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Non-intrusive optical diagnostics of co- and counter-swirling flames in a dual swirl pulverized coal combustion burner

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HIGHLIGHTS

- Dual swirl-stabilized pulverized coal flames are evaluated with co- and counter-swirl.
- Behavior of internal recirculation zone and stagnation point is revealed using the PIV.
- Heat release characteristics are investigated using the flame color measurements.

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ABSTRACT

Optical non-intrusive measurements are performed to a 10 kW$_{th}$ laboratory-scale dual swirl pulverized coal combustion burner in order to elucidate the behaviors of internal recirculation zone (IRZ) and heat release region. The pulverized coal flame is operated with four different swirl combinations: co-swirling (low- and high-swirl) and counter-swirling (low- and high-swirl). The flow field is measured using particle image velocimetry (PIV). The IRZ area increases for the high-swirl conditions than that in the low-swirl conditions. With changing from co- to counter-swirl combination, the IRZ appearance changes from a heart- to an elongate-shape IRZ because double stagnation points for the co-swirling flames merges to one stagnation point for the counter-swirling flames. For the co-swirling conditions, a tube-type vortex is detected at the end of the IRZ near the double stagnation points. However, it is not present in the counter-swirling conditions. From two-color pyrometry, the overall temperature in the high-swirl flames is lower than the low-swirl flames. For the counter-swirling flames, higher temperature is observed due to the better mixing, which allows for a more intense combustion reaction of pulverized coal particles. Flame color measurements (OH and CH chemiluminescence band light emission) shows that the devolatilization of coal particles is observed at more upstream region comparing with the heat release reaction for volatile gas combustion. For the high-swirl flames, the CH* band intensity for heat release decreases, however its overall dimension increases. For the counter-swirling flames, the higher heat release is observed.

1. Introduction

Reducing NO$_x$ emissions from coal-based thermal power plants is still a major interest because of the increasing coal consumption for primary energy production by large countries such as China and India [1]. Accordingly, additional benefits such as minimize CO emissions and unburned carbon in fly ash are required of NO$_x$ reduction systems. Opposed wall-fired boiler is widely used because of its flame control independence and little gas temperature deviation in the horizontal flue gas pass [2]. Low NO$_x$ emissions with high burnout performances for pulverized coal combustion can be achieving by combining technology between properly designed low-NO$_x$ burner (LNB) and well installed over fire air (OFA) [3]. An important aspect in the LNB design for the opposed wall-fired boilers is the control of internal recirculation zone (IRZ) with maintaining a fuel-rich environment. The reductive reaction for the fuel-nitrogen to pyrolyze into N$_2$ would be much more possible when the oxygen in the primary air stream is consumed by nitrogen-free volatiles, and some of the nitrogen is evolved within oxygen deficiency atmospheres [4]. Therefore, to extend particle residence time in the oxygen lean IRZ is of great important factor to reduce NO$_x$ emissions from the LNB. The IRZ is produced by swirl flows as a result of local pressure differences, and its behavior and shape depend on variations in swirl controls and burner operating conditions.

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There are previous studies on the IRZ control with swirl flows [5–13]. Gu et al. [5] investigated numerically the influences of aerodynamics of swirling flow and particle motion on the NO_x emission in a swirl number (S_n = 0.5, 1.03, and 1.2). They concluded that the longer the effective time of IRZ, the lower the NO emission is and the larger the particle penetration depth, the lower the NO emission will be. Ti et al. [9] investigated the effect of the outer secondary air cone length of the centrally fuel-rich pulverized coal swirl burner on the combustion characteristics and NO_x emissions in a 0.5 MW pilot-scale facility. They showed that the IRZ size is increased with increasing outer secondary air cone lengths, and thus the NO_x emission is decreased with increasing the cone length. The effect of the swirl combinations (co- and counter-swirl) on flow and mixing patterns, levels of turbulence, flame stability, and combustion performances has been studied [14–20]. The above studies show that the swirl modification of the burner is a critical factor to enhance the flame stability, NO_x emission, flow mixing, and combustion characteristics.

Therefore, a deeper understanding based on detailed measurements of pulverized coal swirling flames is demanded for the development of low-NO_x combustion systems. In this context, the non-intrusive optical diagnostics has been applied in pulverized coal combustion for flow and combustion measurements in the past two decades [21–33]. A summary of experimental measurements performed in coal flames using advanced technologies, including laser Doppler velocimetry (LDV) [21–25], phase Doppler anemometry (PDA) [26,27], shadow Doppler particle analyzer (SDPA) [28,29], and particle image velocimetry (PIV) [30–32] is presented in Table 1. Recently, the PIV techniques attempted to measure the coal particle velocity field. el Gendy et al. [30] have applied PIV to pulverized oxy-coal laminar flames to measure the flow field under different global equivalence ratios and for different particle sizes. Balusamy et al. [32] have implemented LDV and high-speed stereo PIV to unconfined coal swirling flames. Balusamy et al. also investigated the structure of coal flames under oxy–fuel combustion using optical diagnostics including simultaneous Mie/OH planar laser-induced fluorescence (PLIF)/laser-induced incandescence (LII), and 2-d LDV techniques [33]. However, detailed observations of the IRZ behavior with stagnation point of the coal swirling flames are rarer, there are very few experimental measurements in terms of the structure of pulverized coal swirling flames. Furthermore, it is still indispensable to investigate swirl combinations, including co-swirl and counter-swirl, for controlling the IRZ behavior regarding burner aerodynamics for NO_x reduction.

In this study, flow and combustion characteristics are investigated in a dual swirl pulverized coal combustion (DSPCC) laboratory-scale burner. The influences of co- and counter-swirl flows on flame appearance, IRZ behavior, and heat release region are evaluated using optical non-intrusive measurements. Flame color measurements such as particle temperature (0.7–1.1 μm), radical OH^* (431.4 nm), and radical CH^* (516.5 nm) are performed to investigate local flame reactions. These wavelength measurements produce 2-d maps which are based on the local point data. In order to understand the complex features for swirl flows, mean and turbulent flow characteristics of the flame are presented by using 2-d PIV technique.

2. Experimental methodology

2.1. Dual swirl pulverized coal combustion (DSPCC) burner

A laboratory-scale burner has been designed with the goal of testing dual swirling pulverized coal flames including co- and counter-swirl configurations. The schematic diagram of the double swirl pulverized coal combustion (DSPCC) burner, swirlers, and flow arrangements are shown in Fig. 1. The burner consists of three coaxial tubes and double axial swirlers, as shown in Fig. 1(a). Fig. 1(b) shows photographs of the axial inner and outer swirlers. The each swirler consists of six evenly spaced vanes of 2 mm thickness at angles of 40°, 60°, and 80° to the burner exit plane. Pulverized coal particles are carried by a methane–air mixture through the annulus 1, as shown in Fig. 1(a) and (c). A methane–air mixture is supplied into the annulus 2. The screw-type coal feeder (FEEDCON-μM, Nisshin Engineering) is used to supply the pulverized coal particles to the burner. The mass flow rate of coal is metered by regulating the rotational speed of the DC motor driving the screw of the feeder. The air and methane flow rates were controlled by a mass flow controller (KOFLOC-3660, Kojima instruments).

2.2. Coal properties and experimental conditions

An Australian bituminous coal, Whitehaven, is used in this study. The results of the proximate and ultimate analyses, as well as the net calorific value (NCV) are listed in Table 2. The coal sample is milled and sieved, and its diameter is estimated by using a laser diffraction particle size analyzer (LS 13 320, Beckman Coulter) as listed in Table 2. The particle response time, corresponding to the mean diameter of 118 μm for a bulk density of 593 kg/m^3 is around 25 ms, with an associated Stokes number of around 0.69, which clearly indicates that most of the particles may effectively follow the fluid's motions and turbulent fluctuations.

Table 1
Summary of experimental flow measurements performed in pulverized coal flames using optical non-intrusive diagnostic techniques.

Burner/combustor	Flame type	Advanced technology	Measurement	Refs.
Pulverized coal swirl burner, 0.8 MW_{th}	Swirl flame (unspecif.)	LDV	Axial and tangential velocities	[21]
Pulverized coal down-fired reactor, 0.2 MW_{th}	Swirl number (S_n) = 0, 0.5, 1.0, 1.5	LDV	Velocities, species (CO, CO_2, NO, O_2)	[22,23]
Oxy–fuel pulverized coal furnace, 100 kW_{th}	S_n = 1.2	LDV, two-color pyrometry	Velocities, species, temperatures	[24,25]
Laminar flat flame burner	Laminar coal flame	PDA, photography	Ignition delay, gas temperature, velocity	[26]
1:40 scale model for 600 MW_e utility boiler	Cold flow	PDA	Velocity, particle concentration	[27]
Turbulent pulverized coal combustion burner, 5 kW_{th}	Jet flame, *Re* = 2544	LDV, SDPA, OH-PLIF with Mie, OH/CH-chemiluminescence, two-color pyrometry	Velocity, particle diameter, temperature, gas–species, flame structures	[28,29]
Laminar oxy-coal burner	Laminar coal flame	PIV	Velocity, Mie images	[30]
Swirling combustor	S_n = 0.91	PIV	Velocity, temperature, O_2, CO, CO_2, NO	[31]
Laboratory-scale burner, 22 kW_{th}	S_n = 0.77, swirl flame, air and oxy–fuel flames	High-speed stereo PIV, two component LDV, photography, OH-PLIF/Mie/LII	Mie, velocity, flame structure, heat release rate, soot formation	[32,33]
Dual swirl pulverized coal combustion burner, 10 kW_{th}	S_n = 0.71, 1.3, 4.79, co- and counter-swirl	PIV, photography, two-color pyrometry, OH/CH-chemiluminescence,	Velocity, temperature, IRZ, stagnation point, heat release region	This study