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Experimental investigation of flame stabilization inside the quarl of an oxyfuel swirl burner

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HIGHLIGHTS

- New generic oxycoal burner optimized for simulations and detailed experiments.
- Measurements in oxyfuel and air atmospheres.
- Measurements of flow field and reaction zone inside quartz quarl.
- Flame regime switches from non-premixed to premixed.

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ABSTRACT

A more detailed understanding of coal combustion as required for predictive engineering is still lacking. To gain insights into physically relevant sub-processes the community follows a stepwise approach. Experiments have been conducted starting from lab-scale gas-assisted coal flames up to self-sustaining industrial-scale coal combustors in the MW-range. In the intermediate range, however, experiments are sparse. To close this gap in this contribution a new generic test rig is presented that is suitable for operating gas-assisted coal flames. In close similarity to a burner designed for oxycoal combustion the nozzle and quarl assembly exhibit most important characteristics of a state-of-the-art combustor. Quarl and combustion chamber provide excellent optical access such that advanced laser diagnostic methods can be applied for detailed studies of flow and scalar fields. Geometrical requirements for future numerical simulations such as easy meshing of the nozzle have been considered during the re-design of the burner. Although prepared for gas-assisted oxycoal firing, in a first step various gas flames operated in air and oxyfuel atmospheres are investigated here. The focus of the present study is on flame stabilization. The leading edge of the flame is located inside the quarl such that the optical access to this most important region is a mandatory requirement. For non-reacting and reacting conditions flow fields inside the quarl and the combustor are studied using stereoscopic particle image velocimetry (SPIV). To visualize reaction zones and flame stabilization regions planar laser induced fluorescence of the OH molecule (OH-PLIF) and broadband chemiluminescence (CL) measurements are performed for reacting conditions. It is observed that close to the nozzle the leading edge of the flame stabilizes as a diffusion flame in the slow moving shear layer located between the central recirculation zone and the fuel inlet. Further downstream the flame stabilizes in the high-momentum annular jet flow generated by the primary and secondary flow. Most probably it has switched to the premixed regime.

1. Introduction

For power generation coal is one of the most important primary energy carriers. On the one hand coal combustion is expected to further increase; on the other hand man-made emissions of the greenhouse gas carbon dioxide (CO_2), which are a likely cause for the ongoing climate change, need to be reduced [1]. Effective

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strategies for CO_2 reduction and/or capture and storage (CCS) need to be explored. A promising technology is the oxyfuel process where air is substituted by oxygen and exhaust gas is recirculated to control flame temperatures. As a result the exhaust consists of high CO_2 concentrations which can easily be compressed and stored. This technology has a high potential to be retrofitted to existing power plants. For the development of coal combustion technologies especially under oxyfuel conditions deeper insights into the underlying chemical and physical phenomena are needed as a basis for advanced methods and tools for the development process of new combustion technologies. Experimental and numerical modelling for investigations of oxyfuel combustion have been summarized by Chen et al. [2]. Experimental work characterizing the flame structure and its interaction with the turbulent flow field within coal combustion is rare and even fewer investigations deal with coal combustion under oxyfuel conditions.

The majority of previous investigations within pulverized coal combustion systems rely on invasive diagnostics. Non-intrusive optical diagnostics in comparison have the advantage of high spatial and temporal resolutions, but measurements within coal combustion environments are challenging. Previous work using optical diagnostics within coal combustion can be classified in three categories: Measurements on single coal particles within laminar flow reactors [3–6], gas-stabilized coal flames within unconfined flow configurations [7–9] and self-sustained coal flames within enclosed combustors ranging from 100 kW lab-scale to several 100 MW large-scale systems [10–16].

Available optical diagnostics for the characterization of two-phase flows are often limited to low particle densities and their dynamic range in respect of particle size is limited. In-situ measurements in coal flames are therefore challenging because the penetration depth of light radiation is limited due to extinction with increasing number of particles and distance through the two-phase flow [16]. Therefore many measurements using optical diagnostics were applied to single coal particles introduced into defined gas environments at elevated temperatures. For example, a 3-color pyrometer was used to capture the temporal evolution of the coal particle temperatures [3] and extended 2-color pyrometer were utilized for measuring temperatures and velocities [17,18]. Particle ignition and volatilization was characterized by high-speed chemiluminescence imaging [4] and high-speed laser induced fluorescence of the hydroxyl radical (OH-LIF) [5]. Particle velocities and residence times were quantified by Zhang et al. [19] using a high-speed camera.

The complexity was increased by another series of experiments by adding a larger amount of coal particles into unconfined turbulent gas-assisted flames [7–9]. In a turbulent jet flame particle size distributions of the non-spherical particles were measured by a shadow Doppler particle analyzer [9]. Combined OH-PLIF and Mie scattering enabled examining the spatial relation of combustion reaction zones and pulverized coal particles [7]. In a swirling flow configuration this approach was combined with laser-induced incandescence (LII) to additionally determine the spatial soot distribution [7] and the flow field was recorded by LDV and PIV [8].

Technical realizations of coal combustion systems imply enclosed swirling flows. For a self-sustained coal flame combustion chamber walls at elevated temperatures are needed. Therefore optical access is limited to relatively small windows. For such configurations the flow field was measured by LDV [10–15]. For the large-scale systems (>50 MW) LDV measurements required water cooled lances and fibers introduced into the combustion chamber [11,12,14]. In the harsh environments of large-scale coal particle combustors optical diagnostics are difficult to apply as summarized by Penner et al. [20].

As discussed coal flames typically are stabilized as enclosed swirling flows. Detailed optical measurements of coal flames going beyond previous LDV measurements are limited so far to open gas-assisted coal flames and quantities accessible by non-intrusive optical diagnostics in enclosed combustors are limited due to the challenging environment. For bridging the gap between unconfined gas-assisted and self-sustained coal flames, a new test rig is presented within this work. This concept provides optical access to regions important for flame stabilization while retaining important features of a typical enclosed coal combustor. The design includes a swirling flow with a diverging quarl at the exit of the swirl nozzle optimized for oxyfuel operation based on the work of [15,21]. The quarl design impacts flow formation and hence flame stability. Since the central recirculation zone typically reaches back into the quarl measurements inside the quarl are important [22] but have not yet been reported.

The long term goal of this project aims for a more detailed understanding of some important aspects of coal combustion and to provide a comprehensive database for validation of numerical simulations. For this purpose an experiment is designed providing data for a series of operational conditions with increasing complexity starting from a characterization of the isothermal flow field up to a gas-assisted coal flame. The specific work here presents a first step, including non-intrusive optical measurements covering the non-reactive flows and gas flames inside and outside the quarl. To characterize the flow field, stereo-PIV was performed in non-reacting and reacting conditions. OH-PLIF measurements have been performed to identify the reaction zone. Each measurement was performed in one air and two oxyfuel ($25\%O_2/75CO_2$ and $30\%O_2/70\%CO_2$) atmospheres.

2. Experimental setup

2.1. Test rig

In this study a generic test rig is presented that aims for closing the gap between laboratory-scale gas-flame supported coal burners with comparatively low particle densities and burners for a self-sustained coal flame. The focus is to mimic the near-nozzle region of a coal burner that is important for flame stabilization and combustion of volatiles. For this purpose the geometrical design of the burner nozzle, the quarl, and the expansion to the combustion chamber is in close analogy to a self-sustained oxycoal flame presented in [15]. For more details regarding the design consideration the interested reader is referred to Appendix A.

Although the burner is designed for studying gas-assisted oxycoal flames, in a first step gas flames operated in air and oxyfuel atmospheres are investigated.

The geometry of the burner (nozzle and quarl) is shown at the right-hand-side of Fig. 1. The nozzle of the burner consists of two annular orifices concentrically surrounding a bluff body. Partially premixed fuel-air mixtures are provided by the inner orifice (primary flow) whereas swirled oxidizer issues through the outer orifice (secondary flow). Both streams interact within the quarl. The quarl is shaped as a cone (cone angle 21°) restricting the apex angle of the vortex of the swirling flame. It is made out of quartz to allow for optical measurements in the near nozzle region that is of primary importance for flame stabilization. The swirl of the secondary stream is generated in a mixing volume (plenum) upstream of the nozzle. The swirler assembly consists of four straight channels and another four inclined channels angled by 45°. All channels have a rectangular cross section (straight channels $7.5 \times 11.5\ mm^2$, inclined channels $5 \times 8.5\ mm^2$) to allow for a proper meshing at the intersection of the channels and the plenum. Three centering pins are used to guarantee a concentric alignment of the central