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On gas and particle radiation in pulverized fuel combustion furnaces

Chungen Yin *

Department of Energy Technology, Aalborg University, 9220 Aalborg East, Denmark

HIGHLIGHTS

- Impacts of gas and particle radiation in coal-fired boilers clearly demonstrated.
- Refined air–fuel WSGGM of greater accuracy/completeness/applicability presented.
- Conversion-dependent particle emissivity and scattering factor newly proposed.
- Particle radiation largely overwhelms gas radiation in solid fuel-fired boilers.

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ABSTRACT

Radiation is the principal mode of heat transfer in a combustor. This paper presents a refined weighted sum of gray gases model for computational fluid dynamics modelling of conventional air–fuel combustion, which has greater accuracy and completeness than the existing gaseous radiative property models. This paper also presents new conversion-dependent models for particle emissivity and scattering factor, instead of various constant values in literature. The impacts of the refined or new models are demonstrated via computational fluid dynamics simulation of a pulverized coal-fired utility boiler. Although the refined gaseous radiative property model shows great advantages in gaseous fuel combustion modelling, its impacts are largely compromised in pulverized solid fuel combustion, in which particle-radiation interaction plays the dominant role in radiation heat transfer due to high particle loading. Use of conversion-dependent particle emissivity and scattering factor will not only change the particle heating and reaction history, but also alter the radiation intensity and thus temperature profiles in the furnace. For radiation modelling in pulverized fuel combustion, the priority needs to be placed on particle radiation and a proper description of particle emissivity and scattering factor is required. The refined gaseous radiative property model is still recommended for use in generic combustion modelling because of its inherent potential in improving the results, even though its advantages may be compromised by particle radiation in some cases. The gas and particle radiation modelling method and the conclusions presented in this paper are also applied to oxy-fuel combustion of pulverized fuels.

1. Introduction

Radiation is the dominant mode of heat transfer in a combustor. In a pulverized fuel (PF) furnace, it consists of contribution of both gas and particle phase. In recent years, gas radiation gains a lot of concerns, e.g., proposing or applying new gaseous radiative property models for oxy-fuel combustion [1–5], as a result of significantly high concentration of participating gases under such conditions. For air–fuel combustion, the weighted sum of gray gases model (WSGGM) proposed by Smith et al. [6] is commonly used in computational fluid dynamics (CFD) simulations. This model is examined and a refined air–fuel WSGGM of greater accuracy, completeness and applicability is derived [7]. Compared with gaseous radiative property models, little has been done to particle radiative properties. In PF combustion modelling, few works take into account the dependency of particle emissivity on particle conversion [8–11], and no work accounts for the fact that particle composition greatly influences particle scattering properties. The overwhelming majority either use different constants for particle emissivity and scattering factor, e.g. [12–17], or simply disregard particle radiation assuming its impact is negligible, e.g. [18].

This paper demonstrates the relative impacts and importance of gas and particle radiation on radiative heat transfer in PF furnaces. The different gaseous radiative property models (i.e., the refined air–fuel WSGGM [7] *vs.* the Smith et al. WSGGM [6]) and different particle radiative property models (i.e., the new conversion-dependent particle emissivity and scattering factor *vs.* the commonly

* Tel.: +45 30622577; fax: +45 98151411.
E-mail address: chy@et.aau.dk

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Nomenclature

$a_{\varepsilon,i}$	emissivity weight factor of i-th gray gas in WSHGGM (–)
A	frequency factor in rate coefficient in Arrhenius form (1/s)
A_p	particle surface area (m^2)
$A_{p,i}$	projected area of group i particles ($A_{p,i} = \pi d_{p,i}^2/4$) (m^2)
b	power to temperature in rate coefficient in Arrhenius form (–)
$b_{\varepsilon,i,j}$	emissivity gas temperature polynomial coefficients in WSGGM (–)
C_p	particle specific heat (J/(kg K))
E	activation energy in rate coefficient in Arrhenius form (J/kmol)
$f_{p,i}$	scattering factor of group i particles (–)
h	convective heat transfer coefficient (W/(m^2 K))
$I(\vec{r}, \hat{s})$	radiation intensity at position $\vec{r}$ in direction $\hat{s}$ (W/(m^2 sr))
k_i	absorption coefficient of i-th gray gas in WSGGM (1//(atm m))
L	computational domain-based beam length (m)
m_p	particle mass (kg)
n_i	number density of group i particles (1/m^3)
P	sum of partial pressures of the participating gases (atm)
P_c	partial pressure of carbon dioxide (atm)
P_w	partial pressure of water vapor (atm)
q_r	radiation flux (w/m^2)
R	universal gas constant (8315) (J/(kmol K))
s	path length (m)
t	time (s)
T	local gas temperature (K)
T_p	particle temperature (K)
$T_{p,i}$	temperature of group i particles (K)
T_{Rad}	radiation temperature (K)
U_C	fraction of unburnt char, $U_C = \frac{\text{mass of char in particle}}{\text{mass of char in feed particle}}$ (–)
$U_{VM,C}$	fraction of unburnt combustibles, $U_{VM,C} = \frac{\text{mass of volatiles and char in particle}}{\text{mass of volatiles and char in feed particle}}$ (–)

Greek letters

α	local gas absorption coefficient (m^{-1})
α_p	equivalent particle absorption coefficient (m^{-1})
ΔH	heating effects of each conversion sub-process (J/kg)
ε	total emissivity of local gas mixture (–)
ε_p	particle emissivity (–)
$\varepsilon_{p,i}$	emissivity of group i particles (–)
θ_R	local radiation temperature (K)
σ	Stefan-Boltzmann constant (5.67 × 10^{-8}) (W/(m^2 K^4))
σ_p	equivalent particle scattering coefficient (m^{-1})
ϕ	phase function (–)
Ω	solid angle (sr)
Ω'	solid angle (sr)

used constant values) are implemented in CFD simulations of a pulverized coal-fired utility boiler. The CFD results are compared against each other. Particle-radiation interaction is found to play the dominant role in radiative heat transfer in PF combustion. As a result, attention must be paid to properly address particle radiation.

2. Pulverized coal-fired utility boiler for case study

The pulverized coal-fired utility boiler under study is sketched in Fig. 1(a). All the simulations in this paper are based on the same fuel and operating conditions, as summarized in Table 1. More details about the boiler can be found in [19,20].

3. Modelling of coal combustion in the boiler

3.1. The mesh

The boiler is meshed into 3,191,580 hexahedral cells in total, in which 84 × 74 × 322 = 2,001,552 cells are in the furnace below the furnace exit plane (as indicated in Fig. 1(a)). The mesh on a horizontal cross-section in the furnace is shown in Fig. 1(b). The grid lines generally follow the dominating swirling flow direction, which helps to minimize the numerical diffusion. This mesh has a high quality. The key quality specification is given in Table 2. This mesh is also found to be dense enough to produce practically grid-independent solutions, which will be shown in Section 4.

3.2. Particle motion and conversion and gas phase combustion

The pulverized coal particles are assumed to be spherical, and follow the Rosin–Rammler size distribution as detailed in Table 1. In the simulations, ten particle sizes are considered: 15, 28, 41, 54, 67, 80, 93, 106, 119, and 132 μm. Drag, gravity and pressure gradient force are retained in the equation of motion of the particles to update their trajectories. The turbulent dispersion of particles is accounted for using the stochastic tracking model, in which 10 tries are employed. Totally 43,200 particle streams are tracked in each simulation.

In this paper, it is assumed that all the fuel moisture is removed in mills. The dried coal particles, together with the released moisture vapor, are transported by primary air into the furnace. The same way is widely used in modelling of pulverized coal combustion in utility boilers [19–22], although there are other options, e.g., wet combustion model as used in [23]. When travelling through gas and interacting with gas in the furnace, the coal particles heat up, release volatiles and undergo heterogeneous char oxidation, creating sources for reactions in gas phase. The particle temperature is updated as follows,

$$m_p C_p \frac{dT_p}{dt} = hA_p(T - T_p) + \varepsilon_p A_p \sigma(\theta_R^4 - T_p^4) + \frac{dm_p}{dt}\Delta H \quad (1)$$

All the symbols are explained in the nomenclature. The three terms on the right-hand side represent the convection heat transfer to the particle, radiation heat transfer to the particle, and heating effects of the current particle conversion sub-process (e.g., drying, devolatilization and char oxidation), respectively.

The volatiles are lumped into an artificial species (molecular weight of 23.6398 kg/kmol and formation enthalpy of −5.8429 × 10^7 J/kmol). The two-step global reaction mechanism is used for volatiles combustion with CO as the intermediate species. The finite-rate/eddy-dissipation model is employed for turbulence-chemistry interaction and the rate equations and kinetic data of the two reactions are given in Table 3.

$$CH_{3.6888}O_{0.348}N_{0.094}S_{0.032} + 1.2802O_2 = CO + 1.8444H_2O\ (g) + 0.032SO_2 + 0.047N_2 \quad (R1)$$

$$CO + 0.5O_2 = CO_2 \quad (R2)$$

Due to the large heating rates in suspension-firing and high particle temperatures, CO is the dominant product in heterogeneous char oxidation, (R3). The formed CO undergoes further combustion in gas phase.

$$C(s) + 0.5O_2 = CO \quad (R3)$$

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