CFD Letters www.cfdl.issres.net Vol. 2 (4) – December 2010

The Study of Numerical Simulation of Oxygen-enriched Burner System

Yuesheng Fan[C] andPengfei Si
School of Envir. and Muni. Eng, Xi'an Univ. of Arch. & Tech.
Xi'an 710055,China

Received: 04/07/2010 – Revised 16/09/2010 – Accepted 16/09/2010

Abstract

In order to reduce overall fuel consumption, or partially substitute a "valuable" fuel with a poor one, in electric power plant boilers, oxygen enrichment of combustion air can be very effective. The paper proposes an oxygen-enriched ignition system which based on the existing pulverized coal fired boiler ignition devices. Small coal particle is suitable for this system. The new burner includes inside, outside and middle casings. And it transfer heat in two ways of downstream and upstream. The burner has authorized a patent in China. A numerical simulation theory were used to analysis it. The results indicate that: it can increase the maximum burning velocity $\left(dw/dt\right)_{max}$ and the average burning velocity$\left(dw/dt\right)_{mean}$, and decrease ignition temperature T_i and burnout temperature T_b of pulverized coal. In addition, the pulverized coal fired boilers are easier to be ignited and the comprehensive combustibility index S is improved. At the same time, it demonstrates that it is an effective way to warm-up the pulverized coal in ignition of the boiler in the power plant.

Keywords: oxygen-enriched ; combustion;boilers;pulverized coal

1. Introduction

The boiler in the power plant mainly relies on the pulverized coal combustion. The ignition and combustion of the pulverized coal is difficult than the oil and gas fuel. And the main problem is that it needs a longer ignition time, and behaves unstable combustion at lower load **[1]**. This kind of boiler need to consume a large amount of fuel oil in state of ignition or stable operation with low load, and so researchers have been looking for more economical and practical solutions **[2]**. Although many new fired techniques, which made the pulverized coal furnace burning steadily, have been used, the oil wastage is still vast **[3, 4]**. For a 100 MW power boiler, the ignition and steady-going combustion process will consume oil fuel of 528.6 tons per annually (t/a) **[4]**.In recent years, as membrane technology has become more matures and the oxygen has decreased in cost, oxygen-enriched combustion technology has attracted people's attention.

The ignition temperature of fuel is not a constant, and it is related to combustion condition, heating rate, environmental temperature and others. For example, the ignition temperature of CO in the air is 882K, but in pure oxygen is only 661K. Therefore, the combustion with oxygen-enriched

[C] Corresponding anther: Penfei Si
Email：175987342@163.com
 PII: S2180-1363(10)24137X

not only can reduce the ignition temperature, but also will be conducive to the complete combustion reaction, and thereby it will eliminate the dust pollution from the fundamental **[5]**. On the other hand, after adding enriched oxygen, the combustion products reduce and the theoretical combustion temperature increase. Under common conditions, the enriched oxygen increases every 1% and the theoretical combustion temperature can increase 50K ~ 60 K. Therefore, enriched oxygen will play a positive role in the ignition of pulverized coal **[6]**. Experiments show that the theoretical combustion temperature T, which is got by burning lignite with 26.7% of the oxygen-enriched air or burning anthracite with 21.8% of the oxygen-enriched air, is as much as T which is got by burning heavy oil with ordinary air **[5]**. It indicates that burning coal with enriched oxygen can replace burning coal with oil, and it is of great significance for our country which is more coal and less oil.

The advantages of oxygen-enriched combustion can be classified as followings:

1. To accelerate the burning of fossil fuels

The burning speed of fuel has greatly differences between the air and pure oxygen. Take hydrogen for example, its burning speed is 280 cm/s in the air, compared with the pure oxygen in the combustion rate is 1175cm/s, which is 3.2 times lager than the value in the air and as much as 10.7 times of natural gas. So with rich oxygen aid-combustion, not only can make short flame, increase the burning speed and strength, and get better heat conduction .As temperature increased, it will to the benefit of combustion reaction, thus fundamentally eliminate the soot pollution completely **[5]**.

Oxygen-enriched combustion can also make the coal burning completely; reduce nitrogen and the proportional of other gas which does not participate in the combustion reactions. In other words, it also reduce the waste from exhausting, in order to improve the efficiency of furnace. At the same time, add oxygen-enriched combustion can reduce the corresponding and improve theoretical combustion temperature. Under common conditions, the enriched oxygen increases every 1% and the theoretical combustion temperature can increase 50K ~ 60 K. Therefore, the ignition of pulverized coal will play a positive role **[7]**.

2. To improve flame radiation intensity and strengthen the radiation heat transfer

Due to reduce the amount of nitrogen, both air and smoke reduced significantly. So the flame temperature and emissivity with oxygen in the air of combustion ratio increased significantly, then improve the flame radiation intensity and strengthening the radiation heat transfer too **[7].**

3. To reduce the ignition point of fuel and burnout time

The ignition point of fuel is not a constant value, it relevant with combustion condition, heating speed and environmental temperature. The ignition point of CO is 609℃ in the air，but only 388℃ in the pure oxygen. So with oxygen-enched aid-combustion can reduce the ignition point of fuel, improve the intensity of flame and increase the heat released.

Zhenhai petrochemical Co., LTD tested the burnout time of different sizes of petroleum coke and fly ash powder of coke, ablaze, oxygen concentration and combustion temperature, and the relationship between ignition point, burnout temperature and oxygen concentration, temperature. The powder of fly ash (namely the black smoke comes out from the chimney which calls free-carbon), the rich oxygen aid-combustion in 33 percent compared with air combustion, reduced 18.62℃ of ignition point and 125.58℃ of burnout temperature. The burnout time shortened 144-192 times, the test results were present in Table 1.

4. To reduce the smoke volume

If we use common air for combustion-supporting, not only about four fifths of nitrogen will not participate in combustion, but also take a lot of heat. Usually enriched oxygen increases every 1% and the smoke volume reduces about 2% ~ 4.5%, which can improve the combustion efficiency.

TABLE1: THE IGNITION POINT AND BURNOUT TEMPERATURE UNDER DIFFERENT OXYGEN CONCENTRATION OF PETROLEUM COKE

Diameter of Petroleum coke /mm	Ignition point （□）			Burnout temperature （□）		
	O_2 20%	O_2 33%	bad	O_2 20%	O_2 33%	bad
2.8-4.0	553.83	474.36	79.47	707.70	555.27	152.43
1.0-2.8	516.37	475.56	40.81	727.02	569.14	157.88
0.45-1.0	521.31	473.64	47.67	765.58	568.31	197.27
0.2-0.3	512.34	451.61	60.73	695.74	530.01	165.73
＜0.098	477.97	414.24	63.73	624.06	478.54	145.52
Fly ash powder	520.57	501.95	18.62	668.52	542.94	125.58

5. To increase heat utilization

The use of oxygen-enched for combustion-supporting, can improve the heat utilization. The common air for combustion-supporting, when the temperature of furnace is 1300℃, the use of available heat is 42%. But with 26% of oxygen-enriched air combustion heat, the available heat is 56%, increased by 33%. The greater of oxygen-enched concentration and the higher of the heating temperature, the better of energy saving**[5]**. The literature applied the oxygen-enriched combustion technology to gas combustion furnace which played a remarkable energy saving. As we can see in Fig.1 and Fig.2, when oxygen volume concentration is 45% and the temperature of furnace is 1200□, the proportion of energy saving is 34%.

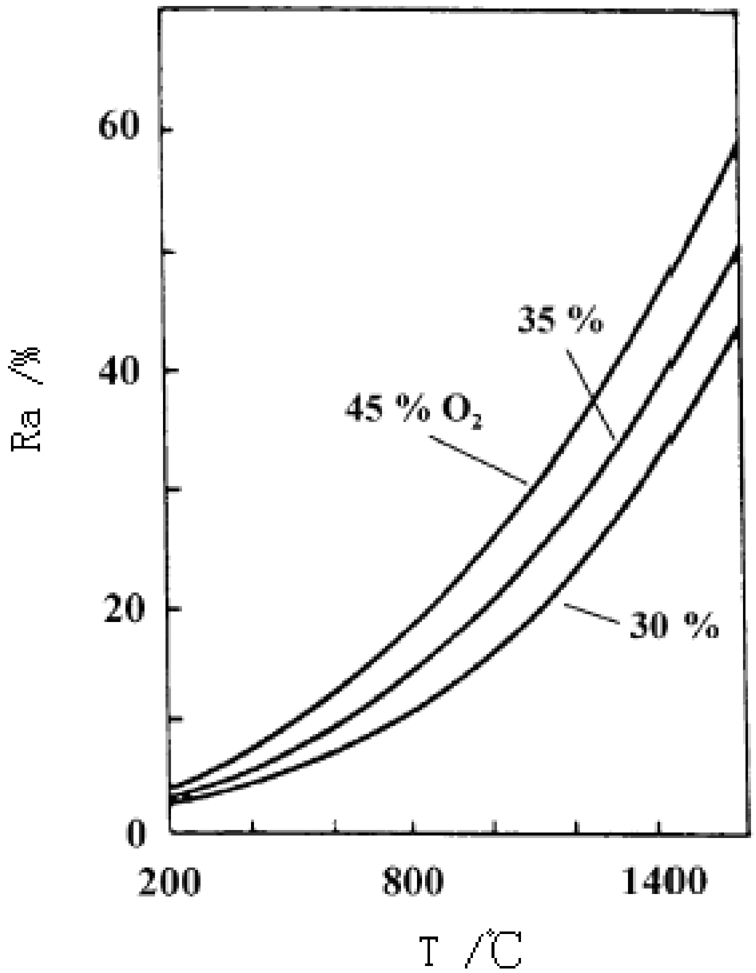


Fig 1 The relationship between smoke temperature and energy saving rate under the different oxygen concentration **[8]**

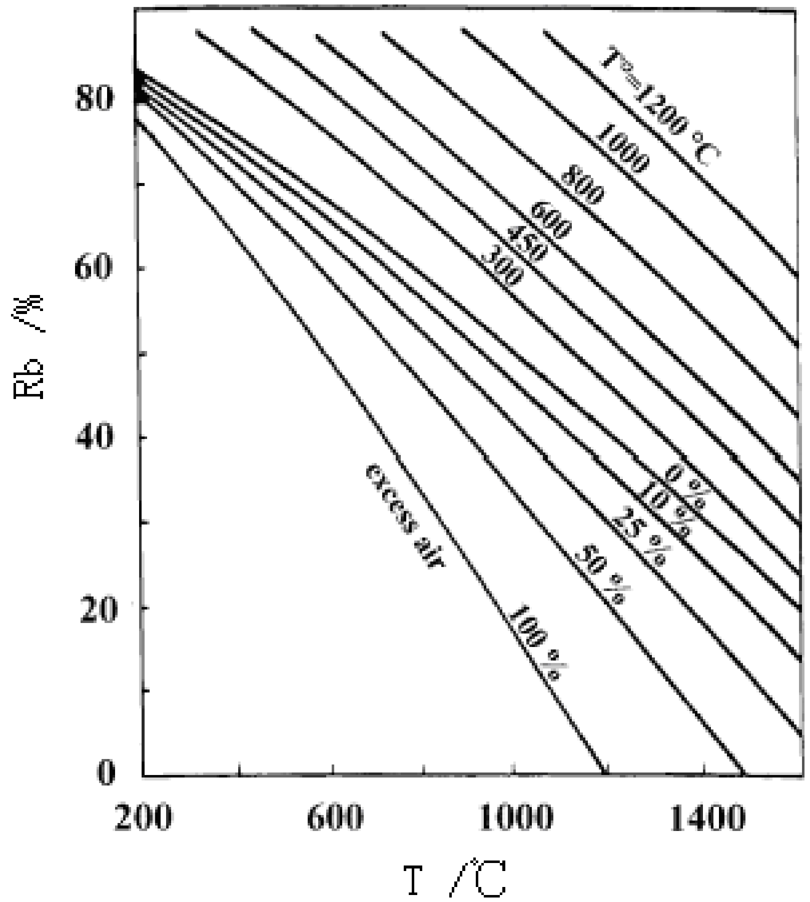


Fig 2 The relationship between unburned proportion of natural gas and exhaust temperature under the different oxygen concentration **[9]**.

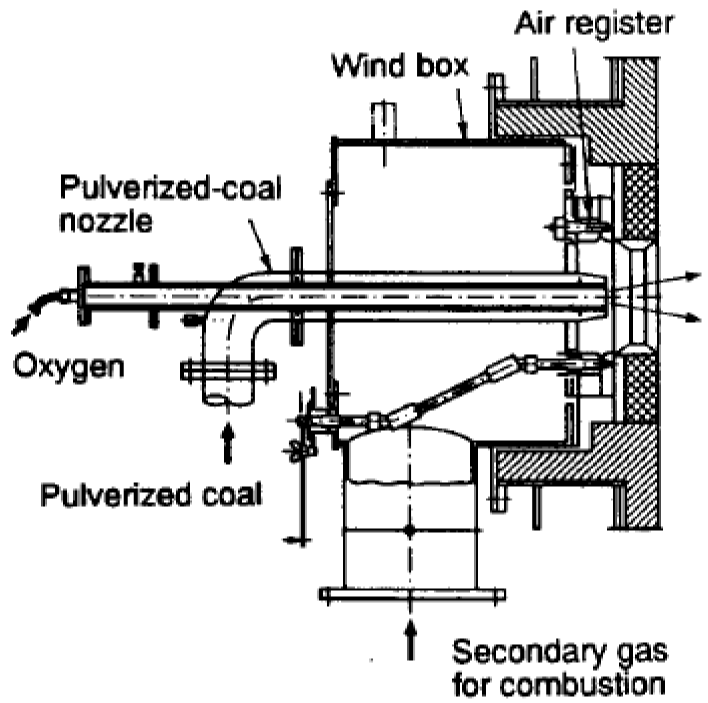


Fig.3 Oxygen-rich ignition burner

Figure 3 shows a form of oxygen-enriched ignition of CO_2 gas circumfluence, which was studied by Kiga. In this paper, a kind of oxygen-enriched burner, which has authorized a patent in

China, will be analyzed theoretically and simulated numerically. It will show some of its advantages, and some available conclusions for optimizing the structure of oxygen-enriched burner.

2. Numerical details

2.1. Governing equations [10-13]

The researches on oxygen-enriched combustion technology about coal-fired boiler is currently concentrated on hybrid combustion technology of oxygen-enriched air and the returned flue gas (CO_2), therefore, in some documents the oxygen-enriched combustion technology is known as the O_2 / CO_2 combustion technology, or air separation / flue gas recirculation technology, or the N_2-free Process and so or. Figure 4 is schematic diagram of experimental oxygen-enriched combustion technology of the United States. The technology mainly consists of three basic steps: air separation, O_2/CO_2 combustion and electric power generation, gas compression and dehydration. In this technology the mixture of oxygen-enriched gas and returned flue gas mixes with the pulverized coal, and then this mixture is ignited.The disadvantages of this technology as follows : firstly, the concentration of oxygen-enriched gas is reduced, in other words, high concentration of oxygen must be enriched in order to achieve the ignition of oxygen-enriched and oil-free; secondly, it can't make oxygen-enriched gas mix well with pulverized coal which is not conducive to the ignition of pulverized coal boilers.

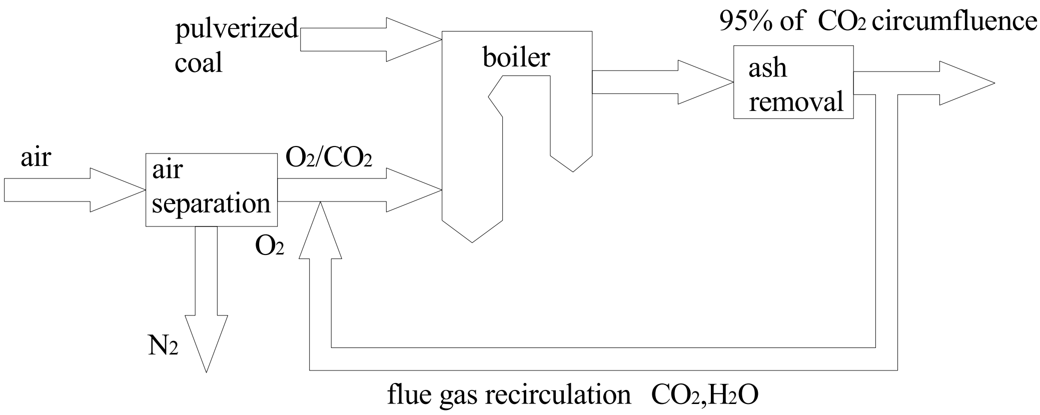


Figure 4 the schematic diagram of traditional oxygen-enriched burner

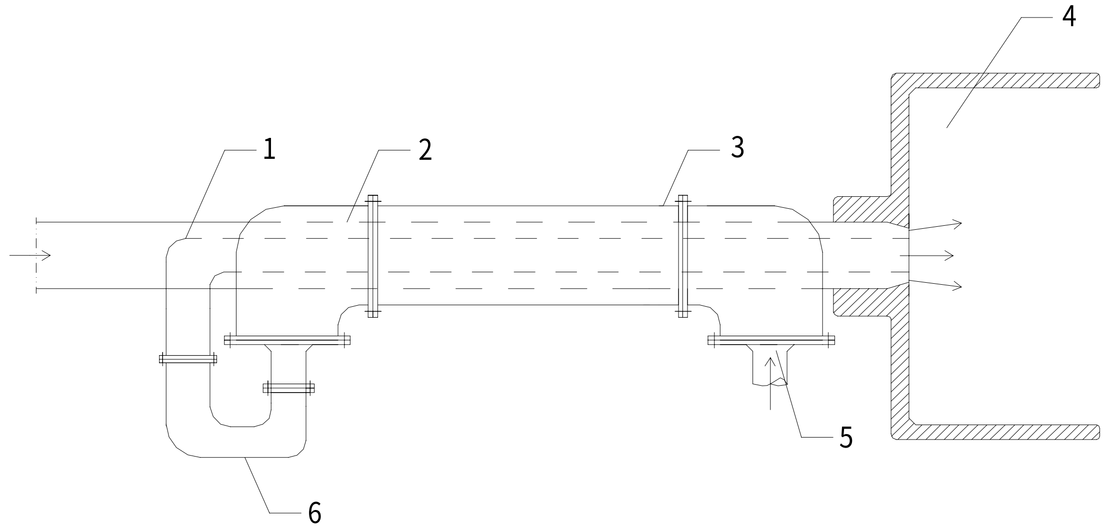
This invention uses oxygen-enriched gas transport pulverized coal, which makes pulverized coal contact well with oxygen molecules in the process of transportation. From Figure 5, we know the specific working principle: oxygen-enriched gas uses pneumatic conveying principle blow pulverized coal into the middle casing pipe. Then on the one hand this mixed airflow uses counter flow principle have heat exchange with returned flue gas in the external casing pipe, on the other hand it uses downstream principle have heat exchange with returned flue gas in the inner casing pipe. Finally, after preheating this mixed airflow is ignited in the boiler furnace. The returned flue gas that accounted for 95% of the total flue gas enter the external casing pipe by circumfluence entrance, and then enter the inner casing pipe. After two times of heat exchange the returned flue gas enters the boiler furnace and circumfluence cycle will continuous like this.

Jiang Xiumin and others **[14]** introduces a comprehensive parameter combustibility index S to represent the whole combustibility of pulverized coal, that is

$$S = \frac{R}{E}\frac{d}{dT}\left(\frac{dw}{dt}\right)\bigg|_{T=T_i} \cdot \frac{(dw/dt)_{\max}}{(dw/dt)\big|_{T=T_i}} \cdot \frac{(dw/dt)_{mean}}{T_b} = \frac{(dw/dt)_{\max}\cdot(dw/dt)_{mean}}{T_i^2 T_b} \tag{1}$$

where $(dw/dt)_{\max}$ is maximum burning velocity, $(dw/dt)_{mean}$ average burning velocity, $(dw/dt)\big|_{T=T_i}$ combustion velocity under the ignition temperature, and R/E represent the activity of coal.

Because this new type of oxygen-enriched burner uses oxygen-enriched gas transport pulverized coal, pulverized coal particles will be wrapped by the oxygen-enriched gas, largely increasing the contact area between oxygen molecule and particles. The maximum burning velocity $(\mathrm{dw/dt})_{\max}$ and the average burning velocity $(\mathrm{dw/dt})_{\mathrm{mean}}$ are improved, and ignition temperature of pulverized coal T_i and burnout temperature T_b are decreased. Besides, pulverized coal is preheated by heat exchanger that has three casing pipes, and its initial temperature is raised, which makes it easier to be ignited. The above structural optimization of oxygen-enriched burner can effectively increase the comprehensive combustibility index S, and improve the whole combustion process and ignition of pulverized coal.



1—inner casing pipe, 2—middle casing pipe, 3—external casing pipe, 4—boiler furnace, 5— import of returned flue gas, 6—connection pipe

Figure 5 the schematic diagram of new type of oxygen-enriched burn

2.2. Solver details [15, 16]

First of all, build the structure model of oxygen-enriched burner, and mesh the possible area of fluid flow. We use the professional 3D modelling software for solid modelling, and input it to the pre-processing software to mesh. The calculation area and meshing is shown in Figure 6.

Using respective boundary conditions in imports of middle and external casing pipe of the oxygen-enriched burner, and combining the N-S equations (RANS) with the standard k-ε turbulence model, the three-dimensional numerical simulation has been used to calculate the flow field of safety valve. In the rectangular coordinate system, for the incompressible fluid, in the condition of neglecting heat exchange, the standard k-ε closed model equations are expressed in the form of Hamilton operator ∇, and using the kinematic viscosity ν in place of the dynamic viscosity μ, there will be equations like this:

$$\nabla \cdot \overline{U} = 0 \tag{2}$$

$$\frac{\partial \overline{U}}{\partial t} + \nabla \cdot (\overline{U} \otimes \overline{U}) = -\frac{1}{\rho}\nabla p + (v + v_t)\nabla^2 \overline{U} \tag{3}$$

$$v_t = \frac{\mu_t}{\rho} = \frac{C_\mu k^2}{\varepsilon} \tag{4}$$

$$\frac{\partial k}{\partial t} + \nabla \cdot (\overline{U} k) = \frac{v_t}{\sigma_k}\nabla^2 k + \frac{G_k}{\rho} - \varepsilon \tag{5}$$

$$\frac{\partial \varepsilon}{\partial t} + \nabla \cdot (\overline{U}\varepsilon) = \frac{v_t}{\sigma_\varepsilon}\nabla^2 \varepsilon + \frac{\varepsilon}{k}[C_1 \frac{C_\varepsilon}{\rho} - C_2 \varepsilon] \tag{6}$$

$$G_k = G_\varepsilon = \mu_t \nabla \cdot \overline{U} \cdot (\nabla \cdot \overline{U} \cdot \nabla \cdot \overline{U}^T) \tag{7}$$

Where

U: entrance velocity of medium, m / s;

$C_\mu, C_1, C_2, \sigma_k, \sigma_\varepsilon$: constant of turbulence model, as shown in table 2;

k : per unit quality of turbulent pulse kinetic energy, m^2/s^2;

v_t : kinematic viscosity coefficient of turbulent flow, m^2/s.

TABLE2: CONSTANT OF MODEL

Coefficient	C_μ	C_1	C_2	σ_k	σ_ε
Numerical Value	***0.09***	***1.44***	***1.92***	***1.0***	***1.3***

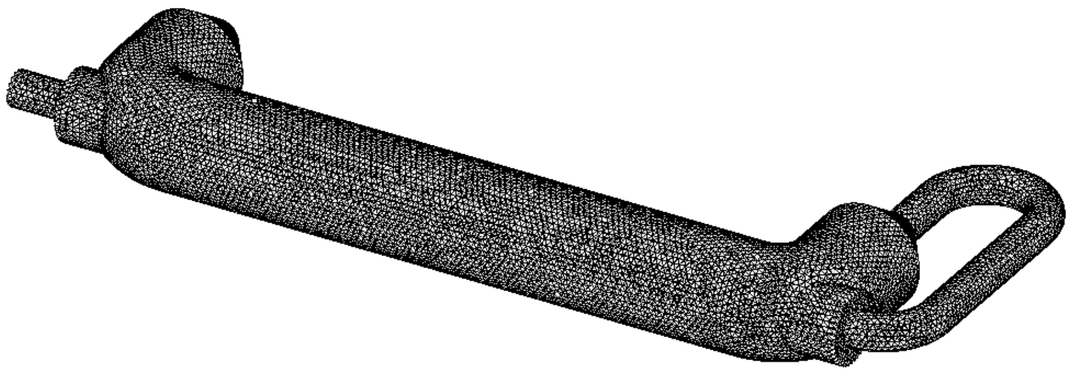


Figure 6. model for numerical calculation

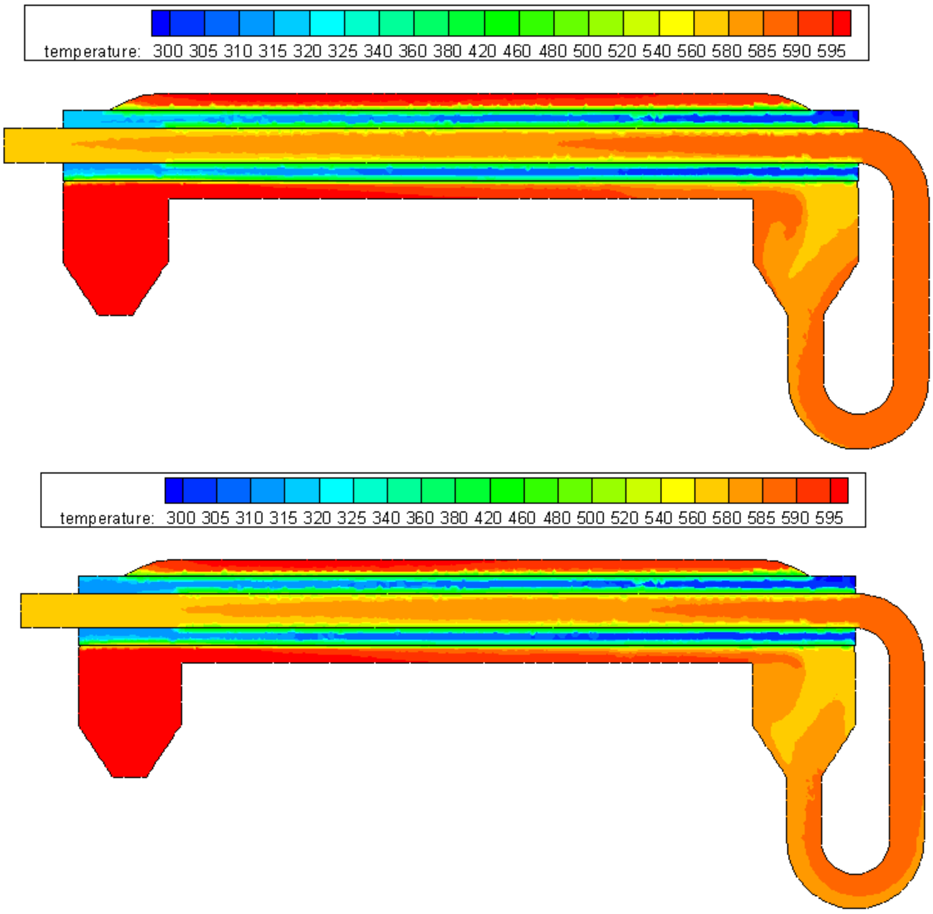
3. Results and discussion

In this paper, static grid simulation method is used to simulate four kinds of working conditions of this new type of oxygen-enriched burner. The velocity of returned flue gas is 49.5 m/s, particle size of pulverized coal is 100μm, air-coal ratio is 2.0 (kg/kg), and inlet temperature of oxygen-enriched gas is 27 ℃. The inlet temperature of returned flue gas and velocity of oxygen-enriched gas are respectively as follows: 327 ℃, 20.5 m/s; 327 ℃, 24.5 m/s; 327 ℃, 26.5 m/s; 527

℃, 15 m / s. the wall of pipe is iron, and its roughness height is 5e-5. There is no slip on the walls of pipe, namely the $v_{wall} = 0$, $w_{wall} = 0$, $k_{wall} = 0$, $\varepsilon_{wall} = 0$.

Figure 7 and Figure 8 shows the temperature field of the burner under the four working conditions. From figure 7, we can see that during the entire heat transfer process there exist temperature boundary layers in the three casing pipes. The boundary layer in middle casing pipe is thicker, and in external casing pipe is thinner. There are two core areas of high temperature in inner casing pipe. In boundary layer of middle casing pipe, the temperature of mixed air that comprises oxygen-enriched gas and pulverized coal is higher, which can reach between 150 ℃ to 190 ℃ in the first working condition. Inside the burner the temperature field distribution under the four working conditions are similar to each other. When only the flow velocity of the mixed air in the middle casing pipe is increased, the length of two core areas of high temperature in inner casing pipe will be reduced, as shown in Figure 9. We also know that there is a core areas of low temperature in middle casing pipe, and the core areas of low temperature in middle casing pipe will be reduced as the flow velocity of the mixed air in the middle casing pipe, as shown in Figure 10.

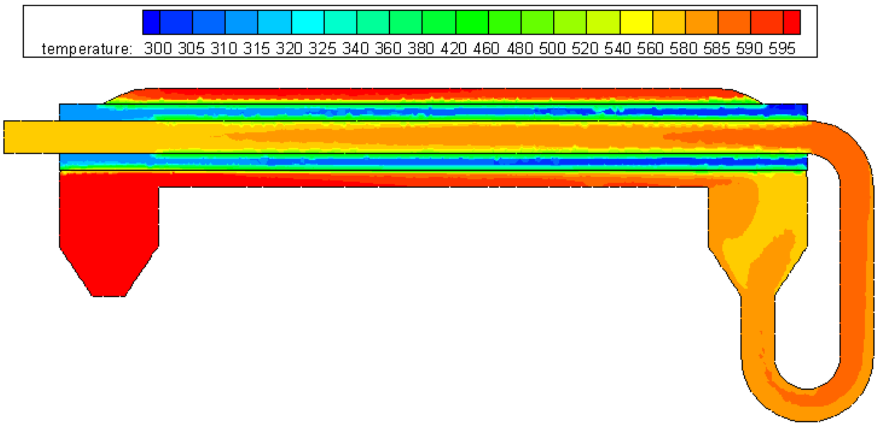
Figure 11 shows the outlet temperature of returned flue gas and mixed air, which comprises oxygen-enriched gas and pulverized coal under four working conditions. The average outlet temperature of mixed air, under four working conditions, is respectively as follows: 46.1℃, 45.5℃, 45.1℃, 101.3℃. The average outlet temperatures of returned flue gas under four working conditions are respectively as follows: 305.1℃, 305.56℃, 306.1℃, 535.3℃. It indicates that the outlet temperature of mixed air that comprises oxygen-enriched gas and pulverized coal is increased after the heat exchange, which will make it easier to ignite pulverized coal. It is equivalent to reducing the ignition temperature T_i of pulverized coal and improving the comprehensive combustibility index S. Therefore, we should adopt all kinds of methods to raise the temperature of mixed air that comprises oxygen-enriched gas and pulverized coal, which can bring huge profits in the power plant.



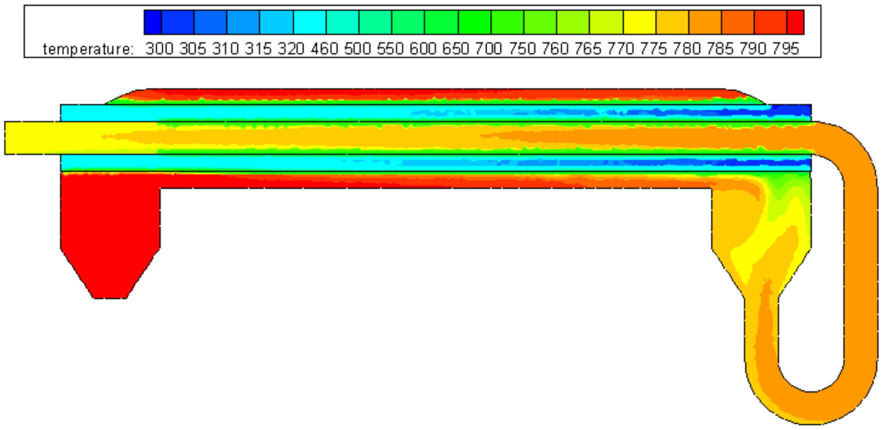
(a)

(b)

Figure 7. the temperature field under (a) the first and (b) second working conditions of the burner



(a)



(b)

Figure 8.. The temperature field under (a) the third and (b) fourth working conditions of the burner

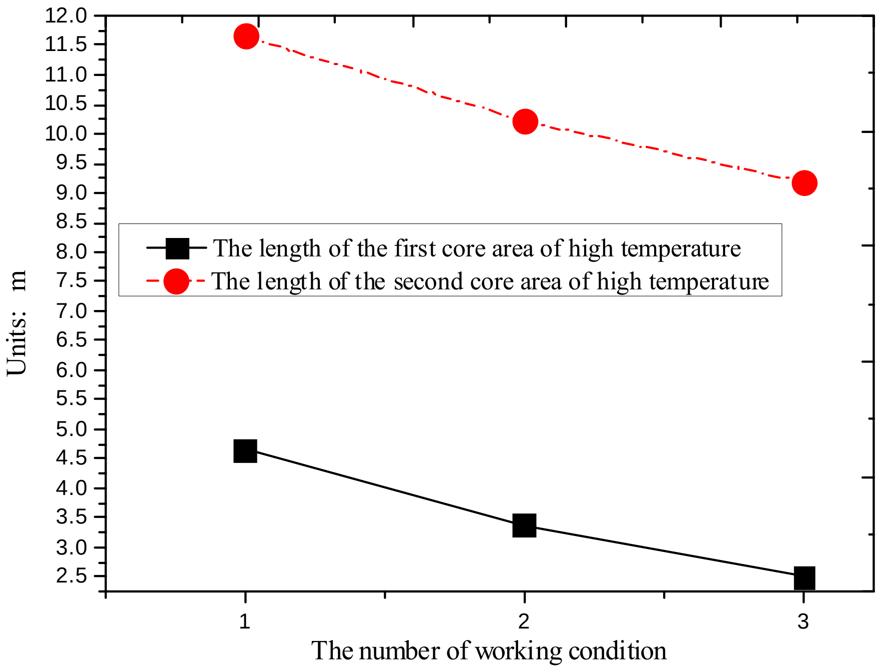


Figure 9. The length of core area of high temperature under three kinds of working condition

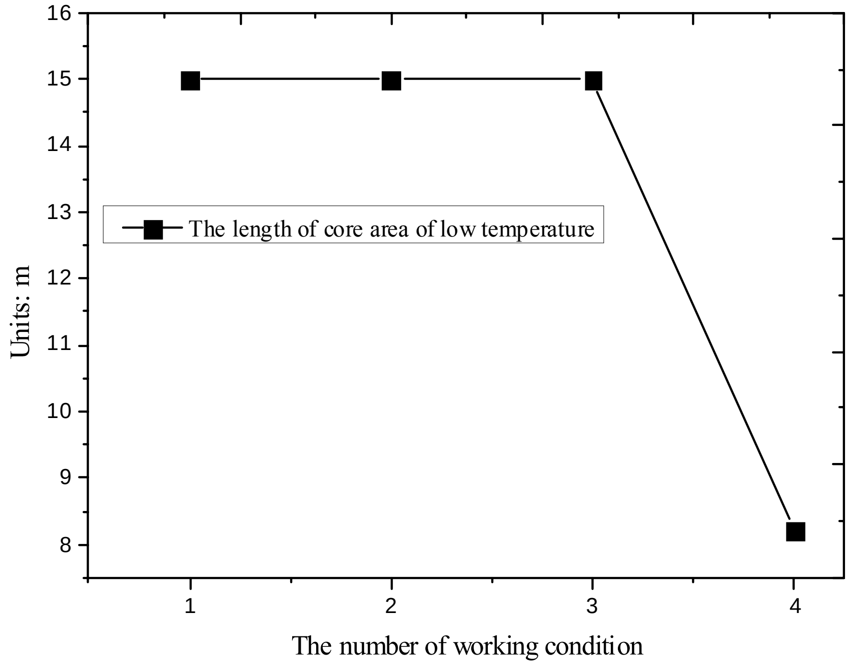


Figure 10. The length of core area of low temperature under four kinds of working condition

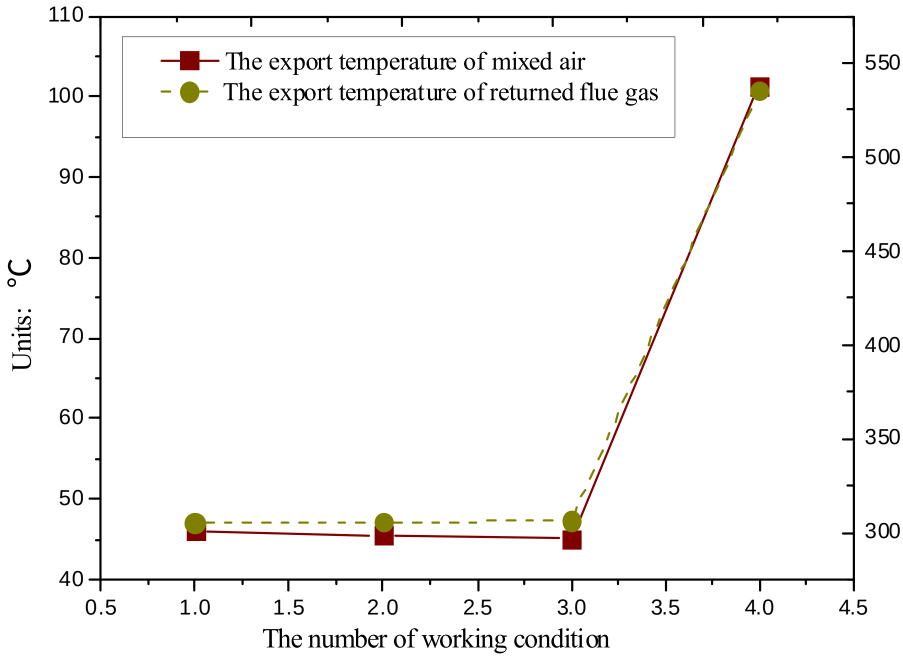


Figure 11. The export temperature of gas flow under four working conditions

4. Conclusion

Based on the analysis of existing power of pulverized coal fired boiler ignition devices, we present a new no oil coal oxygen-enriched ignition system which suitable for small coal particles. This new burner includes inside, outside and middle casings. Between outside and middle casing pipe is the upstream heat transfer system, but inside and middle casing pipe is the downstream heat transfer system. It demonstrates that it is an effective way to warm-up the pulverized coal enough in ignition of the boiler in the power plant.

From the above structural analysis and numerical simulation we can see that using oxygen-enriched gas transport pulverized coal and preheating mixed air with heat exchanger of three casing pipe can increase the maximum burning velocity $(dw/dt)_{max}$ and the average burning velocity

$(dw/dt)_{mean}$, and decrease ignition temperature T_i and burnout temperature T_b of pulverized coal. As a result, the pulverized coal fired boilers are easier to be ignited and the comprehensive combustibility index S is improved. Increasing the flow velocity of the oxygen-enriched gas will reduce heat transfer, and it also reduces the length of the core area of high temperature in inner casing pipe, that is, the heat transfer of inner casing pipe is enhanced and that of external casing pipe is declined. Obviously, the performance of oxygen-enriched burner is enhanced effectively through some structural improvements.

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