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Characterisation of an oxy-coal flame through digital imaging

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ABSTRACT

This paper presents investigations into the impact of oxy-fuel combustion on flame characteristics through the application of digital imaging and image processing techniques. The characteristic parameters of the flame are derived from flame images that are captured using a vision-based flame monitoring system. Experiments were carried out on a 0.5 MW_{th} coal combustion test facility. Different flue gas recycle ratios and furnace oxygen levels were created for two different coals. The characteristics of the flame and the correlation between the measured flame parameters and corresponding combustion conditions are described and discussed. The results show that the flame temperature decreases with the recycle ratio for both test coals, suggesting that the flame temperature is effectively controlled by the flue gas recycle ratio. The presence of high levels of CO_2 at high flue gas recycle ratios may result in delayed combustion and thus has a detrimental effect on the flame stability.

1. Introduction

Oxy-fuel combustion with CO_2 capture from flue gas is regarded as a near-zero emission technology that can be adapted to both new and existing coal-fired power plant. In an oxy-fuel firing system, pulverised fuel is fired in re-circulated flue gas mixed with pure oxygen to produce a high concentration of CO_2 in the flue gas stream which can be sequestrated without costly flue gas separation [1–4]. Oxy-fuel combustion can also reduce significantly the NO_x emission as the recycled NO is reduced or reburnt when it is re-circulated through the system. SO_x emissions per energy of fuel combusted will also be reduced by sulphur retention in ash and deposits [1,5]. However, switching from conventional air–fuel to oxy-fuel brings a number of technical challenges to combustion engineers and plant operators. The increased concentrations of CO_2 and water vapour in the flue gas would substantially increase the emissivity of the furnace gas and thus increase the radiative heat transfer in the furnace [2,3,6]. In addition, the different heat capacity and densities of the main gases, i.e., N_2 and CO_2, will change the mass flows and velocities of the primary and secondary flows (to attain a similar adiabatic flame temperature to the air-firing situation), and thus burner aerodynamics, resulting in changes in fuel ignition properties, flame propagation, shape, and residence time [2,3,6]. Other problems with oxy-fuel combustion include high concentrations of sulphur and mercury and changes in deposition and corrosion in the combustion chamber and flue pass [3]. Therefore, oxy-fuel combustion presents a very different picture from the conventional coal–air combustion.

Oxy-fuel combustion technology is still in its laboratory and demonstration stages. Studies have been undertaken on the understanding of the oxy-fuel combustion process in terms of the changes in flame characteristics (in particular fuel ignition, flame temperature and stability), furnace radiative and convective heat transfer, and flue gas compositions in comparison with the air fired process [7–13]. Bejarano and Levendis [7] conducted a fundamental investigation into the combustion of single coal particles burned in a vertical drop-tube furnace under both O_2/N_2 and O_2/CO_2 environments. Andersson et al. [8] investigated the difference in radiative heat transfers between oxy- and air–coal flames on a pilot-scale oxy-fuel test facility through studies on flame gas temperature (measured by a suction pyrometer) and line-of-sight total radiation intensity (obtained using a narrow-angled radiometer). Khare et al. [9] studied the ignition characteristics of an oxy-coal flame on a 1.2 MW_{th} test furnace, where the measured gas temperature and CFD (computational fluid dynamics) modelling were used to infer the mechanisms of flame ignition changes. Toporov et al. [10] also conducted numerical and experimental investigations into the underlying mechanisms of the aerodynamics of a pilot-scale oxy-coal swirl flame by measuring gas velocity, gas and particle temperatures and gas compositions. Nozaki et al. [11] performed numerical simulations and experiments to investigate the ignition stability of an O_2/CO_2 coal flame on a bench-scale burner, where the gas temperature and emissions along the furnace axis were measured and compared with data for air combustion. Research work related to oxy gaseous fuel flames includes measure-

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ments of temperature and species concentrations of O_2/H_2 flames using Raman/Rayleigh spectroscopic techniques [12] and radiation intensity investigations on propane-fired O_2/CO_2 flames under different flue gas recycle rates and oxygen concentrations [13]. Other activities related to oxy-fuels on large-scale furnaces were also reported by McCauley et al. [14], Zanganeh and Shafeen [15].

Although various advances have been made in oxy-fuel combustion, there is still a gap in knowledge between the current state and the requirement for future application, due to the complicated underlying mechanisms. Current flame visualisation and characterisation techniques have formed an essential base for an in-depth understanding of the oxy-fuel combustion process. The visualisation techniques have been deployed to study coal-fired flames in both laboratory and industrial environments for a variety of applications [16,17,19–23]. Such techniques are conjoined with advanced optical sensing, digital image processing and soft computing algorithms, offering a two-dimensional and non-intrusive means for on-line continuous monitoring and characterisation of flames. This paper is focused on the use of flame visualisation techniques to investigate the characteristics of an oxy-fuel flame. The characteristic parameters of the flame including particle temperature and oscillation frequency were determined from flame images that were captured using a vision-based flame monitoring system. Experiments were carried out on a 0.5 MW_{th} coal combustion test facility. Two types of pulverised coal were tested under different flue gas recycle ratios and furnace oxygen levels. The characteristics of the flames and the correlation between the measured flame parameters and the corresponding combustion conditions are investigated.

2. Methodology

2.1. Flue gas recycle

Flue gas recycle is the process where the flue gas is recycled back into the furnace to establish similar heat flux profiles in the furnace as in conventional air-firing. Fig. 1 is the schematic of an oxy-fuel combustion system with flue gas recycle. In oxy-fuel combustion, the fuel is burnt in a mixture consisting of oxygen produced in a cryogenic air separation unit (ASU) and recycled flue gas, giving a flue gas consisting mainly of CO_2 and H_2O. The recycled flue gas can be either wet or dry, depending on where the recycled flue gas is taken from in the system.

One of the most important parameters in a practical oxy-fuel system is the recycle ratio which is defined as,

$$\text{Recycle ratio} = \frac{\text{Recycled gas mass flowrate}}{\text{Recycled gas mass flow rate} + \text{Product gas mass flow rate}} \times 100\%. \qquad (1)$$

In the present study, recycled flue gas was simulated by using CO_2. The thermal input to the furnace (i.e., coal feed rate) and the primary gas flow ($CO_2 + O_2$) were fixed. The secondary flow ($CO_2 + O_2$) was used as a rig variable in order to establish different recycle ratios, secondary flow rates and percentages of O_2.

2.2. Combustion test facility

The experimental furnace used for the work was the RWE npower's 0.5 MW_{th} combustion test facility (CTF). As shown in Fig. 2, the CTF has a refractory lined combustion chamber with an inner cross-section of 0.8 m × 0.8 m and approximately 4 m long. A water jacket layer is fitted to the outside of the chamber to remove the input energy. A 0.5 MW_{th} International Flame Research Foundation (IFRF) aerodynamically air staged burner was fitted and operated under the baseline operating condition, i.e., without using the burner's low NO_x capability. The furnace also has a number of viewing ports on the centre line of the sidewall, allowing various measurements/sampling to be taken. The CTF was originally designed for air-firing. It had been retrofitted to the once-through oxy-fuel system so as to make it easier to use and more flexible to simulate different recycle configurations, e.g., both wet and dry flue gas, changing oxygen levels in various gas streams. In the present study, however, only the dry case was evaluated.

2.3. Flame parameters and measurement methods

A flame can be characterised by its physical parameters such as size, shape, brightness, temperature and oscillation frequency, depending upon the type of furnace and the target of interest. In this study, two parameters which were measured and used for flame characterisation are flame temperature and oscillation frequency. A vision-based multi-functional flame monitoring system, which was previously described [16], was used to measure the two flame parameters. The system uses CCD (charge-coupled device) cameras to visualise the flame. The flame temperature is computed from flame images based on the two-colour pyrometry [17]. As two-colour pyrometry is derived from the Planck's radiation law, the temperature computed is considered to be the weighted temperature of solid particles in the flame such as soot and char particles. It has been recognised that, due to the physical and chemical variability of the particles involved in the combustion, solid particles in a flame may have different temperatures. This difference depends upon many factors such as the physical and chemical properties of the particles, the rates of heat transfer between the particles, and between particles and surrounding gas. In-depth studies on the radiative properties of soot and coal particles and their effects on the flame temperature can be found elsewhere [18].

The oscillation frequency of the flame is the weighted average frequency of the reconstructed flame signal obtained from a high

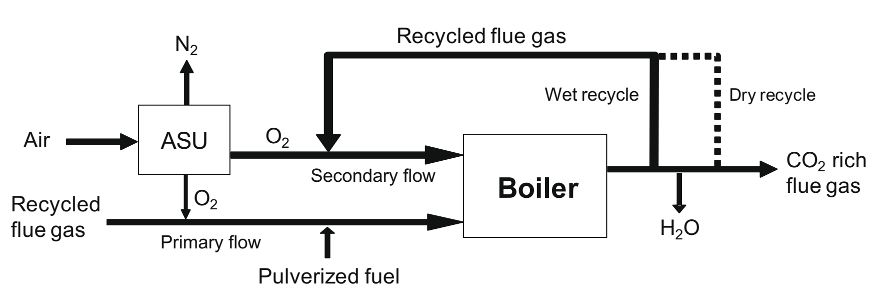

Fig. 1. Schematic of a typical oxy-fuel system.