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Experimental and modelling study on char combustion and gasification at high temperature in a single particle combustor

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1. Introduction

Denmark is making an effort to create an energy system without dependent on fossil energy (e.g. coal) in 2050, and biomass is promoted as an alternative to fossil fuels. In a pulverized biomass combustor, char oxidation and char gasification with H₂O and CO₂ may occur simultaneously [1]. It was found that the heterogeneous char reactions and the CO oxidation in the particle boundary layer influenced significantly the conversion time of coal char particles [2,3]. However, the effect of these reactions on the conversion of millimeter-sized biomass char particles under pulverized fuel combustion conditions has not been studied systematically through experiments and modelling.

The present work aims at developing and validating a comprehensive progressive char conversion model for biomass char under pulverized fuel combustor conditions. Experiments of spherical wood char particles were conducted in a single particle combustor under different temperature and gas atmosphere conditions.

2. Experiments

A single particle combustor (SPC) was designed for combustion studies of fuel particles with local conditions similar to the conditions in pulverized fuel fired boilers. The spherical pine and beech wood particles were selected as the raw material in the experiments. The particle diameters of pine and beech wood particle are 4.00 mm and 4.13 mm, respectively. Table 1 shows the operating conditions of single particle combustion experiments, a low temperature (1208~1221°C) and a high temperature (1357~1449°C) with the corresponding O₂ concentrations of 0.0%, 4.4%, and 10.5%. The H₂O concentration is about 25% to 40%. The averaged gas velocity in the SPC under different operational conditions is shown in Table 1.

The biomass particles taken out at the moment when the flame of volatiles extinguished are considered as initial biomass char particles, and then the mass is measured to estimate the char yield. The char conversion process was recorded by a video camera. The period from the moment when the flame of volatiles extinction is extinguished to the moment when there is only ash remained is defined as char conversion time. The shrinkage during biomass devolatilization is assumed to be 0.2, as compared to apparent wood particles.
Table 1. Operating conditions of the single particle combustor

<table>
<thead>
<tr>
<th>Operating conditions</th>
<th>Measured gas temperature (℃)</th>
<th>gas velocity (m/s)</th>
<th>O₂ concentration (wet basis, vol%)</th>
<th>H₂O concentration (vol%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0% O₂ / 1221 ℃</td>
<td>1221</td>
<td>1.49</td>
<td>0.0</td>
<td>26.8</td>
</tr>
<tr>
<td>4.4% O₂ / 1208 ℃</td>
<td>1208</td>
<td>1.43</td>
<td>4.4</td>
<td>25.7</td>
</tr>
<tr>
<td>10.5% O₂ / 1211 ℃</td>
<td>1211</td>
<td>1.51</td>
<td>10.4</td>
<td>24.9</td>
</tr>
<tr>
<td>0.0% O₂ / 1357 ℃</td>
<td>1357</td>
<td>1.50</td>
<td>0.0</td>
<td>39.7</td>
</tr>
<tr>
<td>4.4%O₂/ 1449 ℃</td>
<td>1449</td>
<td>1.50</td>
<td>4.5</td>
<td>39.0</td>
</tr>
<tr>
<td>10.5%O₂/ 1429 ℃</td>
<td>1429</td>
<td>1.44</td>
<td>10.6</td>
<td>41.8</td>
</tr>
</tbody>
</table>

3. Model description

The single particle describes the combustion (Char-O₂) and gasification (Char-H₂O and Char-CO₂) occurring inside the char particle, and the gas phase reactions (CO oxidation, H₂ combustion, and water gas shift reaction) occurring in the particle boundary layer. The external and internal heat and mass transfer, and particle shrinkage are taken into consideration in the model. The governing equations for species transport and heat transport follow Fick’s law and Fourier’s law, respectively. The effect of Stefan flow on mass and heat transfer is neglected. The specific surface area for the wood char particle is assumed to be a constant of 1.0x10⁶ m²/m³ during char conversion. The shrinkage of a char particle is modelled by assuming ash peel off when the char conversion is over 0.95. Since the mass transfer boundary thickness of each species is different, and they are also not the same to heat transfer boundary thickness, the boundary layer thickness is determined by taking an average of those boundary thickness. The combustion and gasification kinetics of the pine wood char is obtained from a reference [4]. The combustion and gasification kinetics of beech wood char is obtained from reference [5] and [6], respectively. The CO/CO₂ ratio of char oxidation depends on the temperature and oxygen concentration and is calculated by following Tognotti et al. [7]. The homogenous reaction kinetics is from reference [8].

4. Results and discussion

It was reported that the char particle density has significant effects on char conversion time [9], the computed and measured char conversion time is also compared on the basis of char particle density. Fig. 1 (a) ~ (d) show the computed and measured char conversion time of the pine and beech wood char particles gasified and combusted at different temperature (1208~1449℃), H₂O concentration (24.9~41.8%) and O₂ concentration (0.0~10.5%). The measured char conversion times scatter a lot for the case of gasification (0.0% O₂), while the repetition of the experiments with the presence of O₂ is much better. The probable reason is that a small fluctuation of O₂ concentration can lead to significantly different char conversion time for the gasification case. The computed char conversion times are in good agreement with the experimental data for the cases with the presence of O₂. Since the beech wood (1700 mg/kg) particle has much higher potassium than that of pine (150 mg/kg), a shorter char conversion time of beech wood char particles was predicted by both experiments and modelling under same conditions. The contribution of H₂O gasification on total char conversion is about 30% at a low temperature conditions (1208 ℃, 4.4% O₂ and 25.7% H₂O), while, it is about 70% at a high temperature conditions (1449 ℃, 4.4% O₂ and 39.0% H₂O), indicating the operating conditions has significant effects on products distribution.
Figure 1. The computed and experimental char conversion time of the pine and beech wood char particles under different conditions

Fig. 2 show the computed and experimental particle size evolution of the pine and beech wood char particles. It shows that the computed particle size evolutions are in good agreement with the experimental data with the presence of O$_2$ for both pine and beech wood char particles. However, a significant difference between the experimental and modelling results is observed for the case of gasification (0.0% O$_2$). A probable reason is that the assumption of ash peels off immediately once the char conversion reaches 0.95 is not suit the case of gasification. The char particle collapse may occur during char conversion, since it occurs throughout the particle.
5. Conclusion

Combustion and gasification experiments of ~4 mm pine and beech wood particles have been carried out in a single particle combustor under conditions of 1200~1450℃, 0.0~10.6 vol% O₂, and 25~42 vol% H₂O. A comprehensive char conversion model, including heterogeneous char oxidation and char gasification with CO₂ and H₂O, gas phase reactions (CO oxidation, water-gas shift reaction, and H₂ oxidation) in the particle boundary layer, particle shrinkage, and external and internal heat and mass transfer, has been developed to model the experiments. The predicted char conversion time and particle size evolution are in good agreement with both experimental char conversion time and particle size evolution for the cases with the presence of oxygen. However, for the experiments without the presence of oxygen, conversion time and the particle size evolution were not well predicted by current char combustion model. The char oxidation is limited by intra-particle and external mass transfer, while the H₂O and CO₂ gasification are dominated by both mass transfer and gasification kinetics. The contribution of gasification and oxidation on total char conversion is mainly depends on the operating conditions (e.g. O₂ concentration, temperature, slip velocity) and particle size.

References