Estimation of Expected Temperature Using Heat Balance Model and Observation Data

Eun-Byul Kim, Jong-Kil Park1),* and Woo-Sik Jung2)

Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China
1)Department of Civil & Environmental Engineering, Atmospheric Environment Information Research Center (AEI), Inje University, Gimhae 621-749, Korea
2)Department of Atmospheric Environment Information Engineering, Atmospheric Environment Information Research Center (AEI), Inje University, Gimhae 621-749, Korea

*Corresponding author. Tel: +82-55-320-3250, E-mail: envpjk@inje.ac.kr

ABSTRACT
This study considers mean skin temperature to calculate expected temperature using the new heat balance model because the skin temperature is the most important element affecting the heat balance outdoors. For this, we measured the skin temperature in high temperature condition of Korea and applied it to calculate the expected temperature. The calculated expected temperature is compared with the result calculated using previous models which use the estimated mean skin temperature by considering metabolic rate only. Results show that the expected temperatures are higher when measured mean skin temperature is applied to the model, compared to the expected temperature calculated by applying mean skin temperature data calculated using metabolic rate like previous models. The observed mean skin temperature was more suitable for outside conditions and expected temperature is underestimated when mean skin temperature calculated by the equation using metabolic rate is used. The model proposed in this study has a few limitations yet, but it can be applied in various ways to facilitate practical responses to extreme heat.

Key words: Heat balance model, Extreme heat, Climate change, Expected temperature, Skin temperature

1. INTRODUCTION

To ensure the normal functioning of the organs of the human body, the core temperature of the human body should be around 37 ± 1°C in the resting state. To achieve this, a balance is struck between the heat supply and heat loss by exchanges within the body, or with the external environment (Kim, 2013).

Within the human body, metabolic processes generate heat while fueling body movements. To maintain a stable body (or skin) temperature, the human body undergoes constant heat exchange with the external environment.

Some of the representative forms of heat exchange include convection, conduction, evaporation, respiration, and radiation (Fig. 1).

Most heat balance models are based on the assumption that the energy generated in the human body and that consumed during body movements is equivalent to the heat absorbed or emitted through the skin and respiration. However, this balance is also affected by conditions in the external environment. There are a number of models that take into account the heat balance between the human body and the environment.

We reviewed previous models, and found that most of them were fixed; that is, the variables in each module could not be adjusted. In this study, a new heat balance model was used to calculate the expected temperature (°C). The new heat balance model was based on Huang’s model (Huang, 2007) and ASHRAE (2005). The expected temperature is defined as the outdoor temperature that will provide thermal comfort under given external conditions (i.e., mean radiant temperature, relative humidity, and wind speed), and in relation to metabolic rates and clothing insulation.

Most previous models calculated skin temperature using equations which considers only the metabolic rate. However, through this way, the skin temperature cannot be considered correctly. To obtain precise mean skin temperature, it is necessary to measure skin temperature. Therefore we measured skin temperature in the high temperature condition of Korea. The observed skin temperatures were applied to the new heat balance model, and the results are compared with other results which are obtained by using skin temperature calculated by equations based on metabolic rates like previous models. The difference between the expected tempera-
ture obtained by these two way is analyzed: one way is to use measured skin temperature and the other way is to use calculated skin temperature considering the metabolic rate. Finally, we applied these mean skin-temperature data for calculating the expected temperature.

2. DATA AND METHODOLOGY

2.1 New Heat Balance Model

Kim and Park (2014) developed a new heat balance model which estimates optimal expected temperature to satisfy the thermal comfort by improving the mean radiation temperature variable by considering various levels of relative humidity, wind speed, mean radiation temperature, metabolic rate, and clothing insulation. Since the expected temperature is sensitive to the mean radiation temperature, the new heat balance model which considers the mean radiation temperature is relevant to the Korean climate. Therefore, a new heat balance model developed by Kim and Park (2014) is used.

Equation 1 is the new heat balance model used in this study:

\[ M - W = C + R + E + C_{res} + E_{res} + S \]  (1)

Where,
- \( M \) = metabolic rate, W/m²
- \( W \) = mechanical power, W/m²
- \( C \) = convective heat loss from skin, W/m²
- \( R \) = radiation heat loss from skin, W/m²
- \( E \) = evaporative heat loss from skin, W/m²
- \( E_{res} \) = evaporative heat loss from respiration, W/m²
- \( C_{res} \) = convective heat loss from respiration, W/m²
- \( S \) = rate of body heat storage, W/m²

2.2 Mean Skin Temperature

We used a heat balance model developed by Kim and Park (2014). It is sensitive to mean radiation temperature and the experiment using this new model is conducted from August 21 to August 24, 2007 (except on August 22, when it rained). The experimental site was a fitness center at Inje University, Gimhae, Gyeongnam Province, Korea. The subjects were selected by application from among university students in their twenties. Finally, eleven individuals participated in this experiment. At first, we used eight measurement points to examine changes in the human skin temperature (Fig. 2). The measurement points were on exterior to the clothes on the chest (Sensor 1), right cheek (Sensor 2), left chest on skin (Sensor 3), right chest on skin (Sensor 4), right forearm (Sensor 5), back of right hand (Sensor 6), front of right thigh (Sensor 7), and front of right calf (Sensor 8). The actual experiment was conducted for 39 min which is divided into periods of adaptation, main experiment, and resting. The experimental conditions have been described in greater detail in Kim (2013). However, it is found that obtaining mean skin temperature by measuring minimal areas is appropriate to reduce errors of measurement. Therefore, the mean skin temperature is calculated by averaging the human skin temperature measured by Burton’s 3-point method (Burton, 1934) and 4-point method (Ramnathan, 1964).

The 3-point method and 4-point method calculate the mean skin temperature by using Eq. 2 and 3, respectively. The differences between the two methods are the location of the skin temperature measurement points in the body, the number of measurement point, and the weighting of the measured skin temperature when calculating the mean skin temperature. Mitchell and Wyndham (1969) showed that 98% of the subjects exhibited only a small difference between the skin temperature calculated by 4-point method and actual skin temperature and this difference of the temperature do not exceed 1°C. Also, Yao et al. (2007) and Ramnathan (1964) reported that correlation among mean skin temperatures calculated by using 3-point method, 4-point method, 7-point method, and 12-point methods is high. Therefore, using 3-point method and 4-point method is considered suitable for this study.

\[ T_{sk} = 0.5 T_{chest} + 0.14 T_{forearm} + 0.36 T_{calf} \]  (2)

\[ T_{sk} = 0.3 T_{chest} + 0.3 T_{forearm} + 0.2 T_{calf} + 0.2 T_{thigh} \]  (3)

Where,
- \( T_{sk} \) = mean skin temperature, °C
- \( T_{chest} \) = skin temperature of chest, °C
- \( T_{forearm} \) = skin temperature of forearm, °C
- \( T_{calf} \) = skin temperature of calf, °C

Fig. 1. Heat exchange between the human body and the external environment.
In previous studies, Equation 4 was used to calculate mean skin temperature (Huang, 2007; Tucker, 2006).

\[ T_{\text{sk}} = 35.7 - 0.0285 \times M \]  (4)

3. RESULTS AND DISCUSSION

Among the variables of the model, mean skin temperature is calculated using the metabolic rate, as shown in Equation 4. In this study, we examined whether the mean skin temperature calculated by the model matches the measured mean skin temperature.

To do so, metabolic rates that correspond to the experimental conditions were determined, based on the metabolic rates determined by the type of activity, as shown in Table 1. Mean skin temperature was calculated with the help of Equation 4. In a relaxed standing position before the experiment (metabolic rate of 70
mean skin temperature was 33.71°C. When the mean skin temperature reached equilibrium after long exposure to the outdoor environment, the mean skin temperature was 30.71°C. Next, in the adaptation phase, the subject walked on a treadmill at 2 km/h for the first 2 min; then at 4 km/h for the next 2 min. The mean skin temperature that corresponded to the metabolic rate (115 W/m²) was 32.42°C. When the equilibrium was reached, the temperature was 29.42°C. Finally, the exercise was done at 6 km/h (metabolic rate of 220 W/m²), and at a similar rate of 6.4 km/h. The mean skin temperature was calculated to be 29.43°C for these cases, and at equilibrium, was 26.43°C.

Based on these results, the biggest difference in the measured mean skin temperature can be explained as follows. The mean skin temperature (°C) rose with exercise speed on the treadmill (Fig. 3). In sharp contrast, according to Equation 4, mean skin temperature fell as the exercise speed rose. This was at odds with the outcome of this study and with other findings. The mean skin temperature calculated by the model and that calculated using measured data in the experiment differed from 0.12°C to 5.69°C.

To this end, one case of relative humidity varying according to changes in mean radiant temperature was examined. Different metabolic rates were applied by

| Activities                     | W/m² | met |
|-------------------------------|------|-----|
| Resting                       |      |     |
| Sleeping                      | 40   | 0.7 |
| Reclining                     | 45   | 0.8 |
| Seated, quiet                 | 60   | 1.0 |
| Standing, relaxed             | 70   | 1.2 |

Walking (on level surface)

| Speed | W/m² | met |
|-------|------|-----|
| 3.2 km/h (0.9 m/s) | 115  | 2.0 |
| 4.3 km/h (1.2 m/s) | 150  | 2.6 |
| 6.4 km/h (1.8 m/s) | 220  | 3.8 |

Office activities

| Activity                  | W/m² | met |
|---------------------------|------|-----|
| Reading, seated           | 55   | 1.0 |
| Writing                   | 60   | 1.0 |
| Typing                    | 65   | 1.1 |
| Filing, seated            | 70   | 1.2 |
| Filing, standing          | 80   | 1.4 |
| Walking about             | 100  | 1.7 |
| Lifting/packing           | 120  | 2.1 |

Driving/Flying

| Activity         | W/m²         | met  |
|------------------|--------------|------|
| Car              | 60 to 115    | 1.0 to 2.0 |
| Aircraft, routine| 70           | 1.2  |
| Aircraft, instrument landing | 105 | 1.8 |
| Aircraft, combat | 140          | 2.4  |
| Heavy vehicle    | 185          | 3.2  |

Miscellaneous occupational activities

| Activity                              | W/m² | met  |
|---------------------------------------|------|------|
| Cooking                               | 95 to 115 | 1.6 to 2.0 |
| Housecleaning                         | 115 to 200 | 2.0 to 3.4 |
| Seated, heavy limb movement           | 130  | 2.2  |
| Machine work                          |      |     |
| Sawing (table saw)                    | 105  | 1.8  |
| Light (electrical industry)           | 115 to 140 | 2.0 to 2.4 |
| Heavy                                 | 235  | 4.0  |
| Handling 50 kg bags                   | 235  | 4.0  |
| Pick and shovel work                  | 235 to 280 | 4.0 to 4.8 |

Typical metabolic heat generation for various activities (after ASHRAE, 2005).

| Activities                  | W/m² | met |
|-----------------------------|------|-----|
| Resting                     |      |     |
| Sleeping                    | 40   | 0.7 |
| Reclining                   | 45   | 0.8 |
| Seated, quiet               | 60   | 1.0 |
| Standing, relaxed           | 70   | 1.2 |

Walking (on level surface)

| Speed          | W/m² | met |
|----------------|------|-----|
| 3.2 km/h       | 115  | 2.0 |
| 4.3 km/h       | 150  | 2.6 |
| 6.4 km/h       | 220  | 3.8 |

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| Writing                   | 60   | 1.0 |
| Typing                    | 65   | 1.1 |
| Filing, seated            | 70   | 1.2 |
| Filing, standing          | 80   | 1.4 |
| Walking about             | 100  | 1.7 |
| Lifting/packing           | 120  | 2.1 |

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Typical metabolic heat generation for various activities (after ASHRAE, 2005).

Fig. 3. Mean skin temperature (°C) calculated by 3-point method and 4-point method; (a) adaptation phase, (b) main experimental phase, and (c) resting phase.

Fig. 4. Expected temperatures (°C) after varying the relative humidity and mean radiant temperature when (a) the measured skin temperature was applied, and (b) the skin temperature calculated based on metabolic rates was applied (M = 70 W/m², Observed Tsk = 33.83°C).
varying the exercise intensity. Relative humidity was set at 50%, 60%, 70%, and 80%, and the mean radiant temperature ranged from 30°C to 70°C, at 5°C intervals. Other fixed variables were wind speed of 0.1 m/s, outdoor exposure of 1 h, and clothing insulation of 1 clo.

The expected temperature was higher when the measured mean skin temperature was used than when Equation 4 was applied. The outcome was the same for a relaxed standing position (Fig. 4), and for two exercise speeds (3.2 km/h, Fig. 5; 6.4 km/h, Fig. 6). As for the difference between the two cases, the gap was 5°C in a relaxed standing position, 6.5°C at an exercise rate of 3.2 km/h, and 12°C at an exercise rate of 6.4 km/h. This indicated that the gap widened as the exercise grew more intense.

In comparison, at the same mean skin temperature, the gap in expected temperatures changed less than 1°C when relative humidity was varied, indicating its weak influence.

Next, changes in mean radiant temperature caused by variations in wind speed were examined. Among the input variables, the metabolic rate varied in relation to exercise intensity. Wind speed was set at 0.1 m/s, 0.3 m/s, 0.5 m/s, and 1 m/s, and the mean radiant temperature ranged between 30°C and 70°C at 5°C intervals. Fixed variables included relative humidity of 50%, outdoor exposure of 1 h, and clothing insulation of 1 clo.

Similar to the case of varying relative humidity, the expected temperature with varying wind speed was higher than when the measured mean skin temperature
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was calculated using Equation 4. Moreover, the gap in expected temperature relative to varying wind speed, calculated using measured and modeled data, grew wider as exercise became more intensive (Figs. 7-9).

These findings show that expected temperatures are higher when measured mean skin temperature is applied to the model, compared to when data calculate using Equation 4 were applied, and also that the difference in expected temperatures widened as intensity of the exercise increased.

However, it is premature to determine which of the two methods is better, based on these findings. Results from this study showed that using mean skin temperature based on measurements affects expected temperature, but further research should be conducted with more subjects, to ensure the reliability of the data on mean skin temperature.

When calculating expected temperature using mean skin temperature according to Equation 4, the expected temperature fell below 0°C in most cases where wind speed was below 1 m/s. That is, when a person exercises intensely in an outdoor setting, with little wind, the temperature needs to be below 0°C to maintain thermal comfort. This suggests that expected temperatures tend to be underestimated.

The findings thus far, show that there are differences for factors other than mean skin temperature between outcomes calculate using measured data and those calculated using the equation. Thus, the model needs to be enhanced using data based on experimental results.

No enhanced heat-balance model based on measured data has yet been established in Korea, and the results from the present heat-balance model have not translated into measures for responding to actual extreme heat advisories or warnings.

The model proposed in this study has a few limitations, as mentioned earlier, but it can be used in several ways to facilitate practical responses to extreme heat.

The extreme heat that prevailed in July 1994 had an adverse impact on human health. The weather data for 25 July, on which a high death rate was recorded, was examined in order to decide how to apply expected temperature. On 25 July, the highest temperature recorded in Seoul was 33.4°C. The wind speed was low during the day, and the average relative humidity was 50%. Mean radiant temperature cannot be directly retrieved, owing to the lack of globe temperature data, but other observed data showed that when the peak temperature was 30°C, the mean radiant temperature was 55-65°C in 2012. Working from this premise, the trend of changes to expected temperature was analyzed by varying input variables.

The change in the expected temperature relative to different mean radiant temperatures was examined for each of three cases: the subject in a relaxed standing position (\(M = 70 \text{ W/m}^2\)), the subject walking at 3.2 km/h (\(M = 115 \text{ W/m}^2\)), and the subject running at 6.4 km/h (\(M = 220 \text{ W/m}^2\)), with a relative humidity of 50%, wind speed of 0.1 m/s, outdoor exposure of 1 h, and clothing insulation of 1 clo (Fig. 10).

As the figure shows, the expected temperature was highest in the standing position, but fell, as the exercise grew more intense. In a relaxed standing position, if the mean radiant temperature rose, the expected temperature dropped to the same level as in the case of a higher metabolic rate, and a lower mean radiant temperature. That is, when a person is standing comfortably indoors with mean radiant temperature 60°C, the expected temperature is similar to when the person is running at the rate of 6.4 km/h outdoors with a mean radiant temperature of 30°C. This suggests that when a person stands still indoors on a summer day with a high
mean radiant temperature, without doing any exercise at a high metabolic rate, the body is exposed to the same impact as when the person does intensive exercise in a setting of low mean radiant temperature. Therefore, outdoor activities should be assiduously avoided between 1200LST and 1500LST when mean radiant temperature peaks; if they cannot be avoided, the exercise should be kept to a minimum.

Next, changes to expected temperature caused by different mean radiant temperatures were examined for varying wind speed with relative humidity of 50%, metabolic rate of 115 W/m², outdoor exposure of 1 h, and clothing insulation of 1 clo (Fig. 11). It was found that the temperature expected to maintain thermal comfort rose with higher wind speed. However, if the wind blew faster and the mean radiant temperature was 70 °C, the expected temperature was 17.73°C. Considering the fact that the mean radiant temperature is high and the wind speed is low during the day, when a human body is exposed to and affected by high temperature, the influence of high temperature may be even greater in the natural environment.

When outdoor temperature and mean radiant temperature are both high, active measures (such as air conditioning) are needed, in addition to increasing wind speed, to avoid impacts on human bodies from high temperature. Local governments should seek effective measures to protect people who are vulnerable to high temperature but cannot afford air conditioning, for example, by providing shelters for them to escape extreme heat.

To analyze changes in the expected temperature relative to the duration of outdoor exposure, the expected temperature for different mean radiant temperatures were examined, with relative humidity 50%, metabolic rate 115 W/m², wind speed 0.1 m/s, and clothing insulation 1 clo (Fig. 12). The results showed that the expected temperature fell, as the duration of outdoor exposure became longer. The temperature gap between an exposure time of a 0.5 h and exposure of 1 h was greater than that between 1 h and 2 h. This suggests that it may be dangerous to do outdoor activities for long when the outdoor temperature is high, because exposure for more than 0.5 h may have significant adverse effects on the body.

Examination of changes in expected temperature under varying conditions that may affect the body condition during hot summer days confirmed that outdoor activities should be avoided during days when the mean radiant temperature is high. If outdoor activities cannot be avoided, they should be kept shorter than 30 min. Jogging and other activities of similar intensity may have an adverse effect on the body in such heat. An individual might feel more comfortable when the wind speed is higher. However, if the mean radiant temperature is high, it is difficult to feel comfortable without lowering the outdoor temperature, even if the wind speed is high.

For this study, only preliminary analysis of cases of extreme heat was conducted, and it would be advisable to analyze more diverse cases and variables for a broader application of the model. In particular, it is hoped that this study would provide useful data for particular circumstances such as for work environments for laborers at high temperatures, outdoor classes for grammar and junior-high school students, and outdoor military drills.

**4. CONCLUSIONS**

The difference in the expected temperature was exam-
ined in relation to two methods for determining the mean skin temperature, which is one of the variables considered in the proposed model. One method was based on the metabolic rate, calculated using Equation 4, while the other method was based on the actual skin temperature measurements.

The results showed that the expected temperature calculated from the measured mean skin temperature was higher than that calculated using Equation 4. The discrepancy grew wider as exercise became more intense, that is, as the metabolic rate rose.

In this study, we considered only the mean skin temperature among the diverse variables possible with the new model, and showed the discrepancy in the expected temperatures caused by differences in the source of data used to calculate the variable. Various heat-balance models developed in previous studies, at home and abroad, have been introduced in Korea. These need to be tested and improved using actual experiments to yield more accurate outcomes, tailored to the climatic conditions particular to Korea.

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