Analysis of Numerical Simulation on Combustion of Different Fuels in Float Glass Furnace

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Abstract. The feasibility and reliability of numerical simulation model and calculation method are verified by comparing the simulation results with the relevant data collected during the operation of the furnace in the actual plant. Under the condition of constant thermal power of the furnace, the combustion status, temperature distribution and nitrogen oxides formation in combustion space of the furnace are simulated and studied when the fuel is heavy oil and petroleum coke respectively. The study found that large-scale transverse circumfluence is formed in the refining zone in the back of the furnace and the temperature system is stable and consistent whether the fuel is heavy oil or petroleum coke. When the fuel is petroleum coke, the combustion in the furnace is more intense and the temperature of the batch is higher, but the crown is eroded more strongly by high temperature flow. When the fuel is heavy oil, the scope of the high temperature zone whose temperature is higher than 2073K is wider, and the temperature of the glass level and the crown in the furnace is slightly higher, but the production of nitrogen oxides with burning heavy oil is much more than that of burning petroleum coke.

1. Introduction
Float glass manufacturing is a high energy consumption industry, which consumes a lot of fuel in the production process. In order to ensure the cleanliness of glass metal and the whiteness of glass, heavy oil with low ash and high calorific value as the main heating fuel was used in most glass furnaces. However, the high cost of fuel in glass industry has become a bottleneck problem restricting the development of flat glass enterprises. In order to reduce the cost of fuel, glass enterprises have been looking for cheap alternative fuels. Petroleum coke which is the final by-product of petroleum refining has the characteristics of low ash, low volatile, high carbon and high calorific value and its calorific value is close to that of heavy oil, with abundant output and low price. The superiority of petroleum coke in replacing oil fuel has entered the research field of glass enterprises[1-3].

As for the applicability of petroleum coke in glass furnace, the possibility of replacing heavy oil with petroleum coke in glass furnace has been discussed and confirmed by predecessors. In view of practical application, the problem of difficult ignition and burnout of petroleum coke by high temperature air combustion or oxygen-enriched combustion has been put forward. For the mixed combustion of two fuels, the ignition, combustion and burnout characteristics of semi-coke blended pulverized coal combustion under MILD combustion mode were studied by numerical simulation [4]. And the mixed combustion of RDF fuel instead of pulverized coal in cement calciner has also been studied[5]. The selection of mathematical models related to the numerical simulation of glass furnace and the simulation of heat transfer in the furnace have also been reported[6-10].

The combustion characteristics of heavy oil and petroleum coke are quite different. Most studies focus on the combustion and pyrolysis mechanism of different fuels in terms of their thermodynamics and combustion kinetics[11]. In order to expand the application range of petroleum coke and ensure...
the stability of temperature system in glass furnace. The aim of this research is to reveal the difference in combustion, heat transfer and pollutant generation of heavy oil which is a common fuel and petroleum coke which is an economical and promising fuel in float glass furnace by numerical simulation. The results obtained in this study will not only provide important theoretical guidance for optimizing the operation parameters of glass furnace, but will also lay a foundation for further research on gradient combustion of multi-fuel.

2. Geometrical Model

Figure 1 presents the structure and mesh of combustion space of float glass furnace. From figure 1(a) we can see that there are seven pairs of ports, because of the symmetrical structure of the float glass furnace, the combustion is reversed every 20 minutes. When the fuel is burned in one side of the ports, the other side of ports are outlets of flue gas. The combustion space of glass furnace is 39.6m long, 12.3m wide with arc-shaped crown. The spacing of each pair of port is 3.3 meters, The ports of No.1 to No.6 have the same width with 2m, but the width of No.7 port is 1.2m. In addition, three burners are installed under each port except the No.7 port with two burners. Figure 1 (b) shows the mesh of combustion space of glass furnace, with three-dimensional high-quality structured hexahedral mesh.

3. Mathematical Model and Numerical Solution Method

3.1. Mathematical Model and Numerical Scheme

A numerical simulation was carried out using the widely used ANSYS Fluent computational-fluid-dynamics software tool. The following mathematical models are used for the physical and chemical processes in the combustion space of glass furnace.

The standard k-ε model is used for reflecting turbulent flow. To account for the wall effect in the nearby regions, the wall function was introduced to link velocities in the near-wall region. The discrete phase model (DPM) is used for tracking petroleum coke particles and heavy oil droplets after atomization. The non-premixed combustion model is used for describing chemical reaction of combustion. The eddy dissipation EDD model is used for revealing interaction between turbulence and chemical reaction. The DO model is used for describing radiation heat transfer in combustion space, WSGGM model is used for reflecting gas radiation characteristics and gas scattering is neglected. In the algorithm. The pressure and velocity were coupled using the semi-implicit method for pressure-linked equations (SIMPLE) algorithm. In the option of discretization method, STANDARD discrete scheme is chosen for the pressure term. In addition to the first-order upwind scheme for turbulent energy and radiation, the second-order upwind scheme is chosen for the others.

3.2. Boundary Conditions

Due to the difference of calorific value between heavy oil and petroleum coke, the total heat of fuel combustion is consistent when simulating the combustion of different fuels in glass furnace. The calorific value of heavy oil is about 9600 kcal and that of petroleum coke is about 8500 kcal. The consumption of two kinds of fuels can be calculated according to the heat consumption of float glass products. In view of the different combustion characteristics of heavy oil and petroleum coke, the
excess air coefficients of combustion-supporting air are also quite different when these two fuels are used in float glass furnace, but the proportions of fuels in each port are invariant with different fuels to ensure the stability of temperature system in glass furnace. According to the actual operating parameters of glass industry, the percentage of fuel allocated to each port and excess air ratio of each port with fuel of heavy oil and petroleum coke are shown in Table 1.

Table 1. Fuel percentage and excess air ratio of each port

| Port number | No.1 | No.2 | No.3 | No.4 | No.5 | No.6 | No.7 |
|-------------|------|------|------|------|------|------|------|
| Fuel percentage(%) | 14 | 14 | 15 | 16 | 18 | 16 | 7 |
| Excess air ratio of heavy oil | 1.05 | 1.05 | 1.1 | 1.12 | 1.15 | 1.19 | 1.19 |
| Excess air ratio of petroleum coke | 1.29 | 1.25 | 1.5 | 2.03 | 1.72 | 1.52 | 1.56 |

Because the amount of fuel ejected from the burners under each port is equal, combining the heat consumption of the furnace with the fuel distribution ratio in Table 1, the fuel quantity of each burner can be calculated. The particle diameters and droplet diameters were distributed according to the Rosin-Rammler distribution function. The particle temperature of the petroleum coke is 300 K and the droplet temperature of the heavy oil is 380 K.

When numerical simulation on glass furnace was carried out, setting the boundary conditions, the boundary conditions of air inlets and fuel inlets are set as the velocity inlet boundary. By means of heat engineering calculation, combined with the inlet area and excess air ratio of each port in Table 1, the velocity of combustion-supporting air flowing through each port can be calculated. The temperature of the air is 1573 K. All outlet pressures are set to 0.5Pa.

The side wall and the crown are set to heat flux boundary which is one type of the wall boundary. Considering the change regulation of molten glass in glass tank and the temperature system in furnace, the temperature distribution at the bottom of combustion space can be acquired by polynomial fitting. The function relationship between the bottom temperature of combustion space and the length of furnace is introduced into UDF of FLUENT.

4. Results and Discussion

4.1. Results Verification

Figure 2 shows the comparisons of simulated and measured temperature values of each “port leg” when fuel is petroleum coke. The simulated temperature values are close to that of measured. The maximum difference between the simulated and measured values is 10 °C. The temperature values of “port legs” are measured by infrared thermometer whose accuracy is (±2%). Therefore, the difference between the simulated and measured values is within the measurement uncertainty of the thermometer. Table 2 shows the simulated and measured values of the oxygen concentration at the outlets when fuel is petroleum coke. It can be revealed from the table that the measured values of the oxygen concentration at the outlets are slightly larger than the calculated values except for the outlet of No. 3, but the changing trends is consistent. The reason for the difference between the simulated and measured values is that the average concentration of oxygen at each outlet is taken as the surface concentration, while the measured value is sampled by infrared gas analyzer at the lower location of each outlet. It can be found that the simulation results are in good agreement with the actual measured data, which shows that the simulations were reliable.

Table 2. Simulated and measured values of oxygen concentration at each outlet with petroleum coke as fuel

| Port number | No.1 | No.2 | No.3 | No.4 | No.5 | No.6 | No.7 |
|-------------|------|------|------|------|------|------|------|
| Simulated value of oxygen concentration(%) | 4.42 | 5.83 | 7.29 | 9.45 | 8.34 | 6.86 | 6.95 |
| Measured value of oxygen concentration(%) | 4.68 | 4.21 | 7.01 | 10.68 | 8.77 | 7.19 | 7.52 |
Figure 2. Comparisons of simulated and measured temperatures of “port leg” with Petroleum Coke as Fuel

4.2. Gas Flows

Figure 3 shows streamlines pattern in combustion space of the glass furnace, showing the flow streamlines when fuel is heavy oil in Figure 3(a) and when fuel is petroleum coke in Figure 3(b). From Figure 3(a) and (b), it can be observed that large-scale circumfluence in vertical was formed on the right side of the No.7 port, whether the fuel is heavy oil or petroleum coke. The high temperature gas generated by combustion reaction has a long trajectory in the large scale circulation zone of the refining zone, which prolongs the heat exchange time between the high temperature gas at the back of the furnace and the molten glass at the bottom of the combustion space, which is beneficial to the refining of glass. Comparing the streamlines pattern, it can be found that the high temperature gas generated by burning petroleum coke shows better rigidity and an obvious circumfluence zone was formed above the batch in the front of the furnace, which strengthened melting of the batch. Not only because the combustion process of heavy oil is different from that of petroleum coke, while heavy oil enters glass furnace after atomization, was burned after dispersion and evaporation at high temperature, and mixed with high temperature combustion-supporting air. Because the excess air coefficient of heavy oil is smaller, the quality and velocity of high temperature air flow are smaller than that of petroleum coke, so high temperature flow generated by burning heavy oil shows poor rigidity. When the fuel is heavy oil, the gas flow at No.7 port deviated to the outlet of No.6 port with the impacts of the circumfluence in refining zone and entrainment from high-speed airflow injected at No.6 port.

Figure 3. Streamlines pattern in combustion space

Figure 4. Velocity vector chart in central cross section of No.5 port
Figure 4 shows velocity vector chart in central cross section of No.5 port. It can be found that transverse circumfluence is formed whether the fuel is heavy oil or petroleum coke. On the one hand, it effectively prolongs the residence time of high temperature flue gas, on the other hand, the circumfluence zone plays a role in protecting the crown. By comparing Figure 4(a) with Figure 4(b), it can be seen that the velocity of flow is higher and the crown is eroded more strongly by high temperature flow when burning petroleum coke.

4.3. Combustion and Temperature

Figure 5 presents the temperature contour over 2073K. It shows that when the fuel is heavy oil, the area higher than 2073k is larger, that is, the coverage of high temperature flow ("flame") is larger, which is conducive to the radiation heat transfer of molten glass. However the area of low temperature zone in the glass batch is smaller when the fuel is petroleum coke. The reason is that there is a circumfluence zone in the front of the glass furnace when the fuel is petroleum coke, while there is no obvious circumfluence zone when the fuel is heavy oil. The circumfluence zone obviously enhances the heat transfer and melting of the batch. There is no significant difference in the temperature distribution of the side wall.

Figure 6 shows the temperature contour in central cross sections of the No.1 to No.7 ports along the length direction (Z direction). it can be seen that the temperature distribution on central cross sections of the ports is similar, and the high temperature flow is close to the glass level, and the combustion temperature has no obvious difference. The difference is that when the fuel is petroleum coke, the combustion is more intense, and the erosion and ablation of opposite wall and crown by high temperature flow are more serious.

(a) Fuel is heavy oil

(b) Fuel is petroleum coke

Figure 5. Temperature contour over 2073 K

Figure 6. Temperature contour in central cross sections of each port

Figure 7 shows the temperature distribution of combustion zone( the region overlap with port in the direction of height) along the length direction of furnace(X Direction). Figure 8 presents the temperature distribution along the center line of glass level in the length direction of furnace(X Direction). Figure 9 presents the temperature distribution along the center line of crown in the length direction of furnace(X Direction). From Figure 7-9, it can be found that the temperature of the combustion zone is higher when the fuel is heavy oil. Because the excess air ratio is smaller and the
total volume of flue gas is smaller when the fuel is heavy oil, so the overall temperature of the gas flow is higher when the total heat is equal. The heat transfer mode in glass furnace is mainly radiation heat transfer between hot gas and glass level in combustion space, and the radiation heat is proportional to the fourth power of temperature. Therefore, when fuel is heavy oil, the temperature of the glass level and the crown are a little higher. But the temperature distribution curves of glass level and the crown are pretty nearly identical whether the fuel is heavy oil or petroleum coke. The hot spot temperature occurs in the No.4 and No.5 ports. Overall, it meets the "mountain" temperature distribution.

4.4. NOx Prediction

Table 3 shows the molar concentration of NOx and the molar fraction of oxygen in the flue gas when the fuel is heavy oil and petroleum coke respectively at the opposite outlet of each port of glass furnace. It can be found that the concentration of NOx at each outlet is much higher (mostly more than two times) when the fuel is heavy oil, while the molar fraction of oxygen at the outlet is much smaller. Considering the production of NOx, not only the molar concentration of NOx, but also the influence of excess air dilution should be considered. Therefore, the comparison should be made on the premise that the concentration of oxygen is the same. When monitoring industrial exhaust gas, the reference value of oxygen concentration is 10%. After conversion, it can be seen that the NOx concentration at the outlets of glass furnace is still higher when fuel is heavy oil. There are two main reasons for this. On the one hand, when fuel is heavy oil, the high temperature area is larger. Considering the content of N element in fuel and the temperature environment of the furnace, the NOx produced by the furnace is mainly thermodynamic NOx. The production of thermodynamic nitrogen oxides increases with the increase of temperature, and the increase is more and more large. On the other hand, it is known from the literature that the production of NOx is also related to excess air coefficient. The production of thermodynamic NOx and the variation of excess air coefficient are similar to a downward parabola. It means that the production of thermodynamic NOx is the largest when the excess air coefficient is 1, and the production of thermodynamic NOx decreases with the increase of excess air coefficient when the excess air coefficient is greater than 1, and the decline is increasing. This point can also be further
verified by the data in the Table 3. Taking the data of the production of NOx when fuel is petroleum coke as an example, the excess air coefficient increases firstly and then decreases from No.2 port to No.7 port, and the excess air coefficients of the six ports are greater than 1. The excess air coefficient of the No.4 port is the largest. It can be seen from the following Table 3 that the production of NOx decreases firstly and then increases, which is the least at the outlet of No.4 port.

Table 3. The molar concentration of NOx and the molar fraction of oxygen in the flue gas

| Outlet number | NOx/ppm | Mole fraction of O2/% |
|---------------|---------|----------------------|
|               | Heavy oil | Petroleum coke | Heavy oil | Petroleum coke |
| No.1          | 2362     | 1452              | 2.10      | 4.42           |
| No.2          | 2985     | 1397              | 2.09      | 5.83           |
| No.3          | 3414     | 1252              | 3.41      | 7.29           |
| No.4          | 3224     | 1063              | 1.99      | 9.45           |
| No.5          | 3225     | 1150              | 3.57      | 8.34           |
| No.6          | 3466     | 1272              | 4.31      | 6.86           |
| No.7          | 2862     | 1066              | 1.13      | 6.95           |

5. Conclusions

A numerical simulation of an actual float glass furnace was conducted, with the simulation results being in good agreement with the actual production data, indicating the results' credibility. The following conclusions were drawn:

(1) Whether the fuel is heavy oil or petroleum coke, large-scale transverse circumfluence is formed in the clarification zone in the back of the furnace. When the fuel is petroleum coke, obvious circumfluence zone also exists in the front of the furnace, which is also the zone where the batch is located. Longitudinally, the velocity of flow is higher and the crown is eroded more strongly by high temperature flow when burning petroleum coke.

(2) When the fuel is petroleum coke, the combustion in the furnace is more intense, and the area of the low temperature zone in the front of the furnace is smaller, but the temperature in the combustion zone is lower, and the scope of the high temperature zone in the flame whose temperature is higher than 2073K is smaller, and the temperature of the glass level and the crown in the furnace is slightly lower than that in the case of heavy oil.

(3) When the fuel is petroleum coke, the production of nitrogen oxides is less, which is about 50% of that when the fuel is heavy oil.

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7. References

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