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Combustion measurements of type-1 pulverized coal flames operating under oxy-fired conditions

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ABSTRACT

The present study addresses the impact of oxy-fired conditions on type-1 flames generated by an oxidant-staged burner operating with pre-dried lignite and applying wet flue-gas recirculation. Investigations were carried out in a laboratory facility where the combustion takes place in a furnace with a rated capacity of 0.40 MW_{th}. In--flame measurements were performed for oxy-fired conditions operating at three levels of secondary swirl number (1.15, 1.65, and 2.05), while overall O_2 fraction upstream of the burner in oxy-firing was kept at 31 vol %. One air-fired condition at 1.65 secondary swirl number was also investigated. Measurements of local gas temperature and gas species concentrations were performed using standard water-cooled probes with focus on the near burner region. Results showed evidence of radial flame stratification consistent with gradual O_2 admixing to the central fuel jet. Lower temperatures on the flame axis were obtained under oxy-fired condition. In the same region, as a result of CO_2 dissociation and/or gasification reactions by water vapor and CO_2, higher CO concentrations were also monitored, which contributed to lower temperatures. Experimental data also suggested great potential for NO abatement through flame stratification due to type-1 flame pattern.

1. Introduction

Fossil fuels will continue to be a bedrock of global energy system for many decades to come [1]. Within this context, coal use will remain the leading fuel for power generation. While coal makes an important contribution to economic and social development worldwide, its environmental impact is a challenge. With the release of CO_2 to the atmosphere, it becomes one of the primary causes of climate changes. Carbon Capture and Storage technology (CCS) [1,2] is an important step in reducing CO_2 emissions from coal combustion. This technology removes CO_2 from flue gases, and after flue gas treatment, CO_2 is compressed to a supercritical stage before transportation and geological storage [3]. Oxy-fuel combustion has been considered one of the main technologies for capturing CO_2 [4]. Basically, the oxy-fuel process involves combustion of a certain fuel in a mixture of pure O_2 and recycled flue gas. By avoiding the presence of N_2 during combustion process, the amount of CO_2 in the flue gas is concentrated, making it easier to capture [5–7].

Experimental data for pulverized combustion in large-scale furnaces operating under oxy-fired conditions have emerged mainly from studies conducted in once-through reactors [8–10] and vertically oriented down-fired laboratory furnaces [11–14]. Even though once-through reactors provide more operational flexibility, the influence of wet flue-gas recirculation cannot be simulated in most cases. Even though vertically oriented down-fired laboratory furnaces offer many advantages (e.g. they minimize the asymmetrical effects caused by particle deposition and natural convection, as well as facilitate removal of particulates) they create favorable conditions to the combustion process in the case of low confinement ratios. In-flame data obtained in entrained flow reactors and small-scale combustors such as drop tube furnaces with high wall temperatures may increase the radiative heat transfer to the particles, and thereby accelerate the devolatilization and ignition processes, which in turn lead to flame stabilization. These conditions may be desirable for some specific investigations such as determination of coal reactivity [15], although they may be innapropriate for evaluating burner flame pattern, heat transfer, and emission performance. In order to ensure essential physics of industrial scale, furnaces are reproduced (i.e. particle heating rates, gas temperature and composition),

Abbreviations: ANSI, American National Standard Institute; CCS, Carbon Capture and Storage; DIN, Deutsches Institut für Normung (in English: German Institute for Standardization); EN, European standard; GUM, Guide to the Expression of Uncertainty in Measurement; IFRF, International Flame Research Foundation; IRZ, internal recirculation zone; ISO, International Organization for Standardization; STP, standard temperature and pressure (273.15 K and 100 kPa); RTD, Resistance Temperature Detector; VDI, Verein Deutscher Ingenieure (in English: Association of the German Engineers)

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the furnace should be large enough to combine a fully turbulent flow with an appropriately high thermal radiation heat transfer. In short, there is still lack of information on oxy-coal combustion using staged burners under practical conditions, such as those found in full-scale furnaces.

Experimental studies evaluating impacts of burner configurations and operating settings on flame pattern, temperature, and gas emissions were performed by a few authors [16–18] and therefore, it is one of the main focuses of this work. Researchers have also investigated the impacts of the above mentioned parameters on combustion process by using numerical simulations [19]. In overall, most of researchers define burner operating conditions by fixing an overall stoichiometric ratio and flue gas recycle ratio, and then mixing the O_2 feed into the various streams at arbitrary concentrations, or injecting it independently through O_2 nozzles. The challenges to maintaining a stable oxy-coal flame have been the subject of some studies [4].

Flame pattern and stability vary when firing environments are changed from air-firing to oxy-firing as indicated by some studies [12,13,17]. As a consequence, emissions and heat transfer performance are also affected. Although several burner configuration and operating parameters are used in test facilities throughout the world, many authors neglect reference parameters or use dimensionless numbers (e.g. swirl number) in assessing the interpretation of results. Therefore, it becomes difficult to transfer results to other configurations and to industrial-scale burners. Experimental data on oxy-firing available in the literature were obtained by applying burners that generate flame patterns that resemble either type-0 or type-2 flames [12,17,20]. However, no available information on type-1 flames could be found. The possibility of type-2 flames becoming type-0 when switched from air-firing to oxy-firing was reported previously [21]. This is explained by the reduced volume flow rate through burner registers, which in turn decreases the swirl effect.

The combustion of lignite under oxy-fired conditions has been investigated by a few authors [9,13,22]. It was reported that upward adjustments of the O_2 fraction in the oxidant (from 25 to 29 vol%) led to significant local differences in gas composition in the furnace, changes in combustion intensity, and consequently in the flame stability [13]. Nevertheless, CO and NO concentrations at the furnace exit were not affected. Gas concentrations and temperature distributions similar to the air-fired case were achieved when the oxy-fuel flame operated with 25 vol% O_2. However, these experiments were carried out in laboratory facility using dry flue gas recirculation; a higher O_2 fraction in the oxidant is necessary to reach similar flame temperatures in the case of a recycle wet flue gas. Impacts of oxidant staging on emission performance were investigated using a once-through reactor [9]. To keep a similar flame shape and a similar residence time inside the reactor, the total volumetric flow rate of oxidant through the burner was kept the same for all experiments, while the coal feed rate and stoichiometric ratio varied. Effects of operation parameters mainly on NO formation have been also rarely reported and only for dry flue-gas recirculation [22]. Therefore, further investigations for lignite operating with wet flue-gas recirculation are still necessary prior to making predictions regarding large-scale furnaces.

Most of the in-flame experimental data available in the literature is limited to furnace centerlines and very little information regarding the near burner region exists [9,12,14,18]. Another important point is that only mean values have been reported in literature. The absence of experimental errors leads to difficulties in interpreting the experimental data and using them for further validation purposes.

The current work is part of a research program, with the purpose of gaining an in-depth understanding of the lignite combustion behavior under oxy-fired conditions in large-scale laboratory furnace (0.40 MWth). Therefore, it attempts to fill the gap between small laboratory-scale experiments and full-scale furnaces. The oxy-fuel literature has expanded dramatically over the last years. However, it has focused mainly on the impacts of oxy-fired condition on bituminous, sub-bituminous or anthracite coals, leaving lignite relatively unexplored. After recognizing in previous studies that the swirl number and oxidant distribution play an important role in flame stabilization [23], emission performance [24], and heat transfer [25], the present work explores in more details the impacts of oxy-fired condition on flame characteristics through in-flame experimental data. Testing was done to obtain profiles of local mean gas phase temperature and species concentration (O_2, CO_2, CO, CH_4, and NO) for type-1 flame pattern, which has not been addressed previously. Differently from previous studies, the investigated flames were horizontally oriented and the test facility operated with wet flue-gas recirculation. While previous research analyzed the effect of the O_2 content on the oxidant, this work focused on the influence of swirling effects. New experimental data which emphasize the near burner region were reported for three oxy-fired cases at three levels of swirl number (1.15, 1.65, and 2.05) and one air-fired case at 1.65 swirl number. Parallel efforts were also made to provide experimental data followed by uncertainty of measurements.

2. Experimental methods

2.1. Laboratory facility and operating conditions

A detailed description of the laboratory facility can also be found elsewhere [23–26]. The furnace consists of a cylindrical refractory section, where the burner is attached, and the vertical water-cooled section (Fig. 1). The cylindrical section has a 0.95 m inner diameter, and it is 1.093 m long. The vertical section consists of membrane walls with square cross-section of 1.012 × 1.012 m, and a height of 4.40 m; the floor section and the lower 2.20 m are lined with a 0.05 m refractory layer (Fig. 2). Chemically treated water flowing through the membrane walls at temperatures of 180–190 °C decreases the time required to reach steady state and prevent slagging.

The oxidant-staged burner has an output of 0.40 MW_{th} coal (Fig. 3). The primary stream is positioned in the center of the burner and enclosed by two secondary registers, as well as by a tertiary register. The inner secondary stream register was closed to act as a bluff-body. The outer secondary stream is swirled by assemblies, which include vanes set at 30, 45, and 60° in relation to the axial directions and corresponding to 1.15, 1.65 and 2.05 swirl numbers [23]. The outer diameter

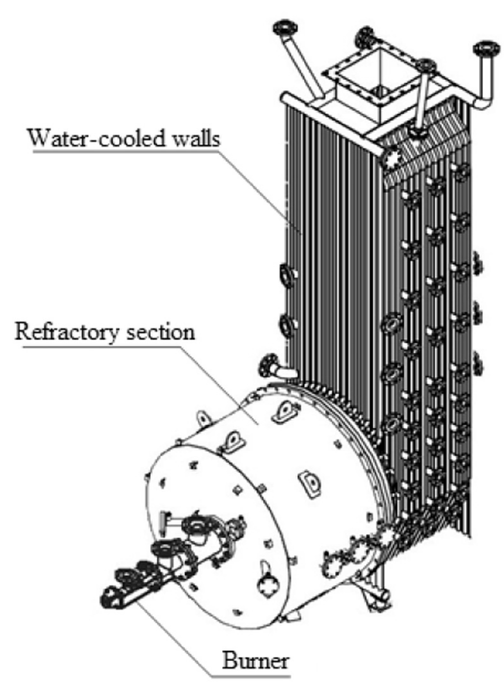

Fig. 1. Laboratory furnace.