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Research article

Quantification of the influence of parameters determining radiative heat transfer in an oxy-fuel operated boiler

Tim Gronarz[a,*], Jan Schulze[a], Mischka Laemmerhold[a], Philipp Graeser[b], Jeanette Gorewoda[b], Vitali Kez[c], Martin Habermehl[a], Martin Schiemann[b], Jochen Ströhle[c], Bernd Epple[c], Viktor Scherer[b], Reinhold Kneer[a]

[a] *Institute of Heat and Mass Transfer, RWTH Aachen University, Aachen, Germany*
[b] *Department of Energy Plant Technology, Ruhr-Universität Bochum, Bochum, Germany*
[c] *Energy Systems and Technology, Technische Universität Darmstadt, Darmstadt, Germany*

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ABSTRACT

Radiative heat transfer is a very important heat transfer mechanism in pulverized coal combustion. To identify the influence of parameters determining radiatve heat transfer and to give recommendations on the required accuracy of corresponding submodels, a 3D-periodic oxy-fuel pulverized coal combustion test case is investigated. Measurement values determined by the authors or elaborate submodels are applied for each parameter and compared to simplified models or empirical constants. To investigate the interaction between particle radiation and the strong spectral dependence of gas radiation in oxy-fuel scenarios, a comparison between spectrally averaged and spectrally resolved calculations performed. To the best knowledge of the authors, for the first time the contribution of the parameters determining radiative heat transfer are quantified and compared in one comprehensive study.

The results indicate a strong influence of coal particle emissivity and scattering phase function as well as the projected particle surface on the radiative source term. For the wall heat flux, the largest influences were found for ash and coal particle emissivity, projected particle surface and the scattering phase function. Additionally, the difference between coal particle and gas temperature was found to have a significant influence on wall heat flux. A comparison of spectrally averaged to spectrally resolved results and the corresponding models for gas radiation (WSGGM and SNBM) yielded similar trends for the influence of each parameter. Thus, based on the models and parameters involved in this study, a spectrally averaged approach seems to be of sufficient accuracy to describe radiative heat transfer in oxy-fuel combustion systems.

1. Introduction

Implementing oxy-fuel combustion for power generation from coal is a promising approach to reduce carbon dioxide emissions of large-scale energy systems. In large scale coal combustion furnaces, thermal radiation is the dominant mechanism for heat transfer. Due to high amounts of CO_2 and H_2O in oxy-fuel conditions, the interaction between thermal radiation and the flue gas is enhanced, compared to air combustion. Additionally, coal and ash particles contribute to the overall radiative heat transfer. Details on radiative transfer in combustion systems can be found in the textbook by Viskanta [1].

The aim of the present study is to evaluate the influence of parameters determining heat transfer by thermal radiation in an oxy-fuel environment. Therefore, detailed models as well as parameters measured by the authors are applied and their influence on radiative heat transfer is quantified and compared to simplified models. Additionally, results of a spectrally averaged calculation are compared to those of a spectrally resolved approach. Based on this study, recommendations on the required level of detail and the required accuracy for each parameter and the corresponding submodel are derived.

The absorption coefficients for CO_2 and H_2O show a strongly irregular behaviour over wave number. Hence, the non-grey nature of gas radiation has to be taken into account when performing heat transfer calculations for oxy-fuel conditions. For this purpose, several approaches like line-by-line calculations [2], narrow-band models [3,4], wide-band models [5] or global models [6] have been developed. Line-by-line calculations are considered as the most accurate modelling approach. However, up to 10^6 spectral lines in the wavelength region of interest for thermal radiation have to be considered. Thus, line-by-line calculations are too time consuming for numerical simulations of real applications, since for

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* Corresponding author.
E-mail address: gronarz@wsa.rwth-aachen.de (T. Gronarz).

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each spectral line the radiative transfer equation has to be solved. Narrow-band models are computationally less demanding, since for this modelling approach, only about 450 bands have to be considered [3,4]. These spectral bands are obtained by subdividing the considered wave number spectrum into sections of approximately 25cm^{-1} width and assuming constant radiative properties within a band. This approach still is too demanding for practical applications. Nevertheless, narrow-band models can be used as reference calculations for comparison with other radiation models [7,8]. Due to its high computational efficiency at fairly good accuracy, the weighted-sum-of-grey-gases model [9,10] is commonly employed in numerical simulations of technical applications (e.g. [11–13]). Further development of weighted-sum-of-grey-gases models over the last few years (e.g. [14–16]) also enabled its use for oxy-fuel conditions.

If particles have to be considered in a combustion simulation, scattering and absorption of thermal radiation by these particles have to be taken into account. Recently, Johansson et al. [17] investigated the influence of particle radiative properties on heat transfer, finding that particle radiation has a significantly larger influence on heat transfer than gas radiation in an oxy-fuel coal combustion environment. It is well known that particle size is a very important parameter to correctly describe the interaction between thermal radiation and particles [18]. Another important parameter is the complex index of refraction m. This value is an input parameter for Mie theory calculations and can be used to determine scattering and absorption properties of particles. The numerical value of m is a function of the material considered, e.g. coal or ash, and depends strongly on wavelength. Some authors reported measurement results for the complex index of refraction for coal (e.g. [19–21]) and ash particles (e.g. [22,23]). However, the values published vary significantly between different studies. Also, no investigation is available that reports the refractive index of coal and the corresponding ash at high temperatures and during burnout. Therefore, in the present study, the emissivity of coal and the corresponding ash particles is determined directly from measurements. Measurement data for scattering phase function and scattering efficiency are not available. Therefore these properties are obtained from Mie theory.

To determine the emissivity of ash particles, several experimental and theoretical investigations on synthetic and real coal ashes are available [24–30]. Mulcahy et al. [26] carried out systematic experimental investigations determining total emissivities of ashes. From these, a dependence of emissivity on both, chemical composition and physical structure of the surface of the particles was found. They also stated a dependence of total emissivity on temperature and thermal history of ashes which later was confirmed by other studies [28,31]. Based on theoretical investigations (Mie theory), Wall et al. [28] developed a general correlation between particle size, refractive index and emissivity. They also found that emissivity increases with particle diameter. This finding was experimentally verified by Boow et al. [32]. The influence of particle size on spectral emissivity was evaluated by Greffrath et al. [27]. Spectral emissivities of coal ashes were also measured by Richards et al. [30], Saljnikov et al. [25] and Shimogori et al. [24]. For the measured spectral emissivities of ashes a similar trend was found: spectral emissivity is low for small wavelengths and increases from values of $\varepsilon = 0.6$ up to approximately $\varepsilon = 1$ at higher wavelengths above $\lambda = 7$ to 8 μm.

Experiments to determine char particle emissivity were presented by several authors. Solomon et al. [33,34] found typical values of $\varepsilon = 0.4$ to 1.0 at $T = 782$ K and non-grey behaviour. Bhattacharya et al. [35] reported non-grey behaviour as well with values between $\varepsilon = 0.55$ and $\varepsilon = 0.8$ at $T = 500$ K. Baxter et al. [36] measured the emissivity of char particles at temperatures between 393 K and 473 K finding non-grey behaviour and values in the range of $\varepsilon = 0.6$ and $\varepsilon = 1.0$. Rego-Barcena et al. [37] measured char emissivity in the temperature range of 1400 K to 1600 K. They found a decreasing char particle emissivity of approximately $\varepsilon = 0.7$ at 1400 K to $\varepsilon = 0.2$ at 1600 K. The trend of a particle emissivity below $\varepsilon = 0.5$ for higher particle temperatures was confirmed by previous measurements of Graeser and Schiemann [38,39] for a bituminous coal and lignite. They found a total emissivity of approximately $\varepsilon = 0.3$ to 0.4 for bituminous coal and $\varepsilon = 0.2$ to 0.4 for lignite at an average particle temperature of approximately 2400 K.

Radiative heat transfer is described by the radiative transfer equation, which is typically solved with numerical schemes such as the discrete transfer method, discrete ordinates or Finite Volume methods, spherical harmonics (e.g. P_n) or Monte Carlo models [1,40,41].

Numerical studies to analyse the influence of different radiative properties on radiative heat transfer in coal furnaces were presented by several authors. Trivic et al.[42] coupled a solver for the radiative transfer equation based on the Finite Volume method with Mie theory for spectrally constant (grey) complex indices of refraction and found a good agreement with results from a very detailed Monte Carlo/Zonal method simulation. Caliot et al. [43] performed a parametric study on the influence of particle scattering phase functions and spectrally constant refractive indices in a generic scattering experiment. They found a difference of about 5% between calculations with anisotropic scattering and negligence of scattering for the particular case they investigated. Mengüç and Viskanta [18] performed a sensitivity analysis for radiative heat transfer in a pulverized coal combustion furnace, employing third order harmonics, a δ-Eddington type phase function and Mie theory for calculation of efficiencies and the amount of forward scattering. They found that the accurate knowledge of number density, temperature and spatial distribution of particles are more critical than detailed information about the complex index of refraction of particles as well as gas concentration. Marakis et al. [44] performed a parametric study for radiative heat transfer in a pulverized coal furnace applying a Monte Carlo method and the P_1 approximation. They investigated the influence of different Henyey-Greenstein type scattering phase functions on wall heat fluxes finding that anisotropic scattering should be taken into account in the case of pulverized coal combustion. Crnomarkovic et al. [45] investigated a numerical simulation of the entire pulverized coal combustion process and concluded that isotropic scattering is a good choice for investigating pulverized coal combustion. Gupta et al.[46] applied a Monte Carlo method to investigate different types of scattering in a furnace with cylindrical geometry. They concluded that modelling scattering as either forward or isotropic scattering yields large errors, whereas a δ-Eddington type phase function can yield reasonable results.

The influence of the parameters determining radiative heat transfer in oxy-fuel pulverized coal combustion processes has not been assessed and compared yet. In this paper, the authors present a comprehensive study that quantifies and compares the contribution of each parameter to heat transfer in oxy-fuel pulverized coal combustion. Based on this study, justification for the application of a specific elaborate model or a simplified approach for each parameter can be derived.

2. Methods

The change of radiative intensity I_λ along a path ds at a wavelength λ is described by the radiative transfer equation as presented by Modest [47]:

$$\frac{dI_\lambda}{ds} = -\left(\kappa_\lambda(r) + \sigma_{\lambda,s}(r)\right) I_\lambda(r,\hat{s}) + \kappa_\lambda(r) I_{\mathrm{b},\lambda}(r) + \frac{\sigma_{\lambda,s}(r)}{4\pi} \int_{4\pi} I_\lambda(r,\hat{s}')\Phi_\lambda\left(r,\hat{s}',\hat{s}\right) d\Omega' \quad . \tag{1}$$