

Design and Operational Analysis on Natural Gas-fired Cupola

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Abstract. Due to environmental regulations and social obligation towards society, more and more attention has been paid to the natural gas-fired for its excellent performance of environmental protection, energy saving and green economy. The present paper is devoted to the design and operational analysis aspects of natural gas-fired cupola. The basic structure of natural gas-fired cupola, including combustion section, melting section, preheating section and cupola well, etc has been discussed. The key technologies of burners, water-cooled grates, lining refractory, refractory balls, air preheater and cupola well are analyzed, and the basic parameters are determined. The melting process is briefly introduced, and the thermal balance of the whole furnace is analyzed. Application of the test in the case shows that natural gas-fired cupola has obvious advantages and high practical value.

1 Introduction

Cast iron is still the most widely used base material in the world[1]. Cupola is still the main equipment for smelting cast iron, which is responsible for melting about 70% of cast iron[2]. Most cupolas use coke as the main fuel, with strong melting capacity, simple structure, low cost of supporting construction. However, the emission of large quantities of SO₂, CO₂ and soot easily pollutes the environment, resulting in high pollution control costs[3]. As a cupola fuel, natural gas burns more efficiently than coke and at a lower cost, and can avoid the trouble of desulfurization, dust removal and other flue gas treatment. In such circumstances China foundry industries are in urgently need of such a melting unit which is not only eco-friendly and energy efficient but also economical. Therefore, the natural gas-fired cupola has broad application prospect. This paper designs the basic structure of natural gas-fired cupola, and discusses the key technologies of burners, water-cooled grates, lining refractory, ceramic balls, air preheater and cupola well, then analyzes the thermal balance of the whole furnace. The purpose is to provide theoretical base and practical references for popularizing and application of natural gas-fired cupola in smelting and metallurgy industry.

2 Design of natural gas-fired cupola

The main features of the gas-fired furnace are as follows: combustion section, melting section, preheating section and cupola well[4], as shown in Figure 1.

Combustion section

Gas-fired burners. The combustion performance is greatly influenced by the burner structure, many structural

parameters which include the load of the burner, the diameter and length of nozzle, the method of mixing gas and air and the installation tilt angle of the burner. The premixed high speed burners are used, including gas nozzles, gas-air mixing Chambers, ignition protection and flameout protection. Four burners are arranged relative to each other, and the gas volume of a single burner is 35 m³/h. In the design, the air-fuel ratio is 9. It can be obtained by calculation that the required air volume is 315 m³/h, and the smoke volume produced is approximately 350 m³/h. According to the relevant design manual, it is recommended that the outlet speed is 100-150m/s and the flue gas

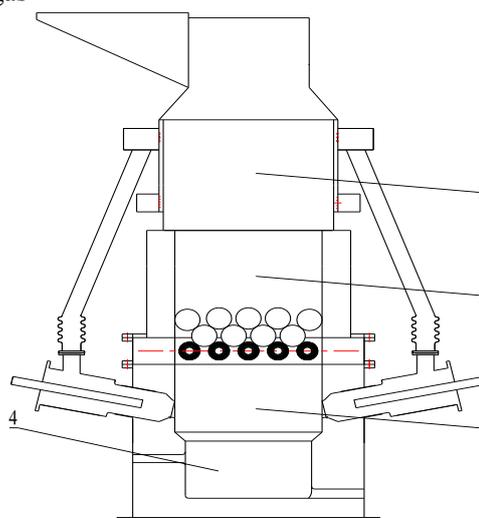


Figure 1. The main features of the gas-fired furnace
1-combustion section, 2-melting section, 3-preheating section
4-cupola well

temperature is 1200°C, then the nozzle size should be 80mm and 82mm, and the outlet speed is about 110 m/s.

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The most important aspect is the angle of orientation of burner with the furnace shell. The burner Angle requires that the flame does not directly collide with the opposite wall to prevent excessive erosion of the lining. It is worth noting that if the tilt Angle is too large, the molten iron will be overheated and oxidized, while if it is too small, the shell temperature will be high, resulting in overheating of the outer wall of the furnace. In consideration of the above two factors, the designed burner tilt angle is 15°.

Water-cooled grates. Water-cooled grates are the key parts of gas-fired cupola which support the ceramic balls that form the melting bed and acts as heat exchanger[4, 5]. They can separate the combustion section from the melting section and ensure the complete combustion of the gas space. They are required to have a certain strength and bending resistance, but also to ensure simple structure, reliable performance and low manufacturing cost as to facilitate maintenance and replacement.

The water cooler grate is made of seamless steel tube of 4mm-thick, with the casing structure which one seamless pipe of a smaller diameter goes into another similar pipe of bigger diameter. The outer surface of the bigger steel tube is coated externally with refractory material which preferably has a composition consisting of 90% alumina with graphite and calcium-silicate. In consideration of the protection of refractory material, the water is introduced from one end of the smaller diameter pipe and gets out through the bigger diameter pipe on the same side. Through calculation, the outside diameter of the bigger tube is 65mm and the wall thickness is 4mm, while the outside diameter of the smaller tube is 50mm and the wall thickness is 4mm. When water temperature rise is controlled at 50°C and water flow is maintained at 1 t/h, the flow rate of water in the outer tube is 0.122m/s and that in the inner tube is 0.040m/s.

Another important point is the grate clearance which is the net distance between the adjacent bigger tube coated with refractory. The grate clearance plays very important

role in maintaining the flow rate of flue for the combustion metallic charge and the permeability of molten iron flowing into the well. Taking the above factors into consideration, the thickness of outer refractory material is 20mm and the grate clearance is 40mm. At this time, the flue flow rate is 25%.

Furnace lining material. The temperature of combustion zone directly affects the melting rate, the temperature of molten iron and the composition of slag. If the temperature is higher, the quality of cast iron is better. Therefore, the furnace lining material is very important. The refractory should withstand high temperature and not melt, and maintain a certain compressive strength, bending strength in high temperature state, but also resist slag erosion and oxygen erosion, at the same time the refractory does not cause damage when the temperature changes dramatically. The test shows that 90% high aluminum cement is suitable for this area and can be reused for 50 times by on-site pouring. During site construction, the proportionally prepared castable shall be stirred evenly, and then clean natural water shall be added. The amount of water added shall be strictly controlled and less is better, then mix them well. When used, it is poured into the mold frame for artificial layered vibration to improve the compactness and uniformity as far as possible. In the construction of refractory in the combustion section, special attention must be paid to the quality of refractory repair near the exit of the burner position, and the gap must be rammed to smooth the surface of the pouring and not leave any uncast corners.

New or repaired refractory should be naturally dried after a period of time, otherwise the surface will appear cracks and affect the service life. When drying and sintering, it shall be baked in strict accordance with the heating baking system in Table 1, and then it can be used normally after finishing. After two or three times of operation, cracks and shrinkage will occur and this part castable refractory needs to be repaired in time.

Table 1. The heating and baking system for refractory castable

Temperature range [°C]	normal -150	150	150-350	350	350-600	600	600-800
Rate of temperature rise [°C/h]	15	heat preservation	20	heat preservation	20	heat preservation	30
Needed time[h]	10-24	24	10	10	12	10	10

Melting section

Ceramic balls. The key to melting is the ceramic balls, whose main function is to store heat, support iron and overheat melt[4]. Therefore, ceramic balls should meet the requirements of high strength and high fire resistance, the resistance to mechanical impact and thermal impact of molten iron, and at the same time, a certain voidage should be ensured to facilitate air flow. In practical use, ceramic balls are non-durable and can be slowly dissolved or decomposed, so it is necessary to add a certain amount of ceramic balls in each batch of burden to supplement its consumption.

The main components of the ceramic ball are 90-95% alumina, 5-8% calcium and aluminum cement and 1-2%. The particle size of the powder is 5-10 microns, and the particle size of the binder is 0.5-5 microns. The above

components are mixed with 8-10% water and placed in a steel die for hand vibration compaction to the desired size and shape. After air dry, the ceramic ball should be placed in water for 24 hours to cure, then can be directly used in the furnace. The fire resistance can reach 1750-1850°C, and the mechanical strength can meet the service requirements. It is worth noting that the higher the ceramic balls, the greater the consumption. The temperature of molten iron is required to be 1450°C, and the height of the ceramic sphere is about 450mm, at which time the consumption of the porcelain ball is 3%. When the temperature of molten iron is required to be 1150°C, the height is about 300mm, and the consumption of porcelain balls is 1.8%.

Preheating section

Air preheating zone. The recovery of waste heat from the furnace can obtain hot air, and the increase of air temperature can significantly increase the combustion temperature[6]. A tube preheater with ribs is designed, which is composed of the inner tube, the outer tube and the upper and lower gas collecting boxes. The thickness of inner tube wall is generally 10mm, and the thickness of outer tube wall is generally 6mm, all of which are made of heat-resistant steel Cr25Ni20. The design parameters are as follows: the height of the rib is 35mm; the thickness is 4mm; the spacing is 30mm; the length is 400mm. The arrangement mode is misaligned to avoid damaging the boundary layer of airflow. In order to reduce the thermal resistance of contact, continuous welding is used between the ribs and the inner cylinder, and the gap between the ends of the ribs and the outer cylinder is less than 2mm. The flue goes through the inner tube, the preheated air goes between inner and outer tube wall. The velocity of flue gas is 4m/s, and the velocity of preheated air inside and outside the cylinder is 8m/s. In order to raise the air preheating temperature, the counter-current arrangement is adopted.

Cupola well

The depth and diameter. In case of gas-fired cupola, the distance between the sand bed and the lower portion of the burner quarrel is considered as Well[4,6], which serves to collect the metal and slag melted above the ceramic bed. The depth requirement of the well is to consider the amount of liquid melting, and the effective depth is the distance between the sand bed and the slag outlet. The researchers[4, 5, 6] have established that temperature loss of metal is 200°C per meter increase in well depth. The cupola produces molten iron intermittently, such as 4 times per hour. The slag hole is found to be appropriate at 20 cm above the sand bed and the metal holding capacity should be 23.2kg/cm-height for a cupola of 2 t/hr capacity. Since, the diameter of cupola may be taken as 70 cm and this size of the tap hole could be counted as 25cm, nearly 150 kg/min liquid metal tapping out .

3 Melting process

After opening the furnace, it is necessary to preheat the furnace first, which is to preheat the ceramic ball, preheat the refractory and make the combustion temperature reach the melting requirements. After the oven reaches the predetermined temperature, the metal charge (bread iron or scrap, etc.) and flux (limestone, etc.) are proportionally placed above the ceramic ball in the melting section. These materials will immediately melt when they come into contact with overheated ceramic balls. The rising gas combustion product continues to heat the ceramic balls and preheat the solid metal material above, and decompose the limestone into a molten state. It also melts the limestone. The rising hot flue exchanges heat with the air needed for combustion in the air preheating section and the resulting hot air is fed into the burner. The cooling exhaust flue is filtered by the dust collector and then discharged into the atmosphere.

Molten iron produced by melting metal material is further heated through ceramic sphere layer and combustion section, and then falls into molten iron section. Finally, molten iron is discharged indirectly through siphon slag iron separation. If the oven is sufficient, the material will immediately melt after feeding, and the iron liquid flow can be observed at the iron outlet groove after about 20 minutes. The molten iron can be discharged after the hearth is filled with liquid iron.

After stop feeding, the surface of the material will fall with the melting of the material. At this point, the flow of natural gas and air should be gradually reduced, but the constant air-fuel ratio should be maintained. When all the liquid iron flows out, the principle of stopping the gas first, stopping the water later, and stopping the wind must be followed to prevent gas explosion and poisoning of workers.

4 Thermal equilibrium analysis

The heat balance of the designed gas-fired cupola is analyzed in the melting process. The experiments are carried out under design conditions and all the test data are measured when stable melting conditions were achieved. Through the arrangement of the original data, the heat of the gas-fired cupola can be divided into five parts: heat for melting, heat taken away by water-cooled grates, heat of preheated air, heat of preheated raw materials and heat loss of flue. Figure 2 shows the heat balance analysis of the whole furnace.

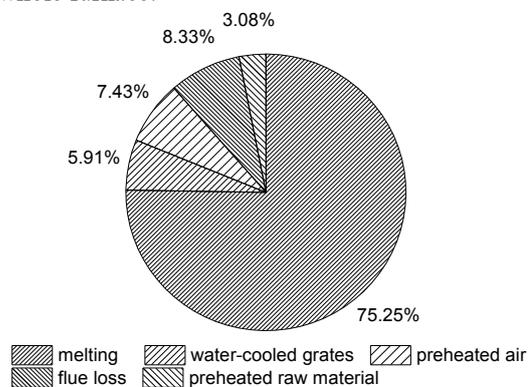


Figure 2. Heat balance analysis of the whole furnace

As can be seen from this pie chart, the heat comprise 75.25 percent of melting, 5.91 percent of water-cooled grates, 7.43 percent of preheated air, 8.33 percent of flue loss, and 3.08 percent of preheated raw material. Compared with other cupolas, the prototype has higher utilization efficiency. This is due to the reasonable design of the burner and air preheater, especially the use of high temperature flue after the melting section to preheat the air, to achieve a higher air preheating temperature and further improve the combustion temperature. The reasonable design of water-cooled grates ensures the complete combustion of natural gas and enough smoke to circulate upward.

5 Summary

This paper designs the basic structure of 2t/h natural gas-fired cupola, including combustion section, melting section, preheating section and cupola well, and analyzes the key technologies of burners, water-cooled grates, lining refractory, ceramic balls, air preheater and cupola well, then determines the basic size. The melting process is briefly introduced, and the thermal balance of the whole furnace is analyzed. The conclusions are as follows:

1) The premix high velocity burners are suitable for melting cast iron. Corresponding to the capacity of the cupola, four burners are mounted symmetrically around the furnace. The outlet speed of the nozzle is about 110m/s, and the angle of orientation is 15°. The casing type water-cooled grates are designed using seamless pipes of suitable sizes, and the gap between two grates provides more than 25 percent permeability for combustion product. The application of refractory heat preservation material is explained and the heating and baking system is established.

2) The function of ceramic ball is analyzed, and the requirement of making ceramic ball is put forward. The higher the ceramic ball, the greater the consumption. The tube preheater with ribs is designed to increase the convective heat transfer coefficient and reduce the wall temperature. The effect of cupola well is analyzed and the depth and diameter of well and the tap hole is determined.

3) According to the heat balance analysis of the whole furnace, up to 75.25 percent of the heat is used to melt, which proves that the gas-fired cupola has higher utilization efficiency.

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