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Influence of particle and gas radiation in oxy-fuel combustion

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ABSTRACT

This work investigates thermal radiation in oxy-fired conditions. Both gas and particle radiation is modelled in an axi-symmetric cross section of a cylindrical furnace and differences in the radiative transfer between air- and oxy-firing are investigated. The particle radiative properties are calculated according to the Mie-theory, accounting for the spectral properties. The scattering by the particles is assumed to be isotropic. For the gas radiation, a Statistical-Narrow-Band (SNB) model is applied as reference. The properties of the combustion gas and the particle load are derived from measurements in a lignite flame in Chalmers University's 100 kW test rig. The wall flux and the radiative source term along the cylinder's diameter are compared to evaluate the difference in radiation between air- and oxy-fuel combustion. Special emphasis is put on the influence of load and distribution of particles, both in the flame and at the furnace exit. The results show that the presence of particles suppresses the influence of gas composition and small differences are seen between the different gas mixtures. It is also concluded that variation of temperature and particle load can have a significant impact on the radiative heat transfer.

1. Introduction

Oxy-fuel combustion has been proposed as one of the key technologies for capture and storage of CO_2 from coal-fired power plants. In oxy-fuel combustion, air is replaced by pure oxygen and recycled flue gases to obtain a flue gas stream with a very low concentration of nitrogen, thus simplifying the capture of CO_2. Efforts are made to commercialise this technology within a relatively near future [1]. This involves rapid scale-up of the process, and there is an urgent need for knowledge of the most important parameters controlling the process and of tools to be used for design of the combustion chambers.

Thermal radiation is an important area for which further research is required in the development of oxy-fuel combustion. Radiation is the main mechanism of heat transfer in a combustion chamber and has a significant influence on the design of heat transfer surfaces. Radiation is emitted and absorbed by both gases and particles. High-temperature zones, especially flames with high particle load, are strong emitters, whereas zones with lower temperature can act as a net absorber of radiation, reducing the heat transfer to the walls. The most important species contributing to the radiative heat transfer are gases, such as CO_2 and H_2O, and particles in the form of fuel, soot, and ash. In oxy-fuel combustion nitrogen is replaced by CO_2 and/or H_2O, depending on whether dry or wet flue gases are recycled, which means that the radiative properties of the combustion gas are changed compared to the air-combustion case. The increased concentrations of CO_2 and H_2O result in a radiatively more active gas, but the influence of the gases is always linked to the particle radiation. In the flame zone, particles typically dominate the radiative heat transfer. Zones with lower particle load, on the other hand, can be more sensitive to the concentration of the gas species, and oxy-fuel combustion can result in zones having a higher absorption compared to air-firing. Previous analyses of radiative heat transfer in coal combustion have investigated the sensitivity of parameters in air-fired conditions and the radiative properties of combustion particles were reviewed by Im and Ahluwalia [2]. They emphasised that a boiler furnace can be characterised by two distinct regions: a high temperature fire-box region with a large concentration of char and soot particles, and an absorption region with only gaseous species and particles originating from the mineral content of coals, i.e. fly-ash particles. Mengüç and Viskanta [3] calculated radiation in a cylindrical furnace based on particle concentration obtained from experimental data using spectrally averaged properties. They concluded that an accurate knowledge of the distributions of particles and temperature is more crucial than the detailed knowledge of the radiative properties of the particles and the gas concentration. The importance to account for the right particle temperature and concentration was also recognised by Densison and Webb [4], who modelled gray radiation based on measured data of gas temperature, gas concentration and particle concentration, while assuming the soot concentration. Marakis et al. [5] carried out a sensitivity analysis of radiative heat transfer in a coal-fired furnace with a simplified treatment of the gas radiation and gray particle

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Nomenclature

d	mean line spacing (cm^{-1})
f_A	projected surface area ($m^2\,m^{-3}$)
G	intensity integrated over all directions ($W\,m^{-2}$)
I_ν	spectral intensity ($W\,m^{-2}sr^{-1}\,cm$)
I	total intensity ($W\,m^{-2}\,sr^{-1}$)
I_b	blackbody intensity ($W\,m^{-2}\,sr^{-1}$)
$I_{b\nu}$	blackbody spectral intensity ($W\,m^{-2}\,sr^{-1}\,cm$)
k	mean line intensity to typical line spacing ratio within a narrow band (cm^{-1})
m	complex index of refraction (–)
P	total pressure (bar)
q^+_{wall}	incident wall flux ($W\,m^{-2}$)
$\nabla\cdot q$	radiative source term ($W\,m^{-3}$)
R	radius (m)
r	radial coordinate (m)
r_p	particle radius (m)
S	total path-length used with spectral data in cm^{-1} (cm)
S_m	total path-length (m)
s	coordinate along a radiative path (–)
$\hat{s}$	unit vector in a given direction
T	temperature (K)
x	particle size parameter (–)
Y	mole fraction (–)
w	quadrature weight (sr)

Greek symbols

β	extinction coefficient (m^{-1})
γ	mean line half-width (cm^{-1})
κ	absorption coefficient (m^{-1} or $bar^{-1}\,m^{-1}$)
λ	wavelength (μm)
τ	transmissivity (–)
σ	scattering coefficient (m^{-1})
ω	scattering albedo (–)
ν	wave number (cm^{-1})
μ	direction cosine (–)
$\Delta\nu$	bandwidth (cm^{-1})
Δs	length of computational cell (m)
Φ	scattering phase function (sr^{-1})
Ω_i	solid angle (sr)

Subscripts

0	wall, starting point of radiative pathway
av	average
b	blackbody
i	cell number
k	band k in narrow-band model
loc	local cell property
n	cell number
p	particle
ref	reference
ν	spectral property

properties. They noticed a large difference in the behaviour of coal and ash particles due to their different optical properties. The importance of ash for the radiative heat transfer was pointed out by Wall et al. [6] and its non-gray nature has been addressed in several studies [7,8]. Research on soot in coal combustion was reviewed by Fletcher et al. [9]. It was seen that large amounts of soot can form in pyrolysis experiments, but data from actual combustors are missing that there is no model available which can link the optical properties of soot to the chemical properties of coal under given combustion conditions. For oxy-fuel conditions there is little work on radiative heat transfer where both gas and particle radiation have been considered. Thus, there is a need to investigate the relative role of gas and particle radiation in these conditions with an enhanced gaseous contribution and to see if results from air-fired environments are applicable to oxy-fuel conditions.

In the present work radiative heat transfer, both from gas and particles, is investigated within an infinitely long axi-symmetric cylinder. Particles considered are coal/char, soot, and ash, treated with separate properties. The cylindrical geometry is chosen due to its simplicity, availability of data for validation of the numerical method applied, and as it approximates the radiation within the cylindrical 100 kW oxy-fuel rig at Chalmers University [10,11] from which data can be taken as input. For the gas radiation, a Statistical-Narrow-Band (SNB) model is applied as reference, while the spectral radiative properties of the particles are calculated from the Mie theory. Scattering of the particles is assumed to be isotropic. Wall fluxes and the radiative source term along the diameter of the cylinder are compared to evaluate the difference in radiative heat transfer between air- and oxy-fuel combustion. The aim is to investigate the relative importance of gas and particle radiation and to determine the effect of the gas mixture on the radiative heat transfer. The conditions examined are both relevant for the flame zone and for the zone downstream of the burners. A sensitivity analysis of the influence of particle load and temperature is included in the study. Also scale effects are addressed by increasing the diameter of the cylinder while maintaining the same profiles of temperature, gas species, and particle concentration.

2. Theory

The radiative transfer equation (RTE) for an emitting, absorbing and scattering medium is

$$\frac{dI_\nu}{ds} = \kappa_\nu I_{b\nu} - \kappa_\nu I_\nu - \sigma_\nu I_\nu + \frac{\sigma_\nu}{4\pi}\int_{4\pi} I_\nu(\hat{s}_i)\Phi(\hat{s},\hat{s}_i)d\Omega_i \tag{1}$$

The first term on the right-hand side expresses the increase in intensity due to emission, the second and third terms express the decrease in intensity due to absorption and scattering. The last term, containing the integral, is increase in intensity due to scattering of radiation from other directions into the direction of interest. The RTE is expressed on spectral basis, and to obtain the total intensity it has to be integrated over the entire spectrum.

The discrete transfer method is used to calculate the radiative intensity field of an infinitely long cylinder, whose concentrations and temperature are symmetrically distributed around the axis and constant in the axial direction. The method solves the intensity along a number of rays, represented by weights and ordinates for the S_6 scheme, taken from the work of Tsai and Özişik [12]. Rays are considered for a number of computational grid points from the cylinder's outer surface to the grid point in the centre (n_r), Fig. 1a. The total number of rays is equal to the number of grid points times the number of rays in each point. The intensity field along the radius is obtained by saving the intensities of these rays in the positions where they cross the radius. To calculate incident scattering along the rays, the last term in Eq. (1), the intensity field along the rays is determined by calculating the distance to the centre of the cylinder and retrieve the intensity field by interpolation