Numerical simulation and optimization design of 200MWe tangentially coal-fired boiler

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Outline

- Background
- Numerical simulation of 200MWe tangentially boiler
- Results of optimum programs
- Conclusion
1. Background
Research on the oxy-fuel combustion

Oxy-fuel combustion in coal-fired plants has become one of the most promising technologies for carbon capture and storage.

Experimental study

- Fundamental research
- Pilot-scale commission

Numerical simulation

- Verify the applicability of the model
- Predict the results of innovative design
- Performance evaluation
For large-scale coal fired boiler, there are some challenges to operate, such as: the temperature deviation, risk of slagging, and combustion efficiency.

It is necessary to research the operation principle in large-scale oxy-fuel combustion.
2. Numerical simulation of 200MWe tangentially boiler
• 13 burner nozzles: 5 primary air, 5 secondary air, 1 cooling air and 2 over fire air.
• The OFA is injected into the furnace with a contrary tangent of 15 direction to the primary air.
• Four groups of front superheaters and some rear superheaters are installed in the upper furnace.
• Select two lines and one plane in upper furnace and furnace exit
Mesh system and Numerical model

- Turbulence: Realizable k-ε
- Radiation: Modified WSGG model
- Devolatilization: CPD model
- Volatile combustion: EDC and modified JL 4-step mechanism
- Char combustion: kinetics/diffusion-limited

- 1.3 million cells
- the maximum skewness value is 0.69
- The radiation model and gas reaction mechanism have been modified in oxy combustion
- These models have been verified in previous works.
Ultimate analysis (wt %)

<table>
<thead>
<tr>
<th>Ultimate analysis</th>
<th>(wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>58.99</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>3.57</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.80</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.53</td>
</tr>
<tr>
<td>Oxygen</td>
<td>8.64</td>
</tr>
</tbody>
</table>

Proximate analysis (wt %)

<table>
<thead>
<tr>
<th>Proximate analysis</th>
<th>(wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash</td>
<td>16.97</td>
</tr>
<tr>
<td>Moisture</td>
<td>10.50</td>
</tr>
<tr>
<td>Volatile matter</td>
<td>27.93</td>
</tr>
<tr>
<td>Fixed carbon</td>
<td>44.60</td>
</tr>
<tr>
<td>Lower heating value (MJ/kg)</td>
<td>22.21</td>
</tr>
</tbody>
</table>

Shenhua bituminous coal, ignites easily, with medium moisture and ash content.

Compatibility operation principle:
- 1) Premixed combustion
- 2) The O₂ concentration in primary air is no more than 18%
- 3) The OFA nozzles is switched off in oxy-fuel combustion
- 4) In oxy-fuel combustion, the primary air momentum matches with that in air combustion.
Typical result

The flue gas mass-averaged temperature (K) profiles of the horizontal section along the height of the furnace from the hopper to superheater.

- In oxy-fuel combustion, flame center is the same with air-fired, but the peak temperature decreased; The similar total heat transfer can be achieved by adjusting the oxygen concentration in oxidant.
• O29, which has a high oxygen concentration in oxidant. The oxidant volume decreases a lot. So the volume of secondary air will decrease too much. The low bottom secondary air momentum has insufficient capacity to lift the torch.

• Due to the OFA nozzles is switched off in oxy-fuel combustion, there was a large temperature deviation in upper furnace. This was mainly caused by the gas residual swirl at the furnace exit.
Optimum program

Program one:
the high CO concentration in hopper

• Define momentum-flux ratio of bottom secondary air to primary air: $B_{MR}$

$$B_{MR} = \frac{\sum (mv)_{bsa}}{\sum (mv)_{bpa}}$$

<table>
<thead>
<tr>
<th>Case</th>
<th>$B_{MR}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>2.1</td>
</tr>
<tr>
<td>O29</td>
<td>1.8</td>
</tr>
<tr>
<td>Case 1 (O29_1.9)</td>
<td>1.9</td>
</tr>
<tr>
<td>Case 2 (O29_2.0)</td>
<td>2.0</td>
</tr>
<tr>
<td>Case 3 (O29_2.1)</td>
<td>2.1</td>
</tr>
<tr>
<td>Case 4 (O29_2.2)</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Program two:
the gas temperature deviation

• Opposing tangential primary air technology: The ratio of opposing tangential momentum moment (Primary air) to the tangential jets (Secondary air): $XJ$

$$XJ = \frac{\sum (mvR)_{ot}}{\sum (mvR)_T}$$

<table>
<thead>
<tr>
<th>Origin design</th>
<th>Case 1 (Pa_3)</th>
<th>Case 2 (Pa_5)</th>
<th>Case 3 (Pa_7)</th>
<th>Case 4 (Pa_9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle</td>
<td>0</td>
<td>3</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Air</td>
<td>0</td>
<td>0.23</td>
<td>0.67</td>
<td>1.09</td>
</tr>
<tr>
<td>O23</td>
<td>0.11</td>
<td>0.32</td>
<td>0.52</td>
<td>0.76</td>
</tr>
<tr>
<td>O26</td>
<td>0.17</td>
<td>0.49</td>
<td>0.79</td>
<td>1.15</td>
</tr>
<tr>
<td>O29</td>
<td>0.25</td>
<td>0.73</td>
<td>1.19</td>
<td>1.74</td>
</tr>
</tbody>
</table>
3. Results of optimum programs
When the $B_{MR}$ improves to the value at Air, the CO concentration in the hopper significantly reduced.

The heat transfer of membrane wall will slightly increase with the increase of $B_{MR}$.

As long as $B_{MR}$ does not exceed the value at Air, the heat transfer of the superheater is unchanged.

So, the ratio $B_{MR}$ should not less than the set point.
Results of the program two (1/3)

The gas temperature deviation in upper furnace is mainly caused by the residual swirl at the furnace exit (P1).

Define the strength of swirling vortex: \( \Delta \)

\[
\Delta = p^2 - 4q = (\text{trace}G)^2 - 4\text{det}(G) \\
= (\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y})^2 - 4\left(\frac{\partial U}{\partial X} \cdot \frac{\partial V}{\partial Y} - \frac{\partial U}{\partial Y} \cdot \frac{\partial V}{\partial X}\right)
\]

- Compared to Origin design, the maximum \( \Delta \) decreases about 30-40\% in Case 2 and Case 3.
- Noteworthy, the direction of rotation in Case 4 reverses, due to \( XJ>1 \).
Results of the program two (2/3)

- The temperature deviation will decrease with the increase of XJ value;
- Case 2, 3 and 4 have a better prediction results of temperature in upper furnace (L1).
- Compared to Origin design, the burn-out ratio of Case 1, 2, 3 keep unchanged, but Case 4 decrease, due to $XJ > 1$.
- So, the case 2, 3 are the better case.
The mole fraction of CO on the wall decreases about 20% in case 3, so it reduces the risk of slagging by weakening the reducing atmosphere near the wall;

In contrary, the CO concentration increase in case 4, and the oxygen decrease, because the direction of rotation is changed;

In all cases, the net heat flux on the wall is unchanged;

In consideration of a broader scope, we recommend the opposing angle is about 5°.
4. Conclusion
Conclusion

Focus on the momentum-flux moment ratio of bottom secondary to primary air and opposing tangential primary air technology, we obtain two optimization in oxy-fuel combustion:

• Ensure the ability of bottom secondary air to lift the torch
  — Ensure the momentum-flux ratio of bottom secondary to primary air is not less than the design values for air combustion.
  — The momentum-flux ratio is 2.1 in this boiler.

• The opposing tangential primary air technology can reduce the gas temperature deviation in upper furnace
  — This technology can also reduce the risk of slagging by weakening the reducing atmosphere near the wall
  — Opposing tangential angle depends on the ratio of opposing tangential momentum moment $X_J$, and the value of $X_J$ cannot greater than 1.
  — The recommended angle of this boiler is $5^\circ$. 
Acknowledgement

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Thank you for your attention!