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STUDY ON HIGH TEMPERATURE AIR COMBUSTION OF DOME COMBUSTION HOT BLAST STOVE[1]

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Abstract

NO_x is the major technical barrier to increase hot blast temperature and prolong campaign life of hot blast stove (HBS) at present. In order to restrain the amount of NO_x formation during combustion process in the HBS, the article studies and analyses the generation mechanism of NO_x production, and calculates NO_x generation rate and amount in HBS by means of thermodynamic generation model. A new dome combustion stove is developed based on high temperature air combustion (HTAC) technology. A comparison on the combustion process and characteristic of conventional HBS and HTAC HBS is performed by application of CFD simulation model. Temperature and concentration field distribution, flame shape and NO_x concentration distribution of two kinds of stove are calculated. The result shows quite symmetrical HTAC stove temperature field distribution. Under the same dome temperature, NO_x generation is 80ppm only, reduced by approximate 76% in comparison with conventional stove. HTAC HBS can obtain higher temperature, energy-saving, emission-reducing, and decrease NO_x emission efficiently, as well as realize long campaign life of HBS.

Key words: Dome combustion hot blast stove; High temperature air combustion; High hot blast temperature; Low NO_x.

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1 INTRODUCTION

High hot blast temperature is the important technological characteristic of contemporary BF. High hot blast temperature can reduce energy consumption, save coke, increase the amount of PCI, ensure BF operation stably, as well as increase energy efficiency, reduce emission of BF gas and CO_2, save energy and protect environment. Therefore, High hot blast temperature is a great technical approach to promote the BF smelt, therefore, high efficiency, low energy consumption, energy saving and emission reducing of contamination will be obtained. Contemporary HBS need provide the higher hot blast temperature over 1250°C ensure its campaign life up to more than 30 years, as well as reduce the emission of contamination, such as CO_2, NO_x etc. In this Way, it can make the HBS realize long campaign life, high efficiency, high blast temperature, low contamination emission.

HBS can be divided internal combustion type, external combustion type and dome combustion type by different structure. Dome combustion hot stove has been developed in 1970s, which conquered the technology disadvantage of internal and external combustion HBS, and its main feature is using dome space as combustion chamber, the independent combustion chamber which furnish inside or outside of stove is canceled. In 1978, Shougang No.2 BF adopted the dome combustion HBS, which was the first large dome combustion HBS applied on industry in the world.[1] This HBS structure is symmetrical, temperature field distribution is reasonable, occupied area is small, and the engineering investment is lower. But conventional dome combustion hot stove is restricted by combustion space. It is easy to result overheat in part of high temperature zone in dome，induce combustion chamber temperature fluctuate acutely and temperature distribution unequal, therefore, the stove heat transfer efficiency and campaign life decrease. At present, the three type HBSs are all conventional stoves, no matter what burner applied, the combustion principle and character has no essential different. Research indicated that when the dome temperature of HBS above 1400°C the content of NO_x in flue gas will be rise rapidly. When the temperature of vapor accompanied by combustion declines to below dew point, the vapor will become water, then NO_x and water combines to form the aid corrosive medium, which will cause the stove steel shell eroded. Consequently, the stove dome temperature is controlled below 1420□ for the conventional HBS, aid to reduce the concentration of NO_x and restrain the aid erode to stove shell, on the other hand, it limit to rise the blast temperature farther. According to the situation, it is necessary to design a high blast temperature, high efficiency and long life HBS to conquer the technology limitation. The stove will burn as unconventional combustion process, provide higher blast temperature for BF and reduce the emission of CO_2, NO_x at the same time.

2 FORMATION MECHANISM OF NO_x DURING COMBUSTION IN HBS

All the oxide of nitrogen produced in fuel combustion are called NO_x generally. It contains N_2O, NO, NO_2, N_2O_3, NO_3, N_2O_4, N_2O_5 and so on. NO_x in combustion main contains NO and little NO_2. NO_x do a lot of harm to human, animal and plant. Also it leads up to actinic smoke, acid rain and destroys to ozone, so it destroys nature ecology. Therefore, it is very necessary to reduce the emission amount of NO_x in fuel combustion and industry.

NO_x amount produced in combustion is affected by some combustion condition, such as combustion model, mix ratio of air and gas, combustion temperature and so

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on. NO_x can be divided into thermal-type, quick-type and fuel-type by its origin and produce approach. Thermal-type NO_x is created by nitrogen of air oxidized during burning in high temperature. Quick-type NO_x is formed in fast reaction happened in flame vanguard. Then fuel-type NO_x is produced when nitrogen of fuel oxidized. If BF gas provided for HBS, fuel-type NO_x will very little as nitride is little in BF gas, so the thermal-type NO_x is the main component in BF gas situation.

2.1 Formation Mechanism of Thermal-type NO_x

The formation of thermal-type NO_x is decided by a group of reaction quietly depend on temperature, and it is called generalized Zeldovich mechanism. This theory considers that the main reactions of thermal-type NO_x formed by nitrogen molecule in O_2-N_2-NO system are following:

$$O_2 + N \underset{}{\overset{K2}{\rightleftharpoons}} O + NO \quad (1)$$

$$N + OH \overset{K3}{\rightleftharpoons} H + NO \quad (2)$$

$$N + OH \overset{K3}{\rightleftharpoons} H + NO \quad (3)$$

Reaction (1) and (2) are called Zeldovich mechanism. When water exists in burning reactant, the OH will exist in combustion product, and reaction (3) will happen. So it is called generalized Zeldovich mechanism. The characteristic of thermal-type NO_x is that the reaction rate is slower than combustion rate. The great mass of NO_x is produced in high temperature field of flame vanguard.

A lot of investigations[2-4] indicated that the reaction of NO is carried between burning reactant behind the combustion zone near the highest temperature zone. Present research implies that NO also formed in combustion zone. The concentration of NO is related to temperature of burning reactant, and the zone which the concentration of NO is the highest located in the highest temperature zone, no matter what the burning reaction is end or not. Another research found that the producing process of NO doesn't complete instantly. The time burning reactant stay in combustion chamber is longer, the concentration of NO in smoke is higher. So increasing flow rate can reduce NO concentration. In a word, the amount of NO mostly relates to the highest temperature of flame, the concentration of N_2 and O_2, and stay time of gas in high temperature zone.

2.2. Reaction Rate of Thermal-type NO_x

The content of NO in thermal-type NO_x is almost 95%, and only little NO will be oxidized to NO_2. The reaction of producing NO doesn't achieve chemistry balance. According to the experimentation and operation by Zeldovich, the reaction rate of NO can be express as follow:

$$\frac{d[NO]}{dt} = 3\times10^4[N_2][O_2]^{1.5}\times\exp[-542000/(RT)] \quad (4)$$

In Equation(4), *[NO], [N2], [O2]* indicate the concentration of NO, N_2, O_2 respectively, unit is mol per cubic centimeter; *T* is reaction temperature, unit is degree kelvin; t is time, unit is second.

According to equation (4), the amount of NO will increase with the time of smoke stay in high temperature zone become more longer. The concentration of oxygen is also affect the amount of NO directly, and the more the oxygen concentration, the more NO amount. Another NO concentration will increase with the temperature rise. Some research indicates that when the temperature higher than

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1400℃, the mass of NO will increase rapidly with the flame temperature increase, and at this time the temperature affect the NO amount definitively

It can calculate the formation rate of NO according to equation (1) to (3) shows in equation (5). Equation (5) considered reaction process of transition reactant and the effect to NO amount by reverse reaction relative to equation (4), thus it is more accurate to calculate NO producing amount.

$$\frac{d[NO]}{dt} = k_1[O][N_2] + k_2[N][O_2] + k_3[N][OH] - k_{-1}[NO][N] - k_{-2}[NO][O] - k_{-3}[NO][H] \quad (5)$$

In equation (5), "*[NO]*, *[O]*, *[N$_2$], [N], [O$_2$], [OH]*" is the concentration of "NO, O, N_2, N, O_2, OH" unit is gmol per cubic meter; "k_1, k_2, k_3" is reaction velocity constant, "k_{-1}, k_{-2}, k_{-3}" is reaction velocity constant of corresponding reserve reaction, unit is cubic meter per·gmol per·second.

The equation reaction velocity constant has been investigated through lots of experimental studies.[5] This data has been accurate evaluated by Hanson and Salimian. In thermal-type NO_x reaction model, the velocity coefficients in equation (5) are $k_1=1.8\times10^8\cdot e^{-38370/T}$, $k_{-1}=3.8\times10^7\cdot e^{-425/T}$, $k_2=1.8\times10^4 T\cdot e^{-4680/T}$, $k_{-2}=3.8\times10^3 T\cdot e^{-20820/T}$, $k_3=7.1\times10^7\cdot e^{-450/T}$, $k_{-3}=1.7\times10^8\cdot e^{-24560/T}$ respectively.

2.3 Approach to Restrain Thermal-type NO_x

Combustion technologies to restrain thermal-type NO_x includes low oxygen combustion, subsection combustion, flue gas recycle method and so on. The basic principle of all these methods is belongs to departure chemistry equivalent combustion method, which make chemistry equivalent not in the range of chemistry equivalent ratio of combustion reaction in partly burning zone, as to restrain the producing of NO_x.

Teensi calculated the effect of dilute combustion air on reducing NO_x production rate. When the burning temperature of hydrocarbon is up to 1995℃, the NOx production rate can be calculated as following:[6]

$$dC_{NOx} / dt = 19750 \text{ ppm/s}$$

When the combustion air diluted by nitrogen, the NO_x production rate will reduce to:

$$dC_{NOx} / dt = 388 \text{ ppm/s}$$

When the combustion air diluted by nitrogen, the amount of NO_x will reduce nearly 50 times, thus diluting the oxygen concentration of the combustion air using inert gases or un-combustion gas can restrain producing of NO_x, and reduce NO_x concentration significantly. This research shows that it is efficiency to restrain the production of NO_x, and it is also the theory base to develop and design the high temperature air combustion (HTAC) HBS.

3 DESIGN AND DEVELOPMENT OF HTAC HBS

3.1 High Temperature Air Combustion Technology

High Temperature Air Combustion technology (HTAC) is a new successful technology in fuel combustion field developed in 1990's.[7-9] HTAC includes two basic technology measures: one is recycling heat of combustion reactant in maximum limit; another is fuel burning on low oxygen atmosphere.

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When the fuel burning under condition of high temperature and low oxygen, the process and pyrology situation in system are markedly different from general combustion process (air temperature is environmental temperature or lower than 600 ℃, the volume fraction of oxygen is not lower than 21%). This technology brought innovatory development to energy transform technology based on combustion, which can recycle residual heat with high efficiency and produce high temperature preheat air and low concentration of NO_x. The technology is considered one of the core industrial technologies in 21st century.

At present HTAC has been adopted in rolling mill heating-furnace gradually, but it has not been applied in BF HBS. Based on HTAC theory, if we apply this technology to the burning process of BF HBS, then mix the smoke created by combustion with the combustion air treated by high temperature preheating, it will be reduce NO_x concentration and make HBS to realize HTAC.

3.2 Develop of HTAC Dome Combustion HBS Structure

The basic principle of HTAC is gas combustion under the condition of high temperature low concentration oxygen atmosphere. Presently it can preheat combustion air above 800℃ using combustion air high temperature preheating technology. Also it can dilute oxygen concentration in combustion zone to get lower than 15 volume fraction oxygen using gas subsection burning and high velocity gas inhale to combustion reactant. The thermal condition of burning process is completely different from conditional in that atmosphere; and gas will release heat with burning in delaying state with low concentration oxygen, which can avoid local high temperature zone in conditional burning.

In one side, combustion model in HTAC HBS can enhance the temperature in whole combustion chamber, and improve the temperature distribution uniformity, as well as reduce gas consumption which means reduce the emission of CO_2. In another side, the stove can restrain the formation of thermal-type NO_x efficiently. On high temperature air combustion condition, though average temperature in stove rise, as eliminate the high temperature part zone of traditional combustion and high temperature fume mixing with air rotated which will reduce concentration of nitrogen and oxygen. On the other side, the gas flow rate and burning reaction rate are very high in stove, so the NO_x concentration will be reduced largely.

Figure 1 shows the basic structure of dome combustion HTAC stove[10]. Four layers or more than four layers gas and air circle channels are located in combustion chamber of dome. Some nozzles are configured in every circle channel. Gas and air jet from nozzle, and burn in combustion chamber. Each nozzle from top to bottom one by one as follow: the first and fourth layers are gas nozzle, and the second and third lays are air nozzle. As the location of gas and air inlet affect the uniformity of gas and air nozzle flow distribution, therefore, each size and space of gas and air show gradually or uniform distribution depending on the number and location of gas and air inlet.

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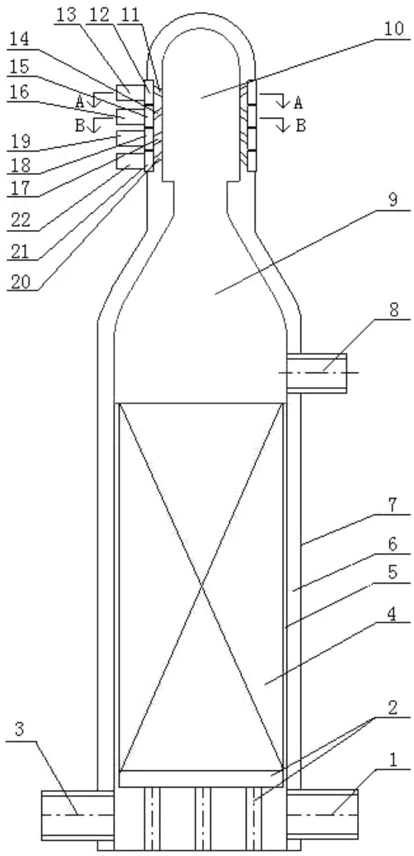

Figure 1. Construction of high temperature and low oxygen dome combustion HBS. 1-inlet of cold air, 2-checker brick supporting grid, 3-outlet of flue gas, 4-checker brick, 5-regenerator chamber, 6-lining, 7-steel shell of stove, 8-outlet of hot blast, 9-combustion chamber, 10-burner of HTAC, 11-gas nozzle of first ring, 12-gas circle channel of first layer, 13-gas inlet of first layer, 14-air nozzle of first ring, 15-air circle channel of first layer, 16-air inlet of first layer, 17-air nozzle of second ring, 18-air circle channel of second layer, 19-air inlet of second layer, 20-gas nozzle of second ring, 21-gas circle channel of second layer, 22-gas inlet of second layer.

The gas jet from the first layer nozzle mixes and burns with air jet from the second air nozzle on rotation diffuse situation, producing the high temperature fume flows downwards along combustion chamber. After the air jet from the third lay nozzle mixed with high temperature fume, the mixed gas will become high temperature and low oxygen combustion air as its temperature can reach 800℃ to 1000℃ and oxygen concentration is lower than 15%. The gas jet from fourth nozzle burn in HTAC atmosphere in combustion chamber, when the combustion process becomes diffused controlled reaction, and the part high temperature high nitrogen concentration zone no longer turn up, then the producing of NO_x be restrained. At the same time, the volume of flame increase. High temperature and strengthen radiation black body uniformity distribute in combustion chamber, and heat transform efficiency improved remarkably, as well as it can make the amount of NO_x and CO_2 emission reduce largely and save energy consume by 25%.

4 COMBUSTION CHARACTERISTICS OF HTAC STOVE.

In order to study the combustion features of HATC stove, the physical models of normal dome combustion stove and HTAC stove, as well as mathematic model of turbulent combustion are established. The temperature distribution, concentration distribution and formation amount of NO_x are studied by CFD simulation method.

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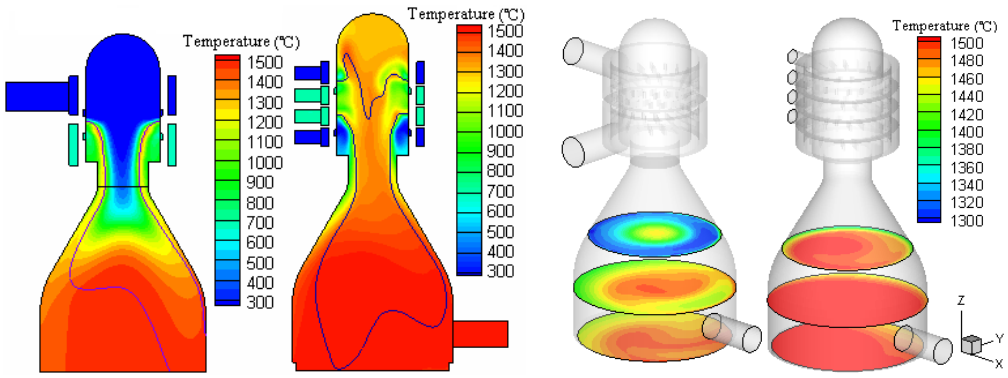
4.1 Temperature Field and Flame Shape

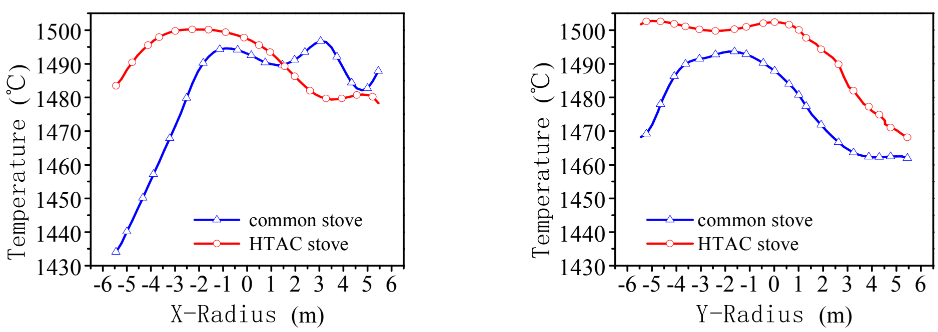
The contrast of temperature fields and flame shapes in the combustion chamber is showed in figure 2 respectively, when the stoves flame temperature of the stoves are both 1510□. Figure 2 (a) shows the normal stove, while (b) shows the HATC one. Figure 2 shows the contrast of temperature field and flame shape on the middle section where X=0 and Y=0. The temperatures are all above 1450□ under the aperture of larynx of combustion chamber in the HACT stove, thus there are no local high temperature zone compare with normal HBS because of high combustion efficiency at the same area. The solid line represents the flame shape, it is concluded that the shorter the flame length is, the bigger the combustion chamber is. If diffuse flame can be formed, the uniform temperature field will be available. It is clear to find in Figure 2 (c) and (d), on the same section of middle and lower part of combustion chamber, the temperature of HATC stove will high than normal stove, and more uniform on the temperature distribution.[11]

The uniform temperature distribution of HBS on the surface of checker is very important to HBS. The uniform temperature distribution of flue gas can improve the heat transfer efficiency and enhance the life of checker. Figure 3 shows the temperature comparison of radical direction on the bottom of combustion chambers, according to the figure that decrease of difference value between the highest and lowest temperature, and obviously the enhance of uniform distribution. The calculation result shows, normal HBS the average of temperature are M_0=98.28%, M_1=99.56% respectively.



(a) (b) (c) (d)

Figure 2. Comparisons of temperature distribution and flame profile.



(a) (b)

Figure 3. Comparison of radial temperature at lower combustion chamber.

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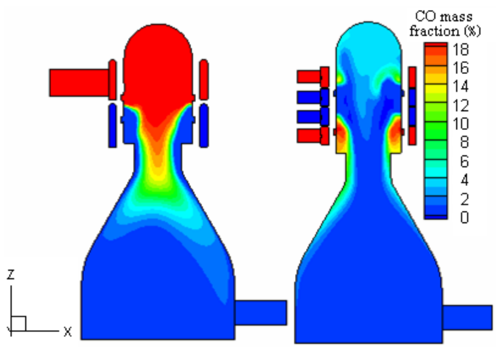
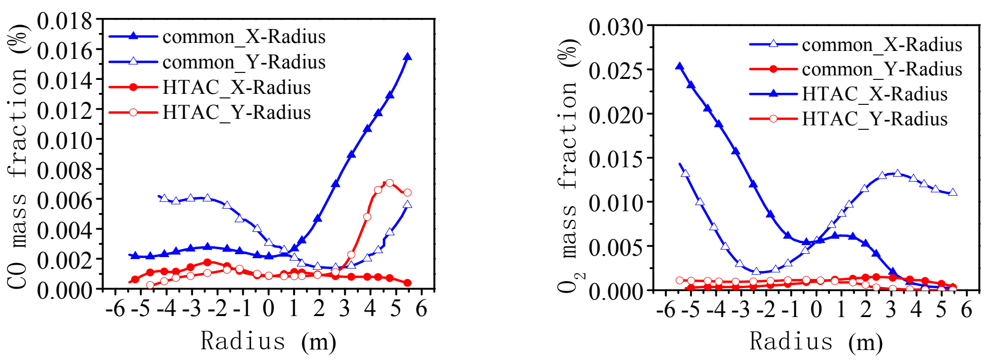
4.2 Concentration Distribution

Figure 4 shows the concentration distribution of CO in two types of HBS. Figure 5 (a) represents the conventional dome combustion stove, and Figure 5 (b) represents the HATC dome combustion stove. According to the comparisons, it is easy to recognize the obvious decrease of CO concentration on the bottom of HATC combustion chamber, which shows the fully reaction. There is large area of dead zone in the spherical crown of normal stove, where a lot of gas existed, which can't ignite, and during the time of stove changing, lots of N_2 consumed to blow to prevent the bomb. When HATC burner adopted, the dead zone is utilized effectively, the CO concentration lowed, the consuming N_2 needed also decreased sharply. The comparison of CO and O_2 on the bottom of combustion chamber is showed in Figure 5. It can be seen from the Figure 5 that uniform of O_2 and CO concentration is lower than the conventional stove, which shows during the HATC environment, the CO and O_2 can mix much fully and enhance the combustion efficiency and reduce the CO consumption.



(a) (b)

Figure 4. Concentration distribution of high temperature and low oxygen HBS.



(a) (b)

Figure 5. Comparisons of concentration at lower combustion chamber.

3.3 Product Amount of NO_x

The NO_x concentration distribution of different stoves is showed in Figure 6. Figure 6 (a) is an indication of normal stove, and Figure 6 (b) is the HTAC stove. The radical concentration on the bottom of combustion chamber is showed in Figure 7. It is concluded that when HTAC burners adopted, the NO_x concentration sharply fall down from 330ppm to 80ppm, which is about 76%. This show the technology of HTAC can remarkable prevent the produce of NO_x on high temperature, which to a great extent

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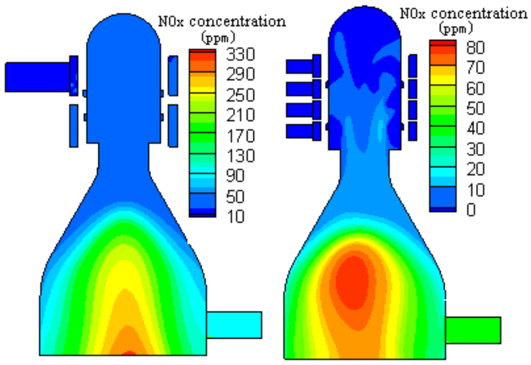
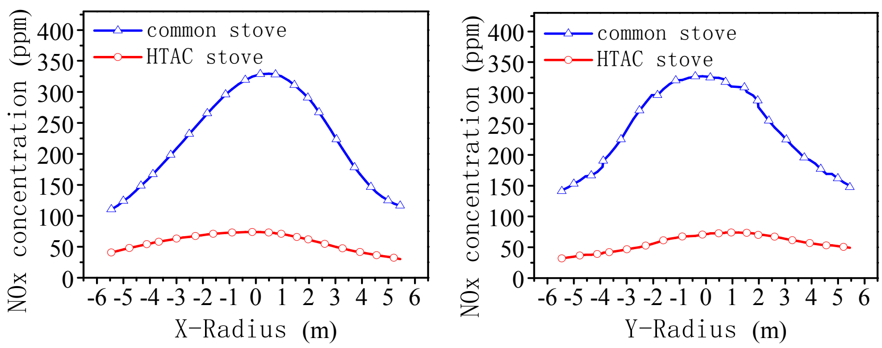
decrease the emission of NO_x, and the decrease of NO_x can reduce acid aqueous by NO_x on the shell and condensate, the life of HBS was enhance by inhibiting the occurrence of intercrystalline stress corrosion. This fully confirmed that the higher blast temperature can be obtained by control the formation of NO_x when adopting HTAC, which give more chance for high blast temperature.



(a) (b)

Figure 6. Comparison of NO_x concentration.



(a) (b)

Figure 7. Comparison of NO_x concentration at lower combustion chamber.

5 CONCLUSIONS

During high temperature combustion in BF HBS, the produce mechanism of NO_x obey generalized Zeldovich mechanism. When the dome temperature reaches 1400℃, NO_x will be formed largely, which will combine with water produce the acid caustic medium and cause the intercrystalline stress corrosion to stove shell, which restrains high blast temperature and shortens the life of stove.

Based on high temperature air combustion (HTAC) technology, The HTAC dome combustion HBS has been designed using combustion air high temperature preheating technology, which can be preheat above 800℃. Also it can dilute oxygen concentration in combustion zone to get lower than 15% oxygen using gas subsection burning and high velocity gas inhale to combustion reactant.

The combustion characteristics of HTAC stove is studied by simulations of convention dome combustion stove and HTAC stove respectively. The result show, when during HTAC condition, the fully combustion of CO and O_2 can be obtained, which enhance the efficiency and higher combustion temperature as well as more even temperature distribution. This concluded if the same blast temperature obtained, less consuming of CO and decrease the emission of CO_2.

The HTAC stove can inhabitant the sharply produce of NO_x in high temperature,

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which to some extent can reduce the emission of NO_x during the combustion period, and prevent the intercrystalline stress corrosion in the stove shell ,thus enhance the life of HBS. The HTAC can obtain high temperature in the dome and increase the blast temperature.

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