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Effects of droplet ratio and void fraction on the attenuation of radiative heat flux in water curtain

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ABSTRACT

The attenuation effects of radiative heat flux in water curtain are theoretically and experimentally investigated along the vertical direction from the nozzle. Based on the boundary conditions of water curtain, the general form of the attenuation efficiency of radiative heat flux is introduced as a function of droplet ratio and void fraction using the vertical 180 nozzle. The droplet ratio is applied to a 50% cumulative distributions (d_{50}) for droplet mean diameters and a 99% that (d_{99}) for the maximum diameters. In addition, the ratio of d_{50}/D (hydraulic diameter of the injection nozzle) is correlated with the -0.39 index of Webber number to estimate the decrease tendency of the measurement values. The void fractions are well curve-fitted by flow rate and distance within $\pm 3\%$ error along the vertical direction for the vertical 180 nozzle. The radiative heat fluxes are obtained by considering the convective term in energy equation. To verify the reliability of the present equation, the attenuation efficiencies of radiative heat flux are obtained from the vertical 60 nozzle. The results show that the predictions and experiments are in good agreement within $a \pm 10\%$ error as flow rate increases in the fully break-up region.

1. Introduction

One of the most interesting subjects in the water curtain for fire protection is the attenuation ability of thermal energy [1–4]. Since cold water injected from the nozzle interacts with hot flue gases, the heat transfer phenomenon takes place between each interface. The mechanism of thermal interaction in the water curtain is described by the energy transport equation, in which conduction, convection, and radiation are combined.

Over the years, many researchers have studied the thermal characteristics of water spray and investigated various experimental, theoretical or numerical methods for the attenuation of radiation [3–10]. Ravigururajan and Beltan [3] introduced a simple model for the attenuation of the spectral intensity through water droplets. They showed the optimal attenuation factor could be determined by the droplet size, which is equal to the wavelength. However, the limitations of this model are the technical method for manufacturing and the real injection phenomenon has not been considered as mentioned in their paper Boulet et al. [4–9] solved the radiative and conductive heat transfer for the full domain of the water curtain using a numerical method. They suggested a semitransparent medium for the spray region and linked this with the radiative part of the problem solved by the discrete ordinate method (DOM). Their results show that as the droplet size decreases, the entire domain temperature lowers. In spite of the numerical complexity, their approach includes the thickness effects of the water curtain, convection in boundary, and droplet distribution for mono-dispersion. Yang et al. also characterized the interaction of water mist with spectral intensity by absorption and scattering based on Mie theory and two-flux model [10]. They presented interesting results that scattering dominates at shorter wavelength in order to increases the penetration depth of radiation-shielding while absorption becomes much more importance for large droplets at longer wavelengths. Most of the previous research has performed the attenuation of spectral intensity with a fixed droplet diameter since it could not be changed after eddy breakup occurred [11–14]. However, it requires complex computation to obtain the attenuation of spectral intensity in non-gray medium. In fire, the design parameters (mass flow rate and droplets distribution) for protecting the heated thermal gases or extinguishing a fire by gray medium assumption are one of the most important objectives. Therefore, from the engineering point of view in fire protection, more simplified model for predicting the radiative heat flux should be developed. In this study, observation of a generalized model that considered the attenuation efficiency of radiative heat flux in gray medium with droplet diameters and void fractions along the vertical direction from the nozzle is presented.

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2. Materials and methods

2.1. Problem description

Fig. 1 shows a schematic diagram of the experiment apparatus, which consists of a heater, the water curtain nozzle (vertical 180), a He–Ne laser device, a high speed camera, a heat flux meter, and K-type thermo-couples. The heater is located at 0.9 m distance from the vertical 180 nozzle. The HELOS/VARIO, which has 31 fraction in band from 0 µm to 3500 µm (R7 Lenz), 1132 mm working distance and 600.7 cm^3 measuring volume. The experiments are performed with two steps. First, the droplet distributions and void fractions are measured at each flow rate, Q_{flow} =21.2 L/min, 27.0 L/min, 30.78 L/min, 34.7 L/min and 37.3 L/min by He–Ne laser device. The void fractions of water curtain are estimated by the reduced voltage of He–Ne laser. In addition, the pictures of the droplet distribution every 90,000 frames/sec to measure the droplet velocity by PIV (Particle Image Velocimetry) method using high speed camera behind the target. Second, the heat fluxes are measured with fixed temperature of heat source for each flow rate. The installation distance of the heat flux meters is especially considered to avoid being interrupted by the water spray. The thermos-couples are attached to the surface of the heater and the target as well as the main stream in the vicinity of the surface. The specifications of the experiment are denoted in Table 1.

2.2. Mathematical method

The energy balance can be arranged as follows [15–17],

$$q''_{total} = q''_{rad} + q''_{conv} + q''_{cond} \tag{1}$$

where q''_{total}, q''_{rad}, q''_{conv} and q''_{cond} are the total heat flux transmitted through the curtain, the radiative heat flux, the convective heat flux, and conductive heat flux, respectively. The problems under consideration in this study can be though as radiative heat in participating medium as shown in Fig. 2. Thus, the convective (q''_{conv}) and conductive(q''_{cond}) terms are neglected. Generally, the radiative transport equation (RTE) for steady state is composed of absorption, emission, and scattering as denoted in Eq. (2) [18–22].

$$\frac{dI_\lambda}{ds} = -\beta_\lambda I_\lambda + k_\lambda I_\lambda^0 + \frac{\sigma_\lambda}{4\pi}\int_{4\pi}\Phi_\lambda(s' \to s)I_\lambda(s')d\Omega' d\lambda' \tag{2}$$

where I, k, s, β, σ, Φ and Ω are, respectively, spectral intensity, Boltzmann constant (1.3807×10^{-23} J/K), the direction of propagation of radiation, extinction coefficient, scattering coefficient, scattering phase function and a solid angle [19–22]. The subscript λ denotes wavelength and all the coefficients of Eq. (2) are independent on the frequency ($\nu = c/\lambda$) due to continuous, homogeneous, isotropic and coherent scattering in the medium. Although these assumptions are open to be criticism on physical ground, this approximation correctly describes all engineering problems when the velocity of fluid is much smaller than the velocity of light [19]. Moreover, inside of the medium is partially filled with water at ambient temperature, the emission term can be omitted from Eq. (2) and azimuthal symmetry for ϕ direction by parallel plan [19–22]. Thus, the governing equation is arranged as Eq. (3) when a single scattering albedo ($\omega_\lambda = \sigma_\lambda/\beta_\lambda$), direction variable ($ds\cos\theta = dy$), optical depth ($\tau = \int\beta dy$) and direction cosine($\mu = \cos\theta$) are applied into Eq. (2) [19–22].

$$\mu\frac{\partial I_\lambda}{\partial \tau_\lambda} = -I_\lambda + \omega_\lambda\int_{\mu'=-1}^{\mu'=1}\tilde{\Phi}_\lambda(\Theta')I_\lambda(s')d\mu' \tag{3}$$

Each term of Eq. (3) is net gain of energy, loss of energy due to extinction and increasing energy within solid angle $d\Omega$ by scattering, respectively.

In this study, we suggest an empirical model based on the RTE theory and the boundary conditions in water curtain. The definition of wavelength averaged values for gray medium is as below [19, 23],

$$\langle\varphi(r)\rangle = \int_{\lambda=0}^{\lambda=\infty} I_\lambda(r,\lambda)\eta(r,\lambda)d\lambda \Big/ \int_{\lambda=0}^{\lambda=\infty} I_\lambda(r,\lambda)d\lambda \tag{4}$$

where φ may be Q_s (scattering efficiency), Q_a (absorption efficiency) or Q_e (extinction efficiency) and Φ(scattering phase function), respectively. Thus, the wavelength averaged intensity of

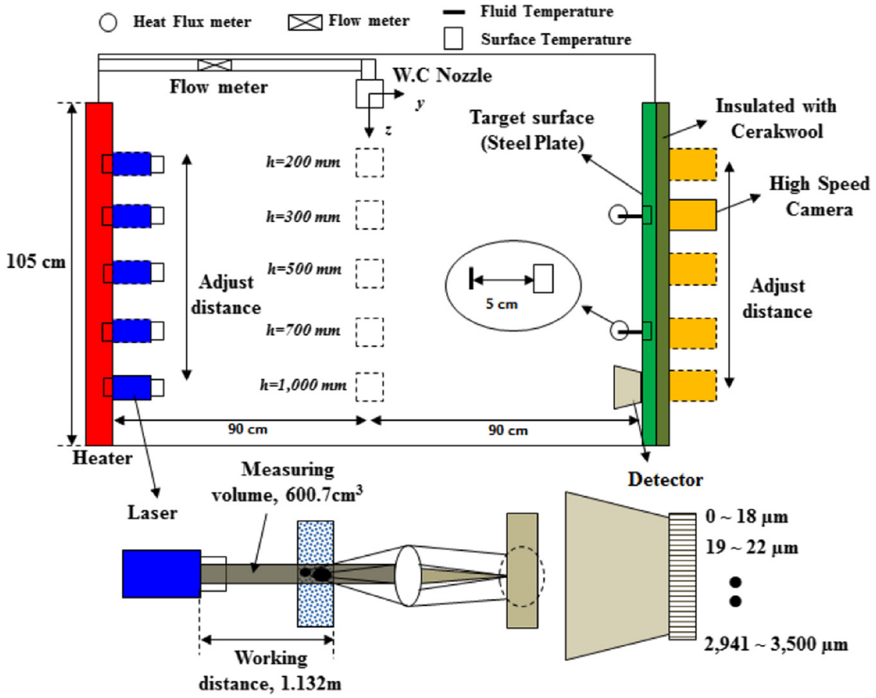

Fig. 1. Schematic diagram of the experiment apparatus.