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Solving model of temperature and humidity profiles in spray cooling zone

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ABSTRACT

Spray cooling technology is being increasingly used to improve the outdoor high temperature environment owing to its energy efficient and environmentally friendly characteristics. However, it is difficult to quantitatively analyze the temperature and humidity distribution in the spray environment due to the uncertainty of the outdoor environment. Based on the moist air theory combined with the heat and mass transfer model of droplets, this study established an analytical model to analyze the effect of spray cooling on the environment temperature and humidity patterns. The developed model can be used to calculate the temperature drop and humidity increase rates under different conditions. The data collected at the Shanghai Expo Axis is used to validate the established model, which shows good agreement with the experiment results. On the basis of these experimental conditions, the temperature drop and humidity increase rates are calculated under different spray pressures, droplet diameters, and airflow rates in the spraying area. It is found that the best spray pressure is 3 MPa when both the cooling effect and the economic feasibility are considered. Second, smaller droplet sizes and lower airflow rates lead to better cooling effect. Third, the local environment humidity has a greater cooling effect compared to the environment temperature. Additionally, this study offers critical analysis of the environment parameters that influence the cooling effect and the cost of the spray cooling system.

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1. Introduction

Spray cooling is a quite popular cooling method that has recently received much attention worldwide to lower the outdoor temperature and produce comfortable conditions in crowded and high temperature environments. This cooling technology has originally been developed abroad, and has been widely used in the United States, Spain, and Japan Expo. The domestic application of this cooling technology started back in the 1990s. Some of the well-known domestic applications are the North Olympic Games, the Paralympic Games, and Hong Kong Disneyland [1]. Recently, the spray cooling technology has been applied to the 2010 Shanghai Expo [2] and has been proven to be quite effective. The extensive application of spray cooling technology has also drawn much attention to study the characteristics of this cooling mechanism. However, limited quantitative research on the spray cooling effect on moist air environment has been conducted, especially on the subject of temperature drop and humidity increase distribution.

Within this context, a lot of experimental research and simulation studies have been conducted by many scholars in the field using actual spray cooling systems and processes in the past years. The recent research finding by Japanese scholars, which had been verified in the summer Aichi Expo in 2005 [3], concluded that the spray system can typically reduce the air temperature by more than 1-2 °C when the air temperature >30 °C and the relative humidity <70% [3,4]. Abdullah applied spray and sunshade strategies on roofs and studied their various influences on the indoor thermal stratification, which revealed that the implemented spray cooling method had a better cooling effect than window shading on the

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Nomenclature

Ar	surface area of a single droplet (m^2)
B	mass diffusive coefficient of a droplet (m^2/s)
Δdi	humidity ratio increment of moist air in the spray area of Δx_i (g/kg)
$d_{A,2}$	humidity ratio of air (g/kg)
$d_{A,1}$	humidity ratio of the droplet surface (g/kg)
ΔD_i	humidity ratio increase of moist air in the sprayed area of Δx_i at the time of τ (kg)
i	enthalpy of air (kJ/kg)
ΔL_i	evaporation mass of droplet group, which is x_i m far from the nozzle during the time of $\Delta\tau_i$ (kg)
$n_{A,r}$	mass diffusion rate per unit area of droplet ($kg/(m^2s)$), the initial evaporative ratio is $n_{A,r1}(kg/(m^2s))$
$n_{A,ri}$	evaporative ratio of the droplet that is x_i m from the nozzle ($kg/(m^2s)$)
N_0	total number of sprayed droplets per unit time ($drop$)
N_A	evaporative mass of the droplet surface (kg/s)
N_i	remaining number of droplets after the time interval τ_i ($drop$)
M_A, M_B	molecular qualities of the droplet and air
$M_{air,i}$	total quality of the moist air which is x_i m from the nozzle (kg)
M_r	quality of a droplet (kg)
P	air pressure of the environment (N/m^2)
$\overline{P}_B$	logarithmic mean pressure value between the partial pressure on the droplet surface and the partial pressure of the moist air in the environment (N/m^2)
P_A	partial pressure of water vapor (N/m^2)
$P_{A,1}$, $P_{A,2}$	partial vapor pressure on the droplet surface or the environment wet air (N/m^2)
$P_{B,1}$, $P_{B,2}$	partial pressure of dry air on the droplet surface or partial pressure of the dry air in the environment (N/m^2)
R_i	the diffusive radius of droplet which is x_i m from the nozzle (m)
R_M	universal gas constant, $R_M = 8135$ $kJ/(kmol{\cdot}K)$
r, r_1, r_2	radius of the droplet, initial radius of the droplet, radius of the droplet after evaporation for the time interval of τ (m)
T,t	environment temperature (K, $°C$)
t_s	wet-bulb temperature of air ($°C$)
v	air velocity (m/s)
V_i	air volume in sprayed area that is x_i m from the nozzle (m^3)
V_A,V_B	molar volume of air or droplet (m^3/mol)
x_i, Δx_i	distance from the measure point to the center of the nozzle and the length element along the spray trajectory (m)
ρ_{air}	air density (kg/m^3)
τ,$\Delta\tau$	spray duration and time element (s)

upper part of the studied buildings [5]. After numerous experimental studies, the spray cooling technology was extensively applied in 2010 Shanghai Expo [6]. Based on field measurements, it is found that the spray zone temperature within 4 m can be reduced by 3 °C when the outdoor temperature is 40 °C [2]. In addition, Farnham also found that the cooling effect of outdoor water mist fan is highly efficient and can easily reduce heat stress and discomfort [7]. Such outdoor cooling technology can increase thermal comfort among crowded population or during large outdoor events [8]. The positive effect of spray cooling on public playgrounds is recognizable.

Barrow [9] reflected on the evaporative cooling mechanism and characteristics when he studied the applications of spray cooling in subway tunnels early in 1995. Only the macroscopic effects were taken into account, while the effect of the microscopic droplets heat and mass transfer on cooling was not considered. In 1997, Kachhwaha [10,11] used experiments and simulation to study the effect of spray cooling in tunnels, in addition to investigate the droplet size distribution of the whole field together with the nozzle speed using photographs. The dry bulb temperature and relative humidity of the air at the entrance of the system were regarded as input values of the numerical simulation in order to obtain the temperature drop and humidity increase rates at the outlet. The heat and mass transfer between the droplets and the moist air environment, and the environmental conditions at different locations were not taken into consideration. In 2006, Barrow [4] carried out a theoretical analysis on the feasibility of using water mist for cooling, and examined the heat and mass transfer of the round droplets in railway tunnels. He reported the temperature and droplet diameter variation in relation to time, and found the relationship between the evaporation time and the initial droplet size. However, this study was limited to a single droplet, and thus, the changes in the heat and mass transfer of the droplets in air at different locations was not investigated. Wu et al. [12] numerically calculated the droplet evaporation rate at a constant temperature and humidity field. The study findings indicated that the environment relative humidity is the most effective factor compared to the Stefan number and the initial droplet diameter. Recently, more research studies on spray environment and spray characteristics were conducted using CFD (Computational Fluid Dynamics) simulations. CFD simulations allow the determination of the humidity distribution of spray environments while avoiding the complexity of humidity measurements in experiments [13]. Several CFD studies and full-scale measurements have been performed in which the cooling performance of spray systems is investigated and thermal comfort is assessed in detail. These research findings indicate that the inlet dry-bulb air temperature, inlet humidity ratio, inlet pressure, and droplet size distribution significantly affect the performance of water spray system [14-17]. However, they did not provide corresponding methods to calculate the effect of each variable.

Based on the field measurements of spray cooling that were carried out in Shanghai Expo area [2,6] combined with the moist air theory, this paper developed a heat and mass transfer model of mist droplets in moist air environment, which can be used to calculate the moist air temperature and humidity caused by the evaporation of water droplets near the spray and evaluate the corresponding spray cooling effect. Meanwhile, the actually measured data of the Shanghai World Expo Axis is used to validate the developed mathematical model, and calculate the temperature drop patterns of the mist droplets in the moist air environment under different conditions.

2. Mathematical model of spray cooling

2.1. The model for the evaporation rate of the mist droplet in moist air

Regardless of the effect of gravity field, the droplet in moist air can be viewed as a spherically symmetric model with a saturated

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