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Radiation driven evaporation for polydisperse water sprays

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ABSTRACT

This study concerns the prediction of radiation heat transfer in evaporating water sprays for a 1D planar media. The spray evolution is described by a Lagrangian sectional approach with the initial diameter size classes defined by normal and log–normal distributions. The spray and the gas-phase radiative properties are recast in terms of cumulative distribution functions (CDF) for use with a correlated-*k* approach to solve the radiative transfer equation (RTE). The spectral properties required for constructing the CDFs for the droplets and gas are determined using Mie theory and the HITEMP databases, respectively. Cases are conducted to explore the sensitivity of radiative energy attenuation to time evolving droplet size distributions as a function of initial distribution, distance to the energy source, volume fraction and temperature. Results from this study show that the PDFs generate a positive skewness due to the size dependent absorption properties of the droplet. These findings suggest that the droplet size distribution can be adequately described by prescribed, non-symmetrical PDFs that are parameterized by lower order moments.
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1. Introduction

The evaporation rate of water sprays is important in fire protection of highly temperature sensitive goods or in areas where water content availability is restricted as a suppression agent. Evaporation from radiation occurs immediately as the interaction of the electromagnetic waves, that carry the radiative energy, with the droplets will lead to absorption and scattering. The evolution of the droplet size distribution in time will change the attenuation of the radiative energy. Water sprays that may be initially spatially homogeneous may become inhomogeneous from radiation heat transfer alone as evaporation takes place. Although it is a fundamental problem in fire suppression, few studies have addressed droplet evaporation by radiation and further research for the optimization of thermal radiation attenuation by water sprays is necessary as pointed out by Sacadura [1] in a recent review on radiation heat transfer in fires. The main challenges due to their computational cost are: (i) solution to the RTE for a scattering media and (ii) calculation of the non-gray radiative properties of the spray.

In early work by Williams [2] analytical expressions were derived for the steady state vaporization of a single water sphere exposed to different radiant fluxes. In his work, absorption coefficients are considered constant and the energy is absorbed at a uniform rate per unit volume. Later work by Harpole [3] presents a complete analysis for the volumetric heating due to radiation absorption using a model based upon electromagnetic wave theory and ray-tracing procedures for spherical water droplets in high temperature environments. Results were presented for different diameter sizes for a single droplet as a function of time. Lage and Rangel [4,5] studied the droplet life time of *n*-decane and water droplets irradiated by a blackbody at 850 K and 2000 K, assuming spherical symmetric conditions. They concluded that radiation heat transfer can be as important as the choice of the liquid-phase droplet model and that the spatial non-uniformity of the imposed radiation has little effect on the overall droplet evaporation time. This fact has been studied more recently by Miliauskas [6–8] and Dombrovsky [9] for interaction of radiation and conduction processes in evaporating droplets. Dombrovsky used Mie theory for his calculations and concluded that thermal radiation is absorbed mainly in the central zone of the droplets for semi-transparent ranges and at the surface of the droplet for absorbing peaks. More recently, Tseng and Viskanta [10] developed a radiative transfer model based on geometrical optics theory, rather than Mie theory, and the solution of the radiative transfer equation inside the droplet including internal circulation to account for temperature non-uniformity. They found that the absorption of radiative energy is important for droplets larger than 100 μm for high temperatures in fire environments considering diffusion processes are dominant.

In the present work, a model is developed to account for the overall radiative attenuation of an evaporating spray in a 1D domain. The initial droplet size probability density function (PDF) is represented by either a log–normal or normal distributions that are typically found in fire suppression systems [11]. The droplet size distribution is tracked in diameter space using a Lagrangian sectional approach [12]. The spectral properties for the water

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droplets and water vapor are obtained using Mie theory [13,14] and the HITEMP database [15], respectively. A narrow band correlated-k method is used to account for the RTE solution on a non-gray basis of the medium composed of produced water vapor and liquid droplets as explained by Modest and Riazzi [16] and Wang and Modest [17]. The RTE is solved using a first order spatial discretization scheme [18] and a S_8 quadrature for the angular discretization [19]. The droplets are irradiated by a diffuse blackbody slab at a prescribed temperature as the source of radiative energy. As evaporation takes place the medium becomes non-homogeneous from spatially non-uniform heat absorption processes requiring the solution of the RTE at every time step. Results are presented for the evolution of the droplets sizes and the heat flux at different times and locations. The strength of this unique modeling description is that the PDF evolution of droplet size from radiation is treated exactly without approximations for either the evolution of the PDF or for the radiation heat transfer in the scattering media. All the codes employed for the present work has been in-house tested and validated with experimental and numerical data in a previous work by the authors [20]. To the authors' knowledge such an approach has not been previously explored for radiation driven evaporation.

2. Mathematical formulation

2.1. Radiative transfer equation (RTE) and radiative properties of water sprays

The problem under investigation is radiation heat transfer in one-dimensional planar media subject to a heat flux from a black body at one of the boundaries. The temperature inside the droplet and the produced water vapor is assumed uniform and constant. All thermo-physical properties are also assumed constant. The media composed of the evaporating spray and the gas phase resulting from this evaporation is always considered as dilute [3] therefore conduction and convection mechanisms are neglected as the main focus of this study are radiation effects. This is perfectly justified as the concentrations for the water vapor are always small as will be shown in the results.

Radiative properties required for the integration of the RTE for a scattering, absorbing and emitting media is given by [21]:

$$\vec{s}\cdot\nabla I_\lambda = k_\lambda I_{b\lambda}(T) - \beta_\lambda I_\lambda + \sigma_\lambda \frac{1}{4\pi}\int_{4\pi} I_\lambda \Phi_\lambda(\vec{s}\,',\vec{s})d\Omega' \quad (1)$$

where I_λ is the spectral radiative intensity which depends on the path-length (s), absorption (k_λ), scattering (σ_λ) and total extinction ($\beta_\lambda = k_\lambda + \sigma_\lambda$) coefficients along with the scattering phase function (Φ_λ). The quantity $I_{b\lambda}$ is the blackbody intensity and depends on temperature. The spectral properties for the water droplets and water vapor are obtained from Mie theory [13,14] and the HITEMP database [15], respectively. A narrow band correlated-k distribution formulation is used from the work of by Modest and Riazzi [16] and Wang and Modest [17] for 242 bands for which initially a Lorentz profile had been employed to determine the spectral values of k from HITEMP. The narrow band k-distribution values of the gas are then obtained at atmospheric pressure for 23 temperatures and 5 different concentrations for water vapor using 10 Gaussian points for each narrow band as in [16]. This procedure was employed and tested in a previous work by the authors for spectral and total solution of the RTE for water sprays [20]. Expressions for the radiative coefficients are given by Mie theory that describes the scattering and absorption of electromagnetic waves in spherical droplets [21,22]. Two physical properties govern the spectral absorption and scattering by a single particle: the size parameter $x = \pi D/\lambda$ (D is the diameter of the droplet and λ the wavelength) and the complex index of refraction $m = n - ik$ (n is the refractive index and k the absorptive index). The optical constants, n and k, for water are obtained from the work of Hale and Querry [23]. The rates of absorption and scattering by a single sphere are given in terms of efficiency factors for the total extinction, Q_{ext}, scattering, Q_{sca}, and absorption, Q_{abs}. These factors are determined from Wiscombe's work on Mie scattering calculations [14] using Lentz's method of continued fractions for Bessel functions [13]. This was adapted to an in-house code that was tested and validated by the authors in a previous study [20]. Fig. 1(a) shows the behavior of the absorption efficiency factor for a single water droplet. The water droplets are nearly transparent for wavelengths less than 2 μm. Fig.1(b) shows a closer examination of the absorption distribution as a function of the size parameters for wavelengths near peak blackbody emission for $T = 1200$ K and 1000 K, respectively. For $\lambda \simeq 2.7$ μm and 6.3 μm, the absorption increases with decreasing size (up to $x = 2$ μm), due to the strong vibrational–rotational bands of water at these wavelengths. However, for other wavelengths the absorption is shown to decrease monotonically. As will be shown in the results, this distribution is important for radiative driven droplet evaporation because, on average, the droplets will

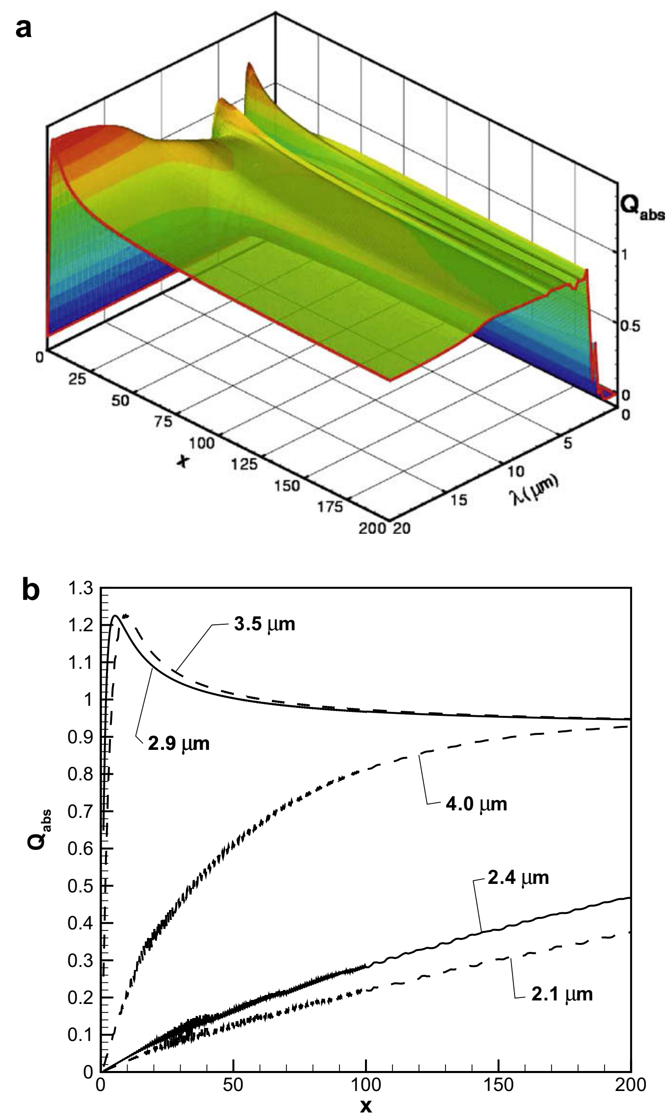

Fig. 1. Results for the absorption efficiency factor, Q_{abs} for water droplets using Mie theory for (a) as a function of size parameter x and wavelength λ and (b) detailed behavior of Q_{abs} for wavelengths near 2.4 μm and 2.9 μm (solid lines) corresponding to blackbody peak emission at 1200 K and 1000 K, respectively.

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