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Optical non-intrusive measurements of internal recirculation zone of pulverized coal swirling flames with secondary swirl intensity

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ABSTRACT

The most favorable condition for NO_x reduction in the swirl burner of wall-fired type boilers is to increase the residence time of pulverized coal particles in the internal recirculation zone which should be fuel-rich environments. The purpose of this study is to elucidate fundamental mechanisms for NO_x reduction in pulverized coal swirling flames by means of the detailed observation of the flow field of the oxygen lean internal recirculation zone. The structure of pulverized coal swirling flames with secondary swirl intensity is studied experimentally by particle image velocimetry and local flame colors based on OH^*, CH^*, and C_2^* chemiluminescence intensities. The results show that the internal recirculation zone is enlarged with increasing the outer swirl intensity because the location of the stagnation point moves toward downstream. Also, the exhaust tube vortex is observed along the centerline in the flames, and started from near the stagnation point. For the combustion characteristics, the maximum temperature reduces as the outer swirl intensity increases, and the flame then moves downstream. The higher outer swirl intensity would be more effective in the low NO_x swirl burner systems because of enhancing a dimension of the internal recirculation zone and reducing a local rate of chemical reaction.

1. Introduction

In pulverized coal combustion, coal particles are injected into the furnace in the form of particle-laden flows. The control of the flow and mixing pattern in pulverized coal flames is the key to favorable flame stability, and carbon conversion efficiency, and is also the essential means of reduction of NO_x emissions and of slagging in boilers [1]. Swirl flows have extensively been used in the low-NO_x burner to increase air/fuel mixing performances regarding above aspect. The size and strength of recirculation zone may be controlled by swirl intensities. The coal particles penetrate into the recirculating flow field with larger particle specific surface areas, higher turbulent mixing rates with air, and enhanced particle heating by convection, owing to recirculation of the hot combustion products [2]. Such proposed swirling flames make it possible to control the rates of coal devolatilization and combustion in the near burner region by regulating swirl and chemical reaction intensities.

In the initial stage of coal combustion in the burner region, the gases devolatilizing from the coal particles ignite and react directly with the primary air. If nitrogenous species are evolved during this initial devolatilization stage, the intimate contact with the available oxygen would allow significant fuel-NO formation [3]. If, however, the oxygen in the primary air stream is consumed by nitrogen-free volatiles and if some of the nitrogen are evolved with such a paucity of oxygen like an IRZ (internal recirculation zone), then there is a possibility whereby fuel-N will pyrolyze to form N_2 [3]. Recently, the influences of swirl intensity, primary zone stoichiometric ratio, and air staging level on combustion and emission characteristics were evaluated in pulverized coal fired furnaces fitted with a swirl burner [4–6]. They concluded that the effectiveness of their contribution to NO_x reduction is not straightforward, and the swirl intensity of the burner especially is the most important factor for the IRZ control in swirl-stabilized coal burner.

For low-NO_x coal particle trajectories, the longer residence time of coal particles in the IRZ, which creates a reducing environment with fuel-rich conditions and lowering the temperature, leads to reduced NO_x emissions. However, the formation mechanisms of this fuel-rich reducing zone for realizing the low-NO_x combustion

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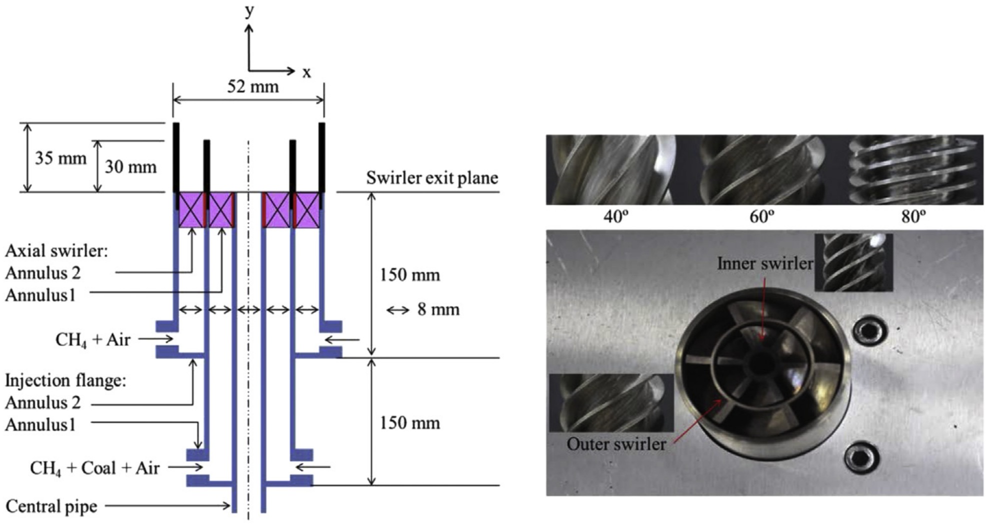

(a) (b)

Fig. 1. (a) Schematic diagram of dual swirl pulverized coal combustion burner, (b) photographs of inner and outer swirlers.

Table 1
Properties of coal.

Coal	Proximate analysis (wt. %, air-dry)				Ultimate analysis (wt. %, dry)						NCV[d] (MJ/kg, as-received)
	M[a]	VM[b]	FC[c]	Ash	C	H	O	N	S	Ash	
Whitehaven	5.02	30.52	51.08	13.38	72.1	4.62	7.38	1.55	0.26	14.09	25.16

Coal	Bulk density (kg/m^3)	d_{10}, <10%	d_{25}, <25%	d_{50}, <50%	d_{75}, <75%	d_{90}, <90%	d_{mean}, mean
		size (μm)					
Whitehaven	593	11.05	37.81	105.6	179.9	244	117.6

[a] M: moisture.
[b] VM: volatile matter.
[c] FC: fixed carbon.
[d] NCV: net calorific value.

Table 2
Experimental conditions.

Parameter	Annulus 1	Annulus 2
Pulverized coal feed rate [kg/h]	0.83	–
[a]Thermal input of coal [kW]	5.65	–
[a]Thermal input of CH$_4$ [kW]	3.26	1.63
Air flow rate [kg/h]	3.1	6.97
CH$_4$ flow rate [kg/h]	3.99	0.32
Reynolds number, *Re*	1617	1635
Swirl number (vane angle, °)	[b]S_i (°)	[c]S_o (°)
	1.3 (60)	0.71 (40), 1.46 (60), 4.79 (80)

[a] Based on the net calorific value.
[b] Inner swirl number.
[c] Outer swirl number.

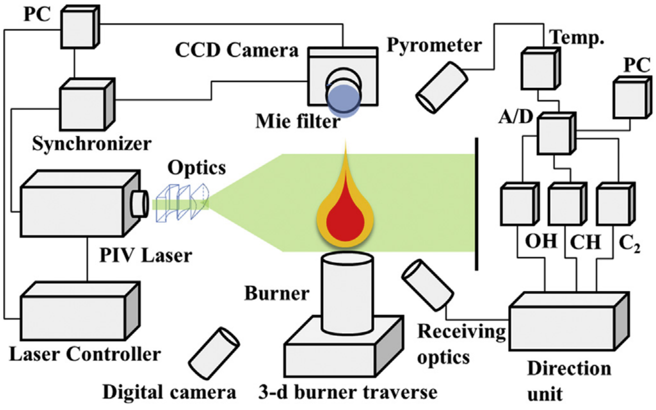

Fig. 2. Schematic diagram of optical measurement system.

have not yet been understood fully. In general, the shear layer in swirl flows leads to the considerable turbulence generation near the swirler. The IRZ reduces the streamwise velocity with enhancing the flame stability. Thus, the present study combines the feature of improved combustion efficiency and flame stability with NO$_x$ reduction by the burner aerodynamics from dual swirl flows. For this purpose, a DSPCC (dual swirl pulverized coal combustion) burner is fitted with a double concentric swirler in the present study. The introduction of swirl from the DSPCC burner provides higher mixing and reaction rates with flame stabilization.

The non-intrusive optical diagnostics has been applied in pulverized coal combustion for flow field measurements in the past two decades [7–18]. Most of the measurements have been carried out in laboratory or pilot scale test facilities owing to their benefits to better control and wider variation of the operating conditions during the experimental tests. LDV (Laser Doppler Velocimetry) [7–11], PDA (Phase Doppler Anemometry) [12,13], and SDPA (Shadow Doppler