(kind of outer glass)						
clear (standard)	2.9	0.69 (0.59)	0.07	1.9	0.25 (0.12)	0.16
reflective	2.9	0.58 (0.50)	0.06	1.9	0.21 (0.10)	0.14
tinted	2.9	0.39 (0.29)	0.09	1.9	0.18 (0.08)	0.14

Notes: 1) In PPW, push fan air volume Vp is 8 lit/sec m^2 and is equal to pull fan air volume. Induced air volume Vs is 16 lit/sec m^2, if blind is closed, and is 24 lit/sec m^2, if blind is open. 2) In AFW, window ventilation rate V is 5 lit/sec m^2. 3) glass thickness is 10 mm in all cases. Inner glass of double glazing is clear. Film coating is inner surface of glass except for reflective glass. 4) Ceramics 30%: clear glass with 30% area ceramics printed, low-e: clear glass with low-e coating, low-e tinted: green tinted glass with low-e coating. 5) Solar properties are at solar incident angle 30°

even when transparent glass is used, while, in case of PPW, it is important to use double glazing with high solar radiation shielding property.

In case of PPW in actual application, a considerable volume of room air is induced through gaps of slats due to the blown air flow from under the window, and the air of equal volume flows into the room from above the blind. When a large quantity of air is blown out because the blown air flow reaches the upper portion of the window, it is impossible to discharge all of the window exhaust air, and a part of the air must be returned to air-handling unit. This is shown in **Fig. 3**. To match this situation, system U-factor and system SC are newly defined, which are based on the processed heat quantity at the air-handling unit.

$$\text{system } U = U + (1 - x_{EX}) U_{EX} \quad \cdots (13)$$

$$\text{system } SC = SC + (1 - x_{EX}) \eta_{EX} / \eta_o \quad \cdots (14)$$

Fig. 4 summarizes system U-factor and system SC in PPW. When outdoor exhaust air ratio is 0.5 or more, thermal performance of window is improved as window ventilation volume is increased.

SIMULATION METHOD

A method to simulate indoor radiation environment is described. Assuming a cross-section of an office building as shown in **Fig. 5**, convection - radiation heat equilibrium equations having 4 air temperature values and 11 surface temperature values as unknown values are solved. The unknown value at the window is window inner surface temperature only. For 10 indoor points, operative temperature (OT) is calculated, and this is used for evaluation of radiation environment.

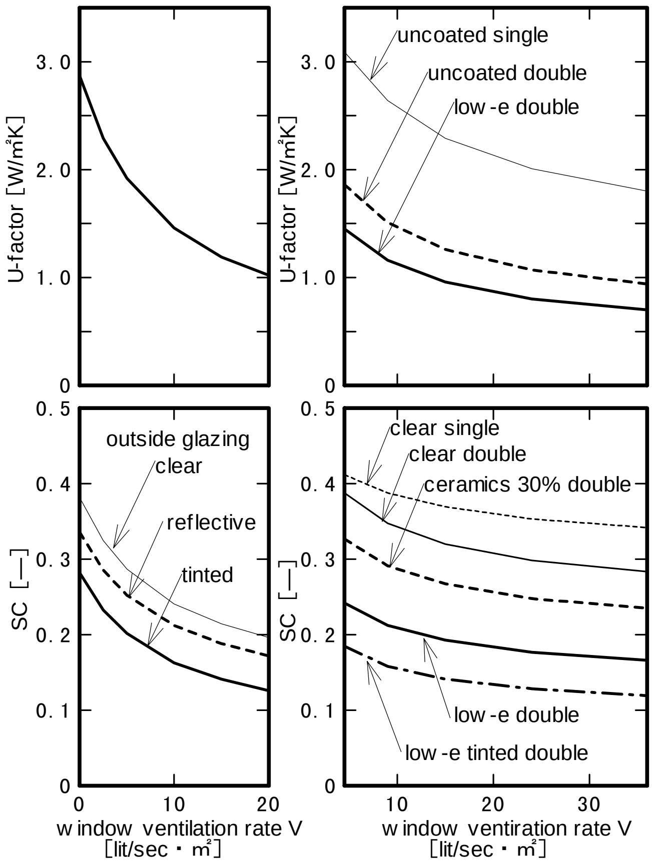

Figure 2: U-Factors and SCs of AFW and PPW with blind

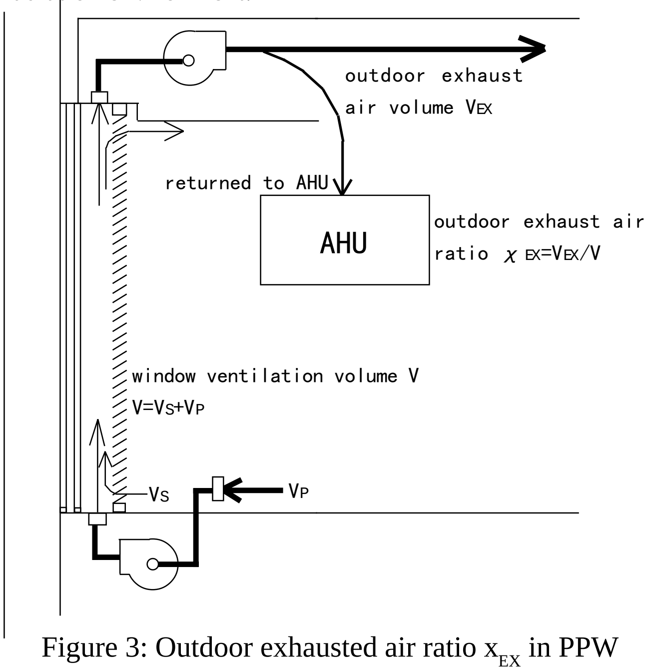

Figure 3: Outdoor exhausted air ratio x_{EX} in PPW

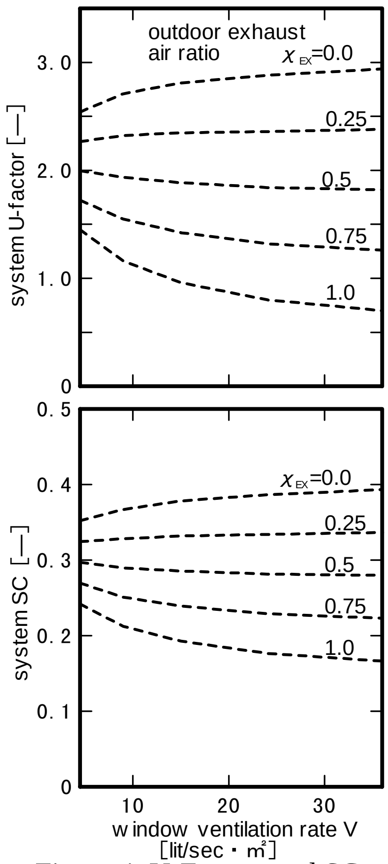

Figure 4: U-Factors and SCs of PPW in various x_{EX} (low-e double glazing with blind)

In the indoor environment simulation model, only window inner surface temperature is treated as unknown value. In the analytical method using temperature at each portion in the window as unknown values as already described, it was tried to decrease unknown values without impairing the accuracy. This is explained in the example of PPW shown in **Fig. 6**. It is assumed that t_{SI} is 0℃. In case t_R is also 0℃ and only t_{Oe} is 1℃, it is defined that heat transfer rate to blind due to convection and radiation is C_O and heat rate into the room due to outflow of the air through gap of slats is C_{OV}. Similarly, in case only t_R is 1℃ and the other is 0℃, it is defined that heat transfer rate to blind due to convection and radiation is C_R. Heat rate into the room due to outflow of air is turned to negative, and this is regarded as $-C_{RV}$. C_O represents convective and radiative component of heat transfer factor for external air temperature, and C_{OV} represents ventilation component of heat transfer factor for external air temperature. C_R and C_{RV} are two components of heat transfer factor for room air temperature. Using these thermal property values, thermal equilibrium equation of window inner surface is given as follows:

$$I_{aSI}/h + C_O(t_{Oe} - t_{SI}) + C_R(t_R - t_{SI}) + \alpha_I(OT - t_{SI}) = 0 \quad \cdots(15)$$

Heat transfer rate from window to space air $q_{WINDOW,C}$ [W] is obtained by the following equation.

$$q_{WINDOW,C} = I_{aP} + \alpha_{CB} \cdot h(t_{SI} - t_R) + C_{OV} \cdot h(t_{Oe} - t_{SI}) + C_{RV} \cdot h(t_{SI} - t_R) \quad \cdots(16)$$

I_{aSI} and I_{aP} are obtained as follows: In case $t_{Oe} = 0$℃, $t_R = 0$℃ and $OT = 0$℃, the values of t_{SI} and t_A with solar radiation on window surface can be obtained by solving the thermal equilibrium equations (1)-(3). I_{aSI} is obtained by the following equation, which has been modified from the equation (15):

$$I_{aSI} = (C_O + C_R + \alpha_I)h \cdot t_{SI} \quad \cdots(17)$$

$q_{WINDOW,C}$ is described by using t_{SI} and t_A as follows:

$$q_{WINDOW,C} = \alpha_{CB} \cdot h \cdot t_{SI} + C_P \cdot \rho \cdot V_S \cdot h \cdot t_A \quad \cdots(18)$$

From the equation (16),

$$q_{WINDOW,C} = I_{aP} + \alpha_{CB} \cdot h \cdot t_{SI} - C_{OV} \cdot h \cdot t_{SI} + C_{RV} \cdot h \cdot t_{SI} \quad \cdots(16)'$$

Using the equations (18) and (16)′, the following equation is obtained.

$$I_{aP} = C_P \cdot \rho \cdot V_S \cdot h \cdot t_A + (C_{OV} - C_{RV})h \cdot t_{SI} \quad \cdots(19)$$

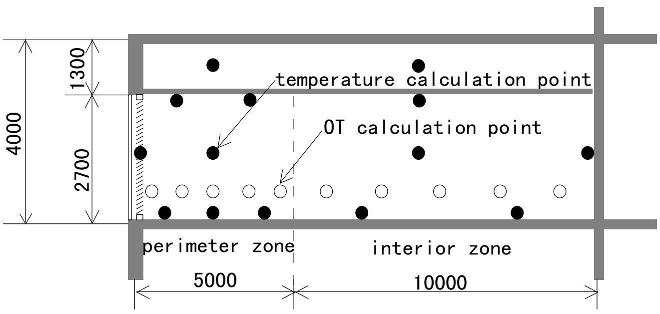

Figure 5: Section of an office building

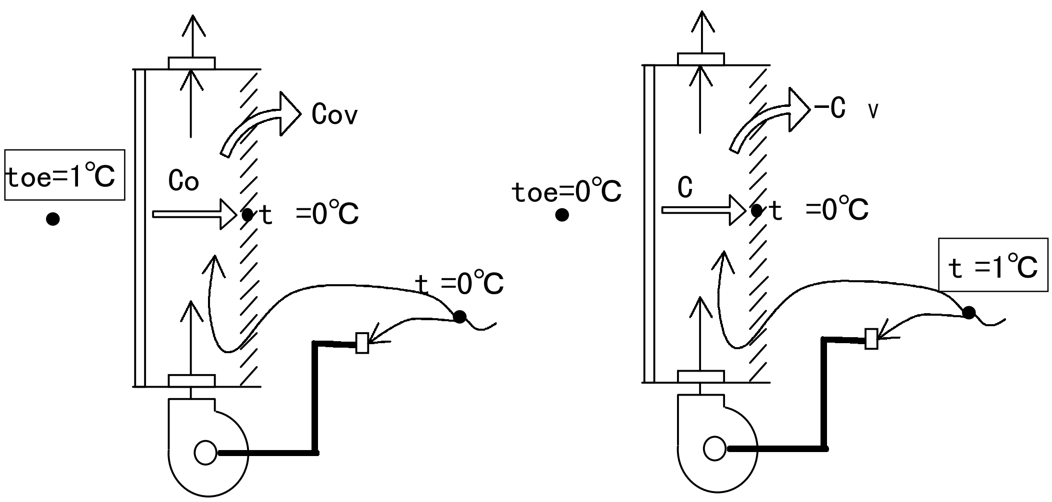

Figure 6: Four thermal properties in PPW

As described above, based on the thermal equilibrium equation around each portion in the window, window thermal property values C_O, C_{OV}, C_R and C_{RV} and the values I_{aSI} and I_{aP} can be obtained. If these values are acquired, the solution using only t_{SI} as unknown value can be used without impairing the accuracy.

EVALUATION METHOD FOR RADIATION ENVIRONMENT

As points of evaluation for radiation environment, a point at 1.5 m from window was selected as window side, and a point at 10 m from the window as interior side. As evaluation index of radiation environment on window side, the difference between operative temperature values (*OT*) in the two cases is used as "*OT* increase on window side" or "*OT* decrease on window side". For setting the comfort limit value, *PMV* is utilized. Comfort range of air-conditioned space is: *PMV* ± 0.5. When *PMV* on interior side is controlled to 0, it would suffice if window side *PMV* is within the range of +0.5 to -0.5. To convert the difference of *PMV* between window side and interior side to *OT*, **Fig. 7** is used. **Fig. 7** shows the relationship between *PMV* and *OT*. If it is assumed that clothing value under design cooling condition is 0.6 clo and it is 1.1 clo under design heating condition, *OT* difference corresponding to *PMV* difference of 0.5 is 1.5Kand 1.8K respectively.

EVALUATION

Using design cooling conditions in Tokyo, window side radiation environment was simulated for various types of window system. As window azimuth, west azimuth was assumed. The other conditions are given in **Table 3**. **Fig. 8** shows hourly temperature fluctuation in general type window, PPW and AFW under the standard condition. *OT* on window side reaches peak value at

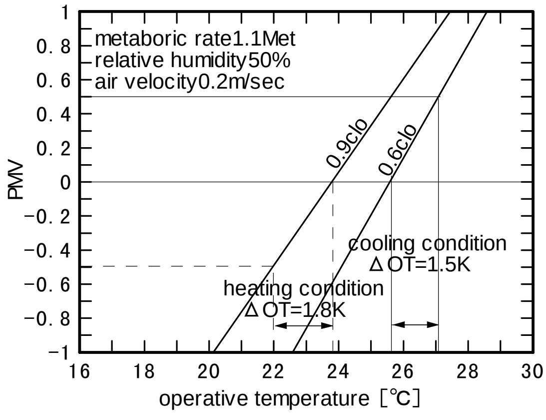

Figure 7: Relationship between OT and PMV

16:00. Even in case of PPW having the lowest *OT* value, the difference between *OT* and room air temperature on window side is 2.2K and *OT* increase on window side from interior side is 1.2K. **Fig. 9** shows the comparison of horizontal distribution of *OT* in various types of glass. The comparison of *OT* increase on window side in the same case is given in **Fig. 10 (a)**. In order to set *OT* increase on window side to lower than the comfort condition of 1.5K, low-e tinted double glazing should be used in case of general type window, low-e double glazing in case of PPW, and tinted glazing should be used as outer glass in case of AFW. In **Fig. 10 (b)**, the relationship between window ventilation volume and *OT* increase on window side is shown. In case of PPW using low-e glazing, comfort condition is satisfied if window ventilation volume is about 10 liters/sec m² or more. In case of AFW, clear single glazing may be used as outer glass if window ventilation volume is 12 liters/sec m².

CONCLUSION

1) Simulation method and evaluation method for window side radiation environment have been described. Four window heat transfer factors were newly proposed, and a method to set up indoor environment simulation model using only window inner surface temperature as unknown value without impairing calculation accuracy on window sector was indicated. Also, using *PMV*, a concept to determine comfort limit value for *OT* increase and *OT* decrease on window side was suggested.
2) By numerical analysis assuming a general type office building, the conditions for PPW and AFW were proposed, which satisfy comfort condition in window side radiation environment under design cooling conditions.

ACKNOWLEDGEMENTS

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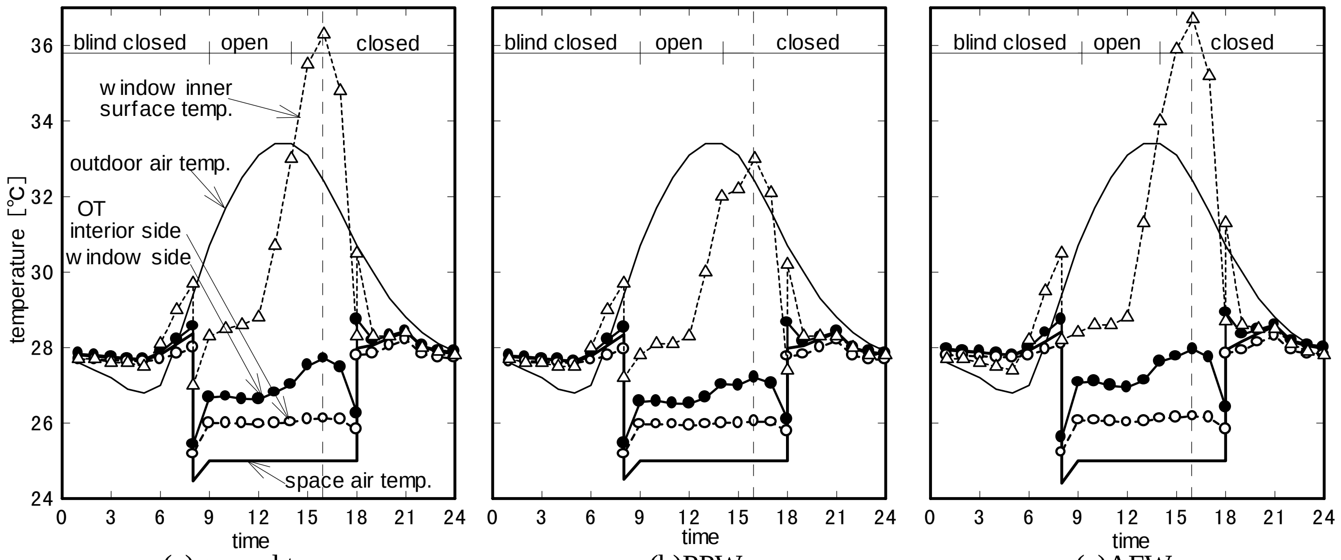
Table 3: Conditions for simulation of office environment

Weather data
cooling design weather data in Tokyo
(TAC2.5% outdoor air temperature
and August design solar radiation)

Space
Space depth: 15m, lighting: 20W/m²
OA Equipment: 5W/m²,
occupancy: 0.2 person/m²

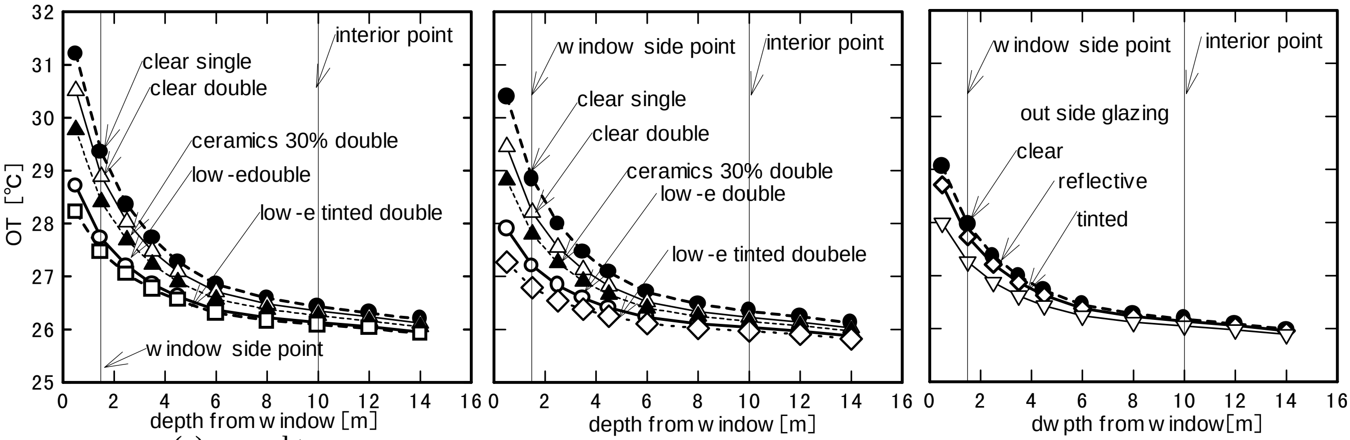
Air-conditioning
Set point space air temperature: 25 ℃
conditioning time: 8:00 ~ 18:00
(pull down: 8:00 ~ 9:00)

Evaluation of radiation environment
at 16:00 (most savior environment)



(a)general type (b)PPW (c)AFW

Figure 8: OT changes under cooling desgin condition（west window）



(a)general type (b)PPW (c)AFW

Figure 9: Horizontal distribution of OT at 16:00 under cooling design condition（west window）

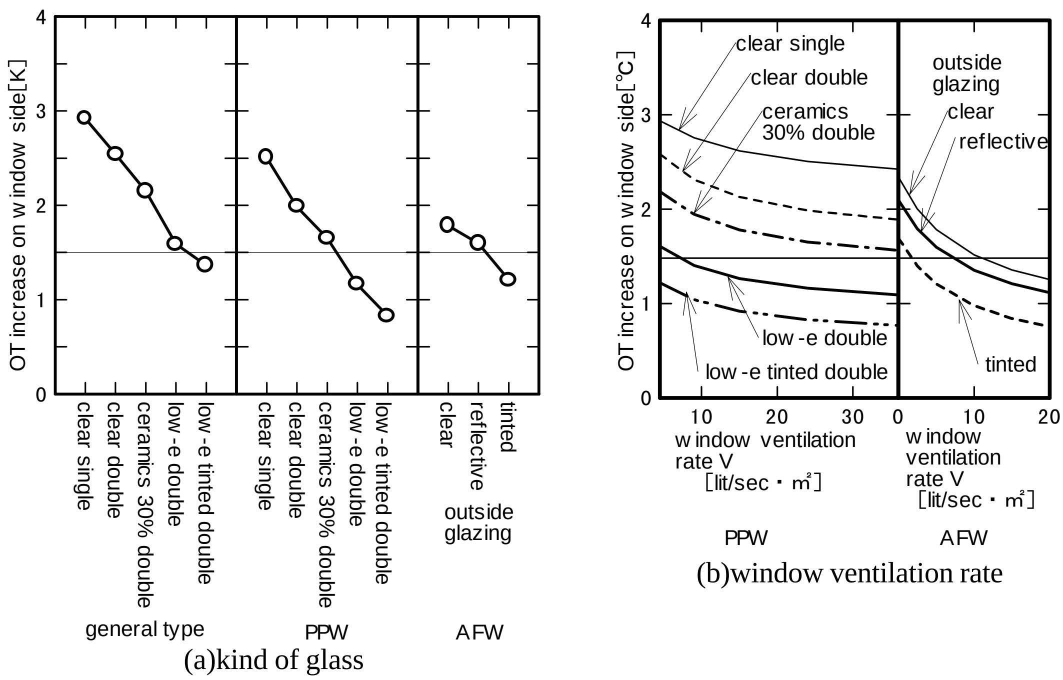


Figure 10: OT increase on window side at 16:00 under cooling design condition（west window）

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NOMENCLATURE

I_{ai} absorbed solar radiation at the portion i in the window[W]
I_{aSI} equivalent absorbed solar radiation at inner surface of window[W]
I_{aP} solar heat gain of perimeter zone mainly due to outflow from window[W]
t_I temperature of the portion i in the window[℃]
t_{Oe} sol air temperature considered effect of nocturnal radiation[℃]
t_R room air temperature[℃]
t_{SI} inner window surface temperature[℃]
t_A temperature of air layer in the window[℃]
OT_w operative temperature for calculation of heat conduction of window[℃]
MRT_w mean radiant temperature for calculation of heat conduction of window[℃]
h window height [m]
α_O outdoor surface heat transfer coefficient[W/ m² K]
α_I inner window surface heat transfer coefficient [W/ m² K]
α_{CG} indoor glass surface convective heat transfer coefficient[W/ m² K]
α_{CB} blind surface convective heat transfer coefficient[W/ m² K]
α_R indoor surface radiative heat transfer coefficient[W/ m² K]
C_{OG} heat conductance between outdoor air and inner surface of glazing[W/ m² K]
C_O convective and radiative component of heat transfer factor for external air temperature[W/ m² K]
C_{OV} ventilation component of heat transfer factor for external air temperature[W/ m² K]
C_R convective and radiative component of heat transfer factor for room air temperature[W/ m² K]
C_{RV} ventilation component of heat transfer factor for room air temperature[W/ m² K]
C_P specific heat of air[J/kg/K]
ρ density of air[kg/m3]
V_S induced air flow rate through gap of slats in PPW[liters/sec m²]
V_P push air flow rate under the window in PPW [liters/sec m²]
V_2 window ventilation rate through outer air layer in AFW[liters/sec m²]
V_4 window ventilation rate through inner air layer in AFW[liters/sec m²]
V_{SA} circulation air rate through gap of slats in AFW[liters/sec m²]
V total window ventilation rate[liters/sec m²]
SC, system SC shading coefficient and system shading coefficient[-]
x_{EX} exhaust air ratio[-]
η_{EX} ratio of exhaust solar heat from window to solar radiation incident on window[-]
η_o solar heat gain factor in 3mm clear glazing
U, system U U-factor (overall coefficient of heat transfer) and system U-factor[W/ m² K]
U_{EX} exhaust heat rate from window in case air
U_{EX} exhaust heat rate from window in case air temperature difference between outdoor and room is 1K[W/ m² K]