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Experimental investigation of pulverized coal flames in CO_2/O_2- and N_2/O_2-atmospheres: Comparison of solid particle radiative characteristics

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ABSTRACT

This work presents experimental results of swirling pulverized coal flames from a 60 kW_{th} combustion chamber based on spectrometric (UV–VIS) measurements comparing conventional air-fuel and oxy-fuel conditions. Radiation of the flames investigated was collected by two different optical systems: first, by a non-intrusive narrow-angle optical system providing integrated line-of-sight radiation data, and second, by an intrusive cold-background optical probe that collects radiation from integrated line-of-sight radiation within a reduced measurement volume. The collected spectra were processed and fitted to the Planck black body radiation function in order to estimate solid particle temperatures and relative radiant fluxes. Atomic and molecular emission lines observed are also identified and compared between the flames studied. The data obtained provide valuable insight to the different flames investigated and helpful explanations of the significant observed differences between the flames. As expected, oxidant composition was found to have a major impact on flame radiation and measured temperatures. Experimental validation data from this type of configuration and flame conditions are scarce, thus, the data may serve as validation data for numerical models.

1. Introduction

Since the early proposal of oxy-fuel combustion by Abraham et al. [1] as an alternative technology for efficient CO_2 recovery from combustion processes, a long path has been covered in terms of technical development of physical and numerical models in order to accurately study, describe and predict the behavior of such flames [2]. Oxy-fuel combustion is a technology in which fuel burns in oxidizing environments composed of O_2/CO_2 gas mixtures instead of air. As a consequence, flue gases from combustion processes are mainly composed of CO_2 enabling a more efficient application of carbon capture and sequestration (CCS) technologies. Nevertheless, changing the composition of the oxidant gases introduces significant changes in the combustion processes compared to conventional air combustion. Flame temperature is one of the most affected parameters, and a fundamental one, having a direct impact on fuel reactivity and respective generated heat fluxes. Detailed reviews about fundamentals of oxy-fuel combustion processes and recent research activities are given by Chen et al. [2], Wall et al. [3], Scheffknecht et al. [4], Stanger et al. [5] and Yin and Yan [6].

Flame temperature and heat flux measurements by means of experimental methods is a challenging area. Pulverized coal flames are a particular type of a highly complex reactive flows in which several thermochemical processes take place simultaneously, at different spatial and temporal scales. In order to measure particle and gas temperatures in coal flames, intrusive and non-intrusive methods can be used. Intrusive methods, like probes with shielded thermocouples, or thermopiles have been used for local temperature and heat flux measurements [7–10]. Unfortunately, intrusive measurement probes often get plugged by ash and coal when used in pulverized coal flames. Also their use may be limited by the temperatures of the reactive medium, which typically requires probe cooling, leading to increased probe sizes which in turn can disturb the flames [11]. On the other hand, non-intrusive measurements rely on optical diagnostics for the determination of gas and particle temperatures. Spectroscopy based methods have been applied in several studies [12–17] in order to exploit the information given by the spectra of coal flames. An example of spectrum-based measurement is two-color pyrometry which has widely been used for coal and ash particle temperature measurements [18–22].

Two-color pyrometry temperature measurements are done by examination of the ratio of radiative intensities emitted by ash and coal particles at two (or more) different wavelengths, relying strongly on the assumption that measured objects behave as gray

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body radiators at these wavelengths [18]. Temperature measurements of single particles in small scale reactors have been achieved with satisfactory results by using two color pyrometry; Joutsenoja et al. [19] measured single particle temperatures and particle sizes in a pressurized entrained flow reactor, Tichenor et al. [20] and later Molina and Shaddix [21] measured temperature, size and velocities of single coal particles in an entrained flow reactor in air and oxy-combustion atmospheres. More recently Schiemann et al. [22] performed measurements of single char particle temperatures, size and velocities by stereoscopic two color pyrometry in a laminar flow reactor. Particle temperature measurements of larger coal flames were also successfully achieved. Tree et al. [9] measured particle-cloud temperatures and heat fluxes of a 0.2 MW_{th} coal flame using a cooled background probe with a two-color pyrometer. Jiang et al. [23] applied CCD-sensor multi-color pyrometry to estimate flame temperatures and emissivities in a coal fluidized bed boiler. Wang et al. [24] used four CCD-sensors to determine two-dimensional temperature distributions based on multi-color pyrometry on a pulverized coal furnace. Draper et al. [25] used CCD two-color pyrometry to measure particle temperatures and emissivities from oxy-coal flames in a 150 kW_{th} facility, whereas Yan et al. [26] combined two-color pyrometry with spectral analysis to determine particle temperatures and emissivities in a solid waste combustion chamber. More recently, Parameswaran et al. [12] used spectral analysis of flame radiation to determine particle temperatures on a pilot scale coal gasifier. Silva and Krautz [27] studied heat transfer of 0.4 MW_{th} oxy-coal flame, measuring temperatures and heat fluxes by means of CCD two color pyrometry. Other studies have also report particle and gas temperature measurements in coal flames by means of Fourier transform infra-red spectroscopy (FTIR). Clausen and Sorensen [13] measured coal particle temperatures in an entrained flow reactor using FTIR and later Andersson et al. [14], as well as Bäckström et al. [15,16] studied flame radiation from oxy-coal flames (100 kW_{th}) using a narrow angle radiometer and FTIR in order to determine particle-gas temperatures and heat fluxes.

Nevertheless, the optical methods discussed above present several limitations when studying coal flame radiation in order to estimate particle temperatures and heat fluxes: (i) coal particles must behave as gray bodies, (ii) limited resolution associated to line-of-sight radiation collection, and (iii) measurements do not discriminate between radiation from coal particles, soot or ash. As a consequence, significant errors may be introduced in the estimation of properties from the measured radiation. Regarding the gray body assumption of coal particles, Habib and Vervisch [17] described quasi-wavelength independent emissivities for coal particles in the spectral wavelength range of 0.5–1 μm and more recently Sun [28] observed that in the same spectral range, emissivities can be assumed to be also constant. On the other hand, studies in the infrared wavelength region by Brewster and Kunitomo [29] and Solomon et al. [30] showed that by using two different techniques (particle extinction method and emission-transmission FTIR spectroscopy), coal shows a very pronounced non-gray behavior in the 1–25 μm spectral range.

In an attempt to overcome the difficulties associated with line-of-sight radiation measurements, two different optical systems have been employed in this study: (i) a classical non-intrusive line-of-sight technique and (ii) an intrusive cold-background optical probe featuring a confined optical path length of 60 mm. With this arrangement, data from the classical line-of-sight technique can be compared to the higher spatial resolution data of the intrusive technique. Flame radiation is evaluated by spectroscopy in the spectral region between 300 and 1000 nm, this includes: near-ultraviolet, visible and the beginning of the near infrared. The interest of studying radiation from flames at these wavelengths rises from the fact that none of the stable product molecules from combustion processes, such as H_2O, CO_2, CO, O_2, N_2, give spectra of appreciable strength in the visible or ultra-violet regions [31]. Furthermore, emissivity of coal particles has been found to be constant at lower wavelengths, and atomic and radical emission from elements in coal can be observed and easily distinguished from black body radiation [17,28].

The main objectives of the present work are to observe and evaluate the spectra from three different pulverized coal flames: two oxy-combustion cases with different O_2/CO_2 concentrations and one conventional air case. The recorded spectra provide information about solid particle temperatures and radiative heat fluxes, atomic and molecular emission lines observed in the spectrum originating from the mineral components present in the coal are also reported. Estimated temperatures, heat fluxes and particular spectral features observed for the three studied combustion cases are compared and discussed in detail.

2. Experimental setup

2.1. Test facility

Flame measurements were carried out at the coal combustion test facility of the Institute of Heat and Mass Transfer (WSA) at RWTH Aachen University. This facility is composed of a vertical cylindrical combustion chamber with 400 mm inner diameter and a maximal height of 4200 mm (cf. Fig. 1). The burner is mounted at the top of the combustion chamber, at the center of a vertically traversable refractory burner port. The internal walls of the combustion chamber are composed of three layers of refractory material, with electric heating elements embedded within the external refractory layer. By means of these heating elements the internal walls of the chamber can be heated up to temperatures between 800 and 1000 °C. The combination of the refractory and the heating elements reduces heat losses from the chamber, allowing the operation of the combustion chamber at different conditions with fairly time constant wall temperatures.

The mid-section of the combustion chamber contains an array of four observation ports enabling probe and optical measurements, with two ports for optical access and two ports for probe access to the flame (Fig. 2). All ports have a clear aperture diameter of 100 mm into the combustion chamber.

For this work, a swirl type burner was employed comprising three concentric annular nozzles and a quarl. This burner was designed [32–34] to enable stable combustion of pulverized coal in oxy-fuel conditions with low oxygen concentrations. Fig. 3 shows the cross section with the most relevant dimensions of the swirl burner used. The innermost annular orifice goes around a center bluff body and is responsible for delivering fuel particles in combination with a carrier gas to the combustion chamber (primary stream). The following outer concentric nozzle delivers the main oxidant gas stream (secondary stream). This stream can be supplied with swirl. Two additional oxidizing streams enter the combustion chamber: the tertiary stream, located at the outer diameter of the burner quarl, and the staging stream which is delivered into the combustion chamber through the annular gap between the internal walls of the chamber and the burner port. This gap is not shown in Fig. 3. Its width is approx. 10 mm. These two last orifices also deliver oxidant gas and serve the purpose of staging the main reaction zone. The delivery of oxidant gases into the combustion chamber is done by means of capillary-tube type thermal mass flow controllers (MFC, Bronkhorst, <1% accuracy).

A twin-screw volumetric feeder combined with a venturi type ejector is employed to obtain a homogeneous and continuous coal