STUDY OF COOLING SYSTEM WITH WATER MIST SPRAYERS —FUNDAMENTAL EXAMINATION OF PARTICLE SIZE DISTRIBUTION AND COOLING EFFECTS —

Yamada Hideki[1], Yoon Gyuyoug[1]
Okumiya Masaya[1], Okuyama Hiroyasu[2]

[1] Graduate School of Environmental Studies, Nagoya University
[2] SHIMIZU CORPORATION

ABSTRACT

A cooling system spraying micro water droplets could prove useful in mitigating temperature increases in urban areas by using heat from water evaporation, a process that consumes only small amounts of water and energy. If water mist is sprayed in a semi-outdoor area, for example under a canopy, it could potentially improve conditions on hot days. However, there is little reference data concerning the design or control of such systems. In order to propose a method for designing and predicting the performance of a water mist system, we discuss differences in cooling effects in the context of particle size distribution of water mist. From the results of numerical fluid analysis, it was observed there is no significant difference in temperature reduction for distribution of different particle sizes. However, the water particles remained in a lower position when the particle size distribution increased.

KEYWORDS

Water mist, Urban heat island, Numerical fluid analysis

INTRODUCTION

In recent years, warming of urban areas in summer has been considered a problem, known as the “urban heat island”. One means of mitigating this effect involves spraying micro water droplets. This method suppresses the temperature rise in urban areas by using the heat of evaporating water, while utilizing only small amounts of water and energy. If water mist is sprayed in a semi-outdoor area, for example under a canopy, it could potentially improve conditions on hot days. Through a field experiment (Yamada et al 2006), we have verified the effectiveness of this method and confirmed a temperature reduction under a canopy of up to about 3°C.

The use of water mist systems is expected to become popular in the future. However, there is little reference data concerning the design or control of such systems. Therefore, the aim of this study is to propose a method for designing and predicting the performance of water mist systems. In this study, we conduct a numerical fluid analysis and then discuss the particle size distribution and the cooling effect of water mist.

OUTLINE OF SIMULATION

The semi-outdoor area, which is 50 m long, 15 m wide and 4 m high, shown in Fig. 1 was analyzed under the assumption that it was a waiting area at an event halltime. The boundary conditions in Table 1 are used. The air temperature and humidity in this area derived from outdoor temperature and humidity parameters of Tokyo summers. (Parameters used were air temperatures of 33.4°C, and humidity of 58%RH). Also, it was assumed that there is the airflow (wind velocity is 0.1 m/s) of the outdoor wind. The roof is made of PVC-coated glass-fiber and the ground is concrete. Sol-air temperature and thermal transmittance were given for the surface of the roof. At the ground surface, a temperature was given, which was estimated in consideration of heat transfer at ground surface. (heat convection, heat difussion to the ground and transmissive solar radiation of the roof)

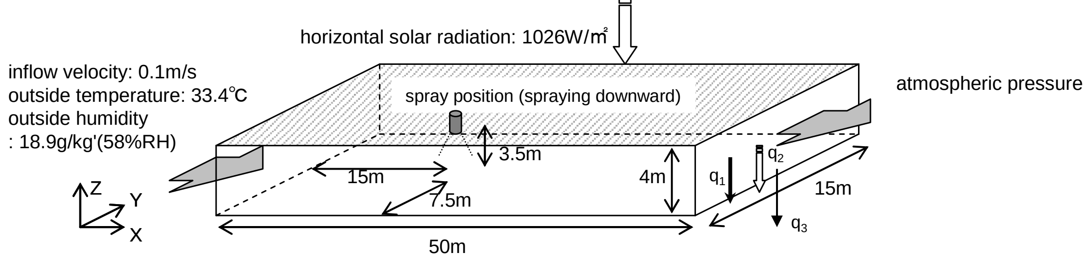

Figure 1. Diagram of calculation area.

Table 1. Boundary conditions.

Surface	Condition
Roof surface (z=4)	Material: PVC-coated glass-fiber plain-weave Thickness: d_t=0.53mm Thermal conductivity: λ_t=0.1125W/m·K Solar absorptance: a_t=10.8% Solar transmittance: τ_t=13.7% Horizontal solar radiation: J=1026W/ m^2 Heat transfer coefficient: α_o=23W/m^2·K Sol-air temperature: 38.2°C
Ground surface (z=0)	Material: concrete paved Depth: d_c=5m Thermal conductivity: λ_c=1.4W/m·K Solar absorptance: a_c=60% Heat transfer coefficient: α_{oc}=23W/m^2·K Underground temperature (annual mean temperature in Tokyo): θ_s=15.6°C Heat balance at ground surface: $q_1+q_2+q_3=0$ Convective heat transfer from the ground: $q_1=\alpha_{oc}$ (θc -θo) Transmissive solar radiation of the roof: $q_2=\tau_t \times a_c \times J$ Heat diffusion to the ground: $q_3=\lambda_c/d_c$ (θ_s- θ_c) Ground surface temperature: θ_c=29.8 °C
Air inflow surface (x=0)	Inflow velocity: 0.1m/s Outside temperature: 33.4°C Outside absolute humidity: 18.9g/kg'
Air outflow surface (x=50)	Pressure: atmospheric pressure
Side surface (y=0, y=15)	Free-slip Adiabatic boundary

Table 2 Spraying conditions

Mass flow rate	0.83g/s
Water temperature	33.4°C
Spray cone angle	50°
Injection pressure	6MPa

Table 3 Atomizer's analysis parameters

Sheet constant[1]	Case1	24
	Case2	12
	Case3	3
Ligament constant[2]		0.5
Atomizer dispersion angle[3]		6

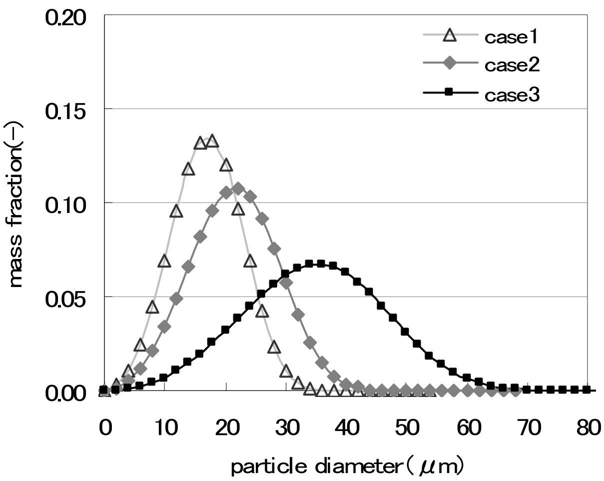

Figure 2. Particle size distributions.

Fluent Ver. 6.3 software package was used for this numerical fluid analysis. In the calculation area, the heat transfer between the water mist particles and air, the evaporation of mist and conservation of momentum are taken into consideration by using the Discrete Phase Model. The pressure-swirl Atomizer Model, which is based on the swirl atomizer used at the venue of Expo Aichi 2005, was adopted for this analysis. Table 2 gives the spraying conditions of the atomizer. While Table 3 indicates the atomizer's analysis parameters. The particle size distribution generated by an atomizer is determined by the spraying conditions given in Table 2 and also by the atomizer's characteristics, that is the atomizer's analysis parameters given in Table 3.

For the purpose of this study, only the sheet constant was varied to generate different particle size distributions under the same spray conditions. Figure 2 shows the particle size distributions for the three cases considered in this analysis[4]. Under the conditions of the above mentioned analysis, we conducted simulations up to a steady state in each case.

DISCUSSION AND RESULT ANALYSIS

Single-Nozzle: Results and Discussion

Figures 3 to 5 show the vertical cross-section temperature contours at the spray location (y=7.5 m) for the three cases. Figures 6 and 7 show the temperature distribution and the absolute humidity distribution at 1.5 m (y=7.5 m, z=1.5 m) above the ground. For each case, the air temperature decreased and the humidity increased about 1.5°C at the spray location (x≈15 m). Also, about 2.5m behind the spray position, it was observed that the maximum air temperature increasing was about 0.5°C. This phenomenon probably occurred because the downward airflow from the mist spray position drew the surrounding warm air. The wind direction diagram of Fig. 8 also confirms this phenomenon. Also, there was no significant temperature reduction at the position behind spray location (from x=20 m to x=50 m).

The absolute humidity increased to about 20.0 g/kg' at the spray location to only about 19.2 to 19.5 g/kg' at the position behind the spray location, representing an increase of 0.3 to 0.6 g/kg'. Figure 9 shows the remaining particle mass distribution at every height of the analysis area. The total mass of remaining particles was smaller for Case 1 than for the other two cases, indicating a fast evaporation rate. In Case 3, which is for comparatively large particles, there was a large mass of particles remaining in the area. When the mass of remaining particles was analyzed as a function of height, the particles remained, even at a height of 1.4 m.

On the basis of the above results, it was found that the temperature reduction does not vary greatly with differences in particle size distribution. However, as the particle size increases, it takes time longer for the particles to completely evaporate, and particles may remain even at low heights.

Thus, it can say that the particle size is an important parameter in mist design when considering the spray height.

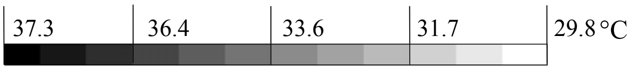

Figure 3. Case 1, air temperature contours at the spray location (y=7.5m).

Figure 4. Case 2, air temperature contours at the spray location (y=7.5m).

Figure 5. Case 3, air temperature contours at the spray location (y=7.5m).

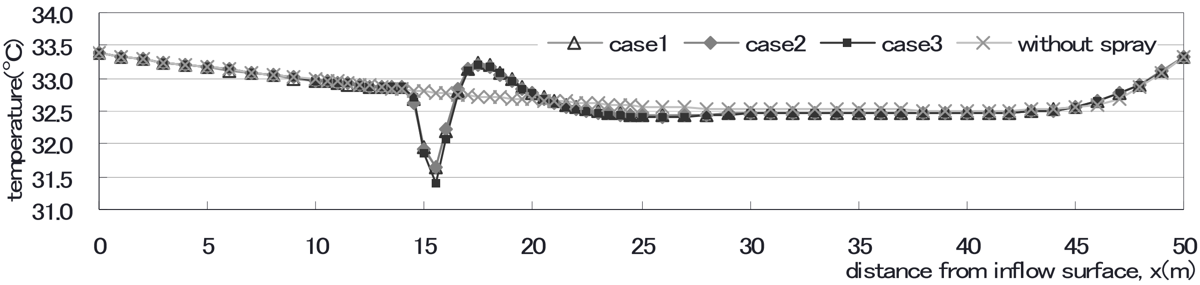

Figure 6. Air temperature dstribution at the spray location of 1.5m height (y=7.5m, z=1.5m).

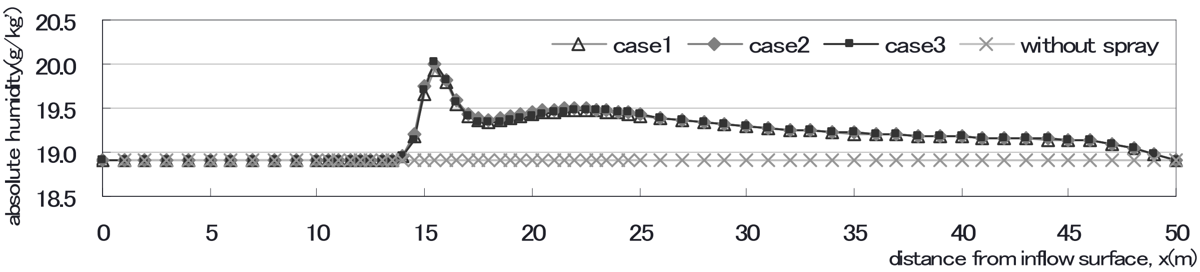

Figure 7. Absolute humidity dstribution at the spray location of 1.5m height (y=7.5m, z=1.5m).

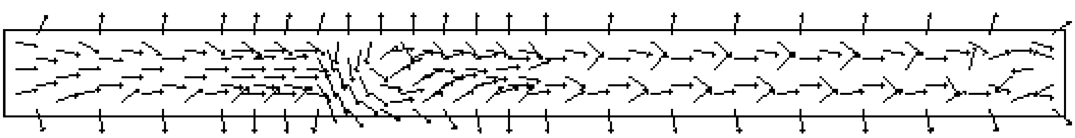

Figure 8. Airflow direction at spray location (y=7.5m)

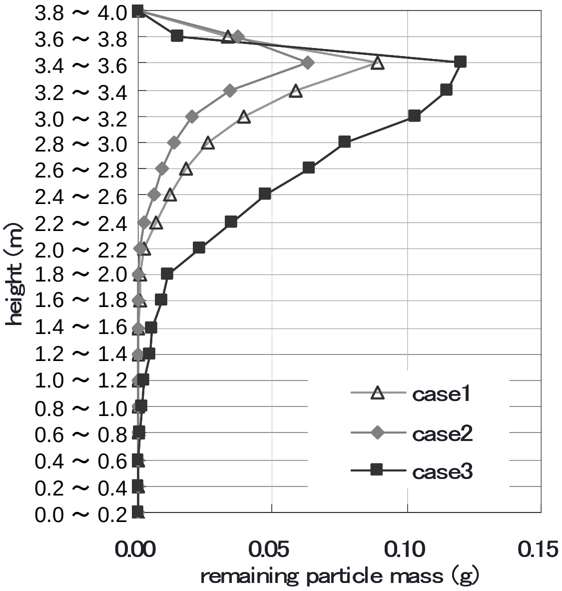

Figure9. Remaining particle mass distribution at each height

Multiple Nozzles: Results and Discussion

This section discusses the effect of particle size distribution when multiple nozzles are arranged at equal intervals. The same calculation conditions were used as for the single-nozzle scenario. Three nozzles were used, and the 2nd and 3rd were installed at 2.5 m intervals from the single-nozzle spray position. The interval was set to 2.5 m intend to reduce the temperature increase behind the spray position. Only Cases 2 and 3, which had large particles, were investigated for particle size distribution. Also, Cases 2' and 3' have the same condition of particle size distributions as Cases 2 and 3 respectivly. Figures 10 and 11 show the cross-sectional (y=7.5 m) temperature contours for Cases 2' and 3'.

Figures 12 and 13 show the air temperature distribution and the absolute humidity distribution at a height of 1.5 m (y=7.5 m, z=1.5 m). Similarly to the case of the single nozzle, there was no significant difference in the temperature reduction for different particle size distributions.

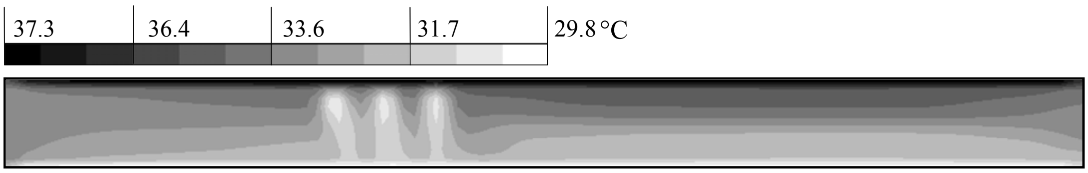

Figure 10. Case 2', air temperature contours at the spray location (y=7.5m).

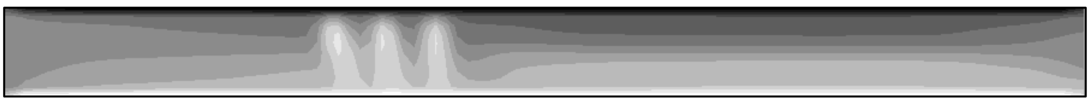

Figure 11. Case 3', air temperature contours at the spray location (y=7.5m).

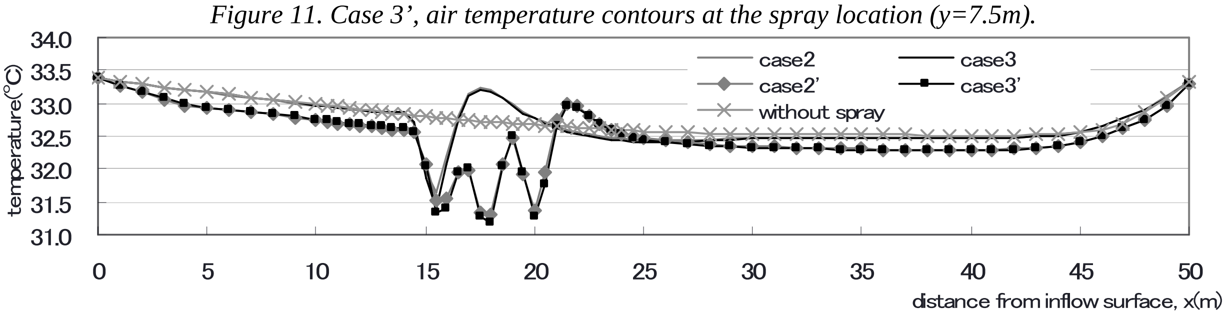

Figure 12. Air temperature dstribution at the spray location of 1.5m height (y=7.5m, z=1.5m).

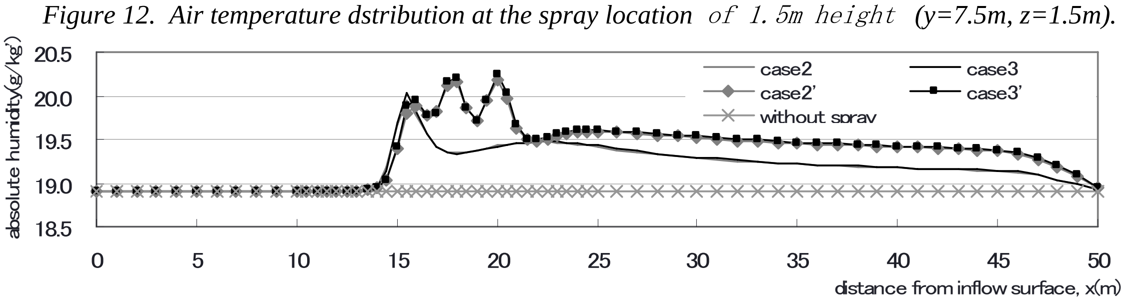

Figure 13. Absolute humidity dstribution at the spray location of 1.5m height (y=7.5, z=1.5m)

The air temperature right below each nozzle was about 31.3°C, which is approximately equal to that in the case of a signle nozzle. Compared with absolute humidity distributon, the humidity just below the 1st nozzle was similar to the single-nozzle case. However, the humidty just below the more behind nozzle was higher than that of ahead. The humidity of the 3rd nozzle was about 0.2 g/kg' greater than that for the corresponding case of the single nozzle.

Figures 14 and 15 show the horizontal distribution of air temperature at a height of 1.5 m for Cases 2 and 2'. In the cases where multiple nozzles are used, the air temperature in front of the 1st nozzle was lower than with the single nozzle. The reason why the difference of temperature distribution was considered that the downward flow by water mist evaporation was greater than in the case of the single nozzle, and that the heat of mist vaporization was diffused more easily because of the downflow due to mist blocking the inflow of outdoor air. This phenomenon may have occurred because the side boundary condition was a wall without of new air inflow or outflow.

Figure 16 shows the particle mass distribution at different heights. In comparing the cases of single and multiple nozzles, we see that the maximum mass of remaining particles was found at almost the same height. As for the minimum height at which particles remained, however, little remained at a height of 1.8 m or lower for both Cases 2 and 2', which had comparatively small particle size distribution. Comparing Cases 3 and 3', which had comparatively large particle size distribution, a small number of particles remained even at a height of 1.0 m for Case 3'.

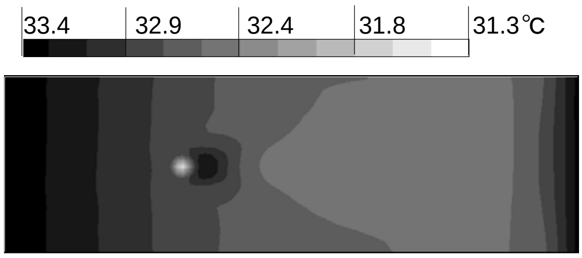

Figure 14. Horizontal distribution of air temperature at a height of 1.5 m with a single nozzle (Case2).

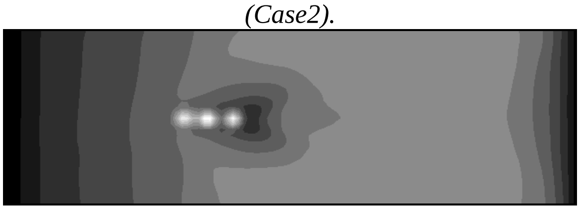

Figure 15. Horizontal distribution of air temperature at a height of 1.5 m with three nozzles (Case2').

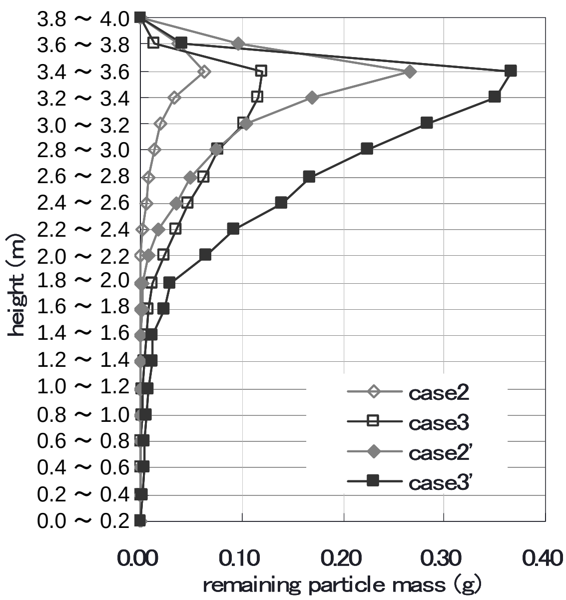

Figure 16. Remaining particle mass distribution at each height.

CONCLUSION

In this basic study on the cooling effect of mist sprays, we discussed the cooling effect in terms of particle size distribution and the height distribution of remaining particles.

A significant difference in the temperature reduction for different particle size distributions was not observed. As the particle size distribution increased, however, the minimum height of remaining particles was lower. Mist particles remained at lower heights when the number of nozzles was increased. And this effect was greater for larger particle sizes.

In general, however, it is known that greater spray pressure is necessary for generating finer mists, and it results increase the pump power.

The above results demonstrate that spray height and particle size need to be selected carefully if the minimum height of remaining particles is to be strictly controlled. In the future, we will study the cooling effect of mist spraying for varying outdoor conditions (air temperature and himidity) and compare the results with actual measurements.

ANNOTATION

[1] The swirl atomizer nozzel contains an internal swirl vane that produce rotational flow. The swirl liquid forms a thin sheet along the inside walls of the injector. Generally, aerodynamic instability causes a wave on the sheet to break up into liquid ligaments and droplets. In this process, the parameter of Sheet constant is determined by the maginitude of the wave, and Sheet constant 12 is recommended by previous

literature. The particle size becomes smaller when this value becomes larger.

[2] If a liquid sheet wave is short, the ligament thickness is proportional to the wavelength. The ligament constant means this constant of proportion. It is given a default value of 0.5 for purposes of this study.

[3] The atomizer dispersion angle is the parameter of dispersion angle as the liquid ligament breaks up into droplets. Since the spray pattern in this study is hollow-cone spray, it was assigned a value of 6°.

[4] The droplets size distribution of the atomizer is determined by the Rosin-Rammler Diameter Distribution Method, and the Spread parameter is 3.5.

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