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SIMULTANEOUS MEASUREMENTS OF OUTDOOR THERMAL ENVIRONMENTS AND PHYSIOLOGICAL RESPONSES OF WALKING PEDESTRIANS

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ABSTRACT

Health hazards in extremely hot summer conditions have increased rapidly with urban heat islands, severe weather, etc. in recent years. Previous studies have assessed thermal environments within target area using SET* and have evaluated acceptable volume ratios based on SET*. Acceptable volume was defined as the volume in which the value of SET* was less than the acceptable maximum limit. Using these methods, health hazard risk is considered to be very high at the points where the thermal index, such as SET*, exceeds the threshold value. However, people in outdoor spaces are often walking in real-life situations in urban street, and do not stay in the same place for prolonged periods of time. Thus, even when there are very hot points in the evaluation area, the health risk may not be high if there are also cool spots nearby.

This study simultaneously measured outdoor thermal environments and human physiological responses to determine the effects of changeable environments (e.g. wind velocity and radiation) on pedestrians walking and standing in outdoor spaces.

Field measurements were performed in pedestrian spaces within the premises of Tohoku University from September 26-30, 2014. Subjects wore clothes with instruments attached to measure physiological variables (skin surface temperature, core temperature, heat flux at skin surface, and blood pressure) and they walked with a cart with attached instruments for meteorological variables (air temperature, relative humidity, globe temperature, wind velocity, and short- and long- wave radiation). In this study, five sets of measurements were carried out to evaluate the influence of four characteristics of outdoor environments that are usually not found in indoor environments: (1) wide ranges of wind velocity, (2) wide ranges of radiation, (3) sudden change in surrounding environments (mostly due to moving to other places), and (4) physiological changes induced by walking.

The results of these measurements were as follows.

(1) When wind velocity is high, skin surface and core temperatures decrease gradually.

(2) Under high MRT situation, skin surface temperature increases rapidly and core temperature increases gradually.

(3) When people move to colder spaces, core temperature increases temporarily; similarly, when people move to hotter spaces, core temperature decreases temporarily.

(4) Skin surface temperature is lower in walking situations than in standing (without walking) situations.

Keywords: Walking pedestrians; Moving measurements of outdoor thermal environment; Outdoor thermal environments; Human physiological responses; Skin and core temperature

1. INTRODUCTION

In recent years, health hazards in extremely hot summer conditions have increased rapidly with urban heat islands, severe weather, etc. Previous studies employed SET* to assess thermal environment within target areas and evaluated acceptable volume ratios based on SET*. The acceptable volume was defined as the volume in which the value of SET* was less than its acceptable maximum limit (Xuan et al., 2012 and Yumino et al., 2015). Based on these methods, the health hazard risk is considered to be very high at the points where the thermal index, such as SET*, exceeds the threshold value. However, people in outdoor spaces are often walking on urban streets, and they do not necessarily stay at the same location for extended periods. Thus, even though there may be very hot points in the evaluation area, health risks may not be high if there are cool spots nearby.

This study performed simultaneous measurements of outdoor thermal environments and physiological responses of pedestrians walking and standing in outdoor spaces in order to determine the effects of changeable environment factors in outdoor spaces (e.g. wide ranges of wind velocity and radiation) on pedestrians.

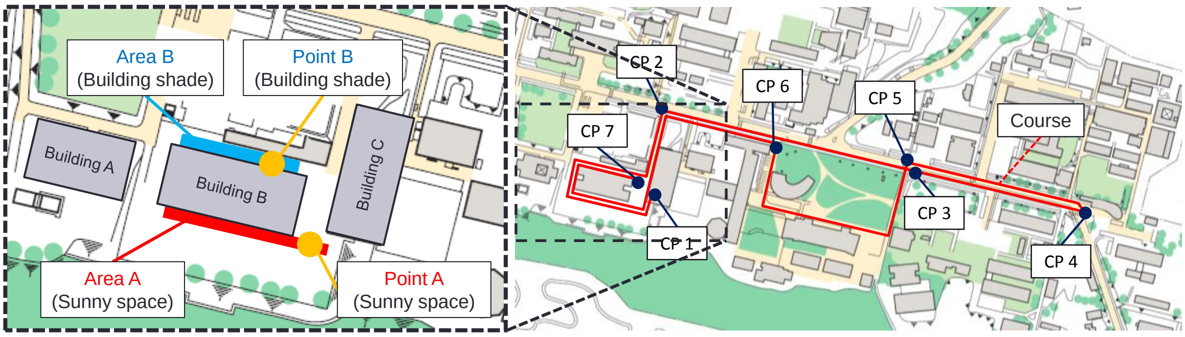
2. FIELD MEASUREMENTS OF OUTDOOR THERMAL ENVIRONMENT AND PYSIOLOGICAL RESPONSES

2.1 Outline of Field Measurements

2.1.1 Case Settings

Field measurements were carried out in the open space within the premises of Tohoku University from September 26-30, 2014. The measurement areas are shown in Figs. 1 and 2.

This study identified four factors that affect human physiological responses in outdoor spaces: (1) wide ranges of wind velocity, (2) wide ranges of radiation, (3) rapid changes in the surrounding environment (mainly caused by moving to other places), and (4) walking. Five types of measurements



(1) Area A and B (2) Course for Case 5

Figure 1. Measurement Areas.

(1) Point A and Area A (sunny space)

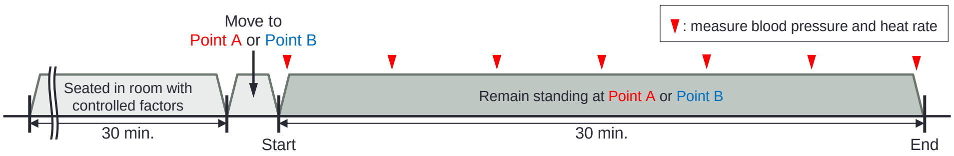
(2) Point B and Area B (building shade)

Figure 2. Photos of Measurement Areas.

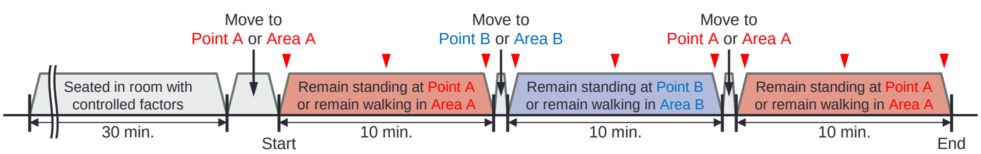
were performed to determine how these factors affected pedestrians. The schedules and factors considered in each case are shown in Table 1 and Fig.3. In Cases 1 to 4, considered the factors were added one at a time in order to assess human physiological responses to each factor, while the physiological responses of pedestrians walking in real outdoor space were measured in Case 5. Subjects remained sitting for 30 min in a controlled room (all meteorological factors were held constant) before each measurement.

Table 1. Schedules and Factors Considered in Each Case.

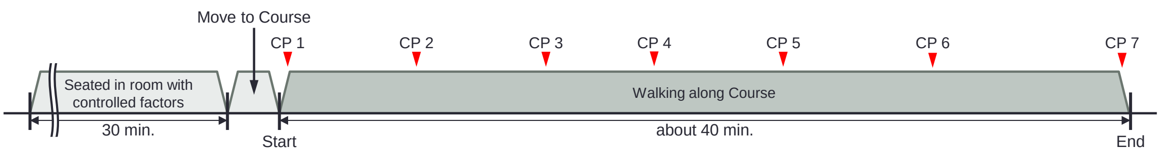
	Schedule	Considered factors
Case 1	Remain standing at Point B (Building shade, Fig. 1 (1)) for 30 min.	Wide ranges of wind velocity
Case 2	Remain standing at Point A (Sunny space, Fig. 1 (1)) for 30 min.	Wide ranges of wind velocity and Wide ranges of radiation
Case 3	Moving from Point A to Point B and Point B to Point A (Fig. 1 (1)), and remain standing for 10 min. at each point.	Wide ranges of wind velocity, Wide ranges of radiation and Rapid changing of surrounding environment
Case 4	Moving from Area A to Area B and Area B to Area A (Fig. 1 (1)), and remain walking for 10 min. in each area.	Wide ranges of wind velocity, Wide ranges of radiation, Rapid changing of surrounding environment and Walking
Case 5	Walking along Course (Fig. 1 (2)).	Walking along real outdoor space



(1) Cases 1 and 2



(2) Cases 3 and 4



(3) Case 5

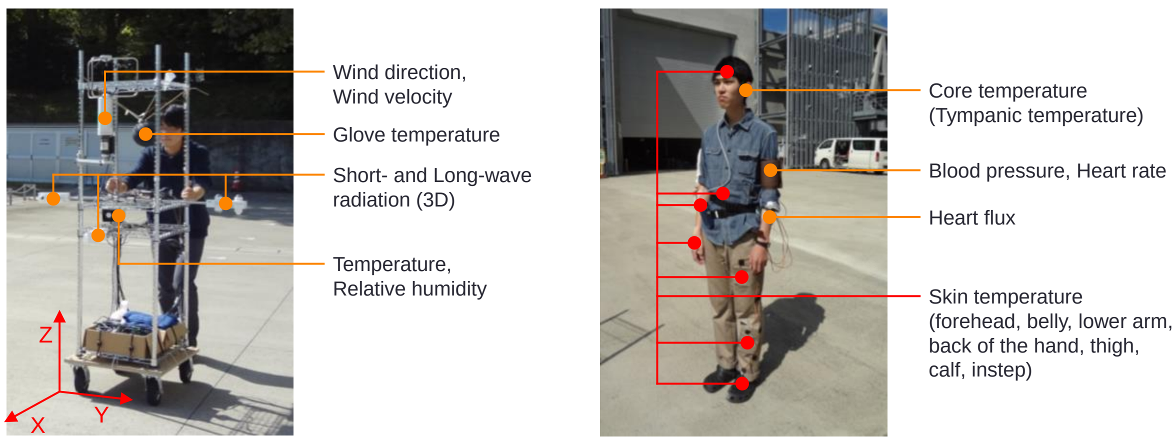
Figure 3. Case Schedules.

2.1.2 Measured Variables

The measured variables are shown in Table 2. Cart with attached instruments were used to measure meteorological variables, including relative wind direction and relative wind velocity (absolute value of the difference between the wind velocity in the area and the moving velocity of the cart), temperature, relative humidity, short- and long-wave radiation, and globe temperature. Three net radiometers were used to measure three-dimensional (3D) radiant heat transports. This enabled us to evaluate short- and long-wave radiant heat fluxes from the front, back, right, left, top, and bottom. Clothing with attached instruments was to measure physiological variables, including skin temperature, core temperature (tympanic temperature), heat flux at the skin surface of the arm, blood pressure, and heart rate. Blood pressure and heart rate were measured at following times (Fig. 3): every 5 minutes for Cases 1 and 2, just after (and before) leaving area and five minutes before leaving the area in Cases 3 and 4, and when the subject reached each check point (CP 1~7 in Fig. 1) in Case 5. The subject remained standing for approximately one minute while measuring blood pressure and heart rate even in Cases 4 and 5. The cart and clothing are shown in Fig. 4. Weight was measured at the beginning and end of each measurement and evaporated sweat was calculated as their difference. Positional information was measured using a global positioning system (GPS) with mobile phone.

Table 2. Measured Meteorological and Physiological Variables and Instruments Used.

Variables	Instruments	Interval	Height
Wind direction, wind velocity	3D ultrasonic anemometer (R.M. Young, CYG-81000)	0.1 s	1.8 m
Air temperature, relative humidity	Thermistor / polymer sensors (T&D, TR-72U) with double blower pipe and sun shield	1 s	1.0 m
Globe temperature	Glove ball with thermocouple	1 s	1.5 m
Short- and long-wave radiation	Net radiometer (EKO, MR-60)	1 s	1.0 m
Skin temperature	Thermocouple (forehead, belly, lower arm, back of the hand, thigh, calf and instep)	1 s	
Core temperature (tympanic temperature)	Thermopile and thermistor (TECHNO SCIENCE, BL-100)	1 s	
Heat flux (lower arm)	Heat flux sensor (CAPTEC, HF-D30)	1 s	
Blood pressure (upper arm), heart rate	Blood pressure monitor (A&D, TM-2431)		
Evaporated sweat	Digital weight scale (A&D, GP-100K)		
Positional information	Mobile phone		



(1) Cart for measurement of meteorological variables

(2) Clothing for measurement of physiological variables

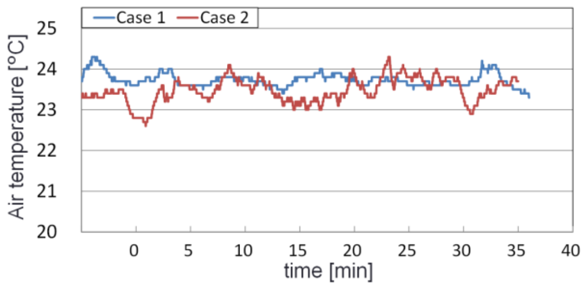
Figure 4. Cart and Clothing with Attached Instruments.

2.2 Results of Field Measurements

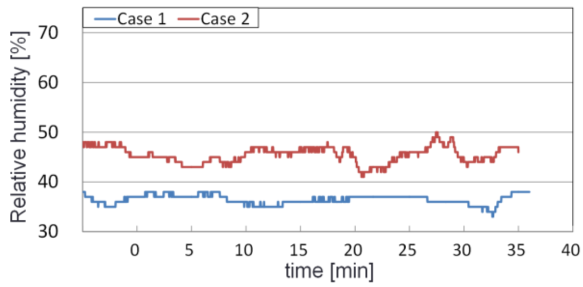
2.2.1 Case 1 (Standing in building shade, blue line in Fig. 5)

Mean skin surface temperature was calculated from seven skin surface temperatures (the forehead, belly, lower arm, back of the hand, thigh, calf, and instep) by weighted averaging based on the seven-point method developed by Hardy and DuBois (J. D. Hardy and E. F. DuBois, 1938). Figs. 5 (6) and (7) show that skin and core temperatures decreased gradually in building shade. In the controlled room environment, meteorological variables were almost equal to those measured at Point B except that wind velocity and skin and core temperatures were kept constant; therefore, we concluded that the decrease in these two physiological variables was caused by the wide ranges of wind velocity in the outdoor space.

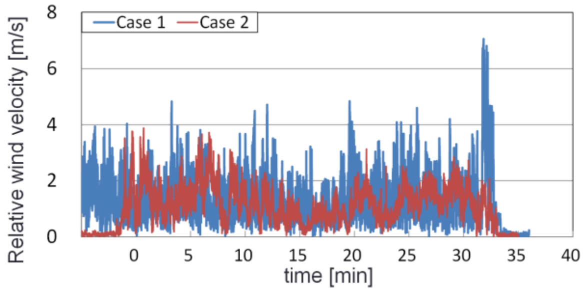
2.2.2 Case 2 (Standing in a sunny space, red line in Fig. 5)



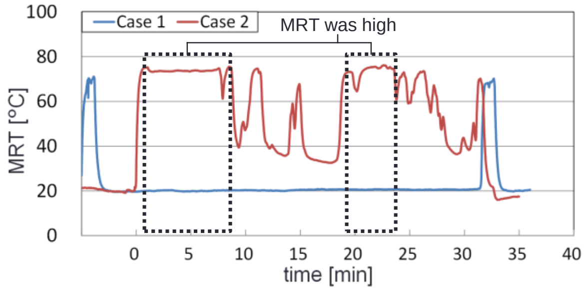
(1) Air temperature



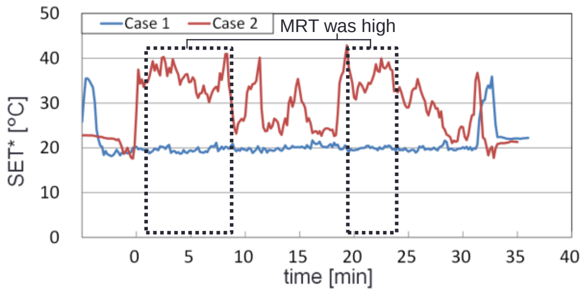
(2) Relative humidity



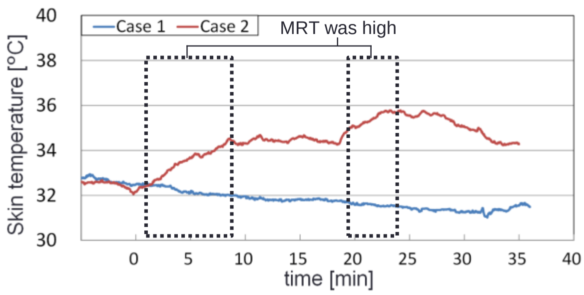
(3) Relative wind velocity



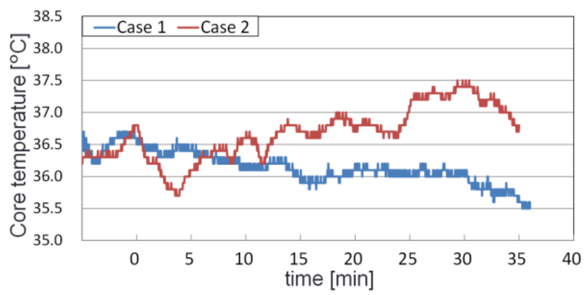
(4) MRT



(5) SET*



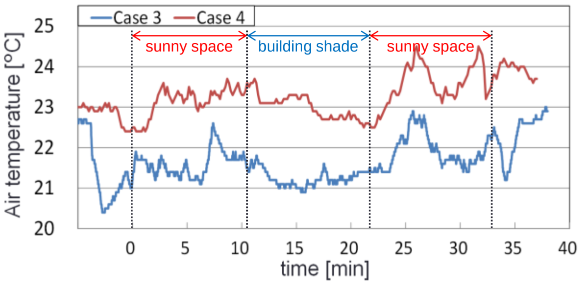
(6) Skin temperature



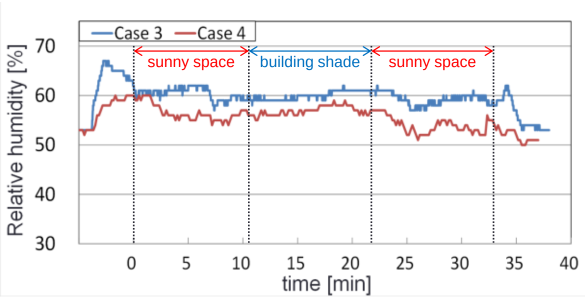
(7) Core temperature

Figure 5. Results of Case 1 (standing in building shade) and Case 2 (standing in a sunny space).

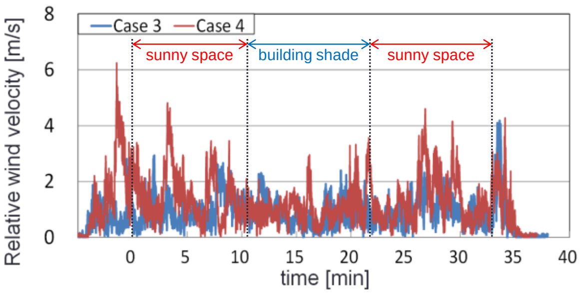
The tendency of SET* was similar to that of MRT, as shown in Figs. 5 (4) and (5). Figs. 5 (4) and (6) show that skin temperature increased when MRT was high; 0-8 and 18-24 minutes after measurement started. Core temperatures had the same tendency as skin temperatures, as shown in Fig. 5 (7). The meteorological variables in Case 2 were almost same as those measured in Case 1, except MRT. This indicates that the increase in those two physiological variables was caused by the wide ranges of solar radiations.



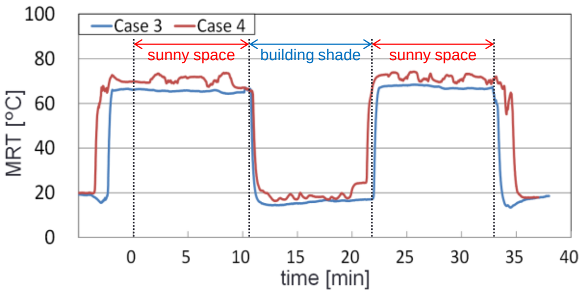
(1) Air temperature



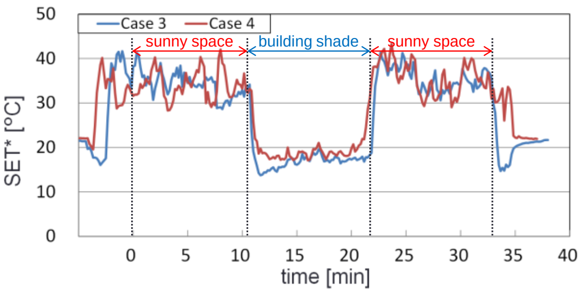
(2) Relative humidity



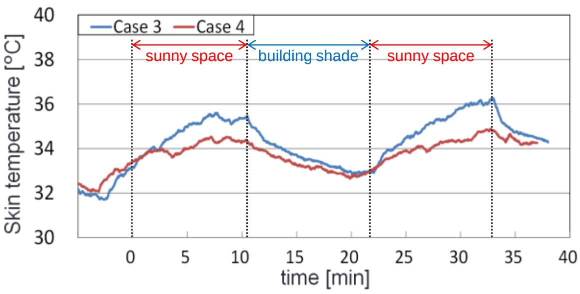
(3) Relative wind velocity



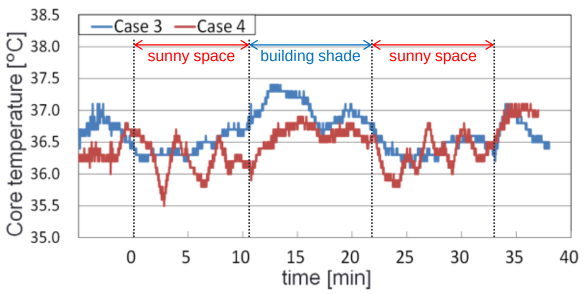
(4) MRT



(5) SET*



(6) Skin temperature

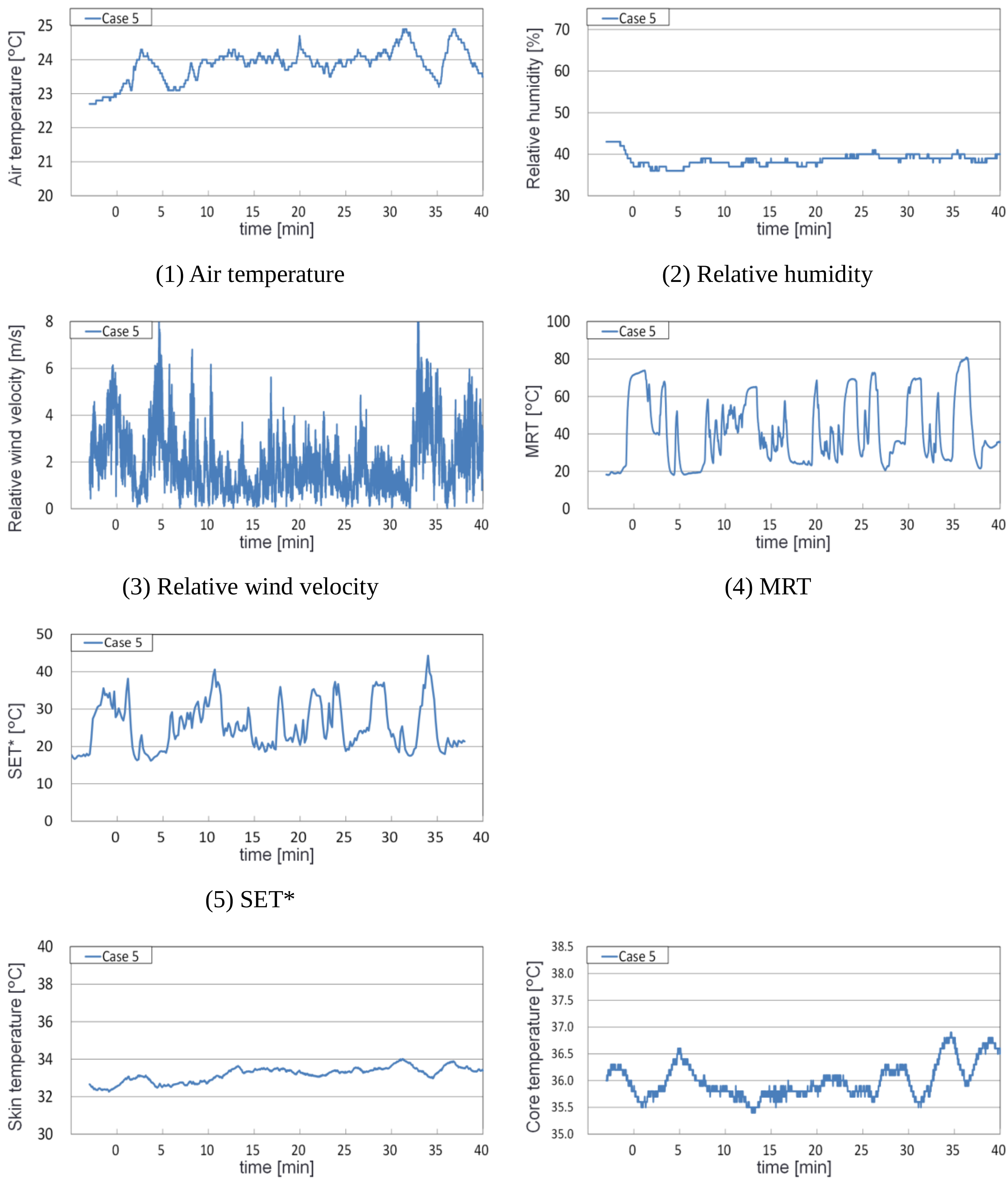


(7) Core temperature

Figure 6. Results of Case 3 (alternately standing in sunny spaces and building shade) and Case 4 (alternately waking in sunny spaces and building shade).

2.2.3 Case 3 (Standing in sunny space and building shade alternately, blue line in Fig. 6)

Skin temperature increased in sunny spaces and decreased in building shade, as shown in Fig. 6 (6). Fig. 6 (7) shows that core temperature values had the same tendency as skin temperature except for just after moving to other points. Approximately 11-13 minutes after starting measurement, when the subject moved from a sunny space to building shade, the core temperature increased temporarily, and



(1) Air temperature (2) Relative humidity

(3) Relative wind velocity (4) MRT

(5) SET*

(6) Skin temperature (7) Core temperature

Figure 7. Results of Case 5 (walking along a course).

deceased temporarily 22-24 minutes after starting measurement, when the subject moved from building shade to a sunny space. The similar tendency was observed in a previous study. Tanaka et al. (2006) reported that core temperature increases temporarily when the subject is exposed to colder environments and decreases temporary when exposed to hotter environments. Skin blood flow increases when the subject is exposed to hotter environments and heat flow from the core to skin also increases, which causes a temporary decrease in core temperature. Conversely, skin blood flow decreases with exposure to colder environments; heat flow from the core to the skin also decreases, causing a temporary increase in core temperature.

2.2.4 Case 4 (Alternately waking in sunny spaces and building shade, red line in Fig. 6)
Skin temperature increased in sunny spaces and decreased in building shade, as shown in Fig. 6 (6). However, the range of the increase in Case 4 (walking) was smaller than that of Case 3 (standing) for the following reasons: latent heat release by evaporation of sweat and partial increase of relative wind velocity from the arms and legs while walking. Core temperature in the sunny spaces changed intricately, as shown in Fig. 6 (7). When the subject walked from west to east, core temperature increased and decreased when the subject walked from east to west. The wind direction was from east to west when Case 4 was conducted, so the relative wind velocity decreased when the subject changed walking direction from toward-east to toward-west. This observation suggests that the subject lost less heat by convection, when the walking direction was changed from toward-east to toward-west, and this caused a temporary decrease in core temperature. Conversely, relative wind velocity became stronger when subject changed the walking direction from toward west to toward east. It means that the subject lost more heat by convection, and this caused a temporal increase in core temperature.

2.2.5 Case 5 (Walking along course, Fig. 7)
The range of variation in skin temperature was smaller in Case 5 than in other Cases, as shown in Fig. 7 (6), likely because the subject was exposed to a very unsteady environment and did not remain in a hot or cold environment for prolonged periods of time. Core temperature changed intricately, as shown in Fig. 7 (7).

3. Conclusions
1) Simultaneous measurements of outdoor thermal environments and human physiological responses were performed to determine how changeable environment in outdoor space affected pedestrians.
2) The results of these measurements were as follows.
(1) When wind velocity is high, skin surface temperature and core temperature decrease gradually.
(2) Under high MRT situation, skin surface temperature increases rapidly and core temperature increases gradually.
(3) When people move to colder spaces, core temperature increases temporarily; conversely, core temperature decreases temporarily when people move to warmer spaces.
(4) Skin surface temperature decrease more in walking situations compared to standing (without walking) situations.

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