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Char particle emissivity of two coal chars in oxy-fuel atmospheres

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ABSTRACT

A newly designed experimental setup for the "in-flight" measurement of the emissivity of burning char particles in the spectral range from 1.25 μm to 5.5 μm is presented. Single coal particles (Colombian bituminous coal and Rhenish lignite) were burned in a flat flame burner under oxy-fuel conditions. As the spectral region from 850 nm to 2.5 μm is dominant for the radiative heat flux at temperatures typical for pulverized fuel combustion, the emissivity is measured spectrally resolved in this region by a fiber spectrometer. Additionally the total emissivity in the range from 2.4 μm to 5.5 μm is measured by an InSb-detector. As particle temperature and diameter are necessary for the experimental determination of the emissivity, two-color pyrometry with simultaneous particle size measurement was carried out in the visible wave length range. There are differences between the emissivities of both coal chars. These initial results represent the first emissivity measurements of pulverized coal char particles under combustion conditions.

1. Introduction

In pulverized fuel combustion systems, particle radiation is the dominating heat transfer process [1]. The radiative heat transfer from burning particles to the surroundings depends linearly on the surface emissivity, this value is of special importance. In oxy-fuel combustion systems, the total emissivity (gas and particles) becomes more important because of the higher partial pressure of H_2O and CO_2. Typical particle temperatures in pulverized coal flames often exceed 1473 K [2]. Thus, the dominating part of thermal radiation is emitted in the spectral range from 500 nm to 5 μm. Typical applications which require the knowledge of char particle emissivity are CFD simulations of pulverized fuel boilers [3–6], where the particle emissivity is needed to calculate particle heating rates and final temperature. These parameters are influencing the heat transfer between a particle and its surroundings, and the calculation of pyrolysis [3,7–9] as well as char burning rates [10–12]. For oxy-fuel combustion, typical particle temperatures are above 2000 K. In both cases (air and oxy-fuel) the energy balance around single burning particles has to be solved, which requires particles emissivity.

Solomon et al. measured the spectral emissivity of a streak of burning particles in an entrained flow reactor [13,14]. They found a dependency of the emissivity on particle size, coal rank and ash yield, and degree of pyrolysis. Major results were a char emissivity significantly lower than unity and non-gray behavior for several coal samples. Bhattacharya and Wall measured the spectral emissivity of coal chars in the spectral range 1–10 μm for different states of burn out. The sample was placed on a holder which was heated up to 1273 K. They also found non-gray behavior [15]. Baxter et al. measured the emissivity of char particle samples placed on NaCl windows in the temperature range 393–473 K. They found emissivities smaller than unity with a typical "dip" in the spectral range 3–5.75 μm [16]. Greffrath et al. calculated the resulting emissivity of ash particles depending on particle size according to Mie theory. They calculated an increasing emissivity with particle diameter which fits to higher reflectance for smaller particles [17]. In summary, the current literature base indicates that the assumption of equal emissivity across the spectral and temperature range as assumed in standard CFD codes [3,8,9] is not appropriate.

Burn out effects, investigated in [15], e.g. the reduction in carbon content with simultaneous enrichment of ash at the particle surface [18], changes of the porosity [19,20] and the carbon structure [21,22] are also known to be influencing factors on the particle emissivity. Itaya et al. investigated the radiation properties of fine char particle clouds. Among others, they found a greater extinction efficiency for a higher carbon content [23].

The current work presents the calibration and results of an experimental setup, which was developed to investigate the spectrally resolved radiation behavior of single burning char particles under real conditions (particle size and temperature, heating rate) in-flight. The combustion setup represents a typical entrained flow

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reactor [11,24–26] for particle combustion combined with an optical device to measure particle temperature and diameter (assuming a spherical particle) by sizing pyrometry with simultaneous measurement of infra-red radiation by two different detectors. A fiber spectrometer was employed to measure the thermal radiation from particles in the region 1.25–2.25 μm. This part of the setup has been initially described in [27] with few results. In the current work, an InSb detector was added to measure the thermal radiation above 2.4 μm to cover the dominating part of thermal radiation. For these measurements, particles (sieving: 160–200 μm) of a Colombian bituminous coal (CBC) and of a Rhenish lignite (RL) were used and their emissivity was determined. The results extend the data base for particle emissivity measurements to higher temperatures.

2. Test-rig and fuels

In Fig. 1, a scheme of the test-rig is shown. The setup consists of several parts: The left part is for the measurement of the particle size and temperature in the visible spectral range. This part is in principle a modified setup of the Sandia National Labs particle sizing pyrometer [11,28]. As the pyrometer part works in the VIS spectral range, photomultiplier tubes (PMT, Hamamatsu H10723-20) are used, the detailed working principles of this part are described in Sections 2.3.1 and 2.3.2. In the center, the detector for the measurement of the radiation in the infrared spectral range is shown. Either a fiber-spectrometer is used in the spectral range of 850 nm to 2.5 μm (Hamamatsu C11118GA) or an InSb-detector (Hamamatsu P5968) is used from 2.4 μm to 5.5 μm. On the right side, the flat flame burner for particle combustion and the collection optics are shown.

2.1. Flat flame burner

Typical combustion conditions are provided by a flat flame burner, which has been described previously [26]. Planar quartz walls (cross section 5 cm · 5 cm) are shielding the gas flow and provide optical access (see also Fig. 1). The flame is driven by methane and the flame temperature as well as the O_2 content can be controlled by the CO_2- and O_2-flows for oxy-fuel combustion. The oxidizer (O_2/CO_2) is guided through a ceramics honeycomb, and CH_4 is injected through 100 micro tubes, which are evenly distributed over the burner cross section. This provides a homogeneous laminar flow of high temperature combustion gases. The burner provides heating rates for the fuel particles up to 10^5 K/s, which are typical for pulverized fuel combustion [29]. The fuel particles are fed on the bottom of the burner and they are carried to the top of the burner through the center by a CO_2 carrier gas flow (< 0.5 l_n/min). With this setup, small particle concentrations with well separated single particles can be fed to enable the detection of single particle signals. For these measurements, particles of the bituminous coal and of the Rhenish lignite were used in an (wet) oxy-fuel atmosphere containing 25% O_2, see Table 1. The distance from the particle inlet was chosen as 150 mm. Former investigations show that pyrolysis is clearly finished at this distance in the system used [26].

2.2. Fuels

The results of the fuel proximate, ultimate, and ash analyses are shown in Table 2.

2.3. Optical components

The radiation is collected by a first off-axis mirror which guides the incoming particle radiation to a coded-aperture. This aperture is used for the determination of the particle size as previously described by Tichenor et al. [28]. Behind this aperture a second off-axis mirror deflects the emitted particle radiation to a Polka-Dot beam splitter which splits up the radiation into visible and infra-red radiation. Note, that for covering the wavelength range 0.5–5 μm the number of available optical materials and components is limited, thus the polka dot beam splitter with its IR-reflection/VIS-transmission characteristics is a suitable device at this position in the beam line. On the reflection side, the IR-detector, which can be either the fiber spectrometer or the InSb-detector, is placed. In front of the detector a lens focusses the IR radiation on the detector's sensitive area to maximize signal intensity and to avoid errors due to incomplete projection. For measurements with the InSb-detector (MIR) a long pass filter with a cut-on wavelength of 2.4 μm is placed to separate the investigated spectral range from that detected with the fiber spectrometer. The radiation in the visible spectral range is guided to a second beam splitter. The radiation in the visible spectral range is detected through bandpass filters with center wavelengths of 550 nm and 700 nm by the PMT. For both filters, the full with half maximum (FWHM) is 10 nm, so incidents of the signals through line emissions of sodium (589.0 nm and 589.6 nm) and potassium (766.5 nm and 769.9 nm) are prevented. A third PMT measures the intensity of scattered laser light. A HeNe-laser is positioned perpendicular to the particle streak and the optical axis of the mea-

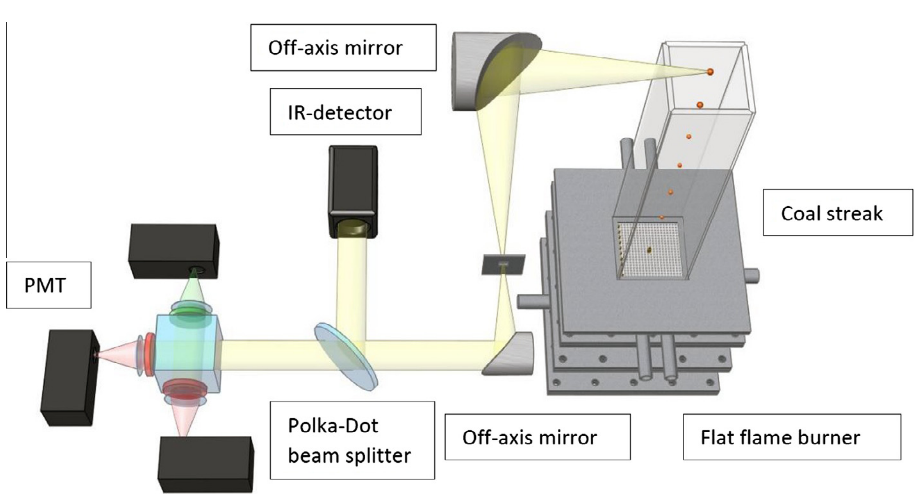

Fig. 1. Scheme of the test-rig. As an IR-detector either a fiber spectrometer or an InSb-detector can be applied.