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Thermal radiation transport in a fluidized dry water system

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ABSTRACT

This paper reports a numerical study on thermal radiation transport in a novel material called dry water. Dry water is a water-in-air inverse foam which consists of micrometer-sized water droplets encapsulated by hydrophobic fumed-silica nanoparticles. First, the size distribution of dry water was measured using a particle size analyzer. Then, the radiation characteristics of dry water were obtained using the Mie theory for coated spheres. One-dimensional, steady radiative transport in fluidized dry water system was modeled using the radiative transport equation (RTE) and was solved spectrally with the discrete ordinates method. The effects of silica coating and water droplet size as well as the volume fraction of dry water particles on reducing radiative heat transfer were studied parametrically. The results obtained using the size distributions from experimental measurements at a volume fraction of 10^{-4} showed that dry water reduced the local radiative heat flux by more than 60% with respect to that by silica particles alone whereas its performance was comparable to that of fine water mists. Moreover, reduction of the diameter of dry water particles from 150 to 50 μm and increasing their volume fraction from 10^{-4} to 10^{-3} decreased the radiative heat flux by 45% and 67%, respectively. Dry water is a novel and unique material that does not require high pressure fluid lines for producing fine mists and features a silica shell that can serve to encapsulate water soluble compounds, retard water evaporation from the core as well as increase scattering. With these unique features, dry water finds diverse engineering applications serving as a base for photo-catalytic nanoreactors, gas and chemical storage and delivery systems, as well as alternative mist systems in firefighting.

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1. Introduction

Dry water is a water-in-air inverse foam consisting of micron-sized water droplets stabilized by hydrophobic silica nanoparticles which form a nanoporous shell [1–4]. It is composed of a continuous gas phase and a discretized aqueous phase which constitutes about 95% of its weight. It flows like dry powders and has a large surface to volume ratio on the order of $200 \times 10^3\ m^2/m^3$ [1–3]. It is a novel material that is environmentally benign and non-toxic. Since its first synthesis by Allan [4] in 1977, dry water has been considered for a number of applications including gas storage [1,2,5–10].

In particular, dry water offers unique advantages for use in fire suppression systems; however, this application has not been considered to date. Currently, water sprays are being used as the mainstream fire suppression systems as water is readily available and has a high latent heat of evaporation [11]. However, these systems require large energy input to be pressurized for achieving fine mists necessary for effective radiative performance. Additionally, overuse of water in conventional fire suppression systems result in parasitic water damage causing unnecessary property damage. As an alternative to water mists, chemical powders and foams are also used as fire suppressants which can chemically suppress the fires and can at the same time act as radiation shields [12–14]. Nevertheless, these do not

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Nomenclature

a	weighing parameter in truncated phase function
A_i	interfacial area concentration (m^{-1})
c	specific heat ($J\,kg^{-1}\,K^{-1}$)
c_0	speed of light in vacuum ($2.9979 \times 10^8 m\,s^{-1}$)
C	cross section (m^2)
D	diameter (μm)
f	weighing parameter in truncated phase function
f_v	volume fraction
g	asymmetry factor
G	irradiance ($W\,m^{-2}$)
h_{coat}	coating thickness (m)
h_0	Planck's constant ($6.6261 \times 10^{-34}\,J\,s$)
I	spectral light intensity ($W\,m^{-2}\,\mu m^{-1}\,sr^{-1}$)
k_B	Boltzmann constant ($1.3807 \times 10^{-23}\,J\,K^{-1}$)
L	length of the system (m)
n	index of refraction
q	heat flux ($W\,m^{-2}$)
q_r	radiative heat flux ($W\,m^{-2}$)
$\hat{\mathbf{s}}_i$	unit vector in a given direction
T	temperature (K)
w_j	weights of the Gaussian quadrature
z	distance from the hot surface (m)

Greek symbols

β	extinction coefficient (m^{-1})
λ	wavelength (μm)
κ	absorption coefficient (m^{-1})
Ω	solid angle (sr)
ϕ	porosity
Φ	scattering phase function
ρ	density ($kg\,m^{-3}$)
σ	Stefan–Boltzmann constant ($5.67 \times 10^{-8}\,W\,m^{-2}\,K^{-4}$)
σ_s	scattering coefficient (m^{-1})
θ	polar angle measured from the surface normal (rad)
Θ	angle between incident and scattered directions (rad)

Subscripts

abs	absorption
b	blackbody
coat	coating of the sphere
cond	conduction
core	core of the sphere
cutoff	cut-off angle in truncated phase function
d	droplet
DW	dry water
eff	effective property
gas	gas phase
HG	Henyey–Greenstein phase function
i	incident
sca	scattering
tot	total
TPF	truncated phase function
turb	turbulent
v	volume
λ	wavelength

have as large latent heat of vaporization as water and can contain toxic or environmentally unfriendly materials.

Dry water features the advantages of both water and particulate systems with a large thermal capacitance and without the need for high pressures for its atomization to form fine mists. Moreover, its silica shell acts to both retard the evaporation of water from the core, increasing the residence time of water droplets in the system as well as providing a scattering medium after all water evaporates. Due to the high temperatures involved, thermal radiation shielding is an important feature of fire suppression systems [15]. However, no study to date reported either the radiative properties of this novel material or analyzed thermal radiation transport in dry water. This study addresses these gaps in the literature and estimates dry water's performance in attenuating thermal radiation in a fluidized system for firefighting applications.

2. Analysis

Fig. 1a shows the system analyzed in this study. It consists of two parallel black surfaces separated by a distance L of 1 m. The top surface is at 2000 K as the thermal radiation source, based on the maximum temperature of a methane/air laminar flame [16,17], and the bottom surface is at 300 K which represents the receiver to be protected. Fluidized dry water consisting of varying size distributions and volume fractions was considered between the two black boundaries. A single dry water particle was modeled as a spherical water droplet that is uniformly coated with a silica layer as schematically shown in Fig. 1b.

2.1. Assumptions

The following assumptions were made in order to simplify the problem mathematically: (1) The system was one-dimensional. (2) The boundaries of the system were black and isothermal. (3) Based on the values reported in the literature [18–20], the refractive index of air as the gas phase of the system was assumed to be 1, whereas the absorption coefficient was negligible within the spectral range of interest from 0.3 to 30 μm. Thus, the gas phase was considered to be non-participating. (4) Dry water particles were modeled as coated spheres [21–23], with spherical water droplets in the core and uniform hydrophobic fumed silica coatings. (5) Independent scattering prevailed for the dry water system considered in this study for the volume fraction range from 10^{-5} to 10^{-3}. Indeed, according to the study by Tien and Drolen [24], independent scattering prevails for particle systems with volume fractions less than or equal to 10^{-3}

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