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Angle Factors Between Human Body and Rectangular Planes Calculated by a Numerical Model

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ABSTRACT

Angle factors between a human body and rectangular planes are calculated by a numerical model. The method presented in this paper, which predicts the thermal radiation field in a space, is based on a numerical integration method proposed in a previous paper. To confirm the validity of the calculated results, predicted angle factors for both standing and seated persons are compared with those from experiments. It was found that the predicted figures matched well with those from experiments except those between the human body and the front floor. Angle factors between surface parts of the human body and rectangular planes including the floor are also discussed here.

INTRODUCTION

A nonuniform indoor climate is often observed in a large enclosure, such as an atrium, and even in a narrow space, such as a passenger compartment in a vehicle. Conventional thermal indices such as SET* (Gagge et al. 1971) or PMV (Fanger 1970) are not considered suitable for these indoor spaces because of nonuniformity. New methods for predicting thermal comfort in nonuniform spaces are needed. In a previous paper (Ozeki et al. 1998a), the authors proposed a numerical simulation method for predicting the effective radiation area and the projected area of a human body for any kind of posture. The validity of this method was confirmed by comparison with Fanger's and Underwood's projected area factors, obtained by a photographic method for both standing and seated postures. It was found that the distribution and intensity of solar radiation to the human body surface could be predicted with sufficient accuracy. In this paper, angle factors between the human body and its surroundings for the prediction of thermal radiation exchange are numerically calculated, based on the numerical integration method proposed by the authors (Ozeki et al. 1996). Predicted angle factors are compared with Fanger's and Horikoshi's subjective experimental results obtained by a photographic method for both standing and seated postures (Fanger et al. 1970; Horikoshi et al. 1990). The distribution and intensity of the thermal radiation exchange between the human body and its surroundings could be predicted with sufficient accuracy.

PREVIOUS STUDIES

Photographic methods have been applied to calculate the angle factors between the human body and its surroundings (Fanger et al. 1970; Horikoshi et al. 1990; Jones et al. 1998). Fanger et al. (1970) measured 78 types of the projected area factors for ten male and female subjects, with and without clothing for standing and seated postures, using a photographic method. They developed the basic relationships for calculating the angle factors. Horikoshi et al. (1990) measured angle factors between standing and seated postures and rectangular planes for three male subjects, with or without clothing, using a photographic method. They used an orthographic lens for measurements. Kalisperis et al. (1991) developed angle factor tables for a variety of inclined surfaces using Fanger's data. Jones et al. (1998) developed projected area data for the whole body and for individual body segments. Conventional photographic methods have a limitation in practice because of taking a very long time for measurements.

Yamazaki et al. (1983) proposed a numerical surface model of the human body by measuring the body surface of a male subject. They calculated angle factors between the human body and points on its surroundings. Miyazaki et al.

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(1995) verified the angle factors between a human body model, which consists of several cylindrical parts, and rectangular planes by the Monte Carlo method. However, their angle factors did not coincide with Fanger's experimental results with sufficient accuracy. Tsuchikawa and Horikoshi (1996) proposed a numerical calculation method for evaluating angle factors between a numerical surface model of the human body and its environment, based on the contour integration method. However, concrete studies have not been conducted. Suzuki and Kakitsuba (1999) proposed a numerical surface model by measuring the body surfaces of two standing male subjects. They compared angle factors between a numerical surface model and its environment, obtained by the contour integration method and the photographic method. Nucara et al. (1999) proposed a simple algorithm for the automatic calculation of angle factors between people and composite plane surfaces. However, it is based on experimental data provided by Fanger (1970). Few studies have been conducted on calculation of the angle factors between a human body and its surroundings for any posture by numerical simulation methods with significant accuracy.

NUMERICAL SIMULATION METHOD

Human Body Model

The configuration of a human body, including the grid system, affects the characteristics of thermal radiation exchange and solar heat gain. Several human body models have been proposed for the following purposes: (1) to calculate the effective radiation area or angle factors between a human body and its surroundings (Yamazaki et al. 1983; Miyazaki et al. 1995; Suzuki and Kakitsuba 1999), (2) to simulate the heat transfer characteristics around the human body by a combined numerical simulation of air flow with thermal radiation and moisture transport (Murakami et al. 1997), and (3) to simulate the temperature controlling system in a human body (Yokoyama et al. 1997). In this paper, a human body model, shown in Figure 1, which represents uneven shapes such as ears, nose, mouth, fingers, and toes in detail, is considered suitable to predict heat transfer characteristics. Body shape is obtained by a commercially available software and then divided into surface elements. The height of this model and the surface area of the whole body are given in Table 1. The height and surface area of the present model are close to those of Fanger's subjects (1970). The human body surface is divided into 4396 quadrilateral surface elements for both standing and seated postures, which enables one to conduct a combined numerical simulation of air flow with solar heat gain (Ozeki et al. 1997) and thermal radiation exchange (Ozeki et al. 1998b) on walls.

Angle Factor Between a Human Body and Its Surroundings

The angle factor $F_{p\text{-}A2}$ between a human body surface and its surroundings is derived in Equation 1 with effective radiation area A_{eff}, angle factor F_{ij} between the ith differential human body surface and the jth differential wall surface, and area A_i of the ith differential human body surface (Fanger et al. 1970).

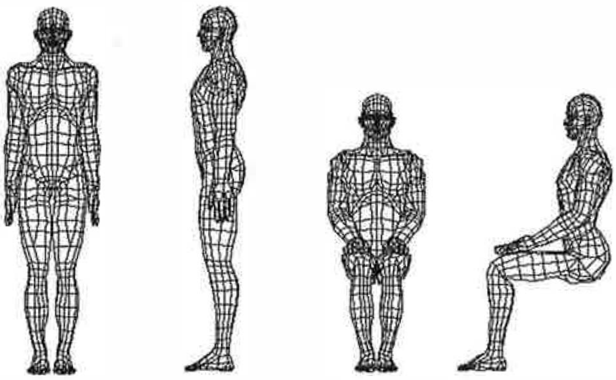


Figure 1 *Human body model (standing and seated posture).*

TABLE 1
Height and Total Surface Area of the Human Body

	Present	Fanger[*]	Horikoshi[†]	Miyazaki	Murakami
Height (m)	1.75	1.72	1.70	1.71	1.65
Total Surface Area (m^2)	1.72	1.74	1.69	1.58	1.69

[*] Mean of ten male and female subjects.

[†] Mean of three male subjects.

$$F_{p-A2} = \sum_i A_i \sum_j F_{ij} / A_{eff} \qquad (1)$$

Angle factor F_{ij} between the ith differential human body surface and the jth differential wall surface is calculated by a numerical integration method for buildings proposed by the authors incorporating the interception of other surfaces (Ozeki et al. 1996). As the procedure for calculating angle factors can deal with any indoor geometry, the present procedure can also be applied to the human body in any posture.

Effective Radiation Area of a Human Body

The effective radiation area of a human body is defined as the surface area of a human body, which directly contributes to the radiation exchange between the body and its surroundings. In the case of a large sphere with a radius r_m, the effective radiation area of a human body A_{eff} is derived in Equation 2 with the angle factor $F_{A2\text{-}p}$ between sphere and human body, as shown in Figure 2 (Fanger et al. 1970).

$$A_{eff} = 4\pi r_m^2 F_{A2-p} \qquad (2)$$

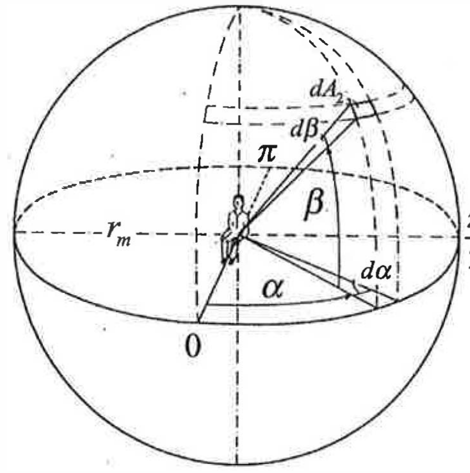


Figure 2 *Notation pertinent to calculation of the effective radiation area (Fanger et al. 1970).*

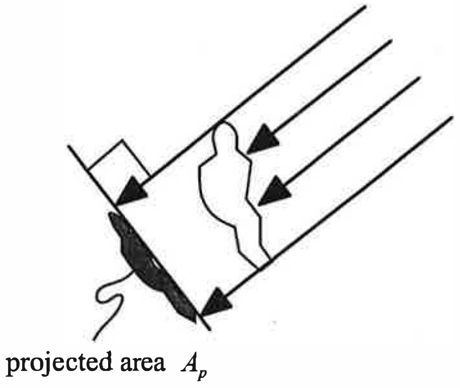


Figure 3 *Projected area of human body.*

By calculating the angle factor $F_{A2\text{-}P}$ with the projected area of a human body A_p on a plane perpendicular to the direction of the differential surface element dA_2, as shown in Figure 3, the effective radiation area can be derived from surface integration of the projected area with a spherical coordinate system (Fanger et al. 1970).

$$A_{eff} = \frac{4}{\pi}\int_{\alpha=0}^{\alpha=\pi}\int_{\beta=0}^{\beta=\frac{\pi}{2}} A_p \cos\beta d\beta d\alpha \qquad (3)$$

To calculate the effective radiation area of a human body in Equation 3, the projected area A_p of a human body irradiated by the parallel rays must be calculated. This projected area is equal to the surface area of the human body where parallel rays reach directly and are projected on a plane perpendicular to the parallel rays, as shown in Figure 3. This area is calculated by the solar heat gain simulation (Ozeki et al. 1997).

EFFECTIVE RADIATION AREA FOR BOTH STANDING AND SEATED POSTURES

To calculate the angle factors between a human body model and its surroundings, the effective radiation area of a human body must be evaluated. In this paper, the effective radiation area is calculated with Equation 3 by a numerical integration method. Ninety-one integration points are set for the numerical integration, namely, 13 different angles in azimuth α and seven different angles in altitude β. Calculated effective radiation areas A_{eff} and effective radiation area factors f_{eff} are shown in Table 2. The effective radiation area and effective radiation area factor for a standing posture are predicted rather larger than those for a seated posture. It means a seated posture has about 5% more decrease of effective radiation area in radiation exchange between a human body and its surroundings than a standing posture. Predicted results for both standing and seated postures meet quite well with those of the subjective experiments obtained by Fanger, within 2% accuracy, although configurations of the present human body and Fanger's are not the same.

ANGLE FACTORS BETWEEN HUMAN BODY AND RECTANGULAR PLANES WITHIN 7 M DISTANCE

Methods

To investigate the accuracy of the calculation method of angle factors for buildings (Ozeki et al. 1996) when applied to the complex human body surface and its surroundings, angle factors between the human body and rectangular planes are calculated. They are compared with the experimental results

TABLE 2
Effective Radiation Area and Effective Radiation Area Factor

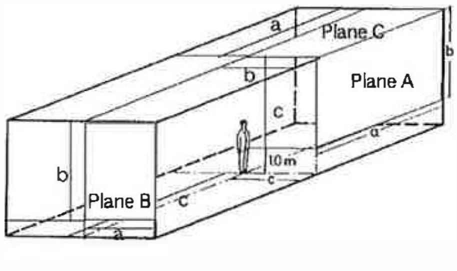
(a) Standing Posture

	Present	Fanger*	Horikoshi*	Miyazaki
$A_{eff}(m^2)$	1.276	1.262	1.312	1.317
$f_{eff}(-)$	0.744	0.725 ±0.013	0.803 ±0.005	0.834

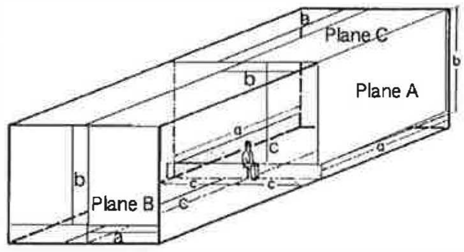
(b) Seated Posture

	Present	Fanger*	Horikoshi*	Miyazaki
$A_{eff}(m^2)$	1.176	1.211	1.214	1.224
$f_{eff}(-)$	0.691	0.696 ±0.017	0.740 ±0.012	0.775

* Obtained from the experiments with nude subjects.



(a) Standing posture



(b) Seated posture

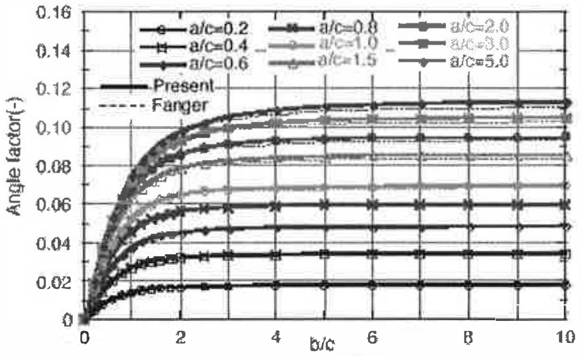
Figure 4 *Rectangular planes around the human body (*c = 7*).*

by Fanger (1970). Three types of rectangular planes for standing and seated postures (plane A, B, C) are set as shown in Figure 4. The distance between the center of the human body and each rectangular plane is set to be 7 m as in Fanger's subjective experiments. Length and width of rectangular planes are set as follows:

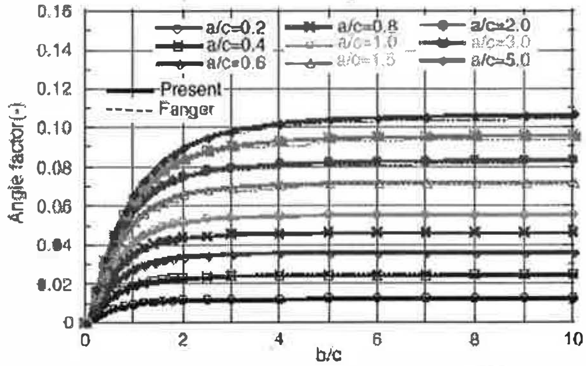
$$a/c = 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 3.0, 5.0$$

$$b/c = 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.5, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0$$

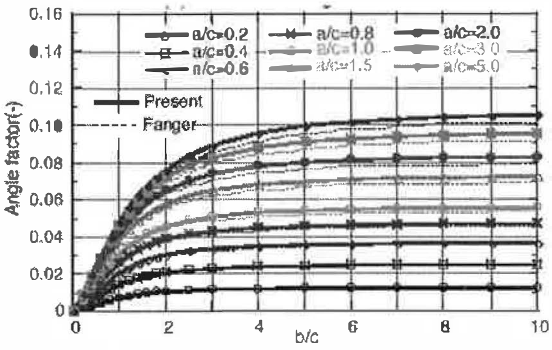
In calculating angle factors between the human body and rectangles in Equation 1, the rectangles are divided into small squares with a length of 0.7 m and the interception of other differential surfaces is taken into account.[1]



(A)-A vertical rectangle on the front wall



(B)-A vertical rectangle on the side wall



(C)-A rectangle on the ceiling

Figure 5 *Angle factors between a standing person and rectangles (*c = 7*).*

Results and Discussion

The diagrams of predicted angle factors in each rectangular plane are shown in Figure 5 for a standing person and in Figure 6 for a seated person. Comparison is shown with Fanger's subjective experimental results (Fanger et al. 1970). The regression coefficient and the coefficient of determination in each rectangle are shown in Table 3.

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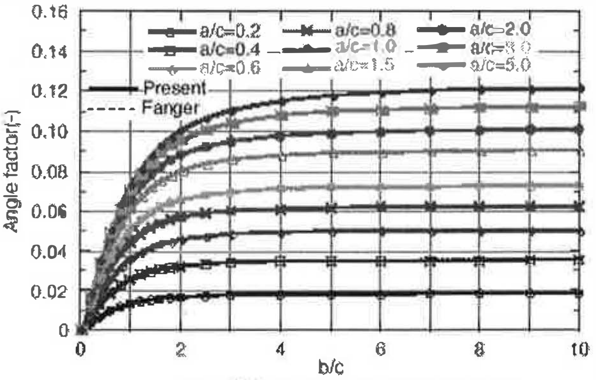
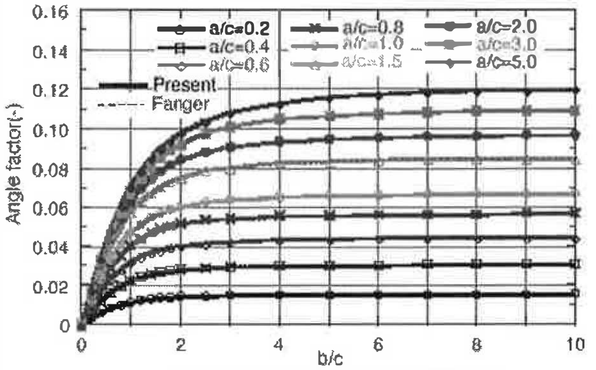
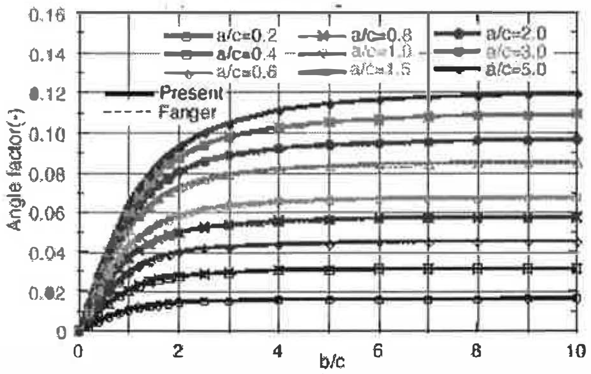
[1] In calculating angle factors between the human body and rectangles, whether the other elements, consisting of the whole human body surface, intercept or not is decided by the interception of all elements consisting of the whole human body surface and lines that connect between the center of the current surface element on the human body and the divided surface element on rectangles. In the case of crossing the line and other elements on the human body, the angle factor between the human body surface and a divided element on the rectangles is 0, that is, completely intercepted. In the case of not crossing the line, the angle factor between the human body surface and a divided element on the rectangles is generally calculated, that is, not intercepted. In the case of crossing the line and other elements on the human body at the side of the other element, the angle factor between the human body surface and a divided element on the rectangles is generally calculated and multiplied by half, that is, 50% intercepted.



(A)-A vertical rectangle on the front wall



(B)-A vertical rectangle on the side wall



(C)-A rectangle on the ceiling

Figure 6 *Angle factors between a seated person and rectangles (*$c = 7$*).*

In each rectangle, predicted angle factors for both standing and seated postures have the tendency of monotonic increase according to the rise of b/c. In the area with a small b/c value, predicted angle factors increase rapidly, and in the area with a large b/c value, predicted angle factors are almost constant.

TABLE 3
Comparison of Angle Factors Between Predicted Results and Measurements by Fanger

(a) Standing Posture

	Front Wall	Side Wall	Ceiling
Regression coefficient	0.992	0.989	0.963
Coefficient of determination	0.999	0.994	0.999

(b) Seated Posture

	Front Wall	Side Wall	Ceiling
Regression coefficient	1.006	0.993	0.993
Coefficient of determination	0.999	0.999	0.999

Comparing predicted results and Fanger's experiments for a standing person, the present results agree well with Fanger's experimental results in the area with a/c less than 1.0. A maximum 3% difference is observed at $b/c = 10$ and $a/c = 5.0$ in each rectangular plane. Comparing predicted results and Fanger's experiments for a seated person, the present results agree well with Fanger's experimental results. The maximum difference between the present results and the experiments is no larger than 1% in regression coefficients and the coefficients of determination in Table 3, suggesting that the present model is able to predict angle factors with sufficient accuracy. The present method is a useful tool for predicting them.

In the calculation of angle factors between a human body surface and a rectangular plane, Fanger introduced the parallel ray method. However, the solid angle method was utilized in the present calculation. As the angle factors introduced by the two methods correspond quite well, no significant difference in either method is found in the evaluation of angle factors in the case where the distance between the center of the person and rectangular planes is 7 m.[2] This tendency corresponds to Horikoshi's subjective experimental results (Horikoshi et al. 1990).

ANGLE FACTORS BETWEEN HUMAN BODY AND RECTANGULAR PLANES WITHIN 2 M DISTANCE

Methods

Angle factors between the human body and its surroundings within 7 m introduced by the present method and those by Fanger's agree well each other. However, Horikoshi points out that the solid angle method should be applied when calculating angle factors between the human body and its surroundings within a 1 m distance. Significant error may occur with the parallel ray method in this case. To verify that the present method can predict angle factors in these cases with enough accuracy, predicted angle factors are compared with Horikoshi's subjective experimental results. The distance between

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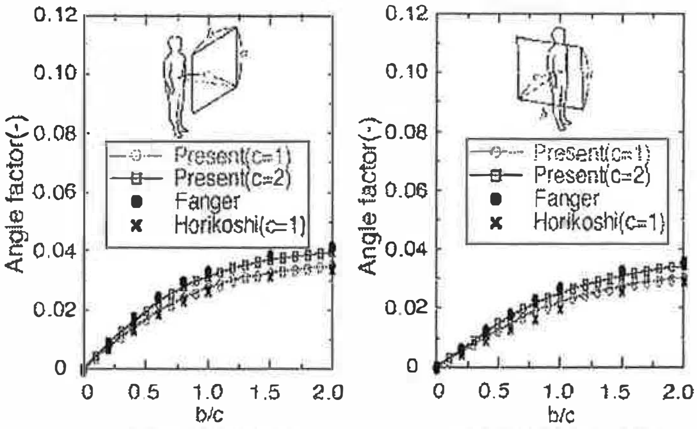
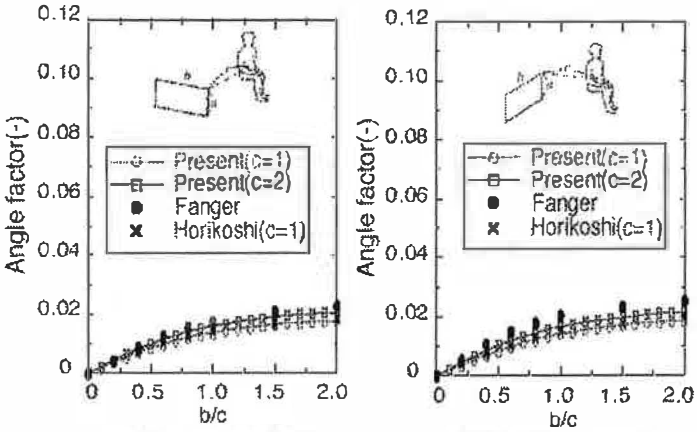
[2] A significant difference in the parallel ray method and solid angle method appears in angle factors when surroundings are close to the human body. The solid angle method is more appropriate than the parallel ray one under this condition. However, in the case of evaluating the solar heat gain, both the solid angle method and the parallel ray method are suitable.



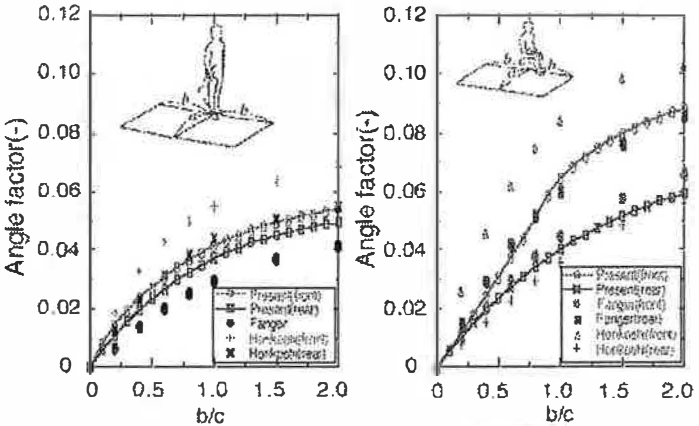
(A) - A vertical rectangle on the front wall: Standing posture (a/c=0.5)

(B) - A vertical rectangle on the side wall: Standing posture (a/c=0.5)



(C) - A vertical rectangle on the side wall: Seated posture (a/c=0.3)

(D) - A vertical rectangle on the back wall: Seated posture (a/c=3.3)



(E) - Rectangles on the floor: Standing posture (a/c=1.0)*

(F) - Rectangles on the floor: Seated posture (a/c=0.3)*

Figure 7 *Angle factors between the human body and rectangles (standing and seated posture).*

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* Angle factor of the floor touching the sole of foot is set 1.0 as in Horikoshi's subjective experiments.

the center of a human body and its surroundings is set no longer than 2 m as in Horikoshi's experimental conditions. Three types of rectangular planes for a standing posture (planes A, B, E) and three types of rectangular planes for a seated posture (planes C, D, F) are set as shown in Figure 7.

Results of Calculated Angle Factors for Vertical Rectangles and Discussion

For a standing posture, calculated angle factors between the human body and rectangles (Figure 7, A and B) in the condition of $c = 2$ correspond well with Fanger's experimental results within 6% accuracy, and calculated angle factors in the condition of $c = 1$ meet well with Horikoshi's within 4% accuracy.[3] No significant difference is found with the parallel ray and solid angle methods in calculating angle factors between the center of the human body and its surroundings with a distance of 2 m. Significant difference is found with parallel ray and solid angle methods in calculating angle factors between the center of the human body and its surroundings when the distance is 1 m. Angle factors predicted by solid angle methods (calculation and Horikoshi's subjective experiment) agree well. For a seated posture, calculated angle factors between the human body and rectangles (Figure 7, C and D) have the same tendency as for a standing posture. It is proved that the present model can predict angle factors with enough accuracy within 2 m distance.

Results of Calculated Angle Factors for the Floor and Discussion

In a standing posture, angle factors between the human body and the rectangle on the front floor are predicted to be larger than those on the rear floor because of feet, as shown in Figure 7(E). In a seated posture, angle factors between the human body and the rectangle on the front floor are predicted to be much larger than those on the rear floor as shown in Figure 6(F). Angle factors between the human body and the rectangle on the front floor go up sharply until $b/c = 1.0$ where feet are placed, and after that, angle factors show a slight rise. Angle factors between the human body and the rectangle on the rear floor correspond well with Horikoshi's subjective experiments for both standing and seated posture. However, significant difference is found between the present and the experimental angle factors concerning the front floor. Further investigation is required to find the reason for this discrepancy.

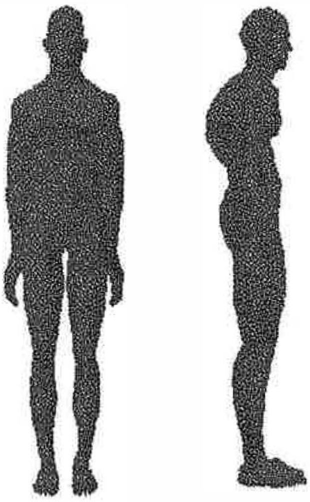

Figure 8 *Human body model (a stoop posture).*

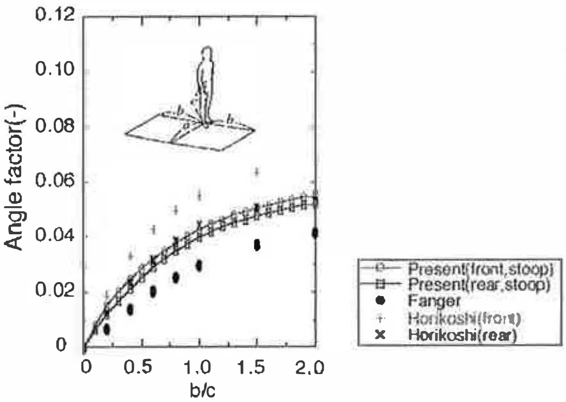

Figure 9 *Angle factors between a stoop posture and rectangles on the floor* (a/c = *1.0).*

Differences in Posture

The influence of body posture on the angle factors for the floor is investigated, conducted with a stoop posture as shown in Figure 8. The effective radiation area of a stoop posture is 1.260 m^2. Predicted angle factors on the front and rear floors are shown in Figure 9; no significant difference is found. Compared with angle factors shown in Figure 7(E),a maximum 3% difference in angle factors is observed on the front floor and a maximum 7% difference on the rear floor. This confirms that the differences between the present stoop posture and the standard standing posture have little influence on angle factors on both front and rear floors.

Effective Radiation Areas of Surface Parts of the Human Body

Angle factors between surface parts of the human body and the floor for both standing and seated postures are calcu-

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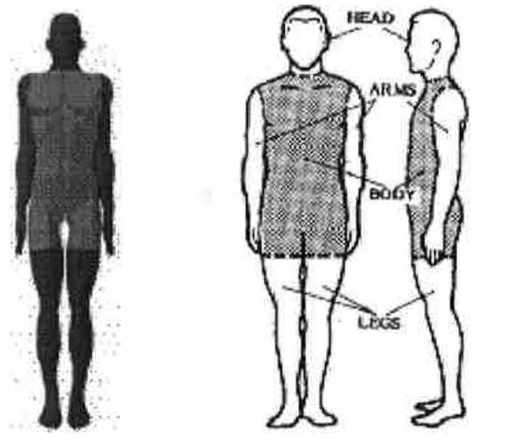
[3] The regression coefficient of the regression equation through the origin is 1.060 and the coefficient of determination is 0.991, where it is obtained by comparing predicted angle factors and Fanger's experiments in the case where the distance between the center of the person and the rectangles is 2 m. On the other hand, the regression coefficient is 0.960 and the coefficient of determination is 0.990 in the case where the distance between the center of the person and the rectangles is 1 m.



(a)Present (b)Tsuchikawa(1991)

Figure 10 *Four surface parts of the human body for calculations.*

TABLE 4
Effective Radiation Areas of Surface Parts of the Human Body

(a) Standing Posture

	Head	**Body**	**Arms**	**Legs**	**Whole Body**
Present	0.12 (9%)	0.52 (41%)	0.26 (20%)	0.38 (30%)	1.28 (100%)
Tsuchikawa	0.17 (12%)	0.61 (42%)	0.25 (17%)	0.47 (33%)	1.44* (100%)

(b) Seated Posture

	Head	**Body**	**Arms**	**Legs**	**Whole Body**
Present	0.12 (10%)	0.45 (39%)	0.29 (25%)	0.31 (26%)	1.17 (100%)

* The summation of the effective radiation area of surface-parts is 1.50 m^2, which is larger than 1.44 m^2 measured for the whole body. This point is considered to be caused by the measurement error and divided surface parts (Tsuchikawa et al. 1991).

lated. The human body is divided into four surface parts (head, body, arms, and legs) as in Tsuchikawa's subjective experiments shown in Figure 10 (Tsuchikawa et al. 1991). Calculated effective radiation areas of surface parts of the human body required for predicting angle factors are shown in Table 4. Effective radiation areas obtained by Tsuchikawa's subjective experiments are also shown in Table 4. The surface part of the human body where effective radiation area is the largest is the trunk, for both standing and seated postures, which is approximately 40% of the whole body. Comparing the ratio of the effective radiation area of surface parts against that of the whole body in both standing and seated postures, no significant difference between the two postures is found for head and body parts. However, a significant difference is found for arms and legs. Comparing the predicted effective radiation areas with Tsuchikawa's experiments for a standing posture, effective radiation areas are predicted approximately 20% smaller for trunk and legs and 30% smaller for the head.

Angle Factors of Surface-Parts of the Human Body

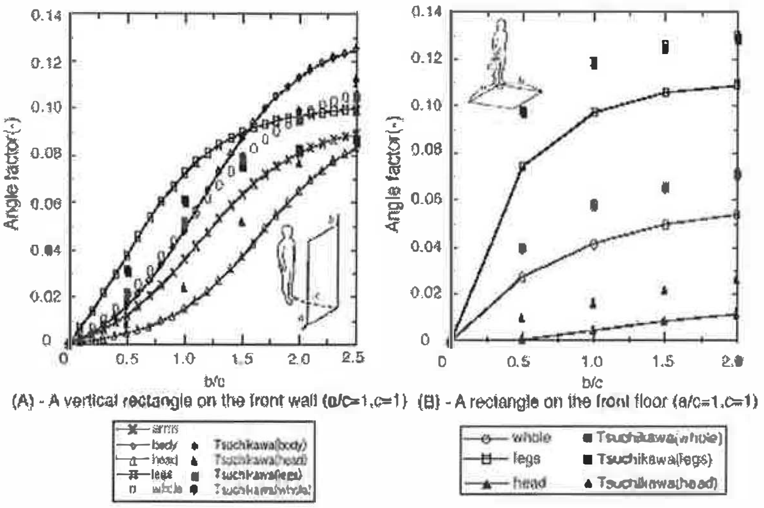
Calculated angle factors between the surface parts of the human body and rectangles on the floor are shown in Figure 11. Comparing angle factors of surface parts on the front wall with Tsuchikawa's experiments in a standing posture, about 18% difference for the head is found, as shown in Figure 11(A), because of the difference in effective radiation area. However, predicted angle factors agree well with experiments, as these results have the same tendency as the subjective experiments by Tsuchikawa. Angle factors of the whole body almost meet with the experimental results. First, it is confirmed that angle factors of surface parts of the human body can be predicted by the present method. Second, comparing angle factors of surface parts on the front floor with Tsuchikawa's experiments, shown in Figure 11(B), the present angle factors are predicted approximately 20% smaller for the legs and over 50% smaller for the head, which leads to a prediction approximately 25% smaller for the whole body. The differences of effective radiation areas of surface parts close to the rectangles are considered to have influence on predicted angle factors.

Comparing angle factors of surface parts on the front floor with those on the rear floor in a seated posture, no significant difference is found in arms and head as shown in Figure 11 (C and D). In the body part, angle factors on the front floor are predicted approximately 30% smaller than those on the rear floor because of the interception of the legs. For the legs, angle factors on the front floor are predicted a maximum four times larger than those on the rear floor, which effects the angle factors of the whole body.

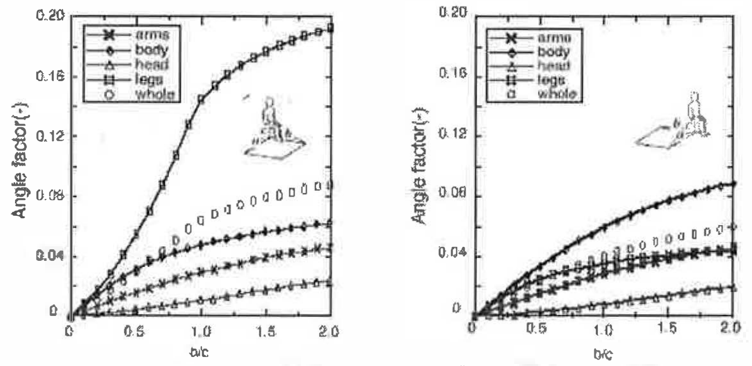
CONCLUSIONS

Angle factors between the human body and its surroundings for both standing and seated persons are calculated based on a numerical integration method proposed by the authors. The results are compared with subjective experimental results. The following conclusions were obtained.

1. The effective radiation area and effective radiation area factors for both standing and seated postures are calculated for predicting angle factors of the whole body. Compared with subjective experiments by Fanger, the results matched well within 2% difference.
2. Angle factors between the human body and representative rectangular planes are predicted in the case where the distance between the center of persons and rectangles is 7 m,



(A) - A vertical rectangle on the front wall (a/c=1,c=1) (B) - A rectangle on the front floor (a/c=1,c=1)



(C) - A rectangle on the front floor (a/c=3.3) (D) - A rectangle on the rear floor (a/c=3.3)

Figure 11 *Angle factors between the human body and rectangles (standing and seated postures).*

as in Fanger's experiments. Predicted results matched quite well with those of Fanger within 4% difference.

3. Angle factors between the human body and representative rectangular planes are predicted in the case where distance between the center of persons and rectangles is no longer than 2 m, as in Horikoshi's experiments. Predicted results correspond quite well with those of Horikoshi within 4% difference, except angle factors on the floor.

4. The influence of body posture on the angle factors for the floor was investigated. Angle factors of surface parts of the human body were also investigated. Differences in configuration of the human body, such as a stoop posture in a standing person, have little influence on angle factors, with a maximum 7% difference. It is considered that the differences of angle factors obtained by the present method and Tsuchikawa's subjective experiments are caused by the differences of effective radiation areas of surface parts close to rectangles.

Angle factors of the whole body and surface parts of the human body in any posture could be predicted by the present method with enough accuracy for practical use. This model is able to predict thermal radiation exchanges between human body surfaces and their surroundings. The method is expected to be useful tool for predicting them.

NOMENCLATURE

A_{eff} = effective radiation area of a human body, m^2
A_i = area of *i*th differential surface element, m^2
A_p = projected area of a human body, m^2
$F_{A2\text{-}p}$ = angle factor between sphere and human body
F_{ij} = angle factor between *i*th differential surface element on the human body and *j*th differential surface element on rectangles

$F_{p\text{-}A2}$ = angle factor between human body and its surroundings

f_{eff} = ratio of the effective radiation area A_{eff} to the total body surface area A_{Du} ($f_{eff} = A_{eff}/A_{Du}$)

dA_2 = differential surface element on the sphere, m^2

r_m = radius of sphere, m

α = azimuth angle

β = altitude angle

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