Validation of thermoregulation human model considering mist wettedness on mist spraying environment

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Abstract. Mist spraying systems can relieve thermal discomfort in extremely hot weather. However, the thermal effect of the mist spraying system on the human body has not been investigated sufficiently. To understand a physical phenomenon between human and surrounding environment, and physiological responses of the human body in mist spraying environment, the thermal state of the human body were predicted using the 2-node model (2NM). Sixty-five subjects’ skin temperatures and four environmental factors (air temperature, mean radiation temperature, relative humidity, and airspeed) were measured simultaneously. The mist spraying system caused the surrounding temperature to fall by 3.6 ± 1.4 °C and relative humidity to rise by 15.9 ± 4.7%. In addition, when the overall skin temperature was predicted using the conventional 2NM with measured environmental factors as an input parameter, the skin temperature was increased in mist spraying environment as opposed to the subject experimental results. However, when the mist wettedness is additionally considered in the thermoregulation human model, the decreasing skin temperature in the mist spraying environment was predictable considering the heat loss of the mist particles evaporated from the body surface. The mean error between the predicted and the experimental results showed a result of 0.4 °C. In conclusion, it was found that the mist wettedness is a key factor to predict human thermal conditions in the mist spraying environment accurately.

1. Introduction
Mist spraying systems are useful to improve human thermal sensations and thermal comfort in hot outdoor environment [1]. However, it is difficult to grasp the influence of its thermal environment on the human body because the outdoor conditions are easily fluctuated. Moreover, the mist spraying environment has a more complex environmental conditions than the outdoor environment since it has a very high humidity due to the mist evaporation. In previous researches, Huang et al. confirmed a cooling effect of the mist spraying system that it could lower an air temperature up to 5–7 °C in a hot environment [2]. Furthermore, it was found that this system could reduce the air temperature by up to 10 °C in climate chamber experiment [3]. However, these studies focused only on the changes in environmental factors, but the variations of human body were not investigated.

Humans have a thermoregulation system through physiological responses such as the sweating, blood flow regulation, and shivering in response to a thermal environment. Furthermore, thermal sensation is greatly linked to physiological responses. The physiological responses occurred by the thermal interaction between the surrounding environment and the human body are closely related to the thermal sensation. Farnham et al. confirmed the forearm temperature changes before and after entering the mist spraying environment in an outdoor environment. The forearm temperature was dropped by 1–3 °C [1]. However, it is still difficult to understand the effect of the mist spraying environment on the human’s physiological responses only by examining the temperature changes on the partial part of the body. In order to investigate its effect on the entire human body, understanding the thermal state of the
overall body is crucial since each part of the body is affected differently by the thermal conditions inside the mist spraying environment. Therefore, in this research, overall skin temperature was measured to confirm the physiological responses in outdoor and mist spraying environment.

Furthermore, to understand a physical phenomenon between human and surrounding environment, and physiological responses of the human body in mist spraying environment, thermal state of the human body were predicted using the 2-node model (2NM). Moreover, mist wettedness was introduced and applied to 2NM to examine how it was predicted in the mist spraying environment, and the validity of the prediction model was investigated in comparison with the experimental results.

2. Field experiment
2.1. Environmental factors
The field experiment was conducted in Institute of Industrial Science, The University of Tokyo, Japan for July 23–August 4, 2018. The environmental factors were measured inside and outside the mist spraying environment: air temperature, radiation, humidity, and air speed. The same types of equipment were used both inside and outside the mist spraying environment for comparison. The details of the measuring instrument and its locations are described in Table 1. The mist spraying system, instruments, and installed positions of instruments are illustrated in Figure 1. All measurements were placed at a height of 1.1 m, which corresponds to the center of the standing human body.

The air temperature and humidity sensors were placed inside the mist spraying environment to measure the air temperature and relative humidity. Moreover, for the cross-validation of the humidity measurements of sensors, relative humidity was additionally measured using an infrared H2O analyzer which could detect the mole fraction of water vapor in the air. As a result, its measurement accuracy of humidity sensor and the infrared H2O analyzer showed almost the same. Further, a hot wire anemometer cannot measure the air speed properly inside of the mist spraying environment since it is also affected by the water droplet. Thus, we measured the air velocity appropriately by using an ultrasonic anemometer. All the measured data were recorded with 1 sec intervals.

The solar radiation greatly influences on the human’s thermal comfort. Therefore, to confirm an independent cooling effect of the diffused mist, experiments were designed to have a similar radiation environment inside and outside the mist spraying environment. The radiation was measured using a shortwave and longwave radiation meter, and a direct solar radiation meter. The condition of direct solar radiation assumed the same both inside and outside the mist spraying environment, the direct solar radiation meter was only installed inside of the mist spraying environment. The mean radiant temperature (MRT) $T_{mrt}$ was calculated to obviously understand the effect of radiation on the human body using Equation (1). In Equation (1), the following measured data was substituted: the upper and lower two-directional longwave radiation, shortwave radiation, and direct solar radiation by tracking the sun.

$$T_{mrt} = \frac{1}{\sigma} \left( f_{\text{eff}} \left( \frac{\alpha}{\varepsilon} \cdot \frac{I_{\text{dH}} + S \uparrow}{2} + \frac{L \downarrow + L \uparrow}{2} \right) + \frac{\alpha \cdot f_p}{\varepsilon} \cdot I_{\text{dn}} \right) - 273.15$$  \hspace{1cm} (1)

where $\sigma$ denotes the Stefan-Boltzmann constant $(5.67 \times 10^{-8}, \text{W m}^{-2} \text{K}^{-4})$, $f_{\text{eff}}$ is the effective body area factor of the radiation assumed as 0.8, $\alpha$ is the absorptivity of the clothed human body by the shortwave

$$I_{\text{dH}} = S \downarrow - I_{\text{dn}} \cdot \sin \beta$$  \hspace{1cm} (2)

$$f_p = 3.01 \times 10^{-7} \beta^3 - 6.46 \times 10^{-8} \beta^2 + 8.34 \times 10^{-4} \beta + 0.298$$  \hspace{1cm} (3)
radiation assumed as 0.7, \( \varepsilon \) is the emissivity rate by the longwave on human body assumed as 0.95. \( S \uparrow \) is the upward shortwave radiation, \( L \downarrow \) and \( L \uparrow \) denotes the downward longwave radiation and the upward longwave radiation respectively. The diffuse solar radiation on a horizontal surface \( I_{dbh} \) was calculated with the downward short radiation \( S \downarrow \), the direct solar radiation on normal surface \( I_{dn} \), and the solar altitude \( \beta \) as described in Equation (2). The project area factor \( f_p \) of a standing human body by the direct solar radiation derived from Equation (3) proposed by Park and Tuller [4].

**Figure 1.** Mist spraying system installed in Institute of Industrial Science, The University of Tokyo, Japan (July 23–August 4, 2018), (a) overall view of mist spraying system, (b) Scene of installed instruments, and (c) floor plan of the mist spraying system and location of the instruments.

### 2.2. Subject experiment

Schematic diagram of the subject experiment protocol is illustrated in Figure 2 and sixty-five subjects participated in this experiment. The experimental procedures were approved by the University of Tokyo Ethics Committee (No. 18-114) and all participants gave written the informed consent. The subjects were all dressed in prepared clothes and clothing level was about 0.5. At the beginning of the experiment, subjects rested in an indoor room for 20 minutes where the temperature was controlled 26 °C, and after the rest, they walked outdoor for 10 minutes. Then they stayed inside the mist spraying environment for 10 minutes.

**Figure 2.** Schematic diagram of the subjective experiment protocol indicating time periods in mist spraying experiment.

Skin temperatures were measured to confirm the thermal state of the human body. The overall skin temperature was calculated by measuring seven local skin temperatures of the body proposed by Hardy and Dubois [5,6]. Local skin temperatures were measured using thermocouples (accuracy was ± 0.5 °C) and data were logged by LR-8430 (HIOKI Corporation, Japan) at 5 seconds intervals. The
thermocouples were attached using surgical tape. The overall skin temperature $T_{overall}$ was calculated using Equation (4) ($T_i$ is the surface temperature of a body segment $i$).

$$ T_{overall} = \sum_{i=1}^{7} \alpha_i T_i $$

where $\alpha_i$ denotes the area fraction of a body segment $i$ and $T_i$ is the surface temperature of a body segment $i$.

3. Thermoregulation human model in mist spraying environment

3.1. Mist wettedness

Mist spraying environment is different from general indoor and outdoor environment, and mist particles are present in the air and attached to the human body surface and evaporation phenomenon appears. Considering the heat loss due to the evaporation of the mist, 2NM can be modified. Schematic diagram of the thermal resistance network model of modified 2NM is illustrated in Figure 3.

2NM is based on the energy balance equations for skin and core part of the body. The energy balance for the core compartment is

$$ S_{core} = M - W - Q_{res} - Q_{core-sk} $$

where $S_{core}$ is heat storage rate in the core component, $M$ is the metabolic rate, $W$ is external work by the muscles. In addition, heat losses occur by respiration $Q_{res}$ and heat flow rate from core to skin $Q_{core-sk}$. The energy balance for the skin compartment is

$$ S_{sk} = Q_{core-sk} - (Q_{rad} + Q_{conv} + E_{sk} + E_{mist}) $$

where $S_{sk}$ is heat storage rate in the skin compartment of the body, $Q_{rad}$, $Q_{conv}$, $E_{sk}$, and $E_{mist}$ are radiative heat loss, convective heat loss, evaporative heat loss via physiological phenomena, and mist evaporative heat loss from the surface of the body, respectively. The heat storage rate of each part of the body equals the rate of increase in internal energy [7]. The storage rate can be described as

$$ S_{core} = \frac{(1 - \alpha_{sk}) m C_p dT_{core}}{A_D dt} $$

$$ S_{sk} = \frac{\alpha_s m C_p dT_{sk}}{A_D dt} $$

where $\alpha_{sk}$ is the mass fraction of the body concentrated in skin compartment, $A_D$ is the total surface area of the body, $C_p$ is specific heat of the body (3490 J kg$^{-1}$ K$^{-1}$) and $m$ is the total mass of the body (kg)

Skin wettedness $\omega_{sk}$ is the ratio of the actual evaporative heat loss on the skin surface to maximum possible evaporative heat loss (completely wet, $\omega_{sk} = 1$) under the same conditions. In the same concept, mist wettedness $\omega_{mist}$ can be defined as the ratio of the actual evaporative heat loss due to the mist on the surface of the body for the maximum possible evaporative heat loss under the same conditions. $E_{sk}$ and $E_{mist}$ can be calculated using Equation (9)–(10).

$$ E_{sk} = \omega_{sk} \frac{(p_{sk} - p_a)}{R_{e,cl} + \frac{1}{f_{cl} h_e}} $$

Figure 3. Schematic diagram of the thermal resistance network model of 2NM model considering mist wettedness
\[ E_{\text{mist}} = \omega_{\text{mist}} f_{cl} h_e (p'_{\text{cl}} - p_a) \]  

(10)

where \( p'_{\text{sk}} \) is the saturated water vapor pressure at the skin temperature, \( p_a \) is partial water vapor pressure in ambient air, \( h_e \) is the evaporative heat transfer coefficient, \( f_{cl} \) is the clothing area factor, \( p'_{\text{cl}} \) is the saturated water vapor pressure at the cloth temperature, and \( R_{e_{\text{cl}}} \) is the evaporative heat transfer resistance of clothing layer.

Mist wettedness in mist spraying environment was measured using heating globe thermometer and same size of globe thermometer and calculated by Equation (11). The heating globe was placed in the mist spraying environment and was constantly controlled at a 35 °C. The other globe thermometer was placed near the mist spraying environment.

\[
\omega_{\text{mist}} = \frac{C}{A} \left( \frac{dT_g}{dt} - \frac{dT_{gh}}{dt} \right) + \varepsilon \sigma \left( T_g^4 - T_{gh}^4 \right) + h_e \left( (T_g - T_{dry}) - (T_{gh} - T_{\text{mist}}) \right) + \frac{H}{A} \prod_n \frac{p_{gh}^* - p_{\text{mist}}}{L_R h_c} 
\]

(11)

where \( C \) is the heat capacity of the globe thermometer, \( A \) is the surface area of the globe, \( H \) is the heat input in heating globe thermometer, \( L_R \) is the coefficient of Lewis relation (16.5, K kPa\(^{-1}\)), \( T_g \) and \( T_{gh} \) are the temperatures of the heating globe and the other globe thermometer, \( T_{\text{mist}} \) and \( T_{dry} \) are the air temperatures around the heating globe and the other globe thermometer, \( h_c \) is the convective heat transfer coefficient of globe surface, \( p_{gh}^* \) is saturated water vapor pressure at the heating globe temperature, and \( p_{\text{mist}} \) is the partial vapor pressure in mist spray environment.

4. Results

4.1. Environmental factors

The results of environmental factors (mean ± SD (standard deviation)) in the outdoor environment and mist spraying environment illustrated in Figure 4. Air temperature changed from 32.9 ± 2.6 °C in outdoor to 32.9 ± 2.6 °C in mist. Relative humidity changed 58.7 ± 6.1% in outdoor to 74.6 ± 7.1% in mist. The MRT in mist spraying environment showed lower than outdoor at about 1 °C. However, outdoor and mist spraying environment did not show much difference in air speed. The measured mist wettedness result showed 0.23 ± 0.08.

![Figure 4](image_url)  

Figure 4. The results of environmental factors in outdoor environment and mist spraying environment.

4.2. Skin temperature

The results of measured and estimated overall skin temperature variations were illustrated in Figure 5. The predictions were calculated based on conventional 2NM and modified 2NM considering mist wettedness. The measured overall skin temperature continuously increased in the outdoor environment and decreased after entering the mist spraying environment. The measured mean overall skin temperature just before entering the mist spraying environment was 34.7 °C, and the estimated result was 35.0 °C.

At the end of the experiment, mean overall skin temperature was 34.1 °C. However, in the conventional 2NM result, skin temperature did not decrease in the mist spraying environment, and the
result was 35.1 °C. In contrast, in the modified 2NM, overall skin temperature tended to decrease in the mist spraying environment, and the result of mean overall skin temperature showed 33.7 °C.

5. Conclusion
The validity of thermoregulation human model was investigated whether the thermal state of the human body was predicted properly in mist spraying environment. The overall skin temperatures of sixty-five subjects were measured and compared with prediction results. The overall skin temperature was predicted by conventional 2NM using measured environmental factors and compared with modified 2NM which is considering mist wettedness. The environmental factors outside and inside mist spraying environment were measured for use in the prediction model. The mist spraying system lowered the air temperature by 3.6 ± 2.6 °C and raised the relative humidity by 15.9 ± 4.7%. In addition, mist wettedness showed the result of 0.23 ± 0.08.

The skin temperature using conventional 2NM showed good results in an outdoor environment at 0.3 °C differences compared with measured results, but accuracy was decreased with 1.0 °C in the mist spraying environment. However, when the mist wettedness is additionally considered in the thermoregulation human model, the mean error between the predicted and the experimental results showed a result of 0.4 °C in the mist spraying environment. In conclusion, it was found that the mist wettedness is a key factor to predict human thermal conditions in the mist spraying environment accurately.

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