SMALL SCALE EXPERIMENT ON THE PLASMA ASSISTED THERMAL CHEMICAL PREPARATION AND COMBUSTION OF PULVERIZED COAL

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Abstract

Ignition and stable combustion of pulverized coal with Nitrogen and Air plasmas are investigated experimentally for some different types of coal. The experimental results show that air plasma has strong effect for ignition and stabilization of coal combustion. In addition, suppression of NO\textsubscript{x} production could be possible even in air plasma. It is possible to ignite and burn stably for the inferior coal that contains volatile matter in the ratio of only 10\% of dry total mass.

1. Introduction

Although problem of global warming has been recognized since the end of last century, it is impossible to quit suddenly the use of fossil fuel for energy supply. Especially, since coal resource is still comparably rich and its localizability is smaller than that of petroleum, that will play an important role of energy supply in the next several tens years.

Since coal is a kind of solid fuel, there are some difficulties in ignition and combustion. Coal includes volatile matter inside of that body and must be heated to high temperature to extract them. In order to increase the heat effect, coal is often burned after the pulverization. When the pulverized coal particles are heated, the volatile component fixed to inner part of coal blows out and is mixed with surround atmosphere. After the temperature reaches high enough to ignition, efficient combustion of coal can be realized if the sufficient air is supplied.

We are now developing a new pulverized coal burner with a plasma torch. In this burner, the pulverized coal is carried to the combustor by nitrogen flow and injected into the nitrogen or air plasma jet. During the travel toward the downstream, the coal is thermally activated in the plasma flame. Namely, the injected pulverized coal particles are heated in the very high temperature field of the plasma and their volatile component comes out to the surround atmosphere. However, coal combustion is not occurred there because of lack of air. Even in the case of air plasma, supplied air for plasma production is too little to burn the supplied pulverized coal. Sufficient air for complete combustion of supplied coal is injected at the downstream of the plasma flow and then the volatile component and fixed carbon is burned out. In this method, the influence of active ions or atoms in the plasma to the coal combustion
is expected in addition to the heat effect of the plasma jet. In the present research, pulverized coal combustion with plasma is investigated experimentally and modeling in simulation shows thermal activation of coal by plasma.

2. Experimental
2.1. Coal Property
In this experiment, three different types of coal are used. Table 1 shows the chemical compounds mass ratio of those coals. The most important difference among them is the volatile component ratio.

<table>
<thead>
<tr>
<th>Coal Characteristics</th>
<th>High Volatile Material Coal</th>
<th>Medium Volatile Material Coal</th>
<th>Low Volatile Material Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture Content (mass%)</td>
<td>68</td>
<td>25</td>
<td>27</td>
</tr>
<tr>
<td>Ash Content (mass%, dry)</td>
<td>131</td>
<td>150</td>
<td>149</td>
</tr>
<tr>
<td>Volatile Content (mass%, dry)</td>
<td>406</td>
<td>270</td>
<td>106</td>
</tr>
<tr>
<td>Fixed Carbon Content (mass%, dry)</td>
<td>483</td>
<td>880</td>
<td>746</td>
</tr>
<tr>
<td>Total Energy (kJ/g)</td>
<td>2730</td>
<td>2800</td>
<td>3000</td>
</tr>
</tbody>
</table>

*Table 1. Mass ratio of chemical compounds.*

All of these coals are pulverized before the experiment and selected by mesh so that the particle size is smaller than 100 μm. Figure 1 presents distribution of pulverized coal diameter.

![Fig.1 Distribution of pulverized coals in size of particles.](image)

2.2. Experimental Setup
Figure 2(a) shows schematic view of experimental setup. The dimensions of combustion chamber are 100mm in inner diameter and 1900mm in length. The chamber consists of fire-resistant part, water-cooling part and iron tube part. In the fire-resistant part with length of 950mm, inner diameter of 100mm a zirconium tube 10mm thick is placed in the center of the chamber and zirconium bricks occupy between the zirconium tube and the outer wall of the
chamber. In order to observe inside of the chamber or insert some probes, there are measurement ports in axial direction.

Measurements of temperature are made through the ports, whose positions are 150mm, 350mm and 750mm from the top of the chamber. The probes are type B (Pt-Rh) thermocouples covered by pure aluminum oxide tubes and set to measure the temperature of the zirconium tube surface.

Exhaust gas is sampled from the port in the iron tube part, which is 1850mm from the top of the chamber. The fraction of O₂, CO₂, CO and the concentration of NOₓ in the flue gas are monitored to evaluate the combustion of coal. The O₂ ratio is measured by magnetic oxygen analyzer. Non-dispersive infrared absorption method is used for the CO₂ and CO ratio, and NOₓ concentration is determined by atmospheric chemiluminescence method.

(a) Experimental Setup

(b) Plasma Torch and Combustion Air Supply Flange

Fig.2 Schematic view of the experimental apparatus.

A plasma torch and a stainless-steel flange for combustion air supply are fixed on the combustion chamber. Their schematic view is shown in Fig.2(b). The flow rate of plasma gas is 14.4slm (standard liter per minute) nitrogen or 19.2slm air. The exit diameter of plasma nozzle is chosen of 4mm. Coal is transported by 16.2slm nitrogen flow and injected through two orifices in perpendicular to the plasma flow at 5mm from the exit of the nozzle. Supplied coal is 30 ~ 50g/min. Combustion air is supplied with 45 degree to the axis through the ring nozzle of the flange. The inner diameter of this section is 40mm. Stoichiometric flow rates of air for combustion are 7.17l/g , 7.35l/g and 7.54l/g for high, medium and low volatile matter coal, respectively.

3. Results and Discussion
The photo of air plasma jet is presented in Fig.3, while the volt-ampere characteristics of nitrogen and air discharges are shown in Fig.4. The discharge voltage of air plasma is higher than that of N₂ plasma under the same current and thus air plasma is more effective for input of power.

![Fig.3 Plasma jet of 9.6 slm of air.](image1)

![Fig.4 Volt-ampere characteristics of plasma torch.](image2)

Both combustion air and input power are important for coal combustion. The result of ignition experiments under various conditions is shown in Fig.5, in which N₂ plasma is used with the high volatile matter coal. Here, Q\text{plasma}, Q\text{supplied coal}, \text{Air}_{\text{supplied}} and \text{Air}_{\text{stoichiometry}} stand for plasma input power, total power of supplied coal, supplied air flow rate and stoichiometric air flow rate for the supplied coal, respectively. In the shadowed area, it is impossible to ignite and burn a pulverized coal.

![Fig.5 Ignition condition of high volatile material coal with N₂ plasma.](image3)

![Fig.6 Minimal condition for ignition of coal.](image4)

Figure 6 shows the minimal condition for ignition of the coal. Air plasma needs less input power for the ignition and the coal combustion is more stable for all types of coal. The power from the coal combustion with air of plasma gas is estimated about 1kW at the maximum, which is comparable to 30% of minimum input power for ignition. This result indicates that combustion effect with coal and plasma gas contributes to the ignition. Although air plasma has good influence for pulverized coal combustion, it is expected that NO\textsubscript{x} generation increases. However, as shown in Fig.7, it is confirmed that NO\textsubscript{x} generation is not enhanced by air plasma after establishing the stable combustion, while NO\textsubscript{x} concentration at the beginning of coal supply indeed has tendency to be higher compared to the case with N₂ plasma.
Fig. 7 Dependence of NO$_x$ concentration in the case of medium volatile matter coal.

4. **Computer Simulation of Yield of Volatile Matter for Medium Volatile Coal**

For computer simulation of the process of pulverized coal volatilization, there were developed one-dimensional models and corresponding software. At developing the model we used the approach proposed in [1, 2]. The limitations of the model are following: (1) the process of combustion is not considered; (2) the outlet of volatile components as well as their heating to the temperature of gas mixture are taken into account; (3) the work of friction force on wall and pressure in the equation of total energy are omitted. The model is based on the following equations:

- conservation of total mass, momentum and energy of heterogeneous flow

\[
\frac{d}{dx} \left( \sum \rho_x w_x + \sum_l \rho_{pl} w_{pl} \right) = 0, \quad \frac{d}{dx} \left( \sum \rho_x w_x^2 + \sum_l \rho_{pl} w_{pl}^2 \right) = -S \frac{dP}{dx} - \delta D_x,
\]

- concentration of coal particles of $l$-group, and their momentum and energy

\[
\frac{d}{dz} \left( N_{pl} w_{pl} S \right) = 0, \quad \frac{d{w}_{pl}}{dx} = m_{pl} C_n \frac{\rho_x (w_x - w_{pl})}{2} + m_{pl} C_n E,
\]

\[
\begin{align*}
\frac{dT_{pl}}{dx} &= 4 \delta R_{pl} \left[ \kappa (T_x - T_{pl}) + \varepsilon (T_x^4 - T_{pl}^4) \right] + \frac{4}{3} \delta R_{pl} \sum \left( Q_{pl} - P_{pl} \right), \quad 1 \leq l \leq N;
\end{align*}
\]

- gas mixture state and conservation of $i$-components of volatile matter in gas flow and inside particles of $l$-group

\[
P = R \delta \sum \kappa_i \frac{d}{dx} \left( S C_i w_x \right) = S f_i, \quad \frac{d}{dx} \left( S C_i w_{pl} \right) = S f_i, \quad 1 \leq i \leq m, \quad 1 \leq l \leq N;
\]

- current content of $i$-components of volatile matter inside particles of $l$-group

\[
\frac{dC_i}{dt} = f_i - f_i A \exp \left( -E_i / R_x T_{pl} \right),
\]

where $\rho$, $w$, $c$, $T$, $h$ are the density, axial velocity, heat capacity at constant pressure, temperature and specific enthalpy, respectively; $P$, $D$ and $S$ are local pressure, diameter and area of reactor channel; $R$, $N$ are radius and number concentration of coal particles; the main subscripts 'g', 'p' and 'v' correspond to gas mixture, coal particles and reactor wall. The kinetic constants $A$, $E_i$, $Q_i$ characterizing yield of different components of volatile matter and chemical heat were computed according to [1, 2].
Above equations were transformed to corresponding system of equations for derivatives of all unknown variables. The Nusselt number determining heat transfer of gas flow to the wall of channel is evaluated in accordance with dependence \( \text{Nu} = 0.019 \text{Re}^{0.8} \), where Reynolds number \( \text{Re} = 4G_v / (\delta D \mu) \). The density of heat flux into the reactor wall for the correlation used is equal to \( q_a = \lambda_x \text{Nu}[h_v - h_u] / D \).

Assuming the main flow with rate \( G_j \) and power \( P_j \) and gas flow \( G_v \) carrying particles to be mixed instantaneously, it is possible to compute initial temperature and velocity of resultant flow. To carry out this operation the following equation of conservation of total energy flux is solved for parameters of resultant flow \( \rho, T, \omega \): 

\[
P_j + G_v (G_j^2 / 2 \rho_j^2 + h_j) = (G_j + G_v) [(G_j + G_v)^2 / 2 \rho^2 + h(\rho)]
\]

In Figure 7 there are presented the results of computing the process of thermal chemical preparation of medium volatile matter coal in air plasma flow. As seen from Fig. 7, b, only 1st and 2nd groups of coal particles are completely lost the volatile matter.

![Fig. 7 Process of yield of volatile matter for medium volatile coal in air plasma jet (P=3 kW, efficiency \( \eta \) 75\%, flow rate of working gas \( G_{\text{plasma}} \)=0.4 g/s, flow rate of coal dust \( G_{\text{coal}} \)=1 g/s, distance from coal injection and its meeting with secondary air \( L=0.07 \text{ m} \))](image)

(a) - total loss of mass by coal (solid curve) and corresponding increasing the flow rate of gas mixture along x-axis (pointed curve); (b) - temperature of gas flow (pointed curve) and coal dust (divided on 5 group in size: 5 \( \mu \text{m} \) (27.3\%); 15 \( \mu \text{m} \) (18.8\%); 30 \( \mu \text{m} \) (27.8\%); 51.5 \( \mu \text{m} \) (16.6\%); 84.5 \( \mu \text{m} \) (9.5\%)), (solid curves); (c) - corresponding curves characterizing velocity of gas flow (pointed curve) and 5 groups of coal particles (solid curves).

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**References**
