Academic Article

Experimental Analysis of Human Thermal Condition During Outdoor Exercise under Summer Conditions

Yasuhiro SHIMAZAKI*[1] Atsumasa YOSHIDA*[2] Shohei TAKETANI*[1]

*[1]Department of System Engineering for Sports, Okayama Prefectural University
*[2]Department of Mechanical Engineering, Osaka Prefecture University

Corresponding author: Yasuhiro SHIMAZAKI, shimazaki@ss.oka-pu.ac.jp

ABSTRACT

Outdoor walking is a common activity in daily life. In order to estimate the human thermal environment, we investigated the relationship between physically measured human thermal states (based on human thermal load) and subjective thermal perceptions. The experiments were performed for 50 min, including 10 min of rest before and after 30 min of exercise, at three distinct velocities: 0 m/min standing, 55 walking, and 167 running, under summer conditions. The results provide valuable information for discussing urban street comfort in relation to human activity. For outdoor walking or running, although radiation is significant, metabolic heat generation has a greater impact on human thermal states. Human thermal load is a useful tool because human thermal states, and changes in them, are herein expressed quantitatively by dividing the energy flow around humans into components. However, there are some limitations to estimating thermal sensation for high-intensity-activity applications.

Key Words: Thermal comfort, Human energy balance, Perception, Pedestrian, Transient

1. Introduction

Factors in climate change, such as global warming and the urban heat-island phenomenon, have become widely known. Increased temperature has also occurred in Japan and because of this, an increasing number of uncomfortable situations, including heat-related disorders and even mortality, have been reported recently outdoors in summer.(1) Therefore, much research has addressed adaptation measures, particularly regarding human thermal perception. In particular, human comfort and thermal sensation have attracted attention as evaluation criteria for assessing the thermal environment. Human thermal perception is generally considered to be predictable from calculations of the human energy balance. This balance is considered to be closely associated with human thermal conditions, of which the six predominant components are known to be temperature, humidity, wind condition, radiation, clothing insulation, and metabolism.(2) It is advisable to include as many factors as possible in studies of thermal conditions, particularly human factors.

International thermal comfort standards such as SET*(3) and PMV(4) were developed based on relatively neutral indoor thermal environments and are commonly used. In reality, humans experience extremely hot situations when active outdoors. Therefore, these indoor standards have limitations when applied to outdoors. Moreover, outdoor human thermal perception is considered to be different from indoor human thermal perception.(5) In addition, there is a lack of available data for establishing or verifying any new index for the outdoor thermal environment.

Radiation has always been the focus in assessments of the outdoor thermal environment, because of the large amount of heat received. Metabolism increases with increasing exercise intensity, and sometimes high-speed walking generates larger amounts of heat than is received in radiation. Thus, in this study, our goal was to obtain information about human thermal states, as well as physiological and mental responses during outdoor walking in summer, related to pedestrian comfort and safety.

2. Procedures

The experiment was performed by observing the physiological reactions and mental actions of human subjects, as the surrounding weather factors and the physiological responses of the human body were measured. The global solar radiation (EKO MR-60), reflected solar radiation from the ground (EKO MR-60), infrared radiation from the atmosphere and ground (MR-60), air temperature (thermistor), 3-D wind velocity (Young CYG-81000), humidity (capacitive hygrometer), and ground temperature (thermo couple T) were measured in 1-min intervals. Field measurements were performed in three distinct outdoor spaces, and within an indoor space at three distinct walking velocities, in the summer of 2013. The thermal-environment assessments were done in two different ways: (a) "Human thermal load," was based on estimating the human energy balance in an outdoor environment[6] and (b) "Thermal perceptions," was based on the sense of satisfaction or dissatisfaction under the prevailing climatic conditions in the outdoor spaces. Measurements were performed to include the effect of surfaces such as black asphalt concrete, green concrete, and natural grass. The surfaces considered were typical of outdoor exercise scenarios. As a reference, the experiment was also performed indoors in a similar manner.

The human thermal load is in itself the heat flux under a given condition and is calculated from Equation (1) as the amount remaining after summing each item of an energy balance. It is an objective value based on an energy-balance formula for the human body, which incorporates varying degrees of physiological factors:

$$Q = M - W + R_{net} - E - C \quad (1)$$

where M quantifies the metabolic variable proposed by Weir [W/m^2] [7], W is the workload [W/m^2], R_{net} is the net radiation [W/m^2], E is the latent heat loss [W/m^2], and C is the sensible heat loss [W/m^2]. In a steady state, and even in an unsteady state due to variations in weather and human factors, the thermal condition can generally be obtained using the overall human thermal load.

Subjects were asked whether they experienced any thermal sensation, and if so, whether they experienced it as comfort or discomfort on a 5-point scale from "discomfort (-2)" to "comfort (+2)". The subjects were also instructed to note their mental reactions every 2 min on a fixed report that employed a 7-point scale from "cold (-3)" to "hot (+3)", as proposed by ASHRAE.[8] At the same time, subjects were asked about their perceptions of perspiration, from "not at all (0)" to "extremely (+3)", and thirst, from "not at all (0)" to "extremely (+3)".

The experiments were performed for 50 min, including 10 min of rest before and after 30 min of exercise, at velocities of 0 m/min standing, 55 walking, and 167 running, under summer conditions. The clothing insulation was 0.41 clo throughout the experiment.

Sensors (thermistors and perspiration meter; at seven points on the skin; sublingual for thermistor) were installed 15 min before the measurements began, at which point the subjects had become accustomed to the devices and returned to their original states. A heart-rate meter (Polar RS800CX) and exhaled gas analyzer (S&Me VO2000) for evaluating the metabolism were also installed at this time. All this equipment was synchronized. The body mass was measured before and after the experiment to observe any weight change from sweating.

A total of 30 healthy males participated in the study (Height 1.72 ± 0.06 m, Weight 63.3 ± 7.0 kg, Age 21.0 ± 1.3 yr). The research was conducted during a hot season in Okayama, with approval from the Research Ethics Committee of Okayama Prefectural University.

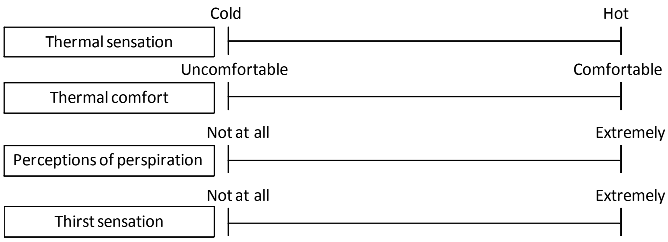

Fig. 1 Topics covered in subjective questionnare

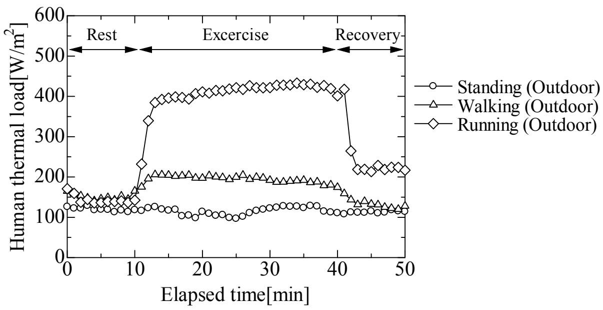

Fig. 2 Time-dependent changes in human thermal load

Table 1 Time-averaged human thermal load

		Rest	Exercise	Recovery
Outdoor	Standing	120	115	113
	Walking	152	195	133
	Running	144	406	244
Indoor	Standing	31	25	23
	Walking	39	73	32
	Running	34	220	81

3. Results

3.1 Human thermal states

For reference, the average air temperature, humidity, wind speed, and solar radiation were approximately 31.0 °C, 53.9% RH, 0.9 m/s outdoors (calm indoors), 704 W/m^2 outdoors, and 0 W/m^2 indoors, respectively.

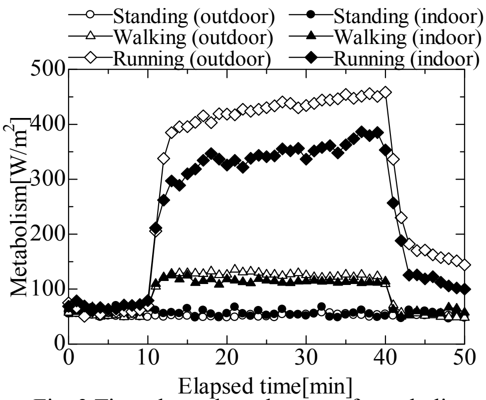

Fig. 3 Time-dependent changes of metabolism

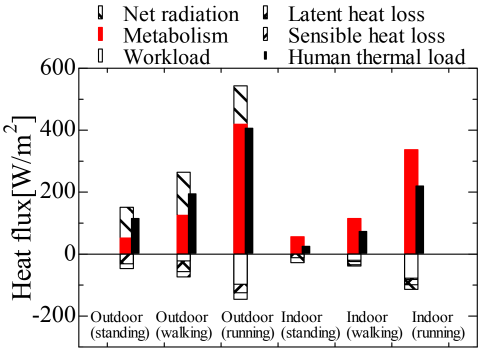

Fig. 4 Human-thermal-load components for exercise

The time-dependent changes in total human thermal load outdoors are shown in Fig. 2. During their rest periods, the subjects behaved similarly, just standing, and their thermal loads were almost the same (approximately 140 W/m^2). The total human thermal load, with subjects standing, remained almost constant and a thermal steady state was reached. Human thermal loads for walking and running rapidly increased after 10 min from the time exercise started. After a short while, human thermal loads settled and thermal steady states were reached. During walking, the human thermal load was approximately 200 W/m^2, and during running, approximately 410 W/m^2. After 40 min from the time walking exercise terminated, the human thermal load rapidly decreased and returned to initial levels. The human thermal load for running also rapidly decreased, however it settled into another level at approximately 220 W/m^2. Human thermal loads indoors showed the same tendencies. The time-averaged human thermal load in each period, and under each exercise condition, is shown in Table 1. Even during rest periods when subjects only stood, there was approximately 100 W/m^2 difference between outdoor and indoor human thermal loads. During exercise periods, the outdoor/indoor difference in human thermal load for walking was approximately 120 W/m^2, and for running, approximately 190 W/m^2. The difference between outdoor and indoor human thermal loads increased with increasing intensity of exercise. Even when the intensity of exercise was the same, the human thermal load outdoors tended to be larger than that indoors.

The time-dependent metabolic changes are shown in Fig. 3. Metabolism was almost constant against time for standing, and was almost constant for other intensity-levels of exercise as well. When subjects stood during rest periods, the metabolic value was approximately 55 W/m^2. There were no significant outdoor/indoor differences in metabolism. The metabolism rapidly increased after walking or running for 10 min. Then, metabolic conditions settled and thermal steady

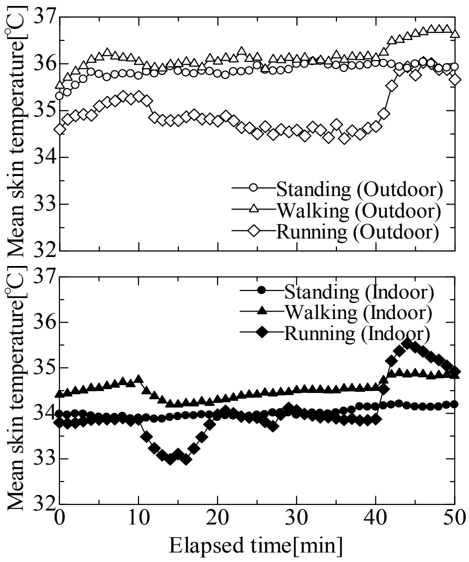

Fig. 5 Time-dependent flux of mean skin temperature

state was reached for walking. The time-averaged metabolism during walking was 125 W/m^2 outdoors and 115 W/m^2 indoors. Metabolism for running also settled at a certain level; however, the value continued to increase gradually. The time-averaged metabolism during running was 419 W/m^2 outdoors and 337 W/m^2 indoors. After finishing the walking exercise, metabolism quickly returned to previous levels. In contrast, during recovery after running, metabolism gradually decreased but did not reach initial levels in the rest period. Metabolism tends to increase with increasing intensity of exercise. At the same time, metabolism tends to become higher outdoors because humans experience environmental heat stress when outdoors during hot periods.

Breakdowns of total human thermal load are shown in Fig. 4. Since there were notable differences in human thermal loads during the exercise period, time-averaged values during the exercise period are shown in the figure. During this period, values for each human-thermal-load component fell within a certain range. Outdoors, for example, metabolic values were approximately 52, 125, and 419 W/m^2 for standing, walking, and running, respectively. Metabolism tended to increase with increasing intensity of exercise. On the other hand, the amount of net radiation (as a heat source) was almost constant, with values of approximately 120 W/m^2 outdoors and 10 W/m^2 indoors. This is the reason that outdoor/indoor human thermal loads were different throughout the experiment. In the experiment, or even under real living conditions, metabolism and net radiation are normally the only heat sources received outdoors. When you look at the ratio of metabolism and net radiation, it is easy to realize which is the more influential factor. As the intensity of activity increases, the effect of metabolism becomes stronger. For outdoor walking or running, although radiation is significant, metabolic generation of heat has a greater impact on human thermal states. Indoors, net radiation has little effect.

Changes in time-dependent mean skin temperature are shown in Fig. 5. The mean skin temperature is calculated according to Hardy and DuBois's formula.(9) You need to understand the skin temperature differences in advance because of personal and environmental ranges. Mean skin temperature is almost constant against time when standing. The time-averaged mean skin temperature when standing was 35.9 °C outdoors and 34.0 °C indoors. Outdoors, the mean skin temperature increased gradually during the rest period. This is because, in humans, the skin temperature is adjusted according to the outdoor environment. When walking, the mean skin temperatures decreased slightly after 10 min. The reduction of the maximum mean skin temperature was approximately 0.3 °C outdoors and 0.5 °C indoors. A short while later, the mean skin temperature during walking reached an almost constant level. The mean skin temperature increased after the walking exercise ended. The mean skin temperature for running subjects made similar moves; however, there was larger variation over time. After the running exercise started, mean skin temperatures dropped because of the decline of blood flow and because of sweating. In addition, heat transfer was promoted by the increased relative wind speed due to body motion. The maximum decrease in the mean skin temperature was approximately 0.5 °C outdoors and 0.9 °C indoors. After running finished, the mean skin temperature rose temporarily. The mean skin temperature was higher outdoors than indoors. The decline in the mean skin temperature at the start of exercise was larger for running than for walking. Since latent heat loss or convective heat transfer is influenced by the difference between the human-skin and

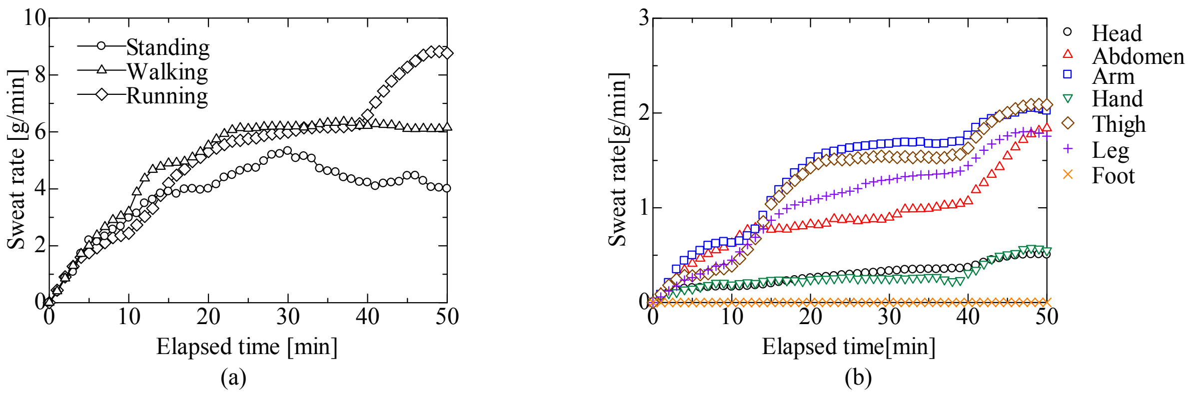

Fig. 6 Time-dependent changes of sweat rate: (a) Total outdoor sweat rate, (b) Regional sweat rate running outdoors

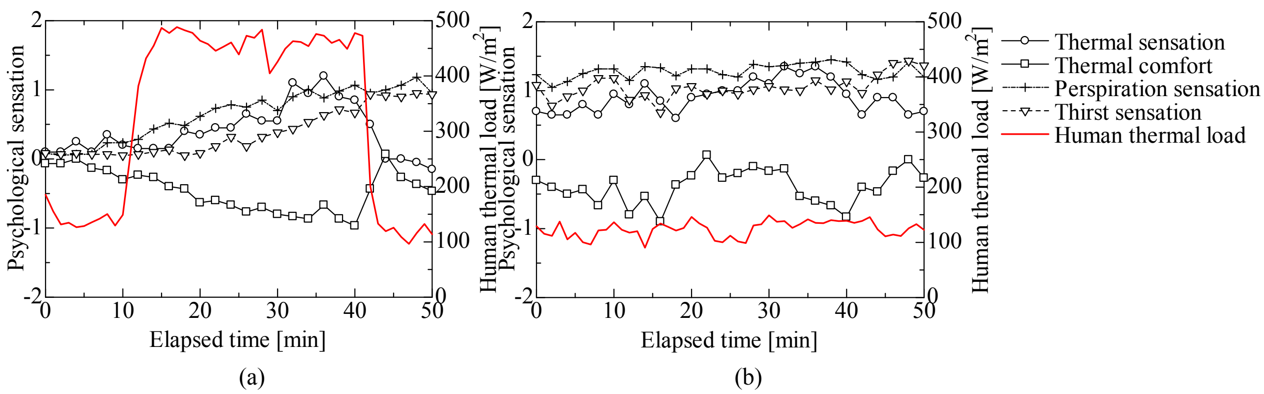

Fig. 7 Time-dependent changes of thermal perceptions and human thermal load: (a) Running outdoors, (b) Standing outdoors

ambient temperatures, and because the ambient temperature was almost constant during the experiment, the time variation of latent heat loss can be determined from changes in the mean skin temperature.

The time-dependent sweat rate changes outdoors are shown in Fig. 6 (a). Evaporative heat release is important, especially for high thermal loads such as occur outdoors. During the rest period, the sweat rate gradually increased due to heat exposure. After 10 min, the sweat rates for walking and running sharply increased because of increasing metabolic-heat generation. Sweat rates for standing and walking settled at a certain level. The sweat rate for running showed another increase during the recovery period. This occasionally happened when the intensity of the exercise was high. The sweat rate increased with increasing intensity of exercise. The maximum sweat rate was 5.3 g/min standing, 5.9 walking, and 8.8 running. The time-dependent regional sweat rates for outdoor running are shown in Fig. 6 (b). Each regional sweat rate made similar moves; however, the feet were not sweating at all. The abdomen, arms, thighs, and legs had up to 2 g/min higher sweat rates. The head and hands have relatively lower sweat rates, because they are exposed directly to wind, and because their sensible heat loss provides a significant advantage for cooling.

The workload in general varies according to intensity of exercise. In our experiment, the workload values, both outdoors and indoors, were approximately 0 W/m^2 standing, 25 walking, and 90 running.

3.2 Thermal perceptions

Examples of time-dependent changes in thermal perceptions outdoors are shown in Fig. 7. As a reference for human thermal states, the human thermal load is also drawn in the figures. Since the thermal stress, or human thermal load, is almost constant while standing, all sensations remain almost constant. For running, perceptions of temperature, perspiration, and thirst increased during the exercise period. Then at the time the exercise finished, sensation of heat dropped rapidly. However, the perceptions of perspiration and thirst continued to increase. Thermal comfort decreased until the exercise finished; then rose rapidly.

4. Discussion

In order to analyze the interconnection between objectively measured human thermal states and subjective thermal perceptions, the relationship between them is shown in Fig. 8(a). In a previous study, a linear relationship between human thermal load and thermal sensation was confirmed. In this study, our results revealed a linear relationship between

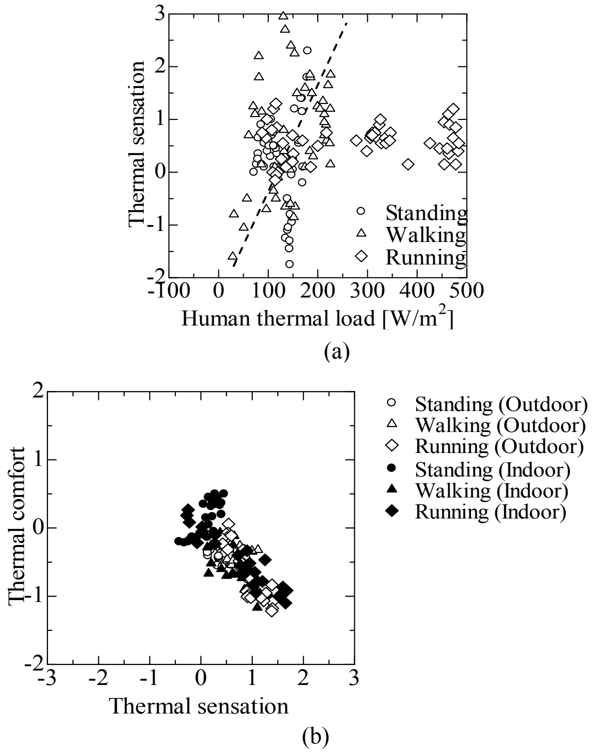

Fig. 8 Thermal perceptions: (a) Relationship between thermal sensation and human thermal load, (b) Relationship between thermal comfort and thermal sensation

human thermal load and thermal sensation for standing and walking. However, another trend was found in running during exercise and afterward, during the recovery period. The thermal sensation for running shows relatively low values during the recovery period, even when humans experience large thermal loads due to substantial generation of metabolic heat. The relationship between thermal comfort and thermal sensation is also shown in Fig. 8 (b). There is a good linear relationship between thermal comfort and thermal sensation in general, therefore one possible reason for not estimating thermal sensation based on thermal load, is because of the outmost transient response of thermal perception. Another reason may be due to the ability to calculate human thermal loads directly.

The main cause of large human thermal loads is increased metabolism during exercise and the recovery period. Convective heat release from humans may be induced, because relative wind speed exists and air-flow becomes turbulent around moving humans. To calculate the latent heat loss, Yang's convective heat-transfer coefficient[10] was adopted and expressed as

$$h = 3.6 \times 6.97\, v^{0.89} \quad (2)$$

where h is the convective heat transfer coefficient [W/m^2/K], and v is wind speed [m/s]. A 167 m/s body movement is simply equivalent to approximately 2.8 m/s wind. Considering the increase in the loss of latent heat by movement, its effect on overall human thermal load is limited. Therefore, there are some limitations for estimating thermal sensation using human thermal load during transient periods of high-intensity exercise, at this stage.

The delayed responses of thermal comfort and thermal sensation were observed just after exercise started, as shown in Fig. 7 (b). Metabolism sharply increases; however, thermal comfort and thermal sensation change gradually. Changes in the perception of perspiration and thirst also are not consistent with human thermal load. Perspiration constantly increased throughout the experiment (Fig. 6), in this sense, perspiration offers an indication of sweat or latent heat loss. A good relationship was observed between the perceptions of perspiration and thirst. Therefore, there are limitations in estimating thermal comfort and thermal sensation for high-intensity activity applications.

5. Conclusions

In order to measure and understand human thermal conditions during outdoor exercise, the participants in the study performed for 50 min, including 10 min of rest before and after 30 min of exercise, at three distinct velocities. We measured the physical and mental responses, and then estimated human thermal states by using human thermal load.

First, we obtained valuable human information with which to discuss urban street comfort in relation to human activity.

Our results indicate that when walking or running outdoors, although radiation is significant, metabolic heat generation has a greater impact on human thermal states. Human thermal load is a useful tool, because human thermal states, and improvements in them, may be expressed quantitatively by dividing the energy flow around humans into components. However, there are some limitations to estimating thermal sensation for high-intensity-activity applications.

References

(1) M. Kondo, Y. Honda, M. Ono, Growing Concern about Heatstroke This Summer in Japan after Fukushima Nuclear Disaster, Environmental Health and Preventive Medicine, 16-5 (2011), pp. 279-280.

(2) ASHRAE, The 2009 ASHRAE Handbook – Fundamentals (2009), ASHRAE, Atlanta.

(3) A.P. Gagge, A.P. Fobelets, L.G. Berglund, A Standard Predictive Index of Human Response to the Thermal Environment, ASHRAE Transactions, 92-2B (1986), pp. 709-731.

(4) P.O. Fanger, Thermal Comfort (1973), McGraw-Hill, New York.

(5) P. Hoppe, Different Aspects of Assessing Indoor and Outdoor Thermal Comfort, Energy and Buildings, 34 (2002), pp. 661-665.

(6) Y. Shimazaki, A. Yoshida, R. Suzuki, T. Kawabata, D. Imai, S. Kinoshita, Application of Human Thermal Load into Unsteady Condition for Improvement of Outdoor Thermal Comfort, Building and Environment, 46-8 (2011), pp. 1716-1724.

(7) J.B.V. Weir, New Methods for Calculating Metabolic Rate with Special Reference to Protein Metabolism. Journal of Physiology, 109 (1949), pp. 1-9.

(8) ASHRAE, Standard 55-2013 - Thermal Environmental Conditions for Human Occupancy (2013), ASHRAE, Atlanta.

(9) J.D. Hardy, E.F. DuBois, The Technique of Measuring Radiation and Convection. Journal of Nutrition, 15-5 (1938), pp. 461-475.

(10) J.H. Yang, S. Kato, S, Murakami, T. Takahashi, T. Hayashi, Measurement of Convective Heat Transfer Coefficient with Using a Experimental and Computational Thermal Manikin (Part 2): Convective Heat Transfer Coefficient of Each Part of a Human Body in Outdoor and Indoor Environment, Proceedings of The Society of Heating, Air-Conditioning Sanitary Engineers of Japan, (2001), pp. 777-780. (in Japanese)

(Received Nov. 12, 2014, Accepted Dec. 27, 2014)