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Particle composition and size distribution in coal flames – The influence on radiative heat transfer

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ABSTRACT

Radiative heat transfer in a 77 kW_{th} swirling lignite flame has been studied. The aim is to characterize different particle types present in a coal flame and to determine their influence on the radiative heat transfer. The study combines extractive particle measurements, radiative intensity measurements and detailed radiation modelling. The size distribution of the extracted particles was measured with a low pressure impactor and some of the size fractions were analysed with SEM–EDX. The measured total radiative intensity is compared with the modelled intensity based on the particle measurements in the same cross-section of the flame. The particle properties were calculated with Mie theory and the gas properties with a statistical narrow-band model. The results show that the contribution of coal/char particles dominates the radiative heat transfer in the investigated cross-section of the flame. The methodology applied in this work shows promising results for characterization of particle radiation in flames of practical size.

1. Introduction

Combustion of solid fuels is an important part of the global energy system. Solid fuels are widely used in heat and power production, but also in various industrial processes. Globally, coal is the dominating solid fuel. In many processes coal is crushed to a fine powder and fed to a number of burners in the combustion chamber, referred to as pulverized coal combustion. High temperature flames are formed inside the combustion chamber, and radiation dominates the heat transfer to the walls [1]. For an efficient design of combustion chambers in new applications, such as oxy-fuel combustion [2,3] or pressurized coal combustion [4], a fundamental understanding of the heat transfer in the combustion chamber is required. Both particles and gases contribute to the radiative heat transfer, but in flames with a high particle concentration, particle radiation normally dominates. The particles present in the furnace are coal (char), soot and ash, and the concentration of the different particles varies throughout the combustion chamber. Within the flames, soot and coal/char are normally the most abundant particles and outside the flames ash particles dominate. The amount of particle radiation depends on the particle concentration, particle temperature, but also on the type of particles present, or more precisely their radiative properties. All of these parameters are difficult to measure, especially in large scale combustion, and available data in the literature from measurements inside the combustion chamber in large facilities is still rather scarce. However, the number of publications related to particle and aerosol characterization in combustion applications is extensive, e.g. studies of soot formation in laboratory flames, emissions of fine particles and ash formation. Fine particles emitted from combustion processes have been recognized as a serious health and climate problem. The important factors for this type of particle formation and their impact on human health can be found in a review by Lighty et al. [5]. Measurements of particles with the aim of either monitoring the emissions, or characterizing the formation of particles are often performed in the stack or close to the particle removal equipment. However, temperatures and particle concentrations in these positions are moderate compared to the flame zone. To measure particle data from the high temperature flame zone is essential when studying radiative heat transfer, but this type of data is rarely found in the literature [6,7]. Such in-flame measurements are challenging due to the high temperatures, problems with condensation and locally high particle concentrations.

Extractive measurements using impactors have previously been used to study combustion generated particles [7–11]. The particles are then size segregated based on their aerodynamic diameter and

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collected on a number of collection plates. The particles can subsequently be analysed to determine if it is coal, ash or soot particles. Some examples of particle sampling with impactors at high temperatures can be found in the literature. Wiinikka et al. [8] presented spatially resolved particle sampling in the high temperature zone of a 8 kW biomass fired combustor. The particles were collected with a low pressure impactor and analysed to study the formation and evolution of fine particulates throughout the combustion chamber. Zhuo et al. [7] studied submicron particles in a 25 kW coal flame and extracted particles from several positions along the centre-line of the flame. Soot particles with a peak in the size distribution at 63 nm were observed in the fuel rich part of the flame. Further downstream these particles were oxidized and the collected particles after the flame zone were dominated by larger sizes. Brunner et al. [10] studied particle formation in a full scale (20.8 MW_{th}) municipal solid waste incineration plant. A new high temperature impactor was designed which enabled *in-situ* particle measurements with the entire impactor inserted into the combustion chamber, while performing measurements in positions with gas temperatures up to 1000 °C.

The use of sophisticated optical measurement systems to study particles in large scale combustion facilities is also challenging and often prevented by limited optical access, high particle load, dust and vibrations [12]. It has been recognized that several of the optical techniques used for e.g. soot diagnostics in small flames need to be further developed to be used in large scale combustion facilities [13,14]. Some optical techniques have been used, but they often require *a priori* knowledge of the flame to obtain a good estimation of the particle load, e.g. which type of particles that is expected to dominate in the flame. There are a few examples of the successful use of optical techniques in large scale applications to estimate the particle load. Stimpson et al. [15] used a two-colour laser extinction technique to estimate the soot volume fraction in a coal flame. Black and McQuay [6] used a laser based system to characterize the particle number density, velocity and particle diameter from 0.5 to 100 μm in the radiant section of a 160 MW coal fired furnace, and showed that the particle number density in the radiant section of the boiler was relatively un-sensitive to changes in the operating conditions of the boiler.

Examples of studies applying detailed radiation modelling to large scale coal combustion are also relatively scarce. Marakis et al. [4] performed a parametric study of the radiative heat transfer in a pulverized coal furnace, but the study did not include any measurements. The importance of scattering was stressed and the coal particles were found to be the dominating particle type when assuming equal gas and particle temperatures. Butler et al. [16] measured the gas and particle temperature and radiative heat flux in a 100 kW_{th} coal flame and also carried out modelling of the radiative heat transfer. The modelled radiative wall flux agreed well with the measured, and the results instead indicated that soot was a primary contributor to the radiative heat transfer in the coal flame studied. It was also concluded that it is important to treat the gas and particle temperatures separately for accurate predictions of the heat transfer. In previous works at Chalmers a 100 kW_{th} oxy-fuel test facility has been used in studies related to large scale combustion of solid fuels [17–20]. In one of these studies [19] a methodology based on combined measurements with a FTIR system and detailed radiation modelling was used to estimate the amount of particles and the particle temperature in a lignite flame similar to the one examined here. It was concluded that coal particles dominated the radiative heat transfer in the investigated cross-section of the flame with only a minor contribution from soot.

From the above mentioned studies it is clear that there is a lack of in-flame particle measurements in flames of practical size, and especially investigations combining particle measurements with interpretations of their impact on the radiative heat transfer. Information whether soot, ash or coal particles may be the main contributor to radiative heat transfer in coal flames varies in the literature. This indicates that measurements are needed for fuels and combustion conditions relevant to the application of interest since the radiative heat transfer depend on these conditions. There is also a need for methodologies combining measurements and modelling to provide more detailed knowledge on these issues. Therefore, this work intends to present a methodology combining experiments and modelling to investigate particle radiation in a self-sustained swirling lignite flame. The work focuses on the impact of different particle types; coal, soot and ash, and their concentration within the flame. The aim is to bring further clarity to what types of particles that is present in the flame and how they contribute to the particle radiation. An additional aim is to test and develop an extractive measurement system which can provide valuable input to the modelling of radiative heat transfer in terms of particle size distribution, total particle concentration and the type of particles found in each size group. Information from the measurements is used in combination with radiation modelling to show the influence from the different types of particles found in the flame.

2. Method

The experiments were performed in Chalmers 100 kW oxy-fuel test rig, a down-fired cylindrical furnace with an inner diameter of 0.8 m. Further details on the test rig can be found elsewhere [17,18,21]. In this work a pre-dried Lausitz lignite with an average diameter of 54 μm was used. Table 1 shows the proximate analysis of the fuel, and Fig. 1 shows the size distribution of the fuel particles. The fuel input was 77 kW_{th} in this study and only air firing was utilized with an air/fuel ratio of 1.18. The rig is equipped with several measurement ports that allow data sampling of flame properties along radial profiles. In this work measurements were performed in the high temperature part of the flame, 384 mm downstream from the burner, with a measured peak gas temperature of approximately 1250 °C in the centre position. The radiative intensity was measured against a cold background with a Narrow Angle Radiometer, and the results and measurement procedure from the investigated cross-section of the lignite flame have been presented previously [19]. The average diameter of the fuel in Ref. [19] was 40 μm (54 μm in this study) but no significant difference was noticed in the results using the two fuel batches. Gas temperature was measured with a suction pyrometer and the gas concentration was analysed with standard gas analysers and with an FTIR analyser. Particles were extracted from two positions in the flame, in the centre position and in the recirculation zone (100 mm from the wall). The particle sampling system is described below.

Fig. 2 shows a schematic picture of the water cooled probe used in the particle sampling measurements. The probe was inserted into the flame and particles were extracted through a conical hole in the probe tip. The flow is perpendicular to the probe and particles were thus extracted from the flame without changing the flow direction of the particles. The velocity in the flame is not exactly known, and perfect iso-kinetic sampling can thus not be obtained. Different suction velocities were, however, tested and these

Table 1
Properties of the coal (as received).

Moisture	9.5 wt.%
Ash	5.0 wt.%
Volatiles	50.0 wt.%
C-fix	35.5 wt.% (calculated)
Net. cal. value	21.3 MJ/kg