PROPERTIES OF PULVERIZED COAL COMBUSTION IN HIGH TEMPERATURE AIR/STEAM MIXTURE

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ABSTRACT

High temperature air combustion (HiTAC) is a promised combustion technology. It has been proved that when the oxygen concentration in the preheated air is diluted, the NOx emission for fossil fuels will be significantly reduced. When this idea is applied to pulverized coal combustion, the same advantages can be expected. Water has high specific heat, and can react with coal in high temperature. When steam is used to dilute preheated air in HTAC of pulverized coal, better combustion properties may be achieved. However, very little data can be found in this aspect, and further work should be done.

This paper presents the work on properties of pulverized coal combustion in high temperature air/steam mixture. Experiments have been performed in a 2.5m long combustion chamber with coal feed rates ranging from 5 kg/h and coal injection velocities ranging from 9 to 30m/s. Coal nozzles with different diameters were used to consider the influence of the transport factor. The combustion air was diluted by steam, whose percentages varied from 0% to 44%. Steam and air were preheated by a high-temperature gas generator, and the preheated oxidizer temperature could achieve 1150 °C. Numerical simulations were also carried out to provide more information about fluid field.

The results show that NOx emission reduces with the dilution by steam for all nozzle diameters and injection velocities. Steam has a significant impact on flame structure. When steam was added, the peak temperature would be remarkably reduced, and the visibility of flame reduced significantly. Even small amount of steam in oxidizer would impact the flame structure. It is also found that with the increase of coal injection velocity, the NOx emission increases.

Key words: HiTAC; coal; steam; NOx; temperature;

INTRODUCTION

The thermal efficiency of industrial furnaces can be significantly increased by preheating the combustion air to a high temperature, using the heat exhaust gases. However, the NOx emission is strongly promoted by elevated temperatures because of thermal NOx mechanics. An effective way of solving this problem is to reduce the oxygen concentration in the oxidizer. This technology is named High Temperature Air Combustion (HiTAC). Many studies on HiTAC have been done in the recent years, and it has been proved that that
HTAC technology has many features that are superior to that in conventional combustion (YANG and BLASIAK, 2004a,b; WEBER et al., 2000; HASEGAWA et al., 2002; TSUJI et al., 2003; LILLE et al., 2005).

High temperature air combustion technology was first applied in gaseous fuel combustion. When this idea is applied to combustion of pulverized coal, the same advantages as for gaseous fuels can be expected, including the enhancement of combustion stability and increase of combustion efficiency, the ability to use low-volatile coal like anthracite, and also lower pollution emissions (KIGA et al., 2000; SUDA et al., 2002; HE et al., 2004; HANNES et al., 2009). Kiga et al. presented the experimental results of pulverized coal combustion in high-temperature and low-oxygen condition. The results indicated that increasing air preheat results in increased combustion efficiency and reduced NOx emission, whereas decreasing the oxygen content of the combustion air leads to large reduction in combustion efficiency, accompanied with a slight decrease or increase in NOx (KIGA et al., 2000). Suda et al. conducted experiments by injecting pulverized coal from a nozzle co-axially placed at the preheated air inlet. The results showed that for both bituminous and anthracite coals, release rate of volatile contents were remarkably enhanced and flame front distances from coal nozzle became less when air temperature increased. NOx emission also became less with temperature increasing (SUDA et al., 2002). The corresponding numerical studies were performed later[11]. Numerical simulation results were of great consistency with experimental results (HE et al., 2004). Hannes et al. carried out a set of experiment to investigate the NOx emission of high temperature air combustion under Ar/O\textsubscript{2} as well as CO\textsubscript{2}/O\textsubscript{2} atmospheres in order to quantify the ratio of fuel NOx to thermal NOx. This investigation showed a high reduction of thermal NO as well as an increase of fuel-NO which was primarily related to the decrease of the peak flame temperature (HANNES et al., 2009).

When steam is induced into the combustion process, the reaction mechanics will be changed. Studies of Kim et al showed that when steam is added into the oxidizer, the concentration of OH radical will increase significantly, while the concentration of O and H will decrease. The result also showed that the OH radicals will affect the formation rate of thermal NO by the radical reaction step N + OH → NO + H (KIM et al., 2002). Subsequent work on the combustion behavior of steam-added mild combustion was done in 2004 (JEONG et al., 2004). The result showed that in mild combustion model, the OH production via the reaction step O+H\textsubscript{2}O → OH+OH was enhanced by the increase of oxidizer-side temperature, while chemical effects of added steam are influenced by the competition between the reactions O+H\textsubscript{2}O → OH+OH and OH+H\textsubscript{2} → H+H\textsubscript{2}O . It was also found that in the whole ranges, steam addition suppresses NOx emission. When steam is used to delute the oxidizer of solid fuels, like pulverized coal, the gasification reactions of fixed carbon should be taken into account, so the reaction mechanics would be more complex, and different combusting properties should be observed. However, few works have been found in the literature of high temperature air combustion of solid fuels, in steam added conditions.
The aim of this work is to both experimentally and numerically study the combustion behavior of pulverized coal in highly preheated air/steam mixture. The temperature of air/steam mixture was heated up to 1150 °C, with the steam concentration ranging from 0% to 44% of mass fraction. The flow rate of pulverized coal was 5 kg/h, and the injecting velocity varied from 9 m/s to 30 m/s. In order to investigate the influence of nozzle diameters on combustion behavior, there nozzles with the diameters of 3, 5 and 6.5 mm was used. The influence of steam mass fraction on NOx emission and flame lift-off distance are described. Additionally, the influences of transport factor and coal injection velocity on NOx emission are also presented. In base of these results, some numerical simulations are made to investigate detailed mechanics.

METHODS AND MATERIALS

Feedstock

The Helensburg coal was used in this work. Table 1 shows the proximate and ultimate properties of Helensburg coal. A Rosin-Ramler approach were assumed to represent the Helensburg coal particle size distribution, as shown in Figure 1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>wet</th>
<th>dry</th>
<th>dry ash free</th>
<th>air dried</th>
</tr>
</thead>
<tbody>
<tr>
<td>moisture</td>
<td>%</td>
<td>6.70</td>
<td>-</td>
<td>-</td>
<td>0.90</td>
</tr>
<tr>
<td>ash</td>
<td>%</td>
<td>11.10</td>
<td>11.90</td>
<td>-</td>
<td>11.79</td>
</tr>
<tr>
<td>volatiles</td>
<td>%</td>
<td>19.41</td>
<td>20.80</td>
<td>23.61</td>
<td>20.61</td>
</tr>
<tr>
<td>fixed carbon</td>
<td>%</td>
<td>62.79</td>
<td>67.30</td>
<td>76.39</td>
<td>66.69</td>
</tr>
<tr>
<td>chlorine</td>
<td>%</td>
<td>0.01</td>
<td>&lt; 0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>sulphur</td>
<td>%</td>
<td>0.32</td>
<td>0.34</td>
<td>0.39</td>
<td>0.34</td>
</tr>
<tr>
<td>carbon</td>
<td>%</td>
<td>70.91</td>
<td>76.00</td>
<td>86.27</td>
<td>75.32</td>
</tr>
<tr>
<td>hydrogen</td>
<td>%</td>
<td>3.73</td>
<td>4.00</td>
<td>4.54</td>
<td>3.96</td>
</tr>
<tr>
<td>nitrogen</td>
<td>%</td>
<td>1.40</td>
<td>1.50</td>
<td>1.70</td>
<td>1.49</td>
</tr>
<tr>
<td>oxygen</td>
<td>%</td>
<td>5.78</td>
<td>6.20</td>
<td>7.04</td>
<td>6.14</td>
</tr>
<tr>
<td>Q water is condensed</td>
<td>MJ/kg</td>
<td>28.95</td>
<td>31.03</td>
<td>35.22</td>
<td>30.75</td>
</tr>
<tr>
<td>Q water is vapour</td>
<td>MJ/kg</td>
<td>27.99</td>
<td>30.17</td>
<td>34.25</td>
<td>29.90</td>
</tr>
</tbody>
</table>

Table 1 Physical and chemical properties of the coal used in the experiments
Test facility and experimental conditions

The test facility has been developed for several years. For the purpose of the coal combustion, test facility was rebuilt, as shown in Figure 2.
A cylindrical combustion chamber of 0.4 m diameter and 2.5m height was used, as shown in Figure 3. Air was heated up to the temperature of 1150 °C by a compact pre-heater, and entered through the top of chamber, with the mass flow of 115 kg/h. The pulverized coal is fed by a horizontal lance, and air was used as transport gas. Water cooled coal lance was used to keep the temperature of transport gas. The volume of combustion chamber was equal to 0.28m$^3$, and surfeit 2.2m$^2$. Two thermocouples were used to measure temperature profile along combustion chamber and temperature in inlet and outlet. Thermocouple tips were located in the middle of inlet and outlet channels. Tip of thermocouples installed 200 mm from the wall. In flue gas channel, two iso-kinetics probes were located for ash collecting and flue gas sampling. Flue gas samples were suck by these probes, and then cooled down after suction probe. CO and CO$_2$ components were measured by Maihak analyzer type MULTOR 610 by using Non-Dispersive Infrared method. To measure O$_2$ component in sample gas, the M&C Analysentechnik analyzer type PMA 25 equipped with paramagnetic detector was used. Measure of NOx was taken by chemiluminescent analyzer made by ECO PHYSICS type CLD 700 EL ht.

![Figure 3 View of the combustion chamber](image)

Table 2 shows the experimental arrangement of tests. Before each test, experimental facility was heated up for 10-12 hours, in order to achieve uniform temperature profile in combusting chamber.

<table>
<thead>
<tr>
<th>Velocity of transport gas in the nozzle</th>
<th>Diameter of coal nozzle</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5 mm</td>
<td>5 mm</td>
</tr>
<tr>
<td>Composition of oxidizer</td>
<td>100% air</td>
</tr>
<tr>
<td>-------------------------</td>
<td>----------</td>
</tr>
<tr>
<td></td>
<td>30 m/s</td>
</tr>
<tr>
<td>100% air</td>
<td>20 m/s</td>
</tr>
<tr>
<td>85% air</td>
<td>9 m/s</td>
</tr>
<tr>
<td>15% steam</td>
<td>30 m/s</td>
</tr>
<tr>
<td>20 m/s</td>
<td>20 m/s</td>
</tr>
<tr>
<td>9 m/s</td>
<td>9 m/s</td>
</tr>
<tr>
<td>30 m/s</td>
<td>30 m/s</td>
</tr>
<tr>
<td>20 m/s</td>
<td>20 m/s</td>
</tr>
<tr>
<td>9 m/s</td>
<td>9 m/s</td>
</tr>
<tr>
<td>30 m/s</td>
<td>30 m/s</td>
</tr>
<tr>
<td>20 m/s</td>
<td>20 m/s</td>
</tr>
<tr>
<td>9 m/s</td>
<td>9 m/s</td>
</tr>
</tbody>
</table>

Table 1 Experimental arrangement

**Numerical strategies**

The air of the numerical simulations were to predict the flow and temperature field and combustion behaviors inside the burner. CFD software FLUENT 6.3.26 was used as the platform of simulations. In this work, three-dimensional governing equations were employed to model the flow in the reactor due to the strong three-dimensional characteristics. In order to simulate the turbulence flow, the standard \( k-\varepsilon \) model is selected. The combustion process was simulated using the Finite Rate/ Eddy-Dissipation model, and single-step devolatilization model was used to modeling the devolatilization process. In order to take account of the gasification of char, a multiple char reaction model was used. Six reactions were considered in this work:

\[
\text{mv} \_\text{coal} + 1.614O_2 \rightarrow 2.763H_2O + CO \quad (R1)
\]

\[
C + 0.5O_2 \rightarrow CO \quad (R2)
\]

\[
C + CO_2 \rightarrow 2CO \quad (R3)
\]

\[
C + H_2O \rightarrow CO + H_2 \quad (R4)
\]

\[
H_2 + 0.5O_2 \rightarrow H_2O \quad (R5)
\]

\[
CO + 0.5O_2 \rightarrow CO_2 \quad (R6)
\]

In order to simulate the NOx emission, the default NOx models of FLUENT was used, and thermal NOx, prompt NOx, fuel NOx and N\(_2\)O intermediate models are all considered.

The kinetic properties of Helensburg coal were set as default values from Fluent, whilst for char were computed on the basis of formulas taken from Orsina et al. ’s work (ORSINA
et al., 2000). It is very likely that assumed kinetic data is not proper for given coal. It is highly recommended to investigate coal itself to obtain this data (e.g. at drop tube furnaces) in order to make modeling more accurate. However the laboratory investigation at the present stage of work were not taken into account. So one has to be conscious that predicted values of NOx, ignition distance and char burnout can differ from those in reality. After all, when taking into account only comparison among different cases (technical issues of burners etc.), this should have more minor effect than major.

RESULT AND DISCUSSION

The influence of steam mass fraction

The influence of steam mass fraction on NOx emission is shown in Figure 4. The NOx concentration in flue gas has been standardized to 6% oxygen concentration. It could be seen that the addition of steam has a significant impact on NOx emission. For all the coal injecting velocities and nozzle diameters, the NOx emission decrease with the increasing of steam in oxidizer. When the concentration of steam in oxidizer increases to 44%, the NOx emission will reduce more than a half.

Figure 5 is the numerical modeling result of the temperature, NO concentration and O$_2$ concentration profiles for several cases with different steam concentrations. The nozzle diameter of these cases is 5mm, and the coal injecting velocity is 30m/s. With the increasing of steam concentration in oxidizer, the peak temperature decrease significantly. The temperature difference of peak temperature and oxidizer temperature at the inlet falls from 1400K to about 600K. The impact of steam on NO emission was shown in Figure 5 (b). In case 1 where their is no steam addition, the peak NO concentration is about 1.5%, but in case 2, when the steam mass fraction in oxidizer reaches 1.5%, the peak concentration of NO drops to less than 0.3%. In case 3 and 4, where the steam mass fractions are 34% and 44%, the peak NO concentration is less than 0.1%. This can be explained by the decrease of thermal NO, which is strongly depend on the flame temperature. Moreover, the low oxygen concentration can also suppress the formation of NOx.

A most important characteristics of steam added combustion is that the concentration of OH radicals in combustiog zone is enhanced significantly, which could underlines one of the chain reactions: N + OH $\rightarrow$ NO + H. In this aspect, the addition of steam may be propitious to the formation of NOx. But form both experimental and numerical results, OH radicals did not promote the formation of NOx significantly. The suppressant mechanism of low peak temperature and oxygen concentration can overbalance the influence of increase of OH radicals.

There exists a difference for NOx emission between numerical and experimental result. The possible reason might be the property setting for pulverized coal in numerical simulation.
Another impact of the steam addition is the visability. When there was no steam in the oxidizer, the flame appeared an orange colour, but when steam was added, even in the 15% steam cases, the flame became invisible.

(a) Coal injecting speed 9m/s

(b) Coal injecting speed 20m/s
Figure 1 Influence of oxidizer composition on NO\textsubscript{x} emission. Tests was made with three different nozzles 3, 5 and 6.5 mm.

(c) coal injecting speed 30m/s

(a) Temperature profiles

(b) NOx mass fractions profiles
The influence of coal injecting velocity

Impact of coal injecting velocity in nozzle on emission of NOx is presented on Figure 6. It can be found that with the raise of coal injecting velocity, the NOx emission shows a trend of increase. Shinji et al. have found that volatile nitrogen played an important role in NOx formation, while more than 90% of the released nitrogen during devolatilization was converted to HCN and NH$_3$ (SHINJI et al., 1994). According to the Feminore mechanism, for equivalence ration less than 1.2, HCN and NH$_3$ will be oxidized to form NO (FENIMORE, 1970). For equivalence ration richer than 1.2, other routes open up and NO is recycled to HCN, inhibiting NO production (MILLER et al., 1989).

In our system, pulverized coal was transported by air, so when the nozzle diameter was fixed, higher coal injecting velocity means more transport air, which means less equivalence ration in the devolatilization zone. At the same time, a high coal injecting velocity may induce better turbulence, which means better mixing of coal and oxidizer during the devolatilisation process. This also leads to less equivalence ration in the devolatilization zone.

Figure 7 is the numerical modeling profiles of rate of fuel NO for several cases with different coal injecting velocities. The nozzle diameter of these cases is 5mm, and the steam mass fraction is 34%. It can be found that the fuel NO formation area increasing with the coal injecting velocity.
(a) Diameter of nozzle 6.5 mm

(b) Diameter of nozzle 5 mm

(c) Diameter of nozzle 3 mm

Figure 6 Influence of coal injecting velocities on NO$_x$ emission
CONCLUSION

Experimental and numerical studies have been done on NOx emission and combustion properties of pulverized coal combustion in high-temperature steam diluted air, and the following conclusions are attained.

- The addition of steam into oxidizer will suppress the formation of NOx. The main reason for that is the decreasing of peak temperature of combustion area, which restricts the NOx formation by thermal NOx mechanism. The increasing of OH radicals due to the addition of steam did not show significant impact on NOx formation. The flame becomes invisible when steam is added into the oxidizer.

- The coal injecting velocity also have impacts on NOx formation. NOx emission increases with the coal injecting velocity. This is due to the change of transport factor and the turbulent mixing of coal and air. High injecting velocity leads to lower equivalence ratio in the devolatilization zone, so that the fuel NOx is prompted.

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