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Academic Article

Development of a measurment instrument and its features for estimating the degree of wetness caused by outdoor misting

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ABSTRACT

Cooling by spraying mist has received widespread attention in Japan as a countermeasure against the detrimental health effects of urban heat islands. Sprayed mist is expected to not only decrease the air temperature by evaporation in the air but also promote evaporative heat dissipation from the skin by wetting. In this study, three cylindrical heated sol-air temperature (SAT) meters of the same configuration were prepared to measure the degree of wetness of their surfaces inside the cloud produced by mist sprayer nozzles. After determining the differences among the three SAT meters, their appropriateness for wetness measurements was evaluated. A piece of wet paper was pasted such that it covered 20% of the surface area of the SAT meter, corresponding to a wet area fraction of 0.20. The wet area fraction was then calculated from the heat balance equation using the results obtained by the three SAT meters and was estimated as 0.21, corresponding to an error of 5% relative to the actual value.

Key words : Urban heat island, Adaptation, Outdoor mist sprayers, Wet area fraction, SAT

1. Introduction

Recently, urban heat islands have caused serious health problems in urban residents and visitors. Mist sprayers are a common countermeasure used against heat stroke. Spraying mist in an outdoor space can change sensible heat to latent heat in the air by the evaporation of the mist and cool the surrounding air. Outdoor mist sprayers have been reported to reduce outdoor temperatures by approximately 1K[1]. In the intervening space between indoor and outdoor environments, they have also been reported to reduce the temperature by 2 - 3K[2].

Outdoor mist sprayers can also be expected to cool human bodies by the latent heat of vaporization. It has been shown that there is a correlation between the skin wetness and average skin temperature at the time of isothermal sensation[3]. Thus, the average skin temperature, thermal sensation, or comfort can be predicted from the measured skin wetness. However, it is difficult to separate the effect of mist from that of sweat, even if the skin temperature of a person standing within the mist cloud is experimentally measured. Developing an evaluation method based on physiological response of test subjects on an actual misting field is a complex task, and a simple method of evaluating the cooling effects under misting conditions is needed.

Farnham, Emura, & Mizuno[4] have evaluated the effect of mist on reducing the surface temperature of the skin using a dry silicone rubber skin analog that they developed to characterize a misting fan system. Because their skin analog contains embedded heat flux and temperature sensors, they were able to directly and approximately measure the heat flux from the skin surface. However, it was difficult to analyze the dependence of heat flux on solar radiation and wind conditions.

The aims of the present study were to develop an instrument for determining the degree of wetness produced by outdoor misting and clarify the characteristics of this instrument. To this end, a cylindrical heated sol-air temperature (SAT) meter that can measure the fraction of the surface area of the cylindrical meter that has been wet by outdoor mist sprayers, hereafter referred to as the wet area fraction, was developed in this study. It is possible to estimate the degree of wetness of the SAT meter based only on measurements of its temperature and environmental parameters. First, the individual differences in surface temperature among the measurements of three heated SAT meters with the same configuration were determined. Second, the measurement accuracy of the wet area fraction and heat transfer characteristics was examined. However, in this study, the relationship between the wet area fraction of the instrument and the wetness of human skin was not explored.

2. **Cylindrical heated SAT meter**

A copper tube (H: 400 mm, D: 75 mm) was spray-painted black. Figure 1 shows the cylindrical heated SAT meter developed for use in this study. The shape of the SAT meter was designed to simulate part of the human body, for example, the arm, the neck or the shoulder. Because exposed parts of the upper body are possibly wet by misting, which causes an increase of a general skin wetness. The SAT meter has the same volume as a globe probe with a diameter of 15 cm, enabling its possible future application as a globe probe substitute.

A 2-m linear heater was attached to the inside of the copper tube using aluminum tape, as shown in Figure 2. Figure 2 shows an exploded view of the inside of the copper tube. T type thermocouples that can measure the inside surface temperature at six points were attached between the linear heaters at 25 mm intervals. Three of the measurement points are arranged in tandem at heights of 100, 200, and 300 mm from the bottom of the copper tube on both the front and back sides. Eight pieces of insulation (H: 50 mm, D: 75 mm; Figure 3) were inserted into the copper tube such that no empty space remained.

3. **Theory**

3.1 **Calculation of the wet area fraction in a verification experiment**

Equations (1)–(3) are the surface heat balance equations for SAT meters I, II, and III. SAT meter I was assumed to be set under a mist sprayer nozzle inside the mist cloud. SAT meters II and III were assumed to be outside of the mist cloud. Simultaneously solving Equations (2) and (3) using substitution yielded the natural convective heat transfer coefficient h_{cn} and solar radiation S; the other parameters in these equations are measureable. The radiant heat transfer coefficient is given by Equations (4) and (5), and the average radiation temperature is defined by Equation (6) (ISO 7726, 1998). Equations (4)–(6) were frequently used in this study.

After h_{cn} and S were obtained, the latent heat flux E_g in Equation (1) was calculated. Finally, the wet area fraction of SAT meter I was evaluated using Equation (7).

3.2 **Calculation of convective heat transfer coefficient**

The heat balance equations for SAT meters I, II, and III are shown in Equations (8) - (10). SAT meter I was assumed to be under forced convection without misting. SAT meters II and III were assumed to be under natural convection without misting. The surface temperature and physical environment factors were substituted into the heat balance equations for SAT meters II and III, which are respectively given by Equations (9) and (10), allowing these equations to be solved simultaneously for the unknown quantities h_{cn} and S. These calculated values were then input into Equation (8), and the forced convective heat transfer coefficient h_{cf} was evaluated. This experimental value of h_{cf} was compared with the theoretical convective heat transfer coefficient of the cylinder calculated using Equations (11) - (13). Equations (12) is the average Nusselt number for a cylinder in a cross flow recommended by Zukauskas[(5)] .

4. **Methods**

4.1 **Surface temperature measurement**

In this study, three cylindrical heated SAT meters were created. To evaluate the latent heat flux and wet area fraction from the heat balance equations for each meter, the accuracy of the surface temperature measurement was confirmed for the SAT meters. The three SAT meters were examined to determine if there were any individual differences in surface temperature among them. The experiment required 30 min for the conditions to reach a steady state, and the output power of the heater was 531.0 W/m^2.

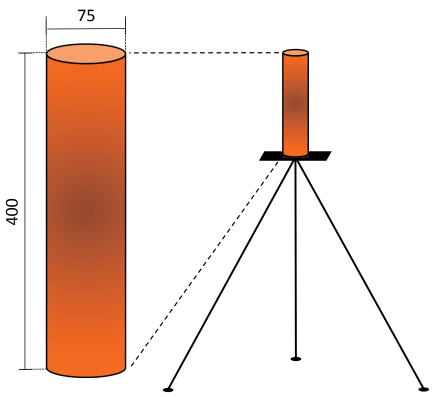


Fig. 1 Cylindrical heated SAT meter

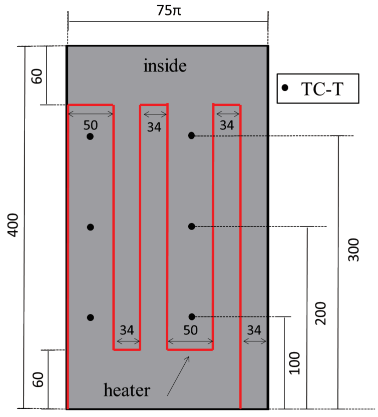


Fig.2 Exploded view of inside

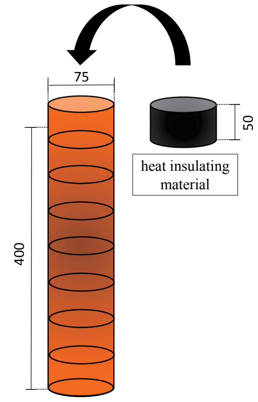


Fig.3 Insulation piece

$$h_{cn}(T_{s1} - T_a) + h_r(T_{s1} - T_r) + E_g = H_{input1} + S \quad (1)$$
$$h_{cn}(T_{s2} - T_a) + h_r(T_{s2} - T_r) = H_{input2} + S \quad (2)$$
$$h_{cn}(T_{s3} - T_a) + h_r(T_{s3} - T_r) = H_{input3} + S \quad (3)$$

$$h_r = 4\sigma(T_m + 273.15)^3 \quad (4)$$

$$T_m = \frac{T_g + T_r}{2} \quad (5)$$

$$T_r = \left[(T_g + 273.15)^4 + 2.50 \times 10^8 \times u^{0.6}(T_g - T_a) \right]^{\frac{1}{4}} - 273.15 \quad (6)$$

$$E_g = LRh_c(P_g^* - P_a)w \quad (7)$$

$$h_{cf}(T_{s1} - T_a) + h_r(T_{s1} - T_r) = H_{input1} + S \quad (8)$$
$$h_{cn}(T_{s2} - T_a) + h_r(T_{s2} - T_r) = H_{input2} + S \quad (9)$$
$$h_{cn}(T_{s3} - T_a) + h_r(T_{s3} - T_r) = H_{input3} + S \quad (10)$$

$$h_{ct} = \frac{\lambda N_u}{D} \quad (11)$$

$$N_u = 0.26 Re^{0.6} Pr^{0.37} \left(\frac{Pr}{Pr_s}\right)^{0.25}, \quad \frac{Pr}{Pr_s} \approx 1 \quad (12)$$

$$Re = \frac{uD}{\nu} \quad (13)$$

$$h_c = 0.865u^2 + 12.3u + 6.48 \quad (14)$$

Table of symbols

T_a	Air temperature	°C
T_g	Globe temperature	°C
T_s	Surface temperature	°C
T_r	Average radiation temperature	°C
h_c	Estimated convection heat transfer coefficient approx.	W/(m²·K)
h_{ct}	Theoretical convection heat transfer coefficient	W/(m²·K)
h_{cf}	Forced convection heat transfer coefficient	W/(m²·K)
h_{cn}	Natural convection heat transfer coefficient	W/(m²·K)
h_r	Radiant heat transfer coefficient	W/(m²·K)
E_g	Latent heat flux	W/m²
W	Wet area fraction	-
H_{input}	Additional sensible heat flux	W/m²
S	Received solar radiation	W/m²
u	Wind speed	m/s
Re	Reynolds number	-
D	Representative length	m
λ	Thermal conductivity of air	W/(m·K)
ν	Kinematic viscosity coefficient	m²/s
Pr, Pr_s	Prandtl number, Pr_s is evaluated at T_s	-
N_u	Average Nusselt number	-
LR	Lewis coefficient	K/kPa
P_g^*	Saturated water vapor pressure	kPa
P_a	Water vapor pressure of air	kPa
σ	Stefan-Boltzmann constant	W/(m²·K⁴)

4.2 Wet area fraction measurement

The estimation accuracy of the wet area fraction of the SAT meter was verified using a piece of wet Japanese paper (L: 300 mm, W: 63 mm) pasted on the surface of the device so that it covered 20% of the surface area, corresponding to a wet area fraction of 0.20. The three SAT meters were installed in an indoor environment under natural convection. A piece of wet Japanese paper was pasted in the position shown in Figure 4 on the front side of SAT meter I, which was presumed to have been inhomogeneously wetted by misting. Its surface temperature was then measured, and the latent heat flux and wet area fraction were estimated from the heat balance equations (Equations (1)–(3)). The environmental parameters are given in Table 1, and the experimental conditions and unknowns are given in Table 2. The experimental layout under natural convection conditions is shown in Figure 5. During the experiment, the Japanese paper was kept wet by using a dropper.

4.3 Convective heat transfer coefficient measurement

To estimate the convective heat transfer coefficient, the three SAT meters were installed in an indoor environment. The experimental layout is shown in Figure 6, and the unknowns are listed in Table 3. SAT meter I was set in front of a misting fan, and its front side was facing the wind. The distance between the fan and SAT meter I was increased from 2 to 5 m in increments of 1 m.

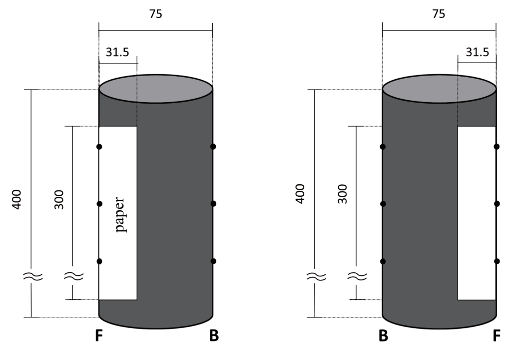


Fig. 4 Position in which the wet Japanese paper was pasted. F and B indicate the front and back sides, respectively.

Table 1: Physical environment parameters

	Measurement	instruments	Recording interval
Physical environment factor	temperature	Temperature / humidity sensor	1sec
	humidity		
	wind speed	3D ultrasonic anemometer	
	Globe temperature	Globe sphere	

Table 2: Experimental conditions and unknowns

No.	I	II	III
Wet paper	with	without	without
Additional heat flux	H_{input1} 531.0W/m^2	H_{input2} 531.0W/m^2	H_{input3} 265.5W/m^2
Unknown value	h_{cn} S w	h_{cn} S	h_{cn} S

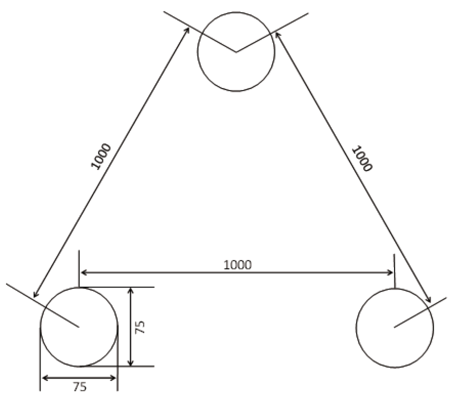


Fig.5 Experimental layout for the estimation of the wet area fraction under natural convection conditions

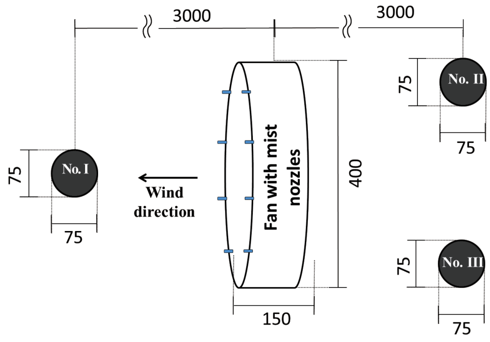


Fig.6 Experimental layout for the measurement of the convective heat transfer coefficient

Table 3: Experimental conditions and unknowns

No.	I	II	III
Convection	Forcing	Natural	Natural
Additional heat flow	H_{input1} 531.0W/m^2	H_{input2} 531.0W/m^2	H_{input3} 265.5W/m^2
Unknown number	h_{cf} S	h_{cn} S	h_{cn} S

5. Result

5.1 Surface temperature measurement

Figures 7 and 8 show the distribution of the surface temperature of the three SAT meters. The surface temperature of the lower part of each of the meters was lower than that of the middle and upper parts because there was some heat loss from the lower edge of the SAT meter. There was little difference between the surface temperatures of the middle and upper parts. The maximum temperature difference among the SAT meters was less than 1.0 K for both the middle and upper parts.

In this study, the surface temperature data of the lower and upper parts were not considered in the calculations; only the data of the middle part were analyzed to solve the heat balance equation on the surface.

5.2 Estimation of wet area fraction using Japanese paper

Figure 9 shows the average surface temperatures of SAT meters I, II, and III over a period of 30 s under steady state conditions. Figure 10 shows the estimated wet area fraction and latent heat flux of SAT meter I. The true value of the wet area fraction was 0.20.

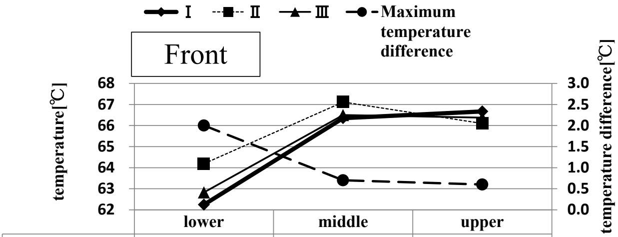
The wet area fraction was estimated to be 0.25 and 0.17 on the front and back sides, respectively, yielding an average of 0.21 for both sides. The difference between the estimated and true values was 0.01, corresponding to an error of 5%. This demonstrates that the wet area fraction can be evaluated using the heat balance equations and the average temperature of the

SAT meter.

5.3 **Relationship between wind speed and convection heat transfer coefficient**

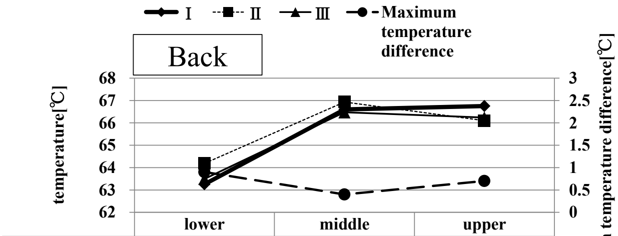
Figure 11 shows the relationship between the wind speed and the convective heat transfer coefficient, where the the solid line is an approximation obtained by fitting the experimental data. Figure 11 also includes theoretical data for reference. At wind speeds of less than 4.3 m/s, the approximation given by Equation (14) resulting from the experiment which is mentioned in 4.3 is applicable. The experimental values were approximately 1.5 times larger than the theoretical values. Because the theoretical values are evaluated for a cylinder in a uniform flow of the infinite width. On the other hand, the experimental values are calculated from the SAT meter which was put in a non-uniform flow by the fan.

The approximate formula for the convection heat transfer coefficient is a function of wind speed, which is useful to reduce measurement devices. For example, there is a method of using a pair of SAT meters, one placed in a mist cloud and the other placed outside. The received solar radiation S and latent heat flux E_g are the only unknowns in simultaneous equations (1) and (2). In this way, the wet area fraction of the SAT meter can be estimated using a fewer measurement devices.



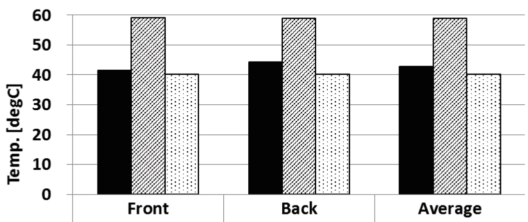
	lower	middle	upper
I	62.2	66.4	66.7
II	64.2	67.1	66.1
III	62.8	66.5	66.4
Maximum temperature difference	2.0	0.7	0.6

Fig.7 Observed surface temperatures of the front sides of the three SAT meters



	lower	middle	upper
I	63.3	66.6	66.8
II	64.2	66.9	66.1
III	63.5	66.5	66.2
Maximum temperature difference	0.9	0.4	0.7

Fig. 8 Observed surface temperatures of the back sides of the three SAT meters



	Front	Back	Average
No. I	41.5	44.2	42.9
No. II	59.0	58.9	59.0
No. III	40.3	40.3	40.3

Fig.9 Average observed surface temperatures of the three SAT meters used to estimate the wet area fraction

6. Conclusions

A measuring instrument for the characterization of the cooling effect of outdoor misting was developed in this study. The following conclusions about the essential features of the instrument were obtained from the experimental results obtained in this study.

(1) It was confirmed that the wet area fraction could be accurately estimated using the cylindrical heated SAT meter by covering a known fraction of the surface with wet Japanese paper. There was a difference of 0.01 between the estimated and true values, corresponding to an error of 5%.

(2) An approximate formula for the convective heat transfer coefficient of the SAT meter was proposed for use at wind speeds ranging from 0 to 4.3 m/s.

In future work, a measurement system and method of using the instrument developed in this study will be developed. Because simple examination is best, fewer measurement devices are desired in an actual misting field.

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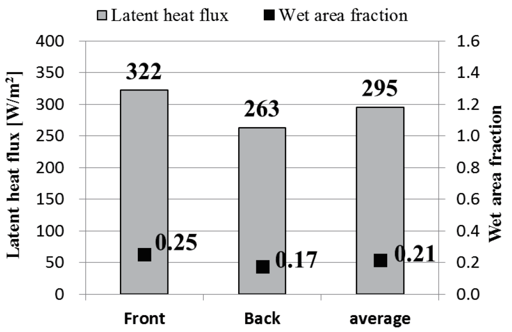

Fig.10 Latent heat flux and wet area fraction of SAT meter I

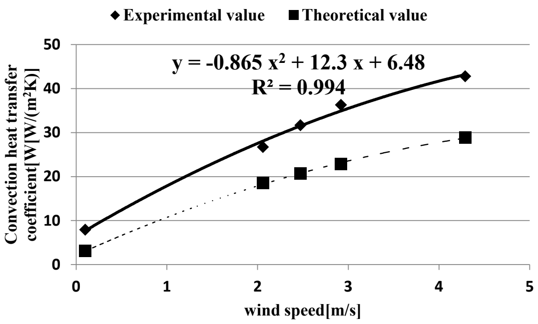

Fig.11 Relationship between wind speed and convective heat transfer coefficient from experimental values and theoretical values

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