Experimental Study on Combustion Adjustment for Dense-dilute Burning through Swirling Burner with Variable Flaring Angle

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Keywords: Swirling burner, Flaring angle, Dense-dilute burning, Coal combustion.

Abstract. A swirling burner with adjustable inner secondary air flaring angle is proposed and a laboratory-scale opposed-firing furnace is built. The effects of burner flaring angle on dense-dilute low-NOx burning are experimentally studied. The temperature distributions along the depth and height direction of furnace are emphatically illustrated. NOx emission and char burnout are compared and discussed. Experiment results indicate that under the dense-dilute burning conditions, variation of burner inner secondary air flaring promotes ignition conditions. Under different conditions of dense-dilute ratio, variation of burner flaring angle can help decreasing NOx emission and improving char burnout. Finally the optimum flaring angle of swirling burner under different dense-dilute ratios is summarized in the form of curves, which could provide reference for exquisite and novel combustion adjustment.

Introduction

Combustion adjustment technology is still a major interest for coal-based thermal power plants, because the coal as primary energy source plays an important role in country development for the countries of large coal storage, such as China and Japan [1-4]. With increasing demands of environment protection recently, low NOx combustion technology is rapidly developed [5-8], including air-staged [9, 10] and fuel-staged or blended method [11] with burners. Great progress has been made in higher control level of NOx emission in coal-firing power plant [6, 9, 12] because low-NOx burning can relieve stress of denitration system in the downstream of the flue. Therefore, burner development and the combustion organization by burner are researched and discussed frequently [13-17]. Many researchers have focused on the burner’s structure and operating parameters. Yonmo Sung et.al studied the effect of secondary air swirl intensity on flame and NOx reduction [12]. Wang et.al experimentally researched effect of inner secondary air vane angles on combustion for NOx reduction in the down-fired utility boiler [18]. Ti et.al discussed the effect of swirl burner outer secondary air vane angles [19] and burner outlet structure [13] on combustion and NOx reduction for wall-fired boiler. Katzer et.al explored the relationship between burner operating conditions and combustion flame characteristics [14]. Zeng et.al studied the effect of coal bias distribution on the slagging with swirl burner organizing combustion [20]. These mentioned parameters of burners are mostly adjustable according to different conditions. However, the flaring angle of burner is mostly still fixed and not utilized in combustion regulation.

This paper introduces a novel swirl burner with adjustable inner secondary air (ISA) flaring angle. In this paper, bias combustion adjustment through adjustable flaring angle of burner is explored. Characteristics of ignition, temperature field, unburned carbon in fly ash and NOx emission are emphatically analyzed. Finally, authors take efforts to reveal the combustion adjustment rule for guidance on engineering application.
Experiment Setup and Research Method

This swirling burner is based on dual register swirling burner structure, which is composed of center pipe, inner/outer primary air (IPA/OPA) pipe and inner/outer secondary air (ISA/OSA) pipe from the inside out, as Figure 1 shows. The center air pipe could provide fresh air or ignition oil if necessary. The inner/outer primary air pipes supply the mixture of air and pulverized coal to furnace. In this experiment, primary air/coal mixture can be injected into furnace separately through inner/outer air channels, to realize dense/dilute combustion. Secondary air is also divided into inner and outer streams according to the dual register burner concept. There is axial swirl vane installed in the inner secondary air duct, which swirls inner secondary air ejection. Outer secondary air is designed as cocurrent stream to disturb the flow field in the later period of burning and enhance air/coal mixing and burnout.

The novel flaring of proposed adjustable flaring angle concept is composed of many metal flakelets partly stacking as circumferential layout, as Figure 1(a) shows. The traditional flaring as a whole is replaced with multiple flakelets around the circumference. Thus, the novel flaring angle varies when rotating the flakelets. Each flakelet is connected with pin on the end of ISA straight pipe. Each pin fixes one linkage and all the linkages are connected by a lattern ring. In the experiment, two steel rods are separately fixed on the lattern ring symmetrically, so as to vary the flaring angle $\beta$ through pulling or pushing the steel rods.

The burner ISA flaring parcels and guides the inside airflow. If this airflow is swirling, the flow form out of spout is impacted by the flaring significantly. Larger flaring angle makes the swirling flow radial extending adequately, so as to strengthen reflux effect and move recirculation zone close to burner spout. On the contrary, smaller flaring angle extrudes rotating airflow jetting from burner, and the swirling effect is attenuated by flaring. Flaring also play a guidance role on outside airflow. The ISA flaring angle directly affects the outlet area of OSA. Large ISA flaring angle would reduce the OSA flow area correspondingly, which increases the airflow velocity and its flow expanding angle, resulting in the mixing delay of inside and outside flow of the flaring.

![Spout photograph](image1)

(a) Spout photograph  (b) Assembly diagram


Figure 1. Schematic diagram of swirling burner.

A laboratory-scaled furnace combustion test system of thermal power input 0.7MW is setup. The combustion test system is comprised of furnace body system, pulverized coal feeding system, air and gas system, water cooling system, ignition system and measurement system.

As Figure 2 shows, the furnace is comprised of lower part and upper part. There is a couple of the proposed swirl burners installed in the front and rear wall separately and symmetrically in the lower furnace. The upper furnace is burnout zone. The size of lower furnace cross section is $1.0 \times 0.8$ m for depth and width, which is surrounded by refractory bricks with a thickness of 0.5 m for heat preservation and insulation. The size of furnace is designed according to some similarity criterions, including kinematic similarity, dynamic similarity, chemical kinetic and heat transfer similarity.

Under each condition, temperature field and features are detailedly measured. In Figure 2, the furnace body sets several measurement holes, part of them locates in the lower furnace along depth direction, part of them locates in the upper furnace along the height direction. Thermocouples are inserted into corresponding hole to some position, and the local temperature can be obtained. At the flue gas exit, sampler takes flue gas to gas analyzer, and fly ash to filter cylinder for offline analysis. Thus the pollution emission and burnout can be measured and deduced.
Figure 2. Combustion test and measurement system.

In order to uniform the experimental results, the position data is nondimensionalized. A system of rectangular coordinate system is built, the original point of which is set as the center of the couple burners axis. The dimensionless depth, width and height of furnace are separately defined as $X=x/a$, $Y=y/a$, $Z=z/a$, where $a$ is the axis distance of front and rear wall burner spout as a reference size. The coal analysis is detailed in Table 1. All the parameters and study conditions are arranged in Table 2.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Proximate analysis/%</th>
<th>Elemental analysis/%</th>
<th>$Q_{net,ar}$ MJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>coal</td>
<td>$M_a$</td>
<td>$A_a$</td>
<td>$V_{daf}$</td>
</tr>
<tr>
<td>coal</td>
<td>6.80</td>
<td>13.59</td>
<td>38.00</td>
</tr>
</tbody>
</table>

Table 1. Coal properties (as received).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio of dense(inner) to dilute(outer) pulverized coal concentration</td>
<td>$\gamma$</td>
<td>-</td>
<td>1,2,3</td>
</tr>
<tr>
<td>Load</td>
<td>$P$</td>
<td>MW</td>
<td>0.7</td>
</tr>
<tr>
<td>OPA flaring angle</td>
<td>$\beta_{OPA}$</td>
<td>°</td>
<td>14</td>
</tr>
<tr>
<td>ISA flaring angle</td>
<td>$\beta$</td>
<td>°</td>
<td>11.4, 17.1, 26.0, 31.7, 35.5</td>
</tr>
<tr>
<td>OSA flaring angle</td>
<td>$\beta_{OSA}$</td>
<td>°</td>
<td>24</td>
</tr>
<tr>
<td>Air temperature</td>
<td>$T_0$</td>
<td>K</td>
<td>343</td>
</tr>
<tr>
<td>Excess air coefficient</td>
<td>$\alpha$</td>
<td>-</td>
<td>1.2</td>
</tr>
<tr>
<td>Air ratio</td>
<td>$V$</td>
<td>-</td>
<td>$V_i=0.1, V_2=0.1, V_3=0.6, V_4=0.2$</td>
</tr>
</tbody>
</table>

Table 2. Study conditions and concerning parameters.

The experimentally obtained NO data were converted to the standard of 6% O$_2$ according to the Equation (1).

$$\text{NO}_x (\text{ppm} @ 6\% \text{O}_2) = \frac{\text{NO}(\text{ppm})}{0.95} \times \frac{21 \times 6 \times 6}{21 \times \text{O}_2(\%)}$$  \hspace{1cm} (1)$$

where $\text{NO}_x (\text{ppm} @ 6\% \text{O}_2)$ is under standard state, 6% O$_2$, (ppm); NO(ppm) is the measured volume fraction of NO, (ppm); O$_2$ is the volume fraction of oxygen, (%); 0.95 is the assumed ratio of NO to total NO$_x$.

Char burnout is impacted by combustion conditions significantly. To evaluate char burnout, the fly ash at the outlet of furnace is sampled and offline analyzed by gravimetric determination method. Then the burnout can be calculated by the formula as follows.

$$\psi = \frac{1-(w_k/w_x)}{(1-w_k)}$$  \hspace{1cm} (2)$$

where $\psi$ is char burnout, $w$ is the ash weight fraction, and the subscript $k$ and $x$ refer to the ash contents in the input coal and char sample, respectively.
Results and Discussion

In the combustion experiment, combined adjusting of dense-dilute burning and variant flaring angle is firstly studied, while the other parameter is fixed. To analyze the combustion characteristic, the gas temperature of measuring point close to the spout along burner axis direction is considered as ignition characteristic temperature, and the highest gas temperature along the furnace height is considered as the indication of combustion intensity.

As Figure 3(a), (b) and (c) show, the ignition characteristic temperature appears above 750°C because of its high calorific value and volatile content. The ratio of dense to dilute coal-airstream $\gamma$ increasing improves ignition on all conditions of different burner flaring angle, which indicates the concentration of primary air-coal mixing stream benefits stable ignition of the test coal.

If coal powder ratio $\gamma$ keeps constant, adjustment of swirl burner ISA flaring angle $\beta$ still affects temperature distribution along the furnace depth. When $\gamma=0$, large flaring angle ($\beta=35.5$) improves reverse flow zone to induce hot gas close to spout while the gas temperature of furnace center is not high. Although this situation benefits ignition, it is possible to burn out the burner spout. When $\beta$ becomes smaller, the temperature distribution along the burner axis appears higher in the center and lower near the spout. The condition of $\beta=17.1$ shows highest temperature near burner spout. When dense-dilute burning mode works, temperature distribution along the burner axis appears higher at center and lower aside. When $\gamma=1$, the condition of $\beta=26.0~31.7$ is in favor of ignition improvement. When $\gamma=3$, the burner with large $\beta$ loses the ability of helping coal ignition. However, the swirl burner with smaller $\beta$ ($\beta=17.1$) ignites coal with comparatively higher gas temperature near the spout.

Figure 4 describes the whole combustion process in the furnace with temperature distribution along the furnace centerline. For all conditions the gas temperature along the furnace centerline rises from burner layer until at outlet of lower furnace, then decreases gradually in the upper furnace in the burnout stage.

![Figure 3. Temperature distribution compare along burner axis direction.](image-url)
The temperature level in lower furnace is both affected by dense-dilute ratio $\gamma$ and burner flaring angle $\beta$. When non-bias combustion or low dense-dilute combustion operates, the impact of $\beta$ on combustion in the lower furnace appears significant. Burners with $\beta=26.0^\circ$-$31.7^\circ$ organize the highest temperature level in the furnace. When dense-dilute ratio $\gamma$ becomes larger, burners with smaller $\beta$ ($\beta=11.4^\circ$-$17.1^\circ$) can organize higher temperature level of furnace.

Figure 5 displays NO$_x$ emissions at the outlet of furnace under different dense-dilute burning. The dense-dilute burning obviously reduces NO$_x$ emission at the outlet of furnace. With increasing of dense-dilute ratio $\gamma$ the reduction of NO$_x$ emission is improved but has limit potential. And, more remarkable, more NO$_x$ emission reduction can be realized through burner flaring angle $\beta$ adjustment. In a word, burner flaring angle can be considered as auxiliary adjustment to control NO$_x$ emission.

Figure 4. Temperature distribution compare along furnace centerline direction.

The experimental char burnout results of different conditions are compared in Figure 6. The conditions with dense-dilute combustion have higher char burnout than that with non-dense combustion. Under non-dense combustion conditions, adjusting burner ISA flaring angle $\beta=17.1^\circ$-$26.0^\circ$ could optimize the burnout more efficiency. Under dense-dilute combustion conditions, burners with $\beta=26.0^\circ$-$31.7^\circ$ optimize combustion to achieve the best effect as Figure 6 shows.

As mentioned before, dense-dilute burning has been applied in NO$_x$ emission control and ignition improvement. Combining with the swirling burner of adjustable flaring angle, combustion can be more improved and optimized on low-load stable burning and low-NO$_x$ combustion. Figure 7 summarizes the optimizing ISA flaring angle $\beta_{opt}$ of swirling burner under different dense-dilute ratios for different combustion targets obtained from this experimental study. The flaring angle $\beta$ variation enriches adjustment method, optimizes combustion precisely and satisfies different combustion requirements.
Figure 5. NOx emission characteristic under different $\gamma$.

Figure 6. Char burnout compare under different $\gamma$.

Figure 7. Suggested $\beta$ adjustment for $\gamma$ variation.

The optimal $\beta$ via dense-dilute ratio $\gamma$ for best fuel ignition performance is displayed. With dense-dilute burning the burners should adjust its ISA flaring angle to $\beta<32^\circ$. The optimal flaring angle $\beta$ responding to the highest $T_{\text{max}}$ of all conditions is shown in Figure 7, almost keeping constant. Proper dense-dilute ratio $\gamma$ could promote flame center temperature. Combination Variation of $\beta$ and $\gamma$ could affect the $T_{\text{max}}$ about 50°C~100°C in this experiment. With enlargement of dense-dilute ratio the burner flaring angle is suggested to become smaller for lower NOx emission. The influence of burner flaring angle on burnout is not simply monotonic. However, it is observed that variation of burner flaring angle could improve burnout in actual combustion optimization.

**Conclusion**

In this study, the swirling burner with adjustable inner-secondary air flaring angle is proposed to organize and optimize the coal combustion. The delicacy adjustment of coal combustion through adjustable burner ISA flaring angle is experimental researched for dense-dilute burning. The effect on ignition, combustion intensity, NOx emission and burnout are discussed.

In the dense-dilute burning for low-NOx emission, variation of burner ISA flaring angle $\beta$ promotes ignition conditions to some extent. Combustion intensity is mainly affected by dense-dilute
ratio $\gamma$ and less impacted by burner ISA flaring angle $\beta$. Under different conditions of $\gamma$, variation of $\beta$ of burner can help decreasing NO$_x$ emission and char burnout.

Finally $\beta_{opt}$ of swirling burner under different dense-dilute ratios are summarized. According to different combustion targets the burner flaring angle could vary conveniently to satisfy each requirement. The curves of $\beta_{opt}$ could provide reference for engineering operation based on this experimental study. The detailed rules for more coal types are worth to be researched in the future work.

Acknowledgment
This work is supported by Natural Science Foundation of Shaanxi Province of China (Program No. 2017JQ5108) and Special Scientific Research Plan of Shaanxi Province Education Department (Program No.17JK0594).

References


