Experimental Study on Evaporative Cooling of Fine Water Mist for Outdoor Comfort in the Urban Environment

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ABSTRACT

Evaporative cooling techniques by spraying mist water have been attracted attention as a mitigation measure of the warming in urban area. However, concrete ways of mist control and what kind of place is suitable for this technique are still unknown. Under the atmosphere suspending fine water mist, measurement of the spatial extent of air temperature drop is difficult because many kinds of thermometers indicate not dry-bulb temperature but wet-bulb temperature. And air temperature around spraying nozzles varies frequently in outdoor space, so measurement of instantaneous air temperature variation is also required for the evaluation of the perceived coolness.

In this paper, firstly we proposed a temperature measuring method using the sound virtual temperature of sonic anemometer-thermometer as a proper air-temperature measuring method for the investigation of water mist cooling. Secondary, in order to evaluate the psychological influences of water mist evaporation, subjective experiments were conducted in the outdoor sunny place.

We succeeded to reveal detailed air temperature variations in outdoor real setting by the new measurement technique. And some proper conditions for effective outdoor application, for example air temperature level and solar radiation shielding, were also clarified.

Introduction

Water-spray cooling systems are increasingly used in Japan to produce a comfortable condition in outdoor environment in midsummer. In popular system, hydraulic nozzles, driven by high-pressure water pumps, are used to atomize the fine water mist in diameter about 30 micrometers. In previous studies about evaporative mist-cooling, range of degree and spatial extent of air temperature drop were measured with thermometers like thermistor or thermocouple (Yoon et al. 2008, Yamada et al. 2008). In the atmosphere suspending fine water mist, however, these kinds of sensors tend to show not true air temperature (i.e. dry-bulb temperature) but wet-bulb temperature. Once these sensors were wetted, they keep wet-bulb temperature until they dry out, so cooling effect is often overestimated (Farnham et al. 2011).

In this paper, firstly a measuring method of air temperature under water atomizing was devised (Kohno and Narita 2012). We focused sound virtual temperature measured by SAT (sonic anemometer thermometer), which is fundamentally not affected by water mist. Absolute air temperature measured by SAT is generally not so precise. But the relative variation of air temperature can be reliable; therefore it is usually used for sensible heat flux measurement by

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eddy correlation method. The only point which needs further consideration is a slight dependency of sound virtual temperature on absolute humidity.

Secondly, we carried out experiments using subjects in outdoor space to investigate effective setting and comprehensive control of water mist cooling. Water atomizing facilities are sometimes used at open space in the sun, for example shopping mall or attraction waiting zone in amusement park. In these cases, almost all people enjoy the momentary coolness by direct wetting of their skin. From the viewpoint of steady comfortable space design in urban area, we have to know the mechanism of the perceived coolness and contribution of skin wetting. In case of outdoor environment, air temperature around nozzles especially varies by turbulent wind. Therefore, the measurement of instantaneous air temperature fluctuation is needed for comfort evaluation. The new technique by sound virtual temperature is a rapid response system, which is expected to be useful for studying the effective nozzle arrangement and the atomizing control.

Air Temperature Measurement under Suspending Fine Water Mist

Sonic anemometer-thermometer (SAT) is the instrument measuring wind velocity from the propagation time of the sound wave between transmitter and receiver. Furthermore, we can measure air temperature fluctuation using this instrument because speed of sound varies with temperature. The temperature measured using sound speed is called “sound virtual temperature”. According to this measurement principle, the sonic anemometer-thermometer is hard to be affected by the water mist adhesion.

Figure 1. Mobile mist atomizer.

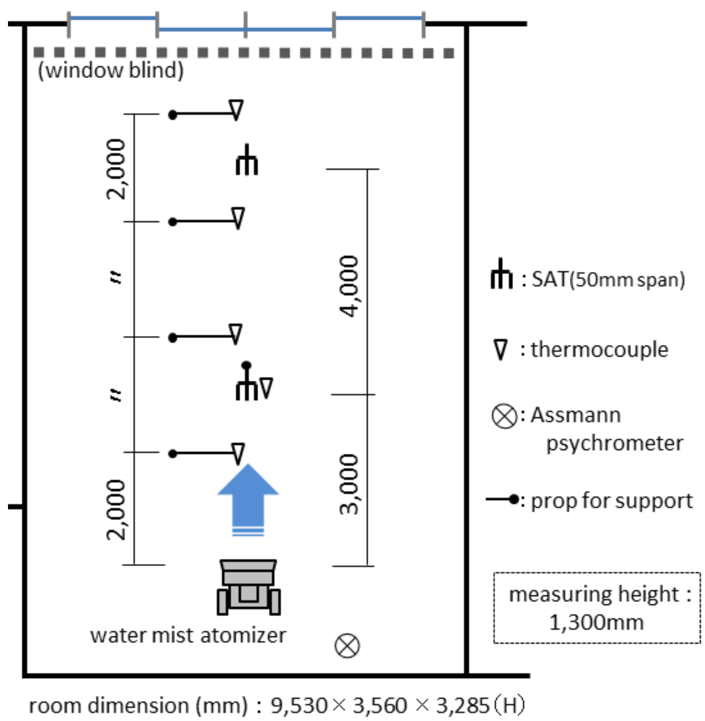


Figure 2. Arrangement of instruments in indoor experiments.

In order to check the accuracy of air temperature using sound virtual temperature, we performed indoor experiment for relatively simple condition compared with outdoor environment. Here, a mobile type water atomization instrument was used (Figure 1). Spraying nozzles were equipped in front of wind fan along a circle pipe, and then fine mist can flow out in any arbitrary direction. The specifications of water mist atomizer are as follows; dimension (mm) = (L)710 x (W)530 x (H)1750, fan diameter = 450 mm, spraying water volume = 0.24 L/min, mean particle size = 30 microns, airflow volume = 85m^3/min.

Both fine thermocouple (TC) and the SAT were set in several distances from the spraying instrument (Figure 2), their output of air temperature were compared. Water spraying was performed only during two minutes but the wind fan was continuous operating. Air volume of blower is not so large compared with the room volume; there found no obvious circulation pattern in the room. As a reference of background, wet bulb temperature measured by Assmann ventilated psychrometer set behind mist atomizer was used in following considerations.

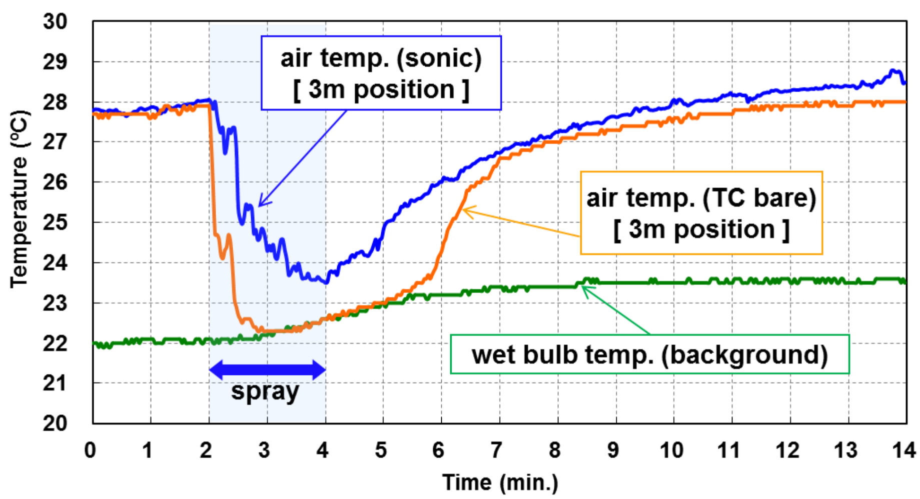


Figure 3. Comparison of air temperature measured by SAT and thermocouple (3m position).

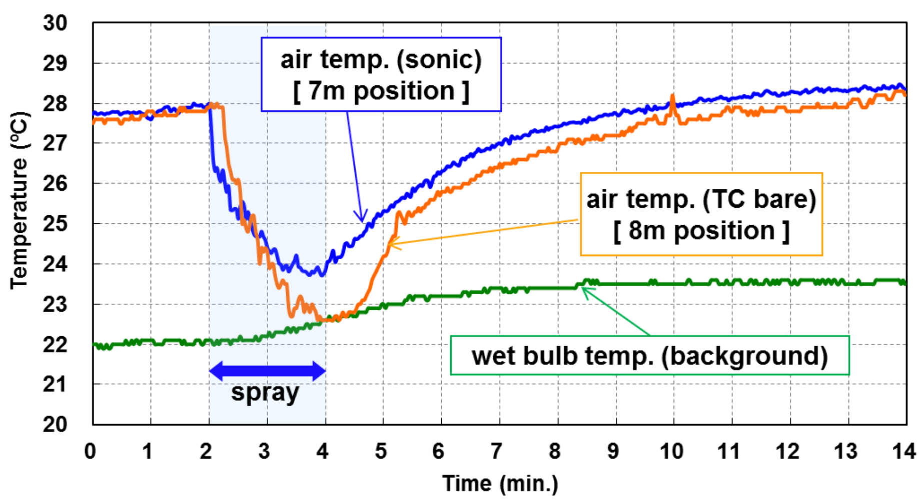


Figure 4. Comparison of air temperature measured by SAT and thermocouple (8m position).

Figure 3 shows the results of air temperature measured by SAT and the thermocouple at 3m position from the nozzles and background wet bulb temperature measured by Assmann ventilated psychrometer. Relative humidity before spraying was 60% and mean wind speed at 3m position was 1.6 m/s. Output of thermocouple showed a sudden temperature drop just after spraying, which suggested the influence of mist adhesion. The temperature drop continued until it coincides with background wet bulb temperature, afterward it changes completely accorded with that of wet bulb temperature. Few minutes after, TC output separated from wet bulb temperature and rose quickly because it dried out. Finally, it showed fairly similar change to SAT output. On the other hand, sound virtual temperature by SAT decreased gradually during spraying and turned to increase when atomization stopped. Its maximum temperature drop was smaller than that of TC output and did not reach to wet bulb temperature.

The same results hold with the nozzles 8 meters far are illustrated in Figure 4. TC output corresponded to wet bulb temperature during a short time, because not so much water mist reached this position and dry out more immediately compared with the position 3 meters far.

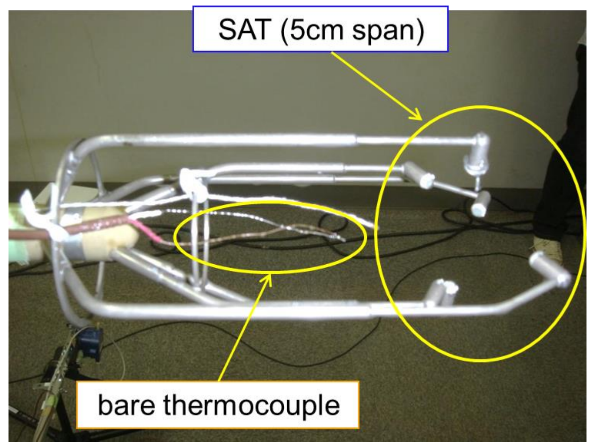


Figure 5. Photos of bagged thermocouple (left) and bare thermocouple (right).

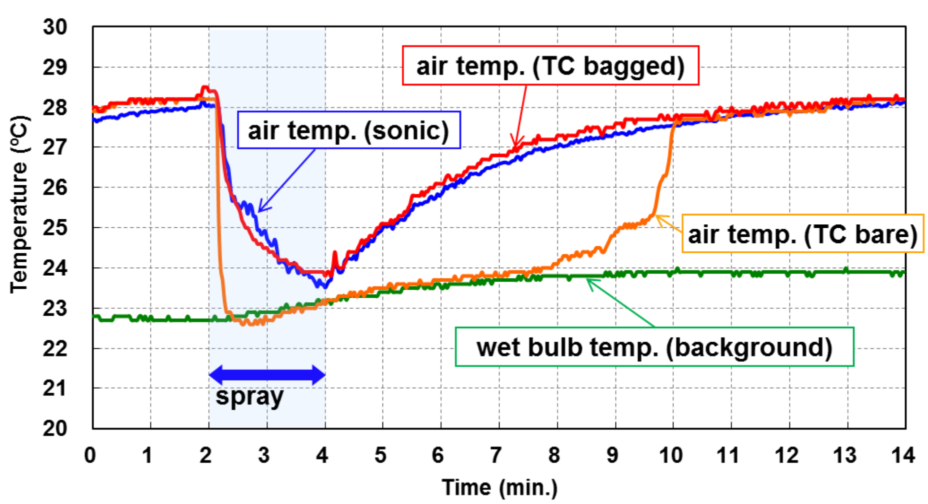


Figure 6. Comparison of the temperature measured by bagged and bare thermocouples (1.5m position).

In addition, we set another thermocouple covered with a small polyethylene bag (Figure 5). This airtight bag was applied during spraying, and then removed quickly when atomization stopped. Normal thermocouple shows wet bulb temperature and keeps it through several minutes after the stop of spraying. On the other hand, air temperature measured by the thermocouple keeping off water mist and that of SAT output are in a good agreement. They decreased only spraying period and increased smoothly after the stop of water spraying (Figure 6).

These results show that it is impossible to clarify actual range and special extent of air temperature drop by water-spray cooling if ordinary thermistor and thermocouple sensors are used. And measurement using sound virtual temperature by SAT is suitable under suspending mist condition. When evaporative cooling techniques by water-spraying are applied for outdoor space, the measurement using SAT is indispensable to evaluate human sensation for comfort because air temperature varies so frequently.

Correction of the dependency of sound virtual temperature on absolute humidity

In order to get the absolute value of the temperature from sound virtual temperature, the correction about the dependency on absolute humidity is necessary. In previous figures, sound virtual temperature was used without this correction because it is sufficient to recognize the error of thermocouple measurement. The relation between air temperature and sound virtual temperature is expressed in the following equation (Kaimal and Gaynor, 1991).

$$T_{vt} = T\,(1 + 0.32e/p) \qquad (1)$$

where T_{vt} is sound virtual temperature (K), T is air temperature (K), and e and p are, respectively, vapor pressure of water in the air and the absolute pressure. Assuming some approximation, the correction of sound virtual temperature due to absolute temperature is expressed as follows (see Appendix).

$$T = (1 - 0.51x)\,T_{vt} \qquad (2)$$

where x is absolute humidity (kg/kg'). To check a magnitude of compensation resulting from absolute humidity, we carried out experiments using glass chamber. The dimension of chamber is 2000 x 1000 x 1000 (mm), and time variations due to 1.5 minutes spraying from single nozzle (water volume is 97.88g) were monitored. The air within the chamber was well-mixed using several small fans and absolute humidity near SAT was measured with open-path infrared absorption hygrometer (LI-COR, LI-7500). Results are shown in Figure 7. The compensation values of temperature are roughly estimated at 1degree in 6.5g/kg' and at 2 degrees in 16g/kg', respectively.

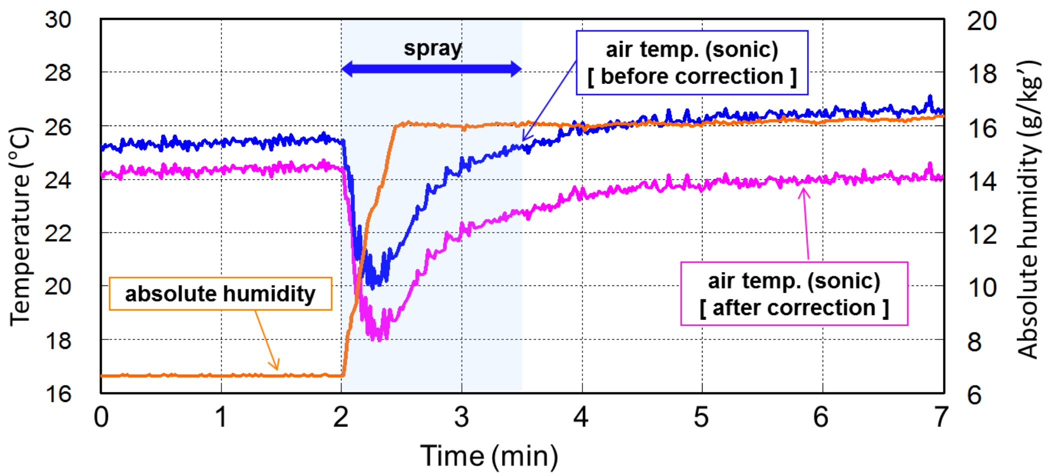


Figure 7. Correction of sound virtual temperature using absolute humidity (chamber experiment).

Subjective experiments for psychological influence of water mist evaporation

In order to establish practical design in evaporative cooling technique by water-spraying, it is necessary to clarify the mechanism of the perceived coolness. Though it is called “dry-mist” in Japan as a registered trademark, almost all people enjoy the momentary coolness by direct wetting of their skin more than the effect of real air temperature drop. Therefore, subjective experiment accompanied with reliable air temperature measurement is important for the evaluation of outdoor comfort. Here, above-mentioned measuring technique using SAT was applied to real scale outdoor experiments.

In midsummer outdoor environment, solar radiation shielding is considered to be most important and effective countermeasure, in particular, to make a comfortable space. We recognize that the effect of evaporative cooling alone is insufficient to create steady comfortable space with no insolation shielding. So in this experiment, water mist spraying technique was combined with various kinds of sunshade to investigate the effective setting and comprehensive control of water mist cooling.

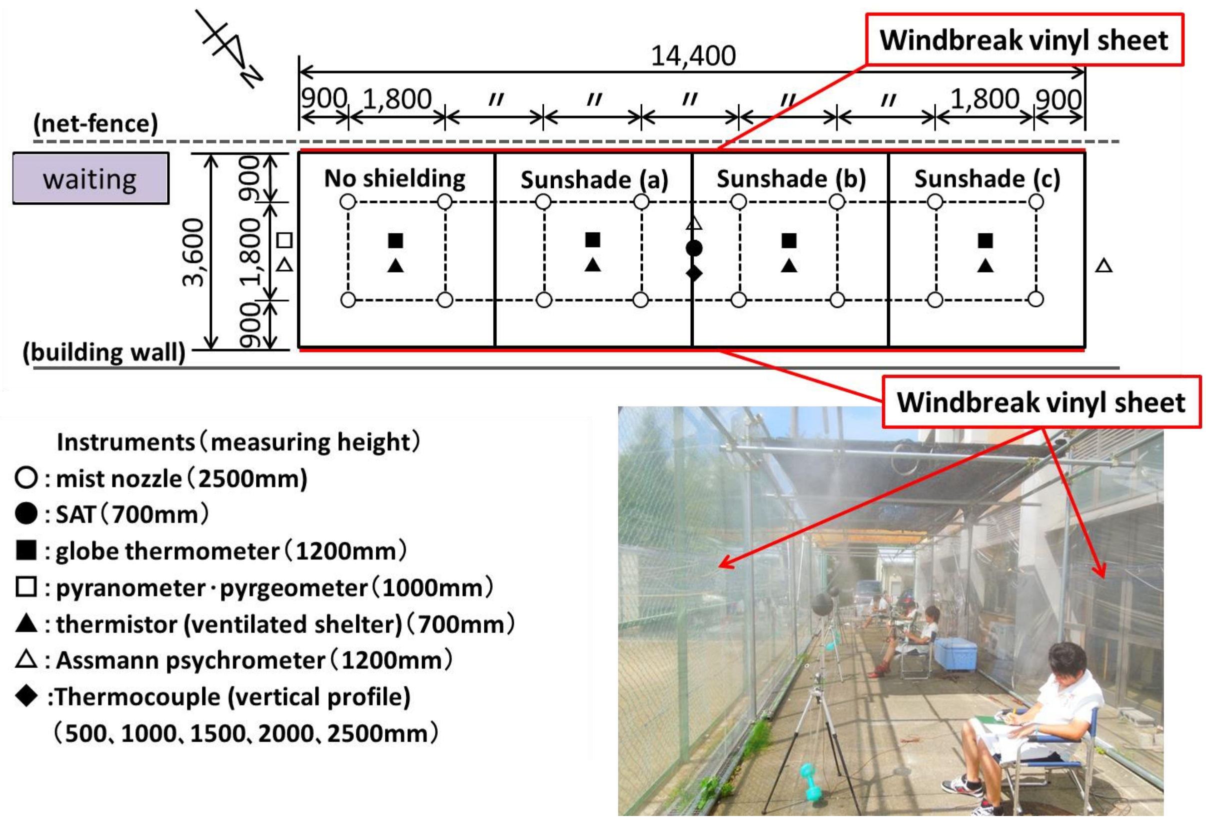


Figure 8. Plane view of experimental area and arrangement of mist nozzles and measuring instruments.

Experiments were conducted under overhead nozzles (1.8m grid) set at height of 2.5m. Experimental site was divided into four zones (each 3,600 x 3,600 mm) with three different sunshades and no shielding. Both sides of experimental site were covered with transparent plastic sheet to control wind effect (Figure 8). Six kinds of sunshades rearranged every day in the two ways of combinations (pattern A and B of Table 1). Subjects move from waiting zone to each experimental zone and sit in the condition for five minute, then answer the questionnaires about thermal sensation and comfort. Above the waiting zone, white cheesecloth (55%), which has medium insolation shield factor, was installed. Total eight subjects (age of 21-25), which consists of seven males and one female, were divided into two groups. They repeated this process shifting experimental zone for six different sunshades (Table 1) both with and without mist spraying.

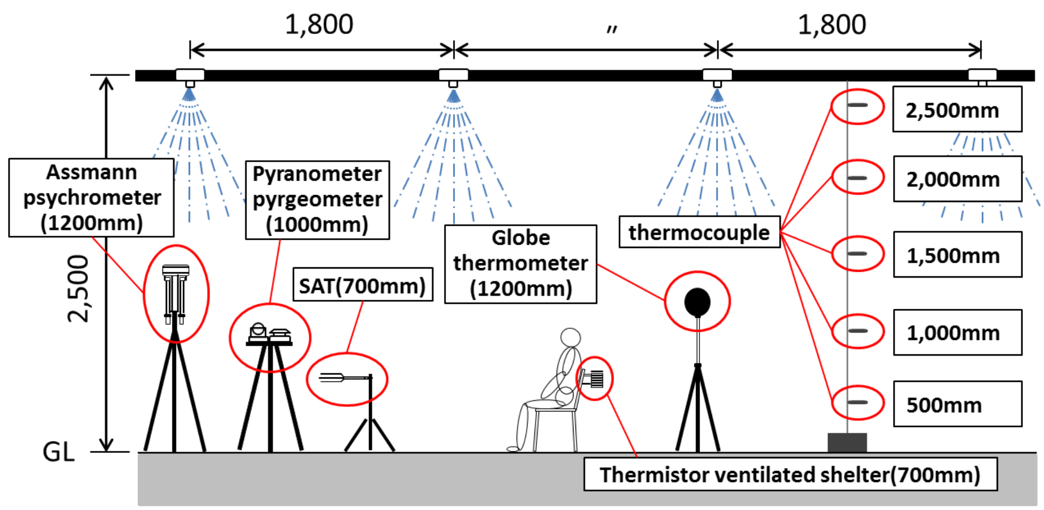


Figure 9. Cross section of experimental area and arrangement of mist nozzles and measuring instruments.

Table 1. Insolation shield factor of six kinds of sunshades used in experiments

Position (see Fig.8)	Pattern A	Insolation shield factor†	Pattern B	Insolation shield factor†
Sunshade (a)	Black cheesecloth (90%*)	85%	Styrofoam	88%
Sunshade (b)	Black cheesecloth (50%*)	71%	White cheesecloth (55%*)	57%
Sunshade (c)	Reed screen	63%	White cheesecloth (10%*)	25%

*:shading rate † : measured value

Instantaneous air temperature fluctuation by mist evaporation at sitting-subjects height (0.7 meters above ground, 1.8 meters downward from the nozzles) was measured by sound virtual temperature using SAT. At this height, we can find approximately 3 degrees of temperature drop on average. As examined the data during water-spray in detail, air temperature fluctuates sharply and temperature drop is distinct in calm condition. In other words, under windy condition, cooling area by mist evaporation is restricted near the nozzles and difficult to reach this position downward 1.8 meters far. As a contribution to thermal comfort, temperature drop by evaporative cooling and wind speed are assumed to compensate each other.

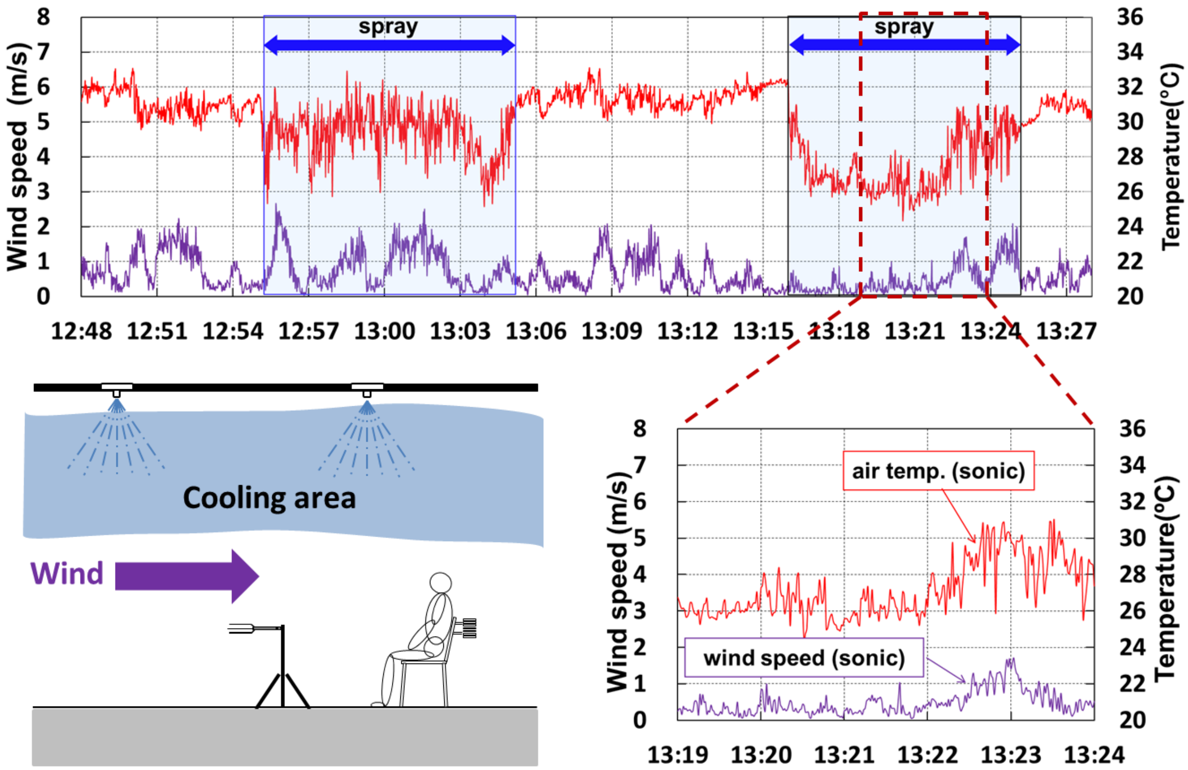


Figure 10. Instantaneous air temperature fluctuation by mist evaporation measured using SAT.

Effects of water spraying on thermal sensation and comfort

We instructed the subjects to evaluate the feeling at sitting position as a comparison with that at waiting zone. Important items of the questionnaire were thermal sensation, thermal comfort, and mitigation effect on heat (Table 2).

Table 2. Voting scales for evaluation of thermal sensation, thermal comfort, and mitigation effect

	Thermal sensation	Thermal comfort	Mitigation effect on heat
7	very cool (cold)	very comfortable	very effective
6	cool	comfortable	successful
5	slightly cool	slightly comfortable	rather successful
4	neutral (same as waiting zone)	neutral (same as waiting zone)	neutral (same as waiting zone)
3	slightly hot	slightly uncomfortable	rather unsuccessful
2	hot	uncofortable	unsuccssful
1	very hot	very uncomfortable	no effect

Figure 11 illustrates the relations between thermal sensation and thermal comfort in each type of sunshades. In cases of “black cheesecloth (90%)” and “reed screen”, which have large insolation shield factors, thermal comfort scores are high even without water-spraying. For example, total percentage of relatively comfortable vote (score range: 5-7) amounts 78% in case of “black cheesecloth (90%)”. Even so, the scores increase by water-spraying (+18%: in black cheesecloth (90%)). Under no shielding condition, thermal sensation vote concentrates upon relatively “hot” area and thermal comfort vote gathers around “uncomfortable” area. And the increase by water-spraying in total percentage of “comfortable” area is very small; +7%.

The relations between thermal sensation and mitigation effect in each type of sunshades were shown in Figure 12 in the same manner as Figure 11. Here, the question of “mitigation effect” is as follows; do you feel the effect as any countermeasures against heat? As water spraying is operated, the evaluation of “effective” becomes higher, especially in the sunshades which have large insolation shield factors. In case of “white cheesecloth (10%)”, though it has not so large shield factor (25%), vote score of mitigation effect is remarkably increased by water-spraying. The total percentage of “successful” area changes from 7% to 63%. So far, it seems reasonable to conclude that water-spraying is effective to improve thermal comfort under condition of more than 25% insolation shielding.

To know the effective condition for evaporative cooling, the dependency of air temperature on thermal comfort was investigated according to the level of wind velocity (Figure 13). In case of “Styrofoam”, which has largest insolation shield factor, thermal comfort vote is almost “comfortable” even though high air temperature, and becomes more comfortable by water-spraying. In case of “white cheesecloth (55%)”, which is characterized by the same shading as in the waiting zone, thermal comfort vote concentrates upon score 4 (same as waiting zone) as a matter of course. Besides, the score obviously shifts to comfortable side by water-spraying, which shows clear positive evidence of water spray cooling. In either case, thermal comfort vote clearly becomes “uncomfortable” when water mist is sprayed in the atmosphere lower than 25 degrees Celsius.

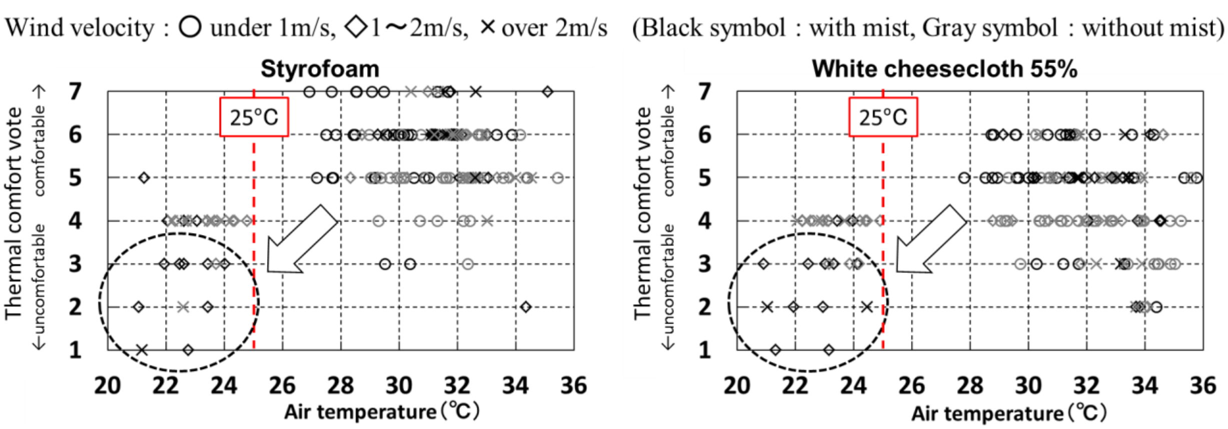
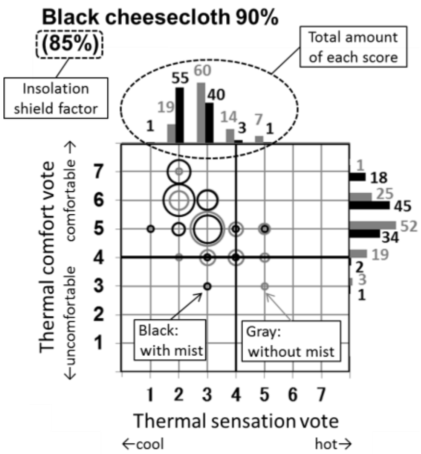
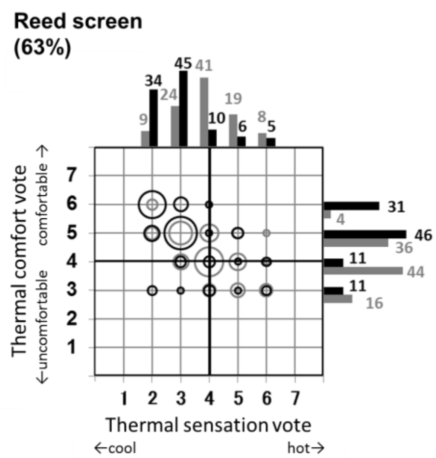


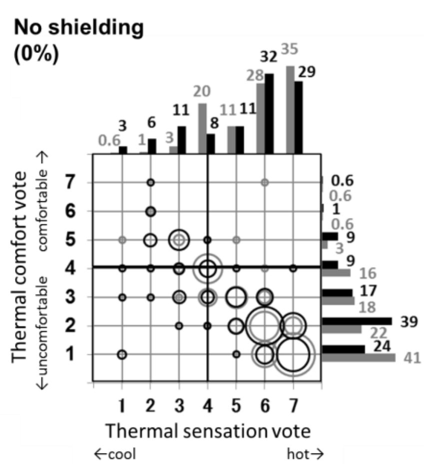
Figure 13. Dependency of air temperature on thermal comfort vote according to wind velocity level.
(left: Styrofoam, right: white cheesecloth (55%))



Range of vote score	without mist	→	with mist	Variation
uncomfortable (1-3)	3%	→	1%	-2%
comfortable (5-7)	78%	→	96%	+18%

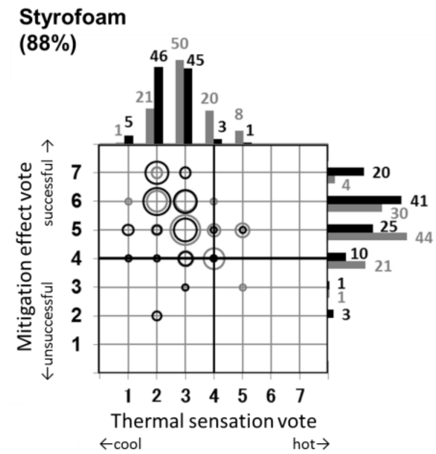


Range of vote score	without mist	→	with mist	Variation
uncomfortable (1-3)	16%	→	11%	-5%
comfortable (5-7)	40%	→	77%	+34%

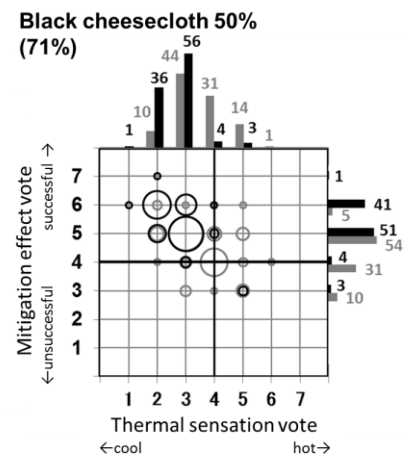


Range of vote score	without mist	→	with mist	Variation
uncomfortable (1-3)	81%	→	80%	-1%
comfortable (5-7)	4%	→	11%	+7%

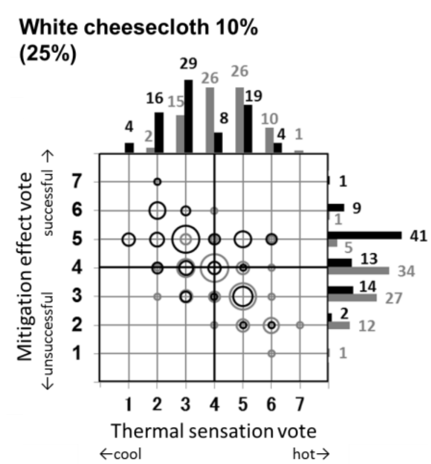
Figure 11. Relation between thermal sensation vote and thermal comfort vote.



Range of vote score	without mist	→	with mist	Variation
unsuccessful (1-3)	1%	→	4%	+3%
successful (5-7)	78%	→	86%	+8%



Range of vote score	without mist	→	with mist	Variation
unsuccessful (1-3)	10%	→	3%	-7%
successful (5-7)	59%	→	93%	+34%



Range of vote score	without mist	→	with mist	Variation
unsuccessful (1-3)	50%	→	21%	-29%
successful (5-7)	7%	→	63%	+56%

Figure 12. Relation between thermal sensation vote and mitigation effect vote.

Conclusion

Under the atmosphere suspending fine water mist, measurement technique using sound virtual temperature is considered to peerless way to reveal instantaneous air temperature fluctuation. Perceived coolness by mist spraying is affected by not only air temperature drop but direct wetting of skin. Besides, in outdoor environment, the turbulence of natural wind causes air temperature to vary frequently around spraying nozzles. So the rapid response method is absolutely required for the evaluation of thermal comfort. Thus, the measurement with SAT is useful to develop the practical design of mist spray cooling technique.

As a result of subject experiments, it is suggested that water mist spraying is effective in improvement of thermal comfort under the condition of more than 25% shading. In case of no shielding, thermal sensation could not shift from discomfort to comfort by only water spray cooling. And if air temperature is lower than 25 degrees Celsius, water mist spraying becomes acting negative for thermal comfort in any sunshade condition.

Air temperature under spraying water mist fluctuated widely. In windy condition, cooling area by mist evaporation tends to be restricted near the nozzles. As a contribution to thermal comfort, temperature drop by evaporative cooling and wind speed are assumed to compensate each other.

Acknowledgments

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Appendix

If the relation $e << p$ is assumed, then

$$(1 + 0.32\, e/p)^{-1} \approx (1 - 0.32\, e/p)$$

Furthermore,

$$0.32\, e/p \approx 0.32\, e/(p - e) \approx 0.32\, q\, (M_d / M_w) \approx 0.51\, q$$

where q is specific humidity (kg/kg), M_d and M_w are the molecular weights for dry air and water vapor. In case of $e << p$, the relation $q \approx x$ can be acceptable, and then the equation (2) is derived from equation (1).

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