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Development and application of a simplified radiative transport equation in water curtain systems

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ABSTRACT

In this study, a simplified radiative transfer equation (RTE) for water curtain is introduced. The scattering phase function, asymmetric factor, single scattering albedo, and efficiency factors are investigated with non-gray and gray medium, respectively. The prediction values by a simplified equation are compared with previous results by the two-flux, P_3 and F_9 methods in non-gray medium. The deviations of reduced intensities are less than 10%. As the droplet size increases more than 100 μm, the asymmetry factor, scattering phase function, and scattering albedo are converged as 0.975, 0.992 and 0.501, respectively. Thus, a more simplified equation for the reduced intensity of radiation can be determined with the exponential function of optical depth.

To correlate the relations between the flow characteristics of water curtain and the optical depth, the droplet mean diameter and the number density are analyzed with a modified gamma distribution function. In addition, the FTIR spectrometer is calibrated to obtain the spectral intensity in the thermal infrared and large droplet region.

Finally, the important engineering parameters such as the mass flow rate, the droplet mean diameter, the number density, the optical depth, and the reduced intensity are systematically investigated. It can be predicted that optical depth ($\tau > 0.89$), number density ($N > O(4 \times 10^6\ \mathrm{m}^{-3})$), droplet mean radius ($r_m < 180\ \mu m$) and flow rate ($Q_{flow} > 1.2$ kg/s) are determined to reduce the radiation intensity less than 50% for the selected water curtain nozzle in this study.

1. Introduction

The water curtain is recognized as a useful technique to mitigate major industrial hazards such as the fire propagation in buildings or other facilities [1–3]. It is possible to attenuate the heat fluxes by using a curtain of free-falling water droplets [1–6]. Thus, the injection pattern of the water curtain has a significant role as a filter between hot flue gases and fresh air [3–7]. The mechanism of thermal interaction in the water curtain can be described by energy transfer theory in which conduction, convection, and radiation are combined. Among them, the radiative transfer equation (RTE) is dominant fire propagation mechanisms; it is of primary interest to investigate and to evaluate the true attenuation of the radiative heat flux when using water [1–9].

RTE is based on the electromagnetic theory, which depends on the refractive index of the medium at each wavelength [10–12]. The difficulty of RTE lies in how to resolve the scattering phase function, which sensitively changes with refractive index and droplets [13–16]. As shown in Fig. 1, only in the special case of small particle limit in Rayleigh scattering asymptotic region, the extinction efficiency factor reaches the absorption efficiency factor [17–19]. Thus, scattering phase function can be neglected. However, in most cases, droplets in water curtain have more than O(∼100 μm) in thermal infrared region as explained in Fig. 1. It proves that the scattering term cannot be neglected in the water curtain.

1.1. Literature survey

Gustav Mie (1908) mathematically resolved the entire electromagnetic field of radiation for sphere particles [11–20]. Nevertheless, various applications have been investigated by the other approximations of RTE due to the complexity of the Mie calculation.

T.S. Ravigururajan and M.R. Beltan (1989) suggested a semi-empirical model equation for the attenuation of radiation in water droplets [21]. They consider the space between the flame and the object,

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Nomenclature

C_0	experimental constant of distribution [−]
C_1	the first radiation constant, 3.7415·10^{-16} [W·m^2]
C_2	the second radiation constant, 0.014388 [m·K]
D	hydraulic diameter of water curtain nozzle [m]
d_m	droplet mean diameter [μm]
$f(r)$	normalized distribution [−]
f_v	volume fraction [−]
g	asymmetry factor [−]
H	real depth of water curtain [m]
I_λ	spectral intensity of radiation [W/(m^3·sr)]
$I_{b,\hat{v}}$	blackbody intensity of radiation [W·m^{-1}]
k	absorption coefficient [m^{-1}]
m	real part of complex index of refraction [−]
n	imaginary part of complex index of refraction [−]
$n(r)$	particle size distribution function [m^{-3}μm^{-1}]
N	number density (number of particles per unit volume) [#/m^3]
Q	Mie efficiency factor [−]
Q_{flow}	mass flow rate [kg/s]
r	droplet radius [μm]
s	unit vector in the direction of ray propagation [−]
T	temperature [K]
α	distribution coefficient of droplets [−]
β	extinction coefficient [m^{-1}]
χ	size parameter [−]
τ	optical depth [−]
ν	frequency [Hz]
$\tilde{\nu}$	wavenumber [cm^{-1}]
σ	scattering coefficient [m^{-1}]
γ	distribution coefficient of droplets [−]
Θ	scattering angle [−]
μ	direction cosine [−]
Φ	scattering phase function [−]
Ω	solid angle [sr]

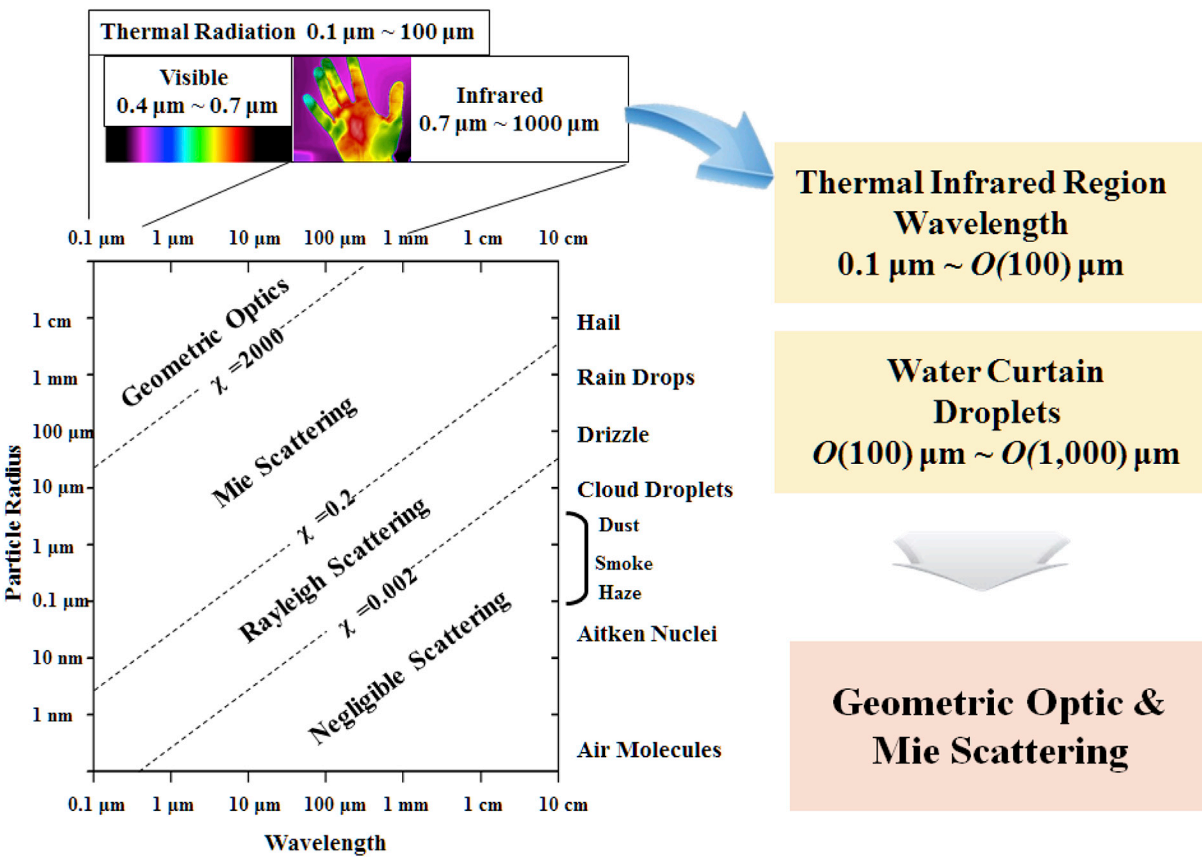

Fig. 1. The geometric optic and the Mie scattering region of the droplets in water curtain.

which is filled with scattering and absorbing medium. However, they adopted the Lambert-Beer law, which neglects the scattering phase function. Despite their efforts, the limitation of this model can be occurred in case of large droplets of the water curtain due to the scattering. Coppalle et al. (1993) suggested a simple solution by using the two-flux method [7]. The fitting equations of A. Coppalle et al. are useful to analyze the non-gray in the participating medium of water. However, to the author's knowledge, there must be a mistake for the converted sign value $(-(1-\omega_\lambda f_\lambda)I_\lambda^-(\tau_\lambda))$ to resolve the RTE with the scattering phase function. The limitation of their results is that the asymmetric factor should not be equal to zero in any other cases. W. Yang et al. (2004) characterized the interaction of water mist using a two-flux method from the assumption that the uniform for hemispherical in the forward and backward directions [22]. They presented interesting results that the scattering dominates the attenuation of radiation at shorter wavelength to increase the penetration depth of radiation shielding. Also, the absorption becomes much more importance for large droplets at longer wavelengths. However, in their present model equation, it is tedious to calculate the reduced intensities. The droplets are relatively small while the droplets of water curtain are O(∼100 μm). Thus, the research scope