Evaluation of the Convective Heat Transfer Coefficient of the Human Body Using the Wind Tunnel and Thermal Manikin

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Abstract
This study was conducted to determine the convective heat transfer rates ($\alpha_c$) of each part of the human body and of the whole body when a human is in a standing or sedentary posture in an outdoor environment. A wind tunnel was used to reproduce the side wind in an outdoor environment, and a naked thermal manikin was used to control the detailed thermal characteristics of the human body. Accurate radiation analysis was employed to evaluate the radiation effect of the thermal manikin. The $\alpha_c$s of the whole body and of each part of the body increased along with the wind velocity in the standing and sedentary postures. In the standing position, the $\alpha_c$s of the head, feet, and hands, the terminuses of the human body, were about 20-30% higher than the average $\alpha_c$ of the whole body. In the sedentary position, the $\alpha_c$s of the head, hands, and arms, the terminuses of the human body, were about 20% higher than the average $\alpha_c$ of the whole body. The $\alpha_c$s in this study were lower than those obtained from the climate chamber. Meanwhile, they were similar to or slightly higher than those from the results in wind tunnels.

Keywords: convective heat transfer coefficient; human body; outdoor environment

1. Introduction
With the spread of global warming and the urban heat island phenomenon, most countries are introducing policies for sustainable architectural structures. These policies include standards for outdoor environments, such as landscaping and outdoor facilities. There is a need to estimate and evaluate the thermal comfort of the outdoor environment for the urban residents. Solar radiation and wind have the most influence on the thermal comfort of the human body in an outdoor environment. Of the two, it is wind that determines the convective heat transfer coefficient ($\alpha_c$) of the human body.

Until now, the $\alpha_c$ of the human body has been defined as an average value for the whole body. Each part of the human body has its own shape, however, and its convection and radiation also vary. Accordingly, only some parts of the human body experience a thermally unpleasant feeling even in the same environment. A methodology involving digital simulation using multi-segmented physiological and human body models was recently suggested to identify the local thermal characteristics of the human body and to evaluate its thermal comfort.

The major studies on the $\alpha_c$s of the whole human body and of each of its parts are as follows: Coin et al. calculated the $\alpha_c$ of the human body under thermal equilibrium, ignoring the heat exchange caused by heat transfer. Ignoring the effect of radiation, he evaluated only the convection of the human body by making the human skin temperature and the wall temperature of the experimental space the same. Through CFD analysis, Murakami et al. calculated the $\alpha_c$ distribution of a simple-shape computational thermal manikin in an indoor space under displacement ventilation. Ichihara et al. calculated the $\alpha_c$ of each part of the human body using the standing and sedentary thermal manikins in a test chamber. Kuwabara et al. proposed the $\alpha_c$ of the whole body using a standing thermal manikin in a wind tunnel. Silva and Coelho calculated the $\alpha_c$ of each part of the human body at a wind velocity of 0-4 m/s, with varied wind directions, using a thermal-manikin experiment. Top et al. analyzed the surrounding air flow properties of a sedentary computational simulation person (CSP) under mixing ventilation, using CFD. Ono et al. proposed the $\alpha_c$ of the whole body of the thermal manikin according to the turbulence intensity of the side wind, using the wind tunnel and CFD.

In addition to the aforementioned studies, many
studies employed simplified human-shape models to calculate the $\alpha_c$ of the human body and calculated the radiative heat transfer coefficient or radiative heat transfer rate using the effective-radiation-area or view factor quoted from other studies. Among the studies where CFD analysis was conducted, a few have calculated the convective heat transfer rate using the human skin and air temperatures, only through convective analysis. Studies have also been carried out on only the standing or the sedentary human body posture to calculate the $\alpha_c$ of the human body for a single posture. Few studies, however, calculated the $\alpha_c$ of each part of the human body by finding the effective-radiation-area and view factors for each part of the human body. Studies comparing the $\alpha_c$ of the human body in the standing and sedentary postures in an outdoor environment are also hard to find.

This study was conducted to determine the $\alpha_c$s of each part of the human body and of the whole body when a human is in a standing or sedentary posture in an outdoor environment. A wind tunnel was used to reproduce the side wind in an outdoor environment, and a naked experimental thermal manikin was used to reproduce the detailed thermal characteristics of the human body.

The calculation method previously suggested by the authors was used for the calculation of the $\alpha_c$ of the human body.

2. Calculation Process for the Convective Heat Transfer Rate ($\alpha_c$)

In this study, the $\alpha_c$ calculation method previously suggested by the authors was employed to calculate the $\alpha_c$ of each part and of the whole body of the thermal manikin. Fig.1. shows such calculation process. A wind tunnel was used to reproduce the side wind in an outdoor environment, and the air temperature ($T_{\text{air}}$) and wall temperature ($T_{\text{wall}}$) were measured during the experiment. A naked experimental thermal manikin was installed to reproduce the human thermal characteristics in the wind tunnel.

The experimental thermal manikin was divided into 16 parts, and the sensible heat transfer rate ($Q_{s,i}$) and skin surface temperature ($T_{sk,i}$) of each part were measured. Each physical quantity obtained was used in the radiation analysis as the boundary condition of the computational thermal manikin and the space to be analyzed. The radiative heat transfer rate ($Q_{r,i}$) obtained in the radiation analysis was subtracted from the sensible heat transfer rate ($Q_{s,i}$) of the experimental thermal manikin to obtain the convective heat transfer rate ($Q_{c,i}$) of each part of the manikin. Using the convective heat transfer rate ($Q_{c,i}$), manikin skin temperature ($T_{sk,i}$), and air temperature ($T_{\text{air}}$) in the wind tunnel, the $\alpha_c$ of each part of the thermal manikin was calculated.

3. Overview of the Experiment

3.1 Overview of the Experimental Space

The experiment was conducted in a wind tunnel (16.5m×2.2m×1.8m), where the side wind could be reproduced. The experimental thermal manikin was installed on the turntable where the measurement was conducted, in a standing or sedentary posture, and in a naked state. It was fixed about 5 cm above the floor so that the wind could be directed at the whole body of the thermal manikin (see Fig.2.).

All the glass that had been installed in the wind tunnel was covered with black paper, because it is difficult to analyze a subject alongside a material with such a reflective characteristic, in the radiation analysis following the experiment. The arms and legs were fixed with strings because the experimental thermal manikin could be shaken by the side wind in the standing posture. The sedentary thermal manikin was seated in a chair specially manufactured so that the value of clo could reach almost 0.

3.2 Air Flow and Temperature

The side wind of a 0.2 m/s to 1.8 m/s wind velocity was reproduced, assuming an outdoor environment. Before the experiment, the wind velocity was measured, using an ultrasonic wind velocimeter, by height (at four positions: 0.2 m, 0.4 m, 1.1 m, and 1.5 m), at the position on which the experimental thermal manikin would be installed, and the turbulence intensity was calculated (see Fig.3.).

As for the profile by height, the wind velocity at
the height of 0.2 m above the floor was lower than the average wind velocity due to the frictional resistance on the floor surface. In addition, the turbulence intensity was 20% of the average, or less, for all the wind velocities, excluding the set velocity 0.2 m/s, and the difference between the upper and lower turbulence intensities was small. The higher the set velocity was, the lower the turbulence intensity. The experiment was conducted after confirming that the wind velocity and turbulence intensity were constantly reproduced.

During the experiment, the average air temperature in the tunnel was kept at 26±0.2˚C. The difference between the upper and the lower air temperatures and between the air and the wall temperatures were kept at 0.5˚C or less.

### 3.3 Experiment Cases

The experiment was conducted for both the standing and sedentary postures in cases 1 and 2, respectively (see Table 1.). In cases 1-1 and 1-2 as well as 2-1 and 2-2, the effect of the wind velocity change on the $\alpha_c$ of each part of the human body under the same metabolic rate was examined. In cases 1-3 and 1-4, the difference in $\alpha_c$ caused by the metabolism and wind velocity for the walking and running conditions was examined. The suggestion of ASHRAE\(^9\) was employed for the correlation between the activity condition and the metabolic rate. As only the sensible heat transfer rate of the experimental thermal manikin could be evaluated, the metabolic rate of the human body was converted into the sensible heat transfer rate\(^9\) and was used as the heat transfer control condition. In addition, because the thermal manikin could not move, cases 1-3 and 1-4 were experimented on with the wind velocities corresponding to the walking and running conditions set as the relative wind velocities.

### 3.4 Measurement Items

The sensible heat transfer rate and skin temperature were measured at 16 points of the experimental thermal manikin, and the air and wall temperatures were measured at 32 and 24 points, respectively. All the measurements were conducted at one-second intervals for 30 min when the temperature properties of the experimental thermal manikin and wind tunnel reached a steady state. The air temperature in the tunnel was

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#### Table 1. Experiment and Radiation Analysis Cases

| Case   | Thermal Manikin Activity | Metabolic Rate [met] | Wind Tunnel Velocity [m/s] | Temp [˚C] |
|--------|--------------------------|----------------------|----------------------------|-----------|
| 1-1    | Resting                 | 1.2                  | 0.2                        | 0.5       |
| 1-2    | Light work              | 1.4                  | 0.9                        | 1.4       |
| Case 1 (standing) | Walking                | 2.0 (73.3)           | 0.9                        | 26        |
| 1-3    | Walking                 | 2.0 (73.3)           | 0.9                        | 26        |
| 1-4    | Running                 | 3.8 (127.6)          | 1.8                        |           |
| Case 2 (sedentary) | Resting                | 1.0 (43.1)           | 0.2                        |           |
| 2-1    | Light work              | 1.2                  | 0.9                        | 1.4       |
| 2-2    | Light work              | 1.2                  | 0.9                        | 1.4       |

( ) * is expressed as sensible heat transfer rate \([\text{W/m}^2]\) for the metabolic rate.

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Fig.3. Wind Velocity and Turbulence Intensity Profiles by Height

Fig.4. Subject Space of the Radiation Analysis
measured at the upwind side of the thermal manikin to prevent the effect of the thermal plume caused by the heat transfer of the experimental thermal manikin.

4. Radiation Analysis Overview

As shown in Fig.4., the size and shape of the wind tunnel were considered in the radiation analysis, with a standing or sedentary analytical thermal manikin inside. The size and area of the analytical thermal manikin were almost the same as those of the experimental thermal manikin. The area of the analytical thermal manikin was 95% of that of the experimental thermal manikin for the standing condition and 97% for the sedentary condition. The surface mesh in the space to be analyzed was formed into triangle shapes so as to reproduce the complex human characteristics of the analytical thermal manikin. The surface mesh was segmented into about 9,000 elements for the standing posture and into about 11,000 elements for the sedentary posture.

The upwind and downwind sides of the wind tunnel were open, with the thermal manikin as the center. The space to be analyzed was determined to be a closed space, however, because radiation analysis is conducted only in closed spaces. The average temperature of all the walls was taken to be the surface temperature of the virtual walls at the upwind and downwind sides.

The analysis program based on the radiocity method developed by Ozeki et al.\textsuperscript{11} was used for the radiation analysis. A radiation factor of 0.95 was applied to the thermal manikin, and 0.94 (the radiation factor of non-metal black paper and black paint as suggested by ASHRAE\textsuperscript{12}), was applied to the wall. The chair under the sedentary experimental thermal manikin was excluded from the analysis because its value of clo was nearly 0, and the area in contact with the thermal manikin was very small. Through radiation analysis, the radiative heat transfer rate of the experimental thermal manikin was calculated.

5. Results of the Radiation Analysis

5.1 Convective Heat Transfer Coefficient in the Standing Condition

(1) Effect of wind velocity on the same heat transfer rate: Fig.5.(a) and Fig.5.(b)

The $\bar{\alpha}_c$ of each part of the experimental thermal manikin increased along with the wind velocity in cases 1-1 and 1-2. The $\bar{\alpha}_c$s of the head, feet, and hands, which are the terminuses of the human body, were about 20–30% higher than the average $\bar{\alpha}_c$ of the whole body. Meanwhile, the $\bar{\alpha}_c$s of the pelvis, chest, and back were about 20–30% lower. Therefore, it was found that the $\bar{\alpha}_c$s of the head, feet, and hands show a greater change according to the increase in wind velocity compared to the $\bar{\alpha}_c$s of the other parts of the human body. In cases 1-1 and 1-2, the $\bar{\alpha}_c$ of the whole body was 5.34–13.89 and 5.10–13.46 W/m\(^2\)K, respectively. The $\bar{\alpha}_c$ of the human body showed a nonlinear increase even though the wind velocity increased linearly.

The experimental thermal manikin that was used in this study was divided into 16 parts, and the average skin temperature and average sensible heat transfer rate of each part were measured. It was thus difficult to analyze the detailed characteristics of the upwind and downwind sides for each part of the thermal manikin. The characteristics of the upwind and downwind sides were reflected on the chest and back, however, and the $\bar{\alpha}_c$ of the chest was about 20% higher than that of the back.

(2) Effect of heat transfer on the same wind velocity: Fig.5.(a), Fig.5.(b), and Table 2.

The comparison of cases 1-1 and 1-2, which have different heat transfer values, at the same wind velocity, showed similar $\bar{\alpha}_c$ values and trends. Accordingly, it was found that a relatively slight change in the activity condition in the standing posture has little effect on the $\bar{\alpha}_c$ of the human body. Regression analysis (99%
reliability) was conducted on the $\alpha_c$s of each part of the human body and of the whole body, according to the wind velocity change (0.2~1.4 m/s), and the results are shown in Table 2. The regression equation of the $\alpha_c$ of the whole body in the standing posture is shown in Eq. 1.

$$\alpha_c = 3.86+6.96V^{1.02} \ [W/m^2K]$$  \ (1)

(3) Effect of activity condition: Fig.5.(c)

The running condition, with a relatively fast wind velocity, showed a higher $\alpha_c$ than the walking condition. The $\alpha_c$s of the head, hands, forearms, and upper arms was about 20% higher than the average $\alpha_c$ of the whole body, while the $\alpha_c$s of the pelvis, chest, back, and thighs was about 20% lower. The change in the $\alpha_c$s of the terminuses, such as the head and hands, was relatively large with the increase in wind velocity, while that in the $\alpha_c$s of the pelvis, chest, etc. was small. The characteristics of the upwind and downwind sides were reflected on the chest and back, respectively, so that the $\alpha_c$ of the chest was greater than that of the back. The $\alpha_c$s of the thighs and pelvis were found to be somewhat lower than the actual $\alpha_c$s due to the chair that was used, which had been specially manufactured for this study (nearly 0 clo). The $\alpha_c$ at a normal chair might be higher because of the increase in the skin temperature of the thighs and pelvis.

Table 2. Regression Equation of the $\alpha_c$ of Each Part of the Human Body in the Standing Posture

| Part       | Convective Heat Transfer Coefficient [W/m²K] |
|------------|---------------------------------------------|
| Foot       | 4.09+8.85V^{0.93}                           |
| Lower leg  | 6.44+6.47V^{1.2}                            |
| Thigh      | 4.21+5.16V^{0.96}                           |
| Pelvis     | 1.84+6.48V^{0.96}                           |
| Head       | 4.85+11.24V^{0.93}                          |
| Hand       | 4.29+10.38V^{0.74}                          |
| Forearm    | 4.23+8.36V^{0.48}                           |
| Upper arm  | 2.96+9.48V^{0.35}                           |
| Chest      | 2.04+7.44V^{0.34}                           |
| Back       | 1.69+5.79V^{0.13}                           |
| Whole body | 3.86+6.96V^{0.12}                           |

5.2 Convective Heat Transfer Coefficient in the Sedentary Condition

(1) Effect of wind velocity on the same heat transfer rate: Fig.6.

The $\alpha_c$s of each part of the human body increased along with the wind velocity in cases 2-1 and 2-2. The $\alpha_c$s of the head, hands, forearms, and upper arms was about 20% higher than the average $\alpha_c$ of the whole body, while the $\alpha_c$s of the pelvis, chest, back, and thighs was about 20% lower. The change in the $\alpha_c$s of the terminuses, such as the head and hands, was relatively large with the increase in wind velocity, while that in the $\alpha_c$s of the pelvis, chest, etc. was small.

The characteristics of the upwind and downwind sides were reflected on the chest and back, respectively, so that the $\alpha_c$ of the chest was greater than that of the back. The $\alpha_c$s of the thighs and pelvis were found to be somewhat lower than the actual $\alpha_c$s due to the chair that was used, which had been specially manufactured for this study (nearly 0 clo). The $\alpha_c$ at a normal chair might be higher because of the increase in the skin temperature of the thighs and pelvis.

(2) Effect of heat transfer on the same wind velocity: Fig.6, and Table 3.

The comparison of cases 2-1 and 2-2, which have different heat transfer values, at the same wind velocity, showed similar $\alpha_c$s values and trends. For the wind velocity of 0.2 and 0.5 m/s, the $\alpha_c$s of the whole body was 4.53 and 6.61 W/m²K, respectively, in case 2-1, and 4.49 and 6.66 W/m²K, respectively, in case 2-2. Accordingly, it was found that a relatively slight change in the activity condition in the sedentary posture has little effect on the $\alpha_c$ of the human body, as for the standing posture. Regression analysis (99% reliability) was conducted on the $\alpha_c$s of each part of the body and of the whole body, according to the wind velocity change (0.2~1.4 m/s), and the results are
shown in Table 3. The regression equation of the $\alpha_c$ in the standing posture is shown in Eq. 2.

$$\alpha_c = 3.6 + 6.59V^{1.2} \text{ [W/m}^2\text{K]}$$

(2)

(3) Comparison of the standing and sedentary conditions: Fig. 7.

The change in $\alpha_c$ when the posture is changed from standing (case 1-1) to sedentary (case 2-2) is shown in Fig. 8., for the same heat transfer rate (1.2 met) and wind velocity (0.2 m/s). The thighs and hands were vertical in the standing posture but became horizontal in the sedentary posture, which led to the horizontal collision of the wind and therefore to a low $\alpha_c$. This is because the boundary layer of wind and temperature is thicker in the horizontal section than in the vertical section, which inhibits the heat transfer with the surrounding environment. Moreover, in this study, the hands of the thermal manikin were placed on the chair's armrest, which might have reduced the effect of the air flow around the hands. As for the feet and lower legs, the effect of the air flow was reduced when the experimental thermal manikin was placed in the sedentary posture because the spaces between the body parts were reduced.

The change in $\alpha_c$ according to the change in the sedentary posture was mainly caused by the fact that the thermal manikin was closer to the wind tunnel floor. Accordingly, the terminuses, such as the thighs, arms, and hands, became closer to the floor with the increase in radiative heat transfer rate and the subsequent decrease in $\alpha_c$.

6. Comparison with Other Studies: Fig. 8.

Fig. 8. shows the $\alpha_c$ values of the whole human body in the standing and sedentary postures obtained in this study, compared with the values obtained in other studies. For the standing posture, the results of this study were almost the same as those of the study conducted by Kuwabara et al. Meanwhile, compared with the results of the studies conducted by Seppanen et al. and Ichihara et al., the $\alpha_c$ was smaller in this study, especially for the higher wind velocities. The wind tunnel test conducted by Silva and Coelho showed smaller $\alpha_c$ values compared to the values obtained in this study. In the sedentary posture, as in the standing posture, the $\alpha_c$ value obtained in this study was smaller than that obtained by Ichihara et al. and by Ishii et al. and was larger than that obtained by Michell et al. and by Silva and Coelho.

It seems that the $\alpha_c$ was smaller than that of the climate chamber because the turbulence intensity was 20% or less for a wind velocity of 0.5 m/s or higher. An absolute comparison cannot be conducted because the existing studies do not have detailed turbulence intensity data. Besides, it seems that the difference in $\alpha_c$ was caused by several factors, including the manikin's posture and the radiation effect corresponding to the size of the experimental space. Especially for the sedentary posture, the effect of the correlation of the human body and the chair would be great. Therefore, a researcher who uses $\alpha_c$ must select reliable data according to the purpose of his/her study.

Table 3. Regression Equation of the $\alpha_c$ of Each Part of the Human Body in the Sedentary Posture

| Part      | Convective Heat Transfer Coefficient [W/m$^2$K] |
|-----------|-----------------------------------------------|
| Foot      | $3.94 + 6.54V^{0.93}$                         |
| Lower leg | $5.87 + 6.11V^{1.5}$                          |
| Thigh     | $2.25 + 6.72V^{0.87}$                         |
| Pelvis    | $2.24 + 6.08V^{1.21}$                         |
| Head      | $5.51 + 8.43V^{1.4}$                          |
| Hand      | $4.67 + 6.66V^{1.41}$                         |
| Forearm   | $5.0 + 8.35V^{1.03}$                          |
| Upper arm | $4.56 + 8.36V^{1.08}$                         |
| Chest     | $2.9 + 5.53V^{1.14}$                          |
| Back      | $1.78 + 5.75V^{1.38}$                         |
| Whole body| $3.6 + 6.59V^{1.2}$                           |

Fig. 8. Comparison of the $\alpha_c$s of the Whole Body Obtained in This Study with Those Obtained in Other Studies

(a) Standing posture

Ichihara et al.: $\alpha_c = 12.1V^{0.48}$
Ishii et al.: $\alpha_c = 11.0V^{0.58}$
Mitchell et al.: $\alpha_c = 8.3V^{0.86}$
Silva and Coelho: $\alpha_c = 4.1V^{3.9}$

(b) Sedentary posture

Seppanen et al.: $\alpha_c = 14.8V^{0.69}$
Ichihara et al.: $\alpha_c = 15.7V^{0.61}$
Kuwabara et al.: $\alpha_c = 3.3V^{0.7} + 6.86V^{0.92}$
Silva and Coelho: $\alpha_c = 3.9V + 3.6$
7. Conclusion

1) This study proposed a regression equation for the convective heat transfer coefficient ($\alpha_c$) of each part of the human body in the standing and sedentary postures, according to the wind velocity change in an outdoor environment. To reproduce the outdoor side wind and human heat transfer, a wind tunnel and an experimental thermal manikin were used in this study. Accurate radiation analysis was employed to evaluate the radiation effect of the thermal manikin.

2) The $\alpha_c$s of the whole body and of each part of the body increased along with the wind velocity in the standing and sedentary postures.

3) In the standing position, the $\alpha_c$s of the head, feet, and hands, the terminuses of the human body, were about 20–30% higher than the average $\alpha_c$ of the whole body. Meanwhile, the $\alpha_c$s of the pelvis, chest, and back, which comprise the trunk of the body, were about 20–30% lower. In addition, the $\alpha_c$ in the running condition was about 1.4 times higher than that in the walking condition. In an outdoor environment, the effect of a change in the human heat transfer on the $\alpha_c$ was small.

4) In the sedentary position, the $\alpha_c$s of the head, hands, and arms, the terminuses of the human body, were about 20% higher than the average $\alpha_c$ of the whole body. Meanwhile, the $\alpha_c$s of the pelvis, chest, back, and thighs were about 20% lower. With the same wind velocity, the effect of a change in the human heat transfer on the $\alpha_c$ was small. Therefore, it seems that in an outdoor environment, the effect of a slight change in activity on the $\alpha_c$ is small.

5) When the posture changed from standing to sedentery under the same heat transfer rate, the $\alpha_c$s of the feet, lower legs, thighs, and hands decreased. This was because the distance between the floor and the human body decreased and the radiative heat transfer rate increased.

6) The $\alpha_c$s in this study were lower than those obtained from the climate chamber. Meanwhile, they were similar to or slightly higher than those from the results in wind tunnels.

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