Flow Field Characteristics in the Combustion Space of a Float Glass Furnace with Co-combustion of Heavy Oil and Petroleum Coke

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Abstract. A numerical simulation was carried out for the combustion space of a float glass furnace in which the heavy oil and petroleum coke were co-fired. The characteristics of gas flow in the combustion space and its influence on the temperature distribution were analyzed. The research shows that after the combustion air coming from inlet 2 to inlet 6 respectively enters the flame space, it flows toward the outlet, and forms a relatively straight “flame” after the fuel is completely burned, eventually forming five high-temperature zones with wide coverage; when the flue gas generated by the combustion reaches the outlet, a part of the flue gas from inlet 2 to inlet 4 is deflected to the left, and a recirculation zone is formed above the batch material zone at the left end, and the O₂ is diluted, so that the fuel at No. 2 zone is not sufficiently burned, resulting in a temperature region being significantly lower than other regions; A part of the flue gas at No. 5 and No. 6 is deflected to the right, forming a recirculation zone above the clarification zone at the right end, so that the combustion at No. 7 is insufficient, resulting in a lower temperature zone at that place, but the influence is weaker than that at No. 1, so the temperature peak at No. 7 is slightly higher than that at No. 1.

1. Introduction
Most float glass furnaces use heavy oil as fuel, but because of the high cost of heavy oil, some glass factories choose to organize combustion by co-firing of heavy oil and petroleum coke, in order to promote rapid ignition and full combustion of petroleum coke using the characteristics of fast burning of heavy oil. Because the combustion characteristics of heavy oil and petroleum coke are quite different, in order to ensure the stability of the temperature field, it is necessary to have a comprehensive understanding of the gas flow pattern and temperature distribution characteristics in the combustion space of the float glass furnace where heavy oil and petroleum coke are used for co-combustion. Since the combustion space of the float glass furnace is a high temperature gas-liquid/solid reactor, the reaction process in the furnace cannot be known by conventional cold mold experiments. At present, most of the research on related problems is carried out by numerical simulation, which has become an indispensable engineering technical means in the research and optimization design of glass furnace thermal process [1-3]. Based on the research results of our research group [4,5], using the internationally widely used CFD commercial software ANSYS Fluent, a numerical simulation was carried out for the combustion space of a float glass furnace in which heavy oil and petroleum coke are co-fired. The gas flow pattern and its influence on the temperature...
distribution were analyzed. The research results can provide theoretical guidance for understanding the gas flow characteristics in the combustion space of the float glass furnace with co-combustion of heavy oil and petroleum coke.

2. Geometry Model and Mesh
The geometric model of the combustion space of the float glass furnace is shown in Figure 1. There are 7 pairs of inlets and outlets; the combustion air enters the combustion space from each inlet and reacts with the fuel, and the generated flue gas escapes from the opposite outlet; the fuel spray gun is located on the breast wall below the inlet; the glass liquid is at the bottom and the crown is at the top. The model was meshed with a high-quality hexahedral mesh, and the combustion regions corresponding to each pair of inlets and outlets were mesh-encrypted, as shown in Figure 2.

![Figure 1. Structure.](image)

![Figure 2. Mesh.](image)

3. Mathematical Models
In the combustion space of the float glass furnace, there are several processes of gas phase flow, gas liquid (heavy oil) / gas solid multiphase flow, heavy oil / petroleum coke combustion and heat transfer. Using ANSYS Fluent software, Realizable k-ε turbulence model, discrete phase model, non-premixed combustion model and DO radiation model were used for numerical simulation.

4. Boundary Conditions and Numerical Solution Method

4.1. Boundary Conditions
The boundary conditions and initial conditions were set based on the actual working conditions, wherein the velocity and temperature (the air temperature is 1570K) was specified at the inlet, the pressure was at an ambient atmosphere at the outlet, and the bottom glass liquid surface, the breast wall and the crown were set as the wall boundary with the usual non-slip conditions applied.

The fuel is heavy oil and petroleum coke, and the calorific values are 3.8*10^7 J/kg and 3.55*10^7 J/kg, respectively. Three spray guns are located under the inlets 1 to 6. The heavy oil spray gun is located in the middle, with petroleum coke spray guns on both sides, and there are only two heavy oil spray guns under No. 7 inlet. The fuel distribution ratio is shown in Table 1. The industrial analysis of petroleum coke is shown in Table 2. The elemental analysis of heavy oil and petroleum coke is shown in Table 3.

| Inlet number | #1 | #2 | #3 | #4 | #5 | #6 | #7 |
|--------------|----|----|----|----|----|----|----|
| Fuel distribution ratio | 14 | 14 | 15.5 | 15.5 | 18 | 16 | 7 |
| Number of fuel spray guns | 3 | 3 | 3 | 3 | 3 | 2 | 

Table 1. Fuel distribution ratio.

| M | A | V | FC |
|---|---|---|----|
| 0.85 | 0.4 | 9.91 | 88.83 |

Table 2. Proximate analysis of petroleum coke.
Table 3. Ultimate analysis of heavy oil and petroleum coke.

| Sample            | Mole Fractions/% |
|-------------------|------------------|
|                   | C    | H    | O    | N    |
| Heavy oil         | 85.20 | 12.00 | 1.40 | 1.10 |
| Petroleum coke    | 88.95 | 3.18  | 4.89 | 1.94 |

4.2. Numerical Solution Method

The SIMPLE algorithm was used to correct the pressure field. The pressure term was solved using the STANDARD discrete format, and the other items were solved using the second-order upwind style. The convergence criterion is that the energy term is less than $1 \times 10^{-6}$, and the remaining items are less than $1 \times 10^{-3}$.

5. Results Verification

Table 4 lists the breast wall temperature values at flue gas outlet. It can be seen that the simulation results are consistent with the actual measured values, indicating the rationality of the simulation results.

Table 4. The breast wall temperature values at flue gas outlet (K).

| Measuring point | Point 1 | Point 2 | Point 3 | Point 4 | Point 5 | Point 6 | Point 7 |
|-----------------|---------|---------|---------|---------|---------|---------|---------|
| Predicated value| 1703    | 1738    | 1798    | 1828    | 1843    | 1816    | 1800    |
| Measured value  | 1687    | 1747    | 1789    | 1818    | 1830    | 1810    | 1780    |

6. Results and Discussions

Figure 3 shows the temperature contour map on the cross section of the fuel injection. It can be seen from Fig. 3 that the combustion air enters the flame space from each inlet, and then burns with the corresponding fuel, forming seven relatively independent high temperature zones, wherein the high temperature zone corresponding to No. 2 to No. 6 covers a large area, and the coverage area of the high temperature zone corresponding to No. 1 and No. 7 is much smaller. Usually this is related to the fuel distribution ratio below each inlet. As shown in Table 1, the amount of fuel below No. 1 and No. 7 is small, so that the coverage area of the high temperature zone generated by combustion is relatively small. However, although the fuel distribution corresponding to No. 2 and No. 1 is the same, the coverage area of the high temperature zone generated by the combustion of the fuel at No. 2 is much larger than that at No. 1. This indicates that the combustion conditions of the fuels at No. 1 and No. 2 are very different. In order to find out the cause of the difference, we should start from the source, that is, the flow pattern of the airflow.

Figure 3. Temperatures contour map on the cross section of the fuel injection.
Figure 4 shows the velocity vector on the cross section of the fuel injection. It can be seen from Fig. 4 that the main flow direction of the airflow is from the inlet of each airflow to the opposite flue gas outlet, wherein the airflow direction from No. 3 to No. 5 is relatively straight, pointing straight to the opposite outlet; the airflow at No. 2 is slightly oriented to the right, this is because the airflow at No. 1 is “squeezed” to the right; similarly, the airflow at No. 6 is slightly to the left, because the airflow at No. 7 is “squeezed” to the left. The flow direction of the airflow at No. 1 is more complicated, some airflows are skewed to the right, and some first turn to the right and then to the left when moving to the outlet; the airflow at No. 7 is relatively thin, and the whole airflow is first to the left, when it is close to the exit, part of it is rightward.

The flow path of the airflow at each inlet corresponds to the distribution characteristics of the high temperature zone formed by the corresponding fuel combustion (see Figure 3).

![Figure 4. Velocity vector on the cross section of the fuel injection.](image)

In order to further ascertain the flow characteristics of the airflow at each inlet, the streamlines of combustion air were displayed, as shown in Figure 5. It can be seen from Fig. 5 that after the combustion air enters the combustion space from each inlet, the main flow direction is from the inlet to the opposite outlet. However, due to the presence of the left batch material area and the right clarification area of the glass tank, the airflow of each stream is selectively deflected. Among them, the airflows of No. 1, No. 2, No. 3 and No. 4 are shifted to the left, and the airflows of No. 5, No. 6, and No. 7 are shifted to the right, and finally, two large recirculation zones are formed in the space above the left batch material and the space above the right clarification zone.

![Figure 5. Streamlines of combustion air.](image)

![Figure 6. Iso-surface of CO concentration of 0.03 colored by temperature.](image)
Different forms of airflow result in different fuel combustion conditions. Figure 6 is the iso-surface of CO concentration of 0.03 colored by temperature, which can reflect the "flame" shape. Fig. 7 and Fig. 8 respectively shows the average component concentration curves and the average temperature curve along the furnace length direction. It can be seen from Figure 6 that the shape of the "flame" produced by the combustion of the fuel below No. 2 to No. 6 inlet is similar, forming three separate and connected "flames". The middle flame is produced by the burning of heavy oil, the flames on both sides are produced by the burning of petroleum coke, and the peak temperature zones are located at the front end of the "flame"; The "flame" formed by the three fuels at No. 1 and the two fuels at No. 7 are connected together. There is no obvious boundary between the flames, and the temperature at the high temperature zone of the flame is lower than the value at No. 2 to No. 6. The "flame" at No. 7 is very long. Combined with the average concentration curves of CO and O₂ in Figure 7, the CO concentration values at No. 1 and No. 7 are relatively high, while the O₂ concentration is very low, indicating that at these two places, the fuel is not burned enough, so that the temperature peaks corresponding to the two places are much lower than the other five (see Figure 8). Observing the average concentration curve of CO₂ in Figure 7, it can be seen that the CO₂ concentration is the lowest at No. 4. From No. 4 to No. 1 and from No. 4 to No. 7, the CO₂ concentration values are on the rise. This is because part of the flue gas rich in CO₂ coming from No.4 to No.1 flows to the left to form a recirculation, and part of the flue gas rich in CO₂ from No.5 to No.7 flows to the right to form a recirculation (see Figure 5). A large amount of reflux flue gas dilutes O₂, causing the fuel at No. 1 to be in an anaerobic combustion state, which causes it to burn very poorly, eventually resulting in a temperature region significantly lower than elsewhere. The fuel at No. 7 was similarly affected, but because the area of the right-end clarification area is large, the impact is weaker than that at No. 1, so the average temperature of the airflow at No. 7 is slightly higher than that at No. 1.

![Figure 7. Average component concentration curves along furnace length direction](image1)

![Figure 8. Average temperature curve along furnace length direction](image2)

7. Conclusions
After the combustion air enters the combustion space from each inlet, it flows toward the opposite flue gas outlet and mixes with the fuel under the inlet to form a relatively straight "flame", which finally forms seven high-temperature areas with wide coverage area from No. 2 to No. 6 and with narrow coverage area at No. 1 and No. 7. When a large amount of flue gas generated by the combustion reaches the vicinity of the outlet, part of the flue gas escapes directly at the outlet, and another part of the flue gas deflects after hitting the wall near the flue gas outlet. The flue gas from No. 4 to No. 1 is deflected to the left, and a recirculation zone is formed above the batch at the left end, resulting in insufficient combustion at No. 1 where the temperature is significantly lower than other places. The flue gases from No. 5 to No. 7 are deflected to the right, forming a recirculation zone above the clarification zone at the right end, and affecting the flow direction and the combustion process of the
fuel at No. 7, making the temperature at that place lower, but the impact on No. 7 is weaker than that on No. 1, so the temperature at No. 7 is slightly higher than that at No. 1.

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