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Significance of particle concentration distribution on radiative heat transfer in circulating fluidized bed combustors

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ABSTRACT

In this study, effect of particle concentration distribution on radiative heat transfer in circulating fluidized bed combustors (CFBCs) is investigated. The aim is to identify how important it is to include axial and radial variations of particle concentration along the splash and dilute zones in radiative heat transfer calculations and to determine the predictive accuracy of simple 0D and 1D approximations for particle concentration distribution in the riser by benchmarking their predictions against a semi-empiric 2D axisymmetric model developed for a wide range of operating conditions and systems. Input data required for the radiation model are provided from measurements carried out in a 150 kWt cylindrical Circulating Fluidized Bed Combustor (CFBC) test rig burning low calorific value Turkish lignite with high volatile matter/fixed carbon (VM/FC) ratio in its own ash. Radiative transfer equation (RTE) is solved for 2-D axisymmetric cylindrical enclosure which contains gray, absorbing, emitting gas mixture with gray, absorbing, emitting, anisotropically scattering particles bounded by diffuse, gray/black walls. Incident heat fluxes and source terms along the riser are predicted by the Method of Lines (MOL) solution of Discrete Ordinates Method (DOM) with Leckner's correlations for combustion gases, geometric optics approximation for particles and normalized Henyey-Greenstein for the phase function. Comparisons reveal that 0D and 1D representations of particle concentration distribution lead to overprediction of incident heat fluxes in both splash and dilute zones, where discrepancy of 0D model is larger. Similarly, errors in source term predictions introduced by simplifying the particle concentration distribution via deploying 0D and 1D models are found to be significantly large. These findings indicate that rigorous evaluation of particle concentration distribution is essential for accurate prediction of radiative heat transfer in CFBCs despite its high CPU requirements.

1. Introduction

Thermal radiation accounts for the majority of the heat transferred in combusting systems where it is constituted of the contributions from the flue gas (H_2O and CO_2) and solid particles; hence gas and particle radiative properties play an important role. In spite of their lower operating temperatures (750–950 °C), radiation is still the predominant mode of heat transfer in circulating fluidized bed combustors (CFBCs) due to higher particle concentrations, at which share of radiation has been shown to exceed 70% [1,2]. Hence, accurate modelling of radiative heat transfer in such systems is of considerable importance and necessitates not only accurate but also computationally efficient methods for radiative property estimation of particle laden combustion gases.

Recent studies [3–7] reveal that in the presence of particles, gas radiation is suppressed and particle radiation dominates the total radiation. Despite the fact that spectral properties of particles demonstrate a less complex behavior contrary to that of gas radiation, modelling of particle radiation involves other challenges. Particle radiation depends on its absorption coefficient, scattering coefficient and scattering phase function which in turn depend on the composition, density, temperature, concentration and size distribution of particles. Chemical composition is what determines the refractive index (RI) of particles [8] and particle radiative properties have been shown to change with its composition [9,10]. On the other hand, investigations of sensitivity of radiative heat transfer predictions to particle size and density reveal that change in size/density leads to significant variation in predicted radiative intensities [9]. This finding is in agreement with another experimental study where it is revealed that accurate representation of particle size and concentration distributions is more critical than the refractive index (hence the chemical composition) in radiative transfer calculations [11]. In fact, particle concentration is usually recognized as the determining factor for both radiative and total heat transfer in the relevant CFBC literature [2,10,12–23].

Even though much effort has been placed in understanding the effect of particle concentration on radiative heat transfer, evalua-

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Nomenclature

a	decay constant (m^{-1})
c	speed of light (m/s)
d_p	particle diameter (m)
D	diameter of the riser (m)
g	asymmetry factor (dimensionless)
g	gravitational acceleration constant (m/s^2)
H	height (m)
I	radiative intensity ($W\ m^{-2}\ sr^{-1}$)
I_b	blackbody intensity ($W\ m^{-2}\ sr^{-1}$)
k	imaginary part of complex refractive index (dimensionless)
K	decay constant (m^{-1})
k_t	time constant with dimension $(m/s)^{-1}$
L_m	mean beam length (m)
m	complex refractive index (dimensionless)
n	real part of complex refractive index (dimensionless)
N_t	number of discrete sizes in particle size measurement
P	pressure (Pa)
Q_{abs}	absorption efficiency
Q_{ext}	extinction efficiency
Q_{scat}	scattering efficiency
$\mathbf{r}$	position vector (dimensionless)
r	coordinate axis in cylindrical geometry (dimensionless)
R	radius of the riser (m)
T	temperature (K)
t	time
u_g	gas velocity (m/s)
u_t	terminal velocity (m/s)
u_0	superficial air velocity (m/s)
w	quadrature weight (dimensionless)
w_i	differential weight of particle size i (dimensionless)
z	axial position (m)

Subscripts

dilute	height of the riser (m)
g	gas
i	quadrature point
j	spectral band number
ℓ	index for a discrete direction
ℓ'	incoming discrete direction
m	ordinate index
m′	incoming ordinate
p	particle
w	wall
λ	wavelength (μm)
ν	wavenumber (cm^{-1})

Superscripts

m	ordinate index
m′	incoming ordinate
ℓ	index for a discrete direction
ℓ'	incoming discrete direction

Greek symbols

α	absorptivity
β	extinction coefficient (m^{-1})
γ	angular differencing coefficient (dimensionless)
δ	thickness of annular layer in core-annulus riser flow (m)
ε	emissivity
$\varepsilon(r, z)$	Voidage at height z and radius r
ε_{mf}	voidage of the bed at minimum fluidization velocity (dimensionless)
η	direction cosine (dimensionless)
Θ	scattering angle (rad)
κ	absorption coefficient (m^{-1})
λ	wavelength (μm)
μ	direction cosine (dimensionless)
ξ	direction cosine (dimensionless)
$\rho(r,z)$	particle concentration (kg/m^3)
ρ	particle reflectivity (dimensionless)
ρ_{exit}	particle concentration at the exit of the riser (kg/m^3)
ρ_p	particle density (kg/m^3)
ρ_x	particle concentration in the dense bed (kg/m^3)
σ	scattering coefficient (m^{-1})
τ	optical thickness
ϕ	azimuthal angle (rad)
Φ	scattering phase function (sr^{-1})
ω	scattering albedo
$\mathbf{\Omega}$	direction of radiation intensity (dimensionless)

tions of the accuracy of previously developed models have raised the following three issues. (i) In some of these studies, radiative heat transfer is estimated by introducing a radiative heat transfer coefficient [2,12–16,19–22], which is usually represented as a function of temperature and cross-sectional average particle concentration. In this macroscopic approach, however, influence of particle laden flue gas properties is not included in radiative heat transfer calculations. (ii) Radiation models have been employed as part of conservation equations for mass, momentum, energy and chemical species where predictions have been compared with experimentally determined values [17,19]. This procedure suffers from two disadvantages: discrepancies between predicted and measured values may be partly due to errors in the experimentally determined data; even if the experimentally determined data are correct, it is impossible to decide whether discrepancies in the predictions are attributable directly to the radiation model (or its submodels) deployed or to inaccuracies in the models used for the prediction of flow, reaction, other heat transfer mechanisms etc. (iii) Radiation model has been tested in isolation from the modelling of other physical processes by using prescribed input data for the operating conditions of the combustor [10,18] such as particle concentration, composition, density and its size distribution, temperature field, gas compositions, solid stream flow rates as full input data are rarely available in the existing literature even for pilot scale test rigs.

These specified disadvantages of previous investigations indicate a lack of isolated radiation models, utilizing full input data based on measurements (ash composition, solid stream flow rates, particle size distribution, temperature field etc.) necessary for the accurate evaluation of particle properties with a concentration distribution in the solution of RTE. Moreover, to the author's best knowledge, no numerical study involving the effect of particle concentration distribution on radiative heat flux and source term predictions is available for particle sizes and conditions of interest for CFBCs.

Objective of this paper is to determine the effect of axial and radial variations in particle concentration on radiative heat flux and source term distributions along the splash and dilute zones and to determine the predictive accuracy of simple 0D and 1D approximations of particle concentration distribution by benchmarking their predictions against a semi-empiric 2D axisymmetric model developed for a wide range of operating conditions and systems. For this purpose, a two-dimensional axisymmetric radiation model based on MOL solution of DOM is extended to include spatial variations in particle concentration in the splash and dilute zones of the lignite-fired 150 kWt METU CFBC test rig.