Study on a Cooling System using Water Mist Sprayers

; System Control Considering Outdoor Environment

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Abstract

This study examines the cooling effect of water mist in relation to variations in outside air temperature and humidity by using numerical fluid analysis. A semi-outdoor space under a canopy where the water mist is sprayed was modeled. The cooling effects of the various water mist sprays were simulated and reductions in the air temperature and the remaining water particle mass distribution were examined. As a result, acceptable conditions for spraying mist are suggested, and the utility of water mist cooling systems for representative cities in Japan is validated.

Keywords: water mist, thermal comfort, evaporate cooling

Introduction

The phenomenon of temperature increases in the summer season of urban areas, creating so-called "heat islands" has become a problem in recent years. As one measure to alleviate this problem, we have considered using the vaporization heat of water mist sprayed, which requires only a small amount of water and a low amount of energy to implement. We also expect that such a method will improve the heat environment in the summer when applied to semi-outdoor spaces under a canopy. We verified the results of the field experiments conducted so far, and confirmed that temperature reductions of a maximum of 3°C are achievable under a canopy.

The goal of this research is to propose the performance predict and design method for the mist system. In this paper, numerical analysis simulations predicting water mist cooling performance were conducted in relation to variations in temperature and humidity, and the outdoor air conditions that are suitable for mist spraying were investigated. In addition, the possibility of applying the mist system in various locations was investigated

Numerical Analysis Model

We assumed an event site waiting area shown in

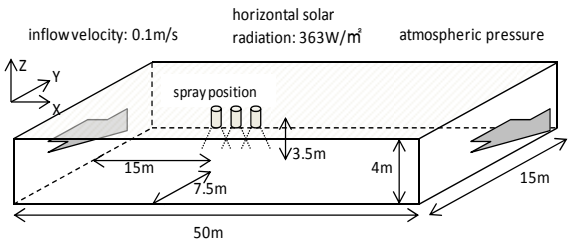


Figure 1 Diagram of calculation domain

Table 1 Boundary conditions

Boundary	Conditions
Roof top surface (z=4m) PVC-coated glass-fiber plain-weave	Thermal conductivity : 0.11 W/m·K
	Solar absorptance :10.8 %
	Solar transmittance : 13.7%
	Heat transfer coefficient : 23 W/m^2·K
Ground surface (z=0m) Concrete paved	Thermal conductivity : 1.4W/m·K
	Solar absorptance : 60 %
	Heat transfer coefficient : 23 W/m^2·K
Upwind / Downwind flow boundary	Upwind : air velocity, 0.1 m/s
	Downwind : atmospheric pressure
Side surface (y=0, y=15)	Free-slip
	Adiabatic boundary

Figure 1 to be a 50-m long, 15-m deep, and 4-m high semi-outdoor space for analysis. The three sprayers are positioned at a height of GL 1.5 m. We then applied the boundary conditions shown in Table 1. In order to investigate the cooling effect of the mist at different outside air temperatures and humidity levels, we fixed the value for the external air inflow at 0.1 m/s, and solar radiation is consumed to 363 W/m^2 which is an average rate for the assumption period. The two boundaries of the rooftop surface and the ground were given a surface temperature and a coefficient of heat convection.

We used the common numerical fluid analysis software Fluent 6.3 for numerical analysis. The Discrete Phase Model was used and we considered the interaction between the mist particles and gas (air), including heat transfer, phase changes, and the momentum conservation law. Also, we adopted the pressure-swirl atomizer model to analyze the nozzle spray conditions shown in Table 2.

Figure 2 shows the value of SET*[1] computed by using of the Expanded AMeDAS Weather Data for the outside air temperature and humidity in Tokyo during the rated year from June to September, 9 am to 7 pm.

When SET* is over 30ºC, it is considered to be an uncomfortable environment, so the mist spraying would be desirable.

We investigated the temperature reduction and the amount of remaining water particles produced by mist spraying under the case of different the temperature and humidity conditions as shown into Figure 2.

Results of Simulations

(1) Investigating the Cooling Effects

Figures 3 show differences in the flat surface temperature contour diagrams with different outdoor air conditions respectively. In order to compare the cooling effects of the mist, each contour diagram is shown with the temperature difference of the inflowing air. Figure 4 plots the temperature on the line segment Y=7.5, Z=1.5 where the nozzle directly below, and on a line segment directly below the nozzle 1meter away on a parallel(Y=8.5m, Z=1.5 m).

Comparing the air temperature reduction due to the different outdoor humidity of 80% (Fig. 3a) and 60% (Fig. 3b). In the case with 80% humidity, we can

Table 2 Spraying conditions

Mass flow rate	0.83 g/s
Water temperature	28.0 °C
Spray cone angle	50 °
Injection pressure	6 MPa

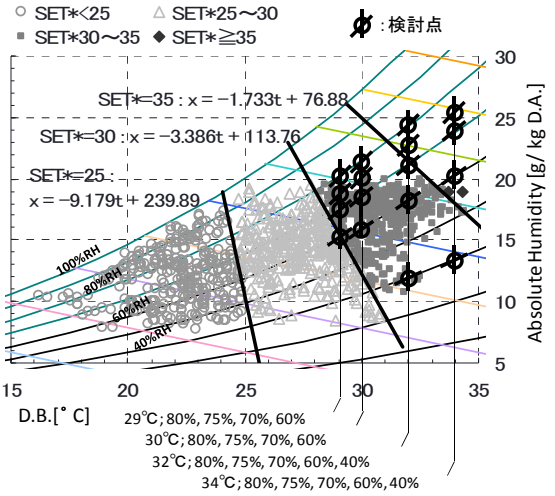


Figure 2 Relation between weather conditions and SET* on the calculation domain

see a relatively uniform temperature difference by observing the nozzle height from the ground surface in the cross-sectional contour diagram. However, the temperature decrease at the planar surface at a height of 1.5 m was focused on the area near the position of the sprayer. In the temperature distribution of the line segment in Figure 4, a temperature decrease of around 2.0°C can also be seen directly below the nozzle. However, at the parallel line segment 1 m away, a temperature decrease of only 0.5°C was observed.

In the case 60% humidity, a large temperature decrease was observed in a narrow area in the vicinity of the nozzle on the downwind side as shown in the cross-sectional contour diagram. And, the temperature decrease in the vicinity of the ground surface upwind was negligible. Also, in the planar surface contour diagram, the range in which a small temperature decrease could be seen was distributed to a relatively wider area. Regarding the temperature distribution on the line segment, the temperature decrease below the nozzle upwind was about 1°C, while downwind a maximum temperature decrease of 2.5°C was observed. Also, at the parallel segment line 1 m away, a temperature decrease of approximately 1°C was observed.

We consider the difference in the cross-sectional temperature distribution when the humidity was 80% (Fig. 3a) and when the humidity was 60% (Fig. 3b) can be explained as follows. In the case of 80% humidity, the particles that descended near the ground evaporated, creating a large temperature decrease in the space. However, in the case of 60% humidity, the particles vaporized rapidly, and the particles evaporate at higher level than the case of 80% humidity.

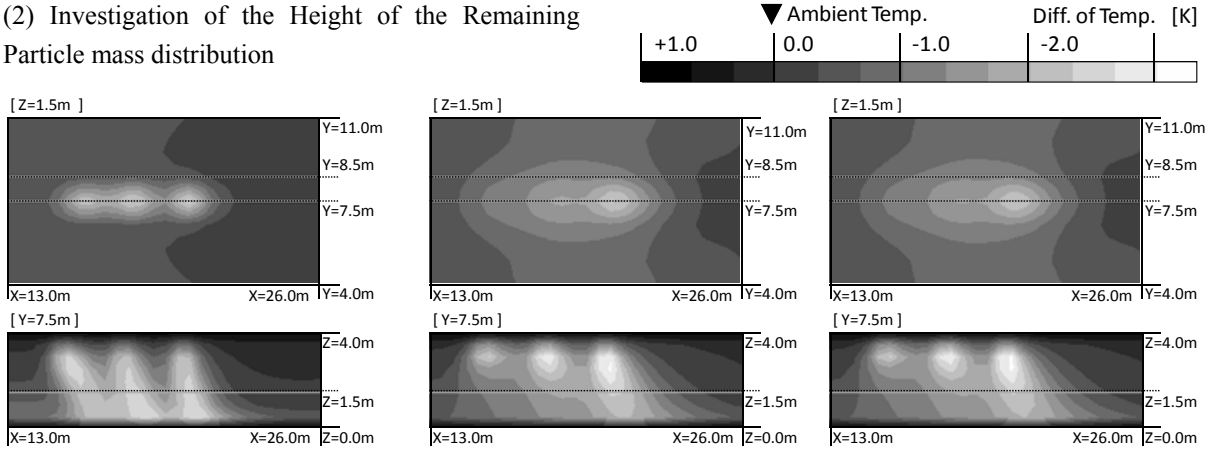
Also, when comparing the case where the outdoor air humidity was 60% and the outdoor air temperature was 30°C (Fig. 3b) with that where outdoor air humidity was also 60% but the outdoor air temperature was higher at 34°C (Fig. 3c), the distribution was almost identical. Thus, if the relative humidity was the same, even if the outdoor air temperature was different, the distribution of the temperature decrease showed the almost same tendencies.

(2) Investigation of the Height of the Remaining Particle mass distribution

Figure 5 shows the total mass of all the water particles remaining within the computational domain for each temperature (only for 30°C and 34°C) and humidity condition.

Regardless of the temperature condition of the case investigated, as the relative humidity of the outside air increased, the mass of the remaining mist particles in the computational domain also increased. Thus, in any outside air temperature condition, when the relative humidity is 80 % at a height of GL 0 to 0.25 m the mist will remain without completely evaporating.

We can expect that this will cause the ground surface to become wet, thus indicating that the environment is unsuitable for spraying. Also, if the design conditions are such that they require it to be in a residence and at a height of GL 1.5 m without the existence of mist, then a suitable condition for spraying is when the relative humidity is less than 70% at any of the temperatures modeled.



a. 30℃/80%RH b. 30℃/60%RH c. 34℃/60%RH

Figure 3 Temperature difference contour diagram at outdoor temperature and humidity conditions of 34°C and 60% RH, respectively

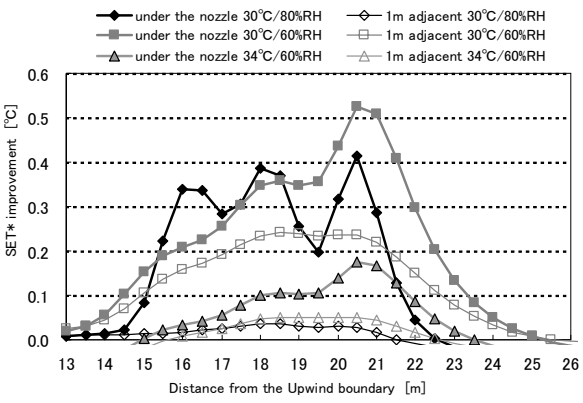


Figure 4 Temperature reduction distribution at each outside temperature condition

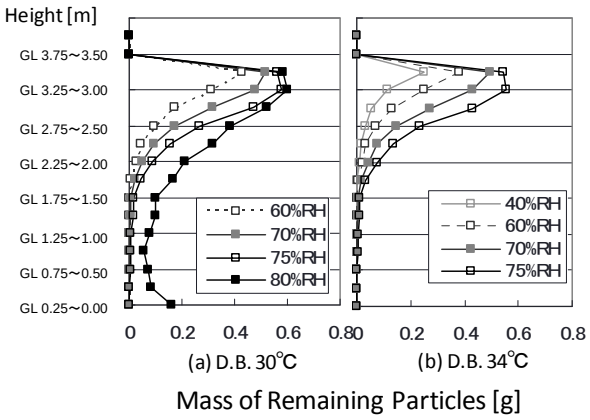


Figure 5 Histograms of mass of remaining particles under different humidities at specific outdoor temperature

Evaluation of Possibility for System Application in Specific Cities

As a condition for spraying mist in the investigation model, the desire was to improve the uncomfortable environment when SET* is over 30°C, and this was the condition in which implementing the mist spray was desired. And, on the basis of the results obtained in the previous section on the height of the remaining particle mass, we can consider the following as the spraying control strategies. The first control strategy is to ensure the ground surface does not get wet (assuming people passing the mist area can accept that it becomes a little wet). The mist spraying system will be on operating while an outside air humidity of less than 75%. The second strategy is to ensure there is no mist remaining in the space above a height of 1.5 m. Then the mist spraying system will be on operating while an outside air humidity of less than 70%.

In order to investigate the possibility of introducing the mist system into various regions, based on the previously mentioned spray control strategies, the aggregate results of the temperature and humidity for each city of Expanded AMeDAS Weather Data for each time are shown in Table 3.

In regards to the desirable number of hours of spraying time for environment improvement (hereafter referred to as the available time for improvement), Naha had the most aggregate periods at 75.7%. We consider that from Tokyo to Fukuoka there is about a 35 to 45% demand for improvement of the environmental conditions. However, in Sapporo and in Sendai, with available times for improvement of 1.5% and 10.2%, respectively, the need for implementing the spray cooling method is minimal.

For regions with a high value of available time for improvement, when spraying using controls to ensure that the ground surface does not get wet (accepting slight wetness in the space), in Tokyo and Osaka spraying is feasible at almost every available time. In Fukuoka and Nagoya, spraying is feasible for almost 90% of the time, so the possibility for implementation is high. In Naha, which had the highest available time for improvement among all the other cities, there are 596 hours of possible spraying time, meaning that spraying can be done in Naha for more hours than in any other city.

Table 3 Time available for spraying for each city for different temperature and humidity

	Desired improvement environment SET*≧30℃	Ground surface do not be wet R.H.≦75%	No mist in residence area R.H.≦70%
Sapporo	18 (1.5%)※1)	6 (33.3%)※2)	4 (22.2%)※2)
Sendai	124 (10.2%)	122 (98.4%)	96 (77.4%)
Tokyo	428 (35.1%)	420 (98.1%)	384 (89.7%)
Nagoya	443 (36.3%)	398 (89.8%)	369 (83.3%)
Osaka	543 (44.5%)	540 (99.4%)	518 (95.4%)
Fukuoka	498 (40.8%)	467 (93.8%)	428 (85.9%)
Naha	924 (75.7%)	596 (64.5%)	315 (34.1%)

Units are number of hours. The aggregate period is from 6/1 to 9/30, from 9:00 to 19:00.

※1) a ratio of corresponding time to entire time 1,220h.

※2) a ratio of corresponding time to the time when improvement environment desired

On the other hand, when using controls so that mist does not remain in the residence space, Osaka had the highest available time for improvement, at 95.4%, followed by Tokyo at 89.7%. It was also possible to spray in Fukuoka and Nagoya at more than 80% of the time, showing a high possibility for implementation. In Naha, the available time for improvement, and hence spraying time, was only 34%. The number of times available for spraying is fewer than the other four cities from Tokyo to Fukuoka. In regions with high humidity such as Naha, system application must be considered with the spraying control scheme.

References

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Note [1] : We consumed that Weight 70 kg, body surface area 1.8m^2 , 0.5 clo, 1.0 met.

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