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Prediction of the radiative heat transfer in small and large scale oxy-coal furnaces

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HIGHLIGHTS

- CFD modelling of radiation in small and large scale oxy-coal furnaces is developed.
- Effects of FSCK and Mie data on radiation are investigated and discussed.
- Non-grey modelling of gas radiation is enhanced in the large furnace.
- A hotter flame and a higher gas radiation are predicted through FSCK and Mie data.

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ABSTRACT

Predicting thermal radiation for oxy-coal combustion highlights the importance of the radiation models for the spectral properties of gases and particles. This study numerically investigates radiation behaviours in small and large scale furnaces through refined radiative property models, using the full-spectrum correlated k (FSCK) model and Mie theory based data, compared with the conventional use of the weighted sum of grey gases (WSGG) model and the constant values of the particle radiation properties. Both oxy-coal combustion and air-fired combustion have been investigated numerically and compared with combustion plant experimental data. Reasonable agreements are obtained between the predicted results and the measured data. Employing the refined radiative property models achieves closer predicted heat transfer properties to the measured data from both furnaces. The gas-phase component of the radiation energy source term obtained from the FSCK property model is higher within the flame region than the values obtained by using the conventional methods. The impact of using non-grey radiation behaviour of gases through the FSCK is enhanced in the large scale furnace as the predicted gas radiation source term is approximately 2–3 times that obtained when using the WSGG, while the same term is in much closer agreement between the FSCK and the WSGG for the pilot-scale furnace. The predicted total radiation source term (from both gases and particles) is lower in the flame region after using the refined models, which results in a hotter flame (approximately 50–150 K higher in this study) compared with results obtained from conventional methods. In addition, the predicted surface incident radiation reduces by using the refined radiative property models for both furnaces, in which the difference is relevant with the difference in the predicted radiation properties between the two modelling techniques. Numerical uncertainties resulting from the influences of combustion model, turbulent particle dispersion and turbulence modelling on the radiation behaviours are discussed.

1. Introduction

Oxyfuel combustion has been regarded as one of the most promising technologies for both new and existing power stations in order to achieve a near-zero CO_2 emission [1,2]. Under oxyfuel conditions, air is replaced by the recycled flue gases (wet or dry) and high purity oxygen in order to control the combustion temperature and produce a high CO_2 concentration in the flue gas. Because of the differences in the thermal properties of the combustion gases (heat capacity and radiation properties), oxyfuel conditions lead to uncertainties in determining the

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Nomenclature

$A_{p,i}$	projected surface area of particle i (m^2)
C_D	drag coefficient
C_L	time scale constant
c_p	specific heat at constant pressure (J/(kg-K))
d	diameter (m)
E	emission (W/m^3)
$f_{p,i}$	particle scattering factor
$\overrightarrow{F}$	an additional acceleration due to the other body forces (m/s^2)
g	asymmetry factor
G	local incident radiation (W/m^2)
h	convective heat transfer coefficient ($W/(m^2$-K))
I	radiation intensity (W/(sr-m^3))
k	kinetic energy (m^2/s^2)
m	mass (kg)
$M_{w,i}$	molecular weight (kg/kmol)
n_i	number density of particles ($1/m^3$)
q	radiative flux (W/m^2)
$Q_{abs,i}$	particle emissivity
Q_p	heat resulting from vaporization and chemical reactions (W)
$Q_{sca,i}$	particle scattering efficiency
r	uniform random number
$\overrightarrow{r}$	position vector
Re	Reynolds number
$R_{i,r}$	net rate of production of a species (kmol/(m^3-s))
$\overrightarrow{s}$	direction vector
$\overrightarrow{s}'$	scattering vector
t	time (s)
T	temperature (K)
u'	velocity fluctuating component (m/s)
V	volume (m^3)
$w_{p,i}$	particle emissivity weighting factor
Y_P	the time averaged mass fractions of the product species
Y_R	the time averaged mass fractions of the reactant

Greek letters

ε	turbulent dissipation rate (m^2/s^3)
ζ	normally distributed random number
θ_R	radiation temperature (K)
κ	absorption coefficient (1/m)
κ_p	equivalent particle absorption coefficient (1/m)
μ	viscosity (kg/m-s)
ρ	density (kg/m^3)
σ_p	equivalent particle scattering coefficient (1/m)
τ_e	eddy lifetime (s)
ϕ	scattering phase function
Ω	solid angle (sr)

Subscripts

b	black body
g	gas
p	particle
λ	wavelength

Abbreviations

AD	air dried
AR	as received
CPD	chemical percolation devolatilization
CTF	combustion test facility
DAF	dry ash-free
DOM	discrete ordinates radiation model
DPM	discrete phase model
DRW	discrete random walk
EDM	eddy-dissipation model
EWB	exponential wideband
FSCK	full-spectrum correlated k
FSK	full-spectrum k
IRZ	internal recirculation zone
LBL	line-by-line
OFA	over fire air
ORZ	outer recirculation zone
RSM	Reynolds stress model
RTE	radiative transfer equation
SLW	spectral-line-based weighted-sum-of-grey-gases
SNB	statistical narrow-band
SWF	scalable wall functions
TRI	turbulence-radiation interaction
WSGG	weighted sum of grey gases

thermal conditions, which plays a critical role in determining the operation and scale-up of the combustors [3]. The role of increased CO_2 and H_2O concentrations on the transport of thermal radiation within the furnace is particularly challenging to predict, however, it is critical to have a detailed understanding of this impact, which will influence the temperature distribution inside the furnace, heat fluxes to the wall, pollutant formation and the flame shape [2,4,5].

Computational fluid dynamics (CFD) has been widely used for simulating combustion processes, and it has also been applied in the modelling of oxy-coal combustion (for the combustion and heat transfer behaviours [6–15], for the effects of oxyfuel conditions on retrofitting [8,9,11,15–19], for the large scale combustors [7–9,15,17,20], etc.). In order to achieve a better prediction of radiative heat transfer for oxy-coal combustion systems, especially for different oxyfuel conditions, such as oxygen concentrations and flue gas recycling ratios, an accurate estimation of the radiation properties of gases and particles needs to be integrated into the CFD modelling approach.

The absorption coefficients for triatomic molecules, such as CO_2 and H_2O, exhibit strong oscillations across the electromagnetic spectrum. However, quantities of interest, such as the net exchange of energy between the combustion medium and the intensity field, as well as the total heat flux to the walls, require an integration of a function of this absorption coefficient across all wavelengths. Standard numerical approaches to resolve this integration, termed the line-by-line (LBL) approach, will typically require 10^5–10^7 discrete intervals, which is prohibitively large [21]. Recently, developments of the Monte Carlo method have been able to provide LBL accuracy within coupled combustion applications [22], however, it is still an active challenge to apply this approach to large-scale multi-phase applications. Narrow band models, such as the statistical narrow band (SNB) and correlated k models, are capable of reducing this burden to a few hundred intervals, however this is still too expensive for CFD approaches, which require the resolution of the radiation intensity field across a fine spatial and angular resolution [21,23]. Wide band models, such as the exponential wide band (EWB) model, further reduce the number of the band intervals [24], however these methods typically have much reduced accuracy over narrow band approaches [21,23,25] and still need to improve in its computational efficiency for the engineering applications [21,26]. Global models, such as the weighted sum of grey gasses (WSGG) [27,28], spectral line-based WSGG (SLW) [29] and full spectrum correlated-k (FSCK) models [30], where the spectral integrity of the gas absorption is discarded in order to solve integral properties of