Experimental Study on the Influence of Preheated Air and Air-fuel Ratio on the Combustion Temperature of Natural Gas Cupola

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Abstract. In order to improve the combustion temperature, this paper took 2 t/h natural gas cupola as an example, designed the performance experimental systems, discussed and analyzed the influence of critical factors such as air-fuel ratio and preheated air temperature on the combustion temperature in the furnace. The results showed that the combustion temperature can reach the highest value by controlling the air-fuel ratio around 9.8. The increase or decrease of air-fuel ratio can reduce the temperature, increasing the amount of air decreased the amount of smoke and taking away a lot of the heat, and decreasing the amount of air resulted in incomplete combustion. The combustion temperature can be increased by increasing the temperature of preheated air. The temperature rise rate is about 35℃ for every 100℃ increase below 200℃, and 55℃ for every 100℃ increase after 200℃.

1. Introduction

Cast iron remains the most widely used metal materials, second only to steel. Foundry industry is one of the most vital trades in equipment manufacturing industries. Our country’s cast iron output has ranked the first place in the world since 2000, and is growing steadily. The total output in 2018 reached 49.35 million tons[1]. Cupola as the main equipment of cast iron smelting has been widely used in the foundry industry at home and abroad[2]. Generally speaking, the federation mode is adopted cupola melting and induction furnace refining. Compared with coke cupola, natural gas cupola has significant advantages of environmental protection, energy saving and high efficiency[3], such as no sulfide emission, low-carbon emissions, high combustion efficiency, no solid waste and no need to store, and so on. Therefore, the widespread use of natural gas cupola has typically much value on theoretical and practical applications in casting industry. Increasing the combustion temperature is helpful to improve the melting rate of molten iron, the temperature of molten iron, the composition of slag and other quality indexes[4]. In this paper, firstly the performance experimental platform was designed and established based on 2t/h natural gas cupola used, then the influence of various factors such as air-fuel ratio and preheated air temperature on combustion temperature was analyzed comprehensively, to provide the basis for the design and application.
2. Combustion temperature
The heating of the material is carried out inside the furnace, which mainly comes from the combustion of methane. In the process of combustion, it is very important to choose and control the combustion air ratio. The volume of flue will increase with the increase of air quantity, thus the furnace temperature will decrease and the smoke loss will be increased.

The theoretical combustion temperature depends on the calorific value of gas, the heat capacity of combustion products, the number of combustion products, the temperature of gas and air and the excess air coefficient. Generally speaking, the calorific value of gas is lower, the theoretical combustion temperature is higher. The increase of excess air coefficient will increase the number of combustion products and decrease the combustion temperature. Therefore, the excess air coefficient should be reduced as much as possible on the premise of ensuring complete combustion. Preheating air or gas can increase enthalpy to increase combustion temperature. The theoretical combustion temperature of furnace can be increased obviously by preheating air quantity.

3. Experimental systems
Experimental equipment. The basic structure of natural gas cupola is composed of combustion chamber, melting zone, preheating zone and well zone[5, 6], as shown in Figure 1. The combustion chamber is the burner installation area and is characterized by operating at the highest temperature. Several layers of ceramic balls are arranged above the water cooled grates which must be installed between combustion chamber and melting zone[7]. The preheating zone refers to the position from the top of the ceramic balls to the feeding opening, whose main function is to contain certain raw materials and accept the heat transfer of updraft. The main effect of well zone is to collect the melting liquid.

The air and gas enter the combustion section through the burner and form the high-temperature flue gas after combustion. The high-temperature flue passes through the water cooler grate and enters the melting section. The ceramic balls in the melting section are heated to the temperature above the melting point to melt the preheated materials above. The air preheating section is above the melting section, and high temperature flue can preheat the air after radiation heat exchange.

![Figure 1. The basic structure of natural gas cupola](image)

1-combustion chamber, 2-melting zone, 3-preheating zone, 4-well zone
Test instruments and equipment. The metering of natural gas and air depends on orifice flowmeter, one of differential pressure flowmeters. The orifice plate is installed on the straight pipe, and a round hole is opened in the center. The cross-sectional area decreases as the gas flows through the orifice. At this time, the flow rate will increase, and the dynamic pressure will also increase, while the static pressure will decrease. Therefore, the pressure drop will be generated before and after the orifice plate. The test data show that the flow is proportional to the square root of the differential pressure. The differential pressure transmitter is used to display the flow in the monitor screen in real time. The range of the natural gas flowmeter is 30-150m³/h, and the measured diameter is DN80. The range of the air flowmeter is 100-1500m³/h, and the measured diameter is DN200. The flow can be changed by changing the opening degree of the electric control valves.

Platinum-rhodium platinum thermocouples are adopted in high temperature measuring of combustion chamber and smelting space, which short-term working up to 1800℃ and long-term operating temperature 1300℃. In the preheating section, the temperature is measured by nichrome silicon thermocouple, which can be measured at 1200℃ for a short time and 900℃ for a long time. The inlet and outlet water temperature is measured by platinum thermal resistance, which the accuracy is high and the range is -200 to 650℃. The measurement of water temperature is more accurate than that of smoke temperature. This is because the coefficient of heat transfer between water and thermocouple is much larger than that of flue. The heat released by the thermocouple through heat transfer can be quickly replenished.

Gas and air pressure can be measured by diffused silicon pressure transmitter and it is pointed out that gas should be used explosion-proof type. The pressure transmitter is insulated with stainless steel case, which can convert the gas pressure parameters sensed by the load cell sensor into a standard electrical signal 4-20mA output.

Measuring-point arrangement. Three measuring points are arranged respectively in combustion chamber and smelting space to measure the temperature at the wall, center and 1/4 position. The average temperature would be available. According to the measurement method of boiler high temperature furnace, metal heat shield is added on the thermocouple, and the root of thermocouple is insulated with heat preservation material. This treatment can reduce thermal and radiation errors and prevent them burnout by the rush of smoke.

Control system. According to the basic requirements of cupola smelting process, the control system should realize the functions of real-time display, alarm and storage of the test data, and can adjust and control solenoid valve, igniter, variable frequency fan, pneumatic valve, etc. The automatic control system is designed based on KINGVIEW 6.55 industrial control software. The monitoring system is configured with two sets of KINGVIEW6.55 software. One is an IO server, which can directly exchange data with on-site ADAM module in real time. In this way, the management and control of on-site production can be realized, and the data can be viewed, analyzed and recorded. The other is the client, which can obtain real-time data from IO server for detection. In order to achieve the rapid processing of data, the system establishes SQL database which can store the collected parameters such as temperature, pressure, flow, switch and so on.

| Name          | Type     | Quantity | Specifications                           |
|---------------|----------|----------|------------------------------------------|
| ADAM4018+     | Thermocouple | 5       | Type K, type B                           |
| ADAM4015      | PT100    | 1        |                                          |
| ADAM4017+     | 4-20mA input | 2       | Orifice flow, CO, O₂                     |
| ADAM4024      | 4-20mA output | 1       | Electric valve                           |
| ADAM4051      | On-off input | 1       | Air pressure, gas pressure, flame detection |
| ADAM4069      | On-off output | 2       | Fan, solenoid valve, ignition, alarm     |
| ADAM4080      | Pulse    | 1        | Oxygen flow rate                         |
| ADAM4520      | R232\485 | 1        |                                          |
Control process. The control process can be divided into four steps according to the smelting process. The first step is to check the equipment, instruments and meters, mainly including electric valve, pressure switch, solenoid valve and ignition controller. The second step is to ignite the fire. Before ignition, the air - electric valve, fan should be opened to the maximum. After the purge, the ignition air electric valve should be opened to the best position. Then the igniter starts electrifying, with the opening of the gas solenoid valve. The flame detector needle can detect electric current. When the output ignition signal is successful, the igniter begins to power off. The fourth step is temperature control during the melting phase. According to the calculation of gas flow, the corresponding valve opening needs to be adjusted quickly. The furnace temperature will rise rapidly only if the burner is kept under the maximum load. As the amount of material decreases during smelting, the burner's valve is gradually lowered to reduce the load. But the burner needs to maintain the melting temperature. Through the detection of air temperature, it is judged that the feeding material is all melted. The last step is to turn off the gas and the air. When all the iron liquid is out, the principle of stopping gas firstly and air finally must be followed to prevent gas explosion and poisoning of workers. The purpose of maintaining ventilation is to lower the air preheater temperature and protect work from damage. After the air preheater is completely cooled, the turbine is turned off.

4. Results and discussion
The drying-out curve. Before firing the gas burners, the natural gas cupola should first open the fan to purge the explosive gas that may be stored in the furnace to prevent accidents. After finishing, the burners are ignited, gradually increasing the gas flow proportional to air flow to preheat the cupola for about 40-60min. This process is known as drying-out. The drying-out curve is shown in Figure 2.

As can be seen from the cartoon, the temperature of the combustion chamber is basically below 400°C in the first 5mins, and rises rapidly to 1050°C in 5-25 minute. Within the first five minutes of heating, the thermal insulation materials absorb a lot of heat, resulting in basically no change in the combustion temperature. With the gradual decrease of heat storage in the furnace, the furnace temperature rises rapidly. As the temperature continued to rise, the heating rate decreased and the temperature basically remained around 1450°C after 60mins. After that, the furnace is basically in thermal equilibrium. At the same time, the central temperature the temperature on the wall is the highest, followed by the temperature at 1/4 position, and the temperature at the wall is the lowest. Four burners are hedged, the air and gas are mixed and burned while scour, and the disturbance is intensified after the collision and confluence in the center of the furnace, so the combustion is the most sufficient, the flame is the most concentrated and the temperature is also the highest.

![Figure 2. The drying-out curve.](image-url)
The effects of the air-fuel ratio. The oven experiment was carried out, and the oven temperature was stabilized. Under the rated load condition of the burner, the gas flow remains constant. By properly adjusting the proportion of the jet air and the preheated air, the preheated air temperature can be kept unchanged or changed within a certain range, preferably not exceeding 20℃. The air-fuel ratio can be changed by changing air flow. The temperature trend of the combustion chamber is shown in Figure 3.

![Figure 3. Effect of air-fuel ratio on average combustion temperature.](image)

From Fig. 3, it is shown that the combustion temperature first increases and then decreases with the increase of the air-fuel ratio, and the maximum value appears around 9.8. At low-fuel ratio, natural gas is not burned completely because of the lack of air, a large number of incomplete combustion products are produced, black smoke is mixed in the chimney. The combustion temperature is low, and the difference from the highest temperature is 130℃. Gas combustion can be ensured by increasing air volume, but too much gas volume increase. The flue gas takes away a lot of heat, resulting in the furnace temperature drop, and the maximum temperature difference of about 50℃. In the melting process, whether the air-fuel ratio is suitable can be judged by the flue color or the flame of fire hole. Smoke mixed with black smoke is insufficient air volume, flame bright blue is too much air volume.

The effects of air preheating temperature. Under the condition that the gas flow is maintained at 110m3/h and the air-fuel ratio is fixed at 9.8, the change of combustion temperature is measured by adjusting the temperature of the preheated air. The average temperature of the preheated air and the average temperature of the combustion chamber were recorded respectively, as shown in Figure 4.

![Figure 4. Effect of air preheating temperature on average combustion temperature.](image)
From the graph it is evident that the temperature of combustion chamber increases gradually with the increase of preheated air temperature. The temperature of the combustion chamber can reach 1400°C rapidly under the cold furnace. Preheated air is subject to heat transfer hysteresis and will rise slowly, taking 30 mins to reach 200°C. The combustion temperature rises slowly when the preheated air is below 200°C and the temperature rise rate is about 30-35°C for every 100°C increase. The combustion temperature increases rapidly with the increase of preheated air temperature after 200°C and the rise rate increases by 50-55°C for every 100°C increase. If the air preheating temperature is higher, the combustion temperature is higher. However, it should be noted that due to the limitation of the heat resistance of steel, the maximum heat resistance temperature of the hot air pipe with different materials should be considered. At the same time, excessive combustion temperature will lead to a rapid increase in NOX content in the flue gas.

5.Conclusion
According to the results of experiment, the paper puts forward some suggestions helpful for natural gas cupola design and application.

In the oven, the combustion temperature can reach 400°C within 5 min, then rise rapidly to 1050°C within 30 minutes, and basically maintain around 1450°C after heating for 60 min. But the rate of temperature rise is gradually decreasing.

The combustion temperature can reach the highest value by controlling the air-fuel ratio around 9.8. The increase or decrease of air-fuel ratio can reduce the temperature, increasing the amount of air decreased the amount of smoke and taking away a lot of the heat, and decreasing the amount of air resulted in incomplete combustion.

The combustion temperature can be increased by increasing the temperature of preheated air. The temperature rise rate is about 35°C for every 100°C increase below 200°C, and 55°C for every 100°C increase after 200°C.

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