

## Numerical Simulation of Flame Temperature Field in Rotary Kiln

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**Abstract:** Rotary kiln is one of the most commonly used thermal technology equipment in metallurgical industry, its thermal stability is directly related to burn into the quality of the material, the gas temperature of inside the kiln is important influence factors of thermal system. So research the airflow temperature distribution inside the kiln, it's very vital significance to understand the status of the rotary kiln in the heated, and real-time control the calcination condition of the materiel in rotary kiln. First, this paper used Fluent Software to make a comparative analysis of several different burners, founded that the flame temperature and shape of distribution was more reasonable when take gas as fuel with cylindrical burner, then built a finite element model of the rotary kiln. Finally, using the Fluent Software to simulate the flame temperature of rotary kiln cylindrical burner and heat flow generated by it under the condition that with different inlet velocity of fuel and air, when take gas and methane as fuel, We found that the velocity of fuel inlet is greater and the temperature of flame is higher in the condition of fully burn but we cannot get the desired flame form which means abnormal combustion when the velocity of fuel inlet more than 160 m/s or less than 40 m/s in the simulation experiment, the velocity of air inlet is greater and the temperature of flame is lower, but the air inlet velocity is too large or too small can't get ideal flame form. At the same combustion condition, the flame temperature of methane combustion is relatively slightly higher, and the flame shape is more slender, but the high temperature flow generated by the two kinds of fuel is not very different. So we can substitute the methane for gas as fuel in the combustion condition is not very strict requirements. According to the combustion simulation for working conditions of the rotary kiln , realized the analysis for rotary kiln flame and the heat flow which was generated by it ,that's indicate this simulation method was feasibility and accuracy. *Copyright © 2013 IFSA.*

**Keywords:** Flame, Combustion, Rotary kiln, Temperature field, Numerical simulation, Simulation.

### 1. Introduction

It is widely use boiler with the continuous development of metallurgical industry, the boiler calcination has been become an indispensable process in beneficiation industry, the technology of boiler calcination is mature. The most widely using in

the equipment of boiler calcination is rotary kiln, due to the development of metallurgy technology, the equipment of metallurgy renewal very quick, the structure of rotary kiln is only by continuously improved to adapt to the demand of new technology, the working condition of rotary kiln is worse, it is work in high temperature for a long time. It is very

necessary to analysis the temperature field and stress field with different structures and working conditions, which in order to make the rotary kiln have the ability to adapt to the harsh conditions, have work state more stable, higher production efficiency and have a longer service life.

Temperature control is very important in rotary kiln working, it is usually adjusted the rotary kiln burner to control the temperature, most of the burner is inserted from the rotary kiln head, the material is heated to the required temperature through the flame radiation and the high temperature flow is generated by it. The common burner consists of coal burner, gas burner and fuel injection, according to the different fuel to make corresponding selection [1].

Qiu Xiatao etc. [2] assumes that the materials calcination and the rotary kiln wall are gray body, divided into several small regions along the axial direction, the material temperature distribution more uniform inside each area, and think that between rotary kiln wall covered and the material without heat transfer. And then build the one dimensional mathematical model of rotary kiln heat transfer with the method of the radiation coefficient, the method is not only a small amount of calculation, and is relatively simple, it is a kind of effective method and practical strong in the process of build heat transfer mathematical model, it also can be used as the theoretical basis in optimization control of rotary kiln and the thermal simulation.

Ma Aichun etc. [3] make alumina materials calcination rotary kiln as the research object, have the internal heat transfer paths of rotary kiln for more in-depth analysis and research, and comprehensive considerate the heat conduction, convection and radiation heat transfer of the high temperature flue gas, rotary kiln wall and material bed, established the one-dimensional heat transfer model of alumina material calcination of rotary kiln in this base. The Runge Kutta method is adopted to the calculate the one dimensional heat transfer model, it is concluded that the temperature data on any cross section of high temperature airflow and materials, research the heat transfer law of relative movement for the sealing of high temperature gas and low temperature material inside the kiln. It can be used for the temperature prediction and parameter optimization of the sealed section of the internal rotary kiln gas and material with this one-dimensional model, in the case of lack of experimental conditions is very effective.

Zhang Zhixiao etc. [4] also analyzes heat transfer process of rotary kiln, on the basis of summarizing the predecessors' research, focuses on the heat transfer mechanism between the material bed and cover rotary kiln wall and effects on various heat transfer coefficient of rotary kiln body movement. At present, the study of material and contact rotary kiln wall mainly in two aspects of the packed bed and transmit bed, among them with packed bed as the research object to create the most representative of the heat transfer Model is thermal Penetration Model (Schlunder Penetration Model), and the Model of

heat transfer between material within the theoretical foundation and rotary kiln and cover rotary kiln wall heat transfer form is the same, so this Model can also be extended to the whole Model of rotary kiln heat transfer area. Schlunder thermal penetration model makes a very big improvement for Zhang Zhixiao and others theory in material and heat transfer mechanism of rotary kiln wall, their biggest achievement is presented for heat transfer mathematical relationship for material and covering rotary kiln wall, and on this basis to establish the internal heating mathematical model of heat transfer process of rotary kiln, compared with the published test data, has good alignment, and verify the accuracy and applicability of Schlunder thermal penetration model. This model is proposed to establish the mathematical relationship of internal heat transfer mechanism of rotary kiln and the heat transfer coefficient provide theory basis for the design of the internal heating type rotary kiln, and has a certain practical value.

Patisson F et al. [5] for the coal decomposition kiln as the research object, in the transfer process of rotary kiln internal material, gas phase material within the volatile combustion kinetics of thermal decomposition and high temperature flue gas, kiln wall and material bed between the heat conduction, convection and radiation heat transfer, material particles in the flow field and calcination, decomposition and cooling bed in dynamic process have done a lot of research on the basis of analysis and description for whole coal decomposition of rotary kiln heat transfer model is established. They adopt the method of numerical simulation to predict the internal temperature distribution of rotary kiln in any position of axial and the content of various gas components and materials. In order to verify the applicability and effectiveness of the model, they measured the related data in actual industrial production and compared the measured temperature distribution inside the kiln and gases, material composition data with the experimental data, the result is consistent, indicated the applicability and effectiveness of the model. Then, they used the model to analysis of the influence of relevant operating parameters of rotary kiln in product process, and put forward improvement measures for the coal decomposition.

Martins M A, et al [6] has done some research on the internal heat transfer process of the rotary kiln, he analyzed the dynamic characteristics and flow characteristics of the materiel phase and gas phase transfer process, and their effect on the influence of internal heat transfer process of rotary kiln. With in the process of rotary kiln calcination material within the physical and chemical reaction process is also considered, and the semi-empirical formula is used to describe the high temperature flue gas, rotary kiln lining and material bed between the process of heat conduction, convection and radiation. On this basis, establish one-dimensional heat transfer mathematical model of a rotary kiln calcination process. At the

same time by using numerical simulation method, within the rotary kiln on the material phase and gas phase and the axial temperature distribution of rotary kiln wall and rotary kiln in exhaust flue gas composition and its percentage is forecasted, the results of the predicted results with the actual industrial production measured are in good agreement. Industrial production process, the internal of the physical and chemical reaction is bound to have impact on heat transfer when the rotary kiln is running, the reaction process itself can not only accompanied by exothermic and endothermic but also makes phenomena of phase transfer in different interphase, so it is necessary to considerate the mass transfer process and its influence of incidental reaction the in analysis of the internal heat transfer process of rotary kiln. The model fully considered the influence on heat transfer for the mass transfer process, so that the model has a certain practical value, but also for future generations of research provides a new basis.

Boateng A. A. and Barr P. V. [7-9] internal heat transfer process of rotary kiln also done A lot of influential works, they mainly is the study of material calcination internal material particle movement rule, the main achievement is rotary kiln internal of quasi three dimensional heat transfer model is established. First using one dimensional axial heat transfer model to describe the heat transfer process between different areas, and then on this basis, the internal particle movement and heat transfer is studied for the material, and then established the kiln body on the cross section of two-dimensional heat transfer model of the material. Considering the rotary kiln on the one dimensional heat transfer model and the axial cross section material after two-dimensional heat transfer model, build the quasi three dimensional heat transfer mathematical model of rotary kiln, the model can't intuitive reflect material bed temperature distribution in three-dimensional space, called a quasi three dimensional heat transfer model. Although the model ignores the influence of the chemical reaction in the kiln, but obviously improve the modeling of the rotary kiln, can more accurately predict the two-dimensional temperature field distribution of rotary kiln wall of axial at any position and inside of material bed. Although their research has some limitations, but also for rotary kiln internal three-dimensional heat transfer model provides an effective way of thinking, work laid the foundation for follow-up study. Expected the two-dimensional temperature field distribution inside the bed at any position and. Although their research has some limitations, but also for rotary kiln internal three-dimensional heat transfer model provides an effective way of thinking, work laid the foundation for follow-up study.

R. T. Bui et al. [10] on the basis of previous studies to establish the three-dimensional model of petrol coke rotary kiln, the gas phase has been added to the 3-D model, makes the model more robust. The model includes several complicated physical phenomena: the relative motion of the gas and

material, heat transfer among materials, combustion, the heating effect of the rotary kiln wall and movement of material particle. Due to model factor is more, the model is more complex, the model adopts the form of tree branches, composed of several related child model coupling. Firstly, the gas, material bed, rotary kiln wall and radiation heat transfer model are established. And the four models contains a molecular model, the gas model includes three molecules of flow movement, fuel combustion and energy model, in which energy molecular model includes both heat conduction and thermal convection; Material flow bed model includes two molecules of flow and energy model, The enthalpy for reference to establish the molecular energy model, according to the gas composition transfer equation to analyze the combustion sub model. They using PHOENICS Software to solve the model, with cylindrical coordinates as coordinate system, the flow model is established, the model is a continuous equation, momentum equation and  $k-\varepsilon$  dual equations of complex turbulence model; Using The Monte Carlo algorithm in PHOENICS Software to solve the radiation sub model. In the analysis of material bed model, think that the flue gas as the Newton fluid, and the viscosity is little of movement layer of surface material, viscosity is more of material at the bottom, on the basis of this hypothesis to solve. Based on the energy balance method, it is set certain boundary conditions to solve the kiln wall model.

In recent years, obtained the rapid development of computer technology, support the development of computer technology related hardware problem has been overcome, makes the numerical simulation Software was used on the computer, for the precise calculation of rotary kiln heat transfer model and its simulation provides an efficient way.

Marias F et al. [11-12] using the auxiliary of computer Software, the model of heat transfer in rotary kiln, the material movement model and the coupling calculation of chemical reaction model and so on aspects to do a lot of attempts, we have accumulated a wealth of practical experience. He made several assumptions: (1) assume that the inside of the rotary kiln thermal conductivity to a certain value; (2) there is no heat accumulation rotary kiln wall; (3) the material of the motion state of roll shape; (4) the space between the material rate for a certain value. On the premise of the above several assumptions and established a heat transfer model of rotary kiln by external heating the model including rotary kiln, the material bed and gas phase model of the three points. Rotary kiln model is mainly used to describe rotary kiln wall, gas phase and material bed between the heat conduction, convection and radiation; Material bed model is mainly used to analyze material movement process, material and material of the heat transfer process between particles in the decomposition process of organic compounds; Gas phase, and the high temperature flue gas flow process is complicated and containing gas radiation,

turbulent flow generated by the integrated process and combustion phenomena, Marias F using a series of mathematics to describe the complex flow process. Finally we use the Fluent and Matlab Software to solve the comprehensive model. Their results are introduced in detail in the analysis in the process of calculation steps, methods and method and procedure to realize the data exchange between the related Software. Through the modeling analysis and iteration, to predict the three dimensional temperature field in the rotary kiln, the distribution of gas phase in the composition of the three dimensional concentration field, the model calculated data compared with data obtained from Pechiney research structure experiment found that has good alignment, the accuracy of the model was verified.

This study that simulates the flame temperature field was analyzed by the Software of fluent, using gambit Software to divide the finite element mesh, then into the fluent module of ANSYS in Workbench to make combustion simulation.

Selected the  $k-\varepsilon$  turbulence model in the analysis process, it was to analysis with chemical component transmission module after activated the energy equation. It was to start calculate after defined the material of fluid and boundary conditions, set the relaxation factor and the number of iteration, the calculated combustion flame temperature nephogram as shown in Fig. 1, the temperature, the approximate shape and high temperature flow distribution of the flame can be seen directly from the temperature nephogram. The advantage of taking this simulation method is that we can see the temperature nephogram everywhere of flame, so it is more persuasive to use this way for simulation.

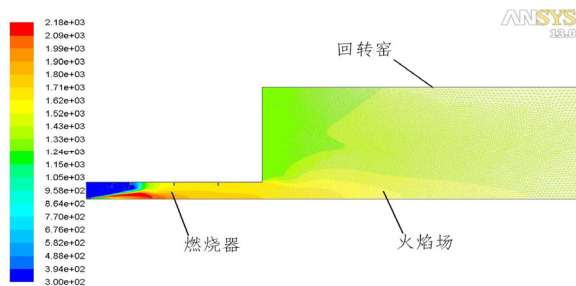


Fig. 1. Uses FLUENT Software to simulate the flame temperature images.

## 2. Analysis the Characteristics of Flame which was Produced by Different Flame Burner

There are many burner styles being used in industrial, in general can be divided into two categories that is direct and swirl, exit flow of the DC burner is direct jet, and the exit flow of swirl burner is rotating jet. The effect of swirl burner is better than DC burner combustion, but the structure is more

complex and manufacturing cost is higher, so usually considering the needs and economic conditions to select the appropriate burner.

Rotary kiln burner commonly used the coal and gas mixing combustion burner in the actual production. Its characteristics: convenient adjust, flexible operate, ejection velocity of each channel can be adjusted according to the demand in operation, it can obtain any degree flame in different need conditions and the calcination temperature is easy to control. Gas combustion system consists of a burner, control valve, adjusted the rate of flow when the gas through the pipeline to the control valve, then input the rotary kiln burner and mix with the first and second combustion-supporting air to burn. The system is flexible for the gas flow adjustment, the entire system consists of a hollow sleeve and a spiral deflector body, gas and combustion air in the burner channel formed dc or swirl to mix evenly, the combustion effect is ideal, at the same time through controlling the speed of the burner inlet air so that the flame shape can independently regulate.

Currently the structures of rotary kiln burner are the following:

- 1) Simple premixed burner;
- 2) Cylindrical burner;
- 3) Three channel burner;
- 4) Four channel burner.

The coal, gas mixed burner that is multi-channel burner structure. Take the same size and speed of fuel inlet, the flame temperature and the shape which was produced by four kinds of burner structure as shown in Fig. 2, Fig. 3, Fig. 4 and Fig. 5 respectively.

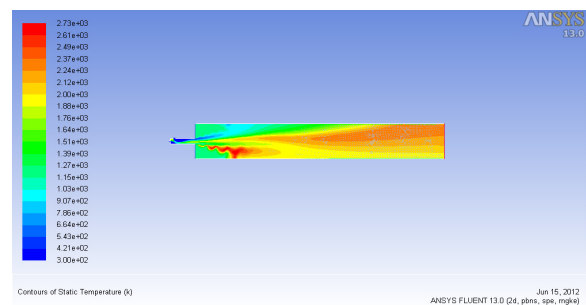


Fig. 2. The flame temperature images of simple premixed burner.

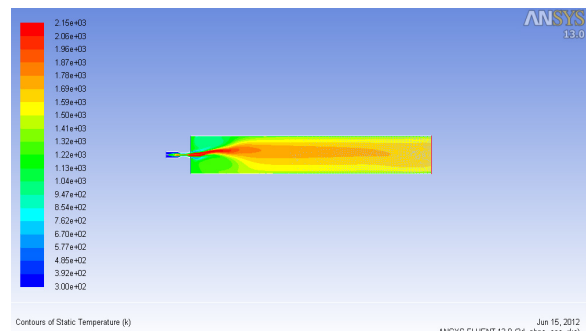


Fig. 3. The flame temperature image of the cylindrical burner.

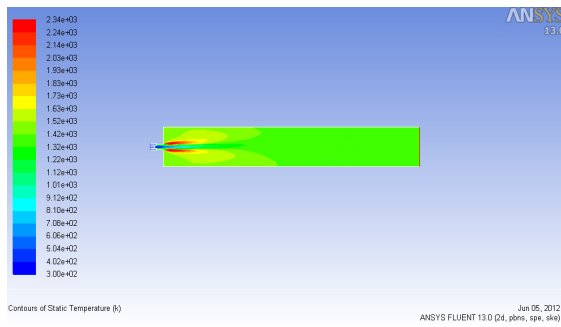


Fig. 4. The three channel burner flame temperature images.

It can be seen from Fig. 2, the maximum temperature of flame which was produced by the simple premixed burner was up to 2730 K, but the flame shape was scattered and there was the phenomenon of flame reflux. It is difficult to control the flame temperature with simple premixed burner and the flame shape is not easy to adjust.

As can be seen from Fig. 3, the cylinder combustion flame temperature was about 2150 K under the same condition of fuel imports, the flame shape was relatively stable, high temperature airflow that was produced by burner was more evenly distributed in the burner radial cross section and the temperature distribution was reasonable.

As we can know from Fig. 4, the flame which was produced by the three channel burner has a hollow phenomenon, and the flame was shorter, airflow temperature was relatively low, but the flame shape was relatively stable.

It can be seen from Fig. 5 the flame which was produced by four channel burner was filled cavity under the same fuel imports condition, the flame is not easy to control, each channel must be reasonable to set the fuel import conditions to get the desired shape of flame. So it is usually used in the pulverized coal combustion, which gas as fuel should not be used.

Through the analysis of flame shape generated by the several burner structures above all, we know that it is more appropriate to select the cylindrical burner structure when the gas as fuel.

### 3. The two-dimensional Model of Rotary Kiln Burner

The study object of this paper is the heat rotary kiln burner of a mine which size is  $\Phi 3M \times 60m$ . It adopts a cylindrical burner with inner diameter of  $\Phi 0.5 m$ , the external size and the boundary conditions of fuel inlet are schematically shown in Fig. 6, the center of the burner is a nozzle with a diameter of 0.012 m. In the process of work, inject the furnace gas to the nozzle with a certain speed into the, the air into the burner with a relatively low speed from the periphery of the nozzle, after the internal mixing to burn.

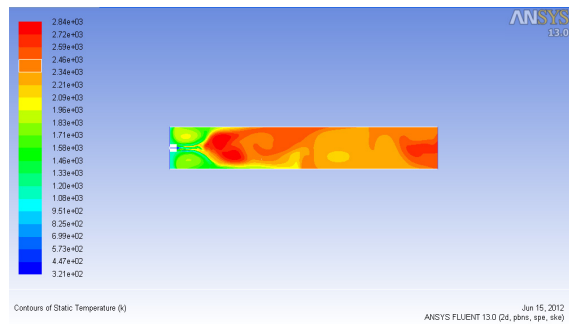


Fig. 5. The four channel burner flame images.

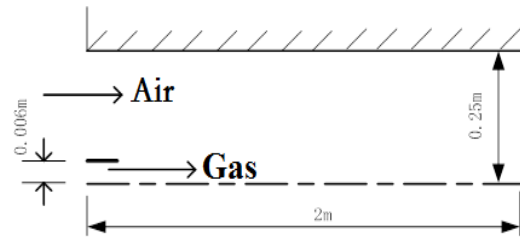


Fig. 6. The external size and the boundary conditions of fuel inlet.

The fuel of the rotary kiln is the gas of generator furnace. The combustion of gas fuel is actually the process of fuel and oxygen occur strong chemical reaction. In essence, the combustion process consists of three stages, namely: the mixture of gas and air; the mix gas heat and ignition; complete chemical reaction and then start normal combustion.

This study makes use of the module of composition transfer and gas combustion in Fluent Software to simulate the process of combustion [15]. According to the three stages of the combustion above, establish the two-dimensional model of rotary kiln burner with the Gambit Software [18] such as shown in Fig. 7.

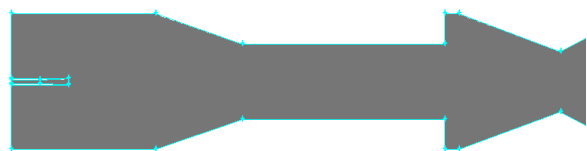


Fig. 7. Two-dimensional model of internal space for burner.

The combustion is not only occurred in the inner burner, it will be further burn in the rotary kiln when fuel burn is not sufficient, therefore, it is not enough to reflect the true of the combustion phenomenon, which establish the model of single burner, the combustion flame may exist in the region should be away from the end of the flame burner within 20 m.

In the premise of not affecting the result of computer, in order to reduce the burden of computer, combine the burner with the rotary kiln model of segment (front 20 m) to analysis the flame temperature field, the established model as shown in Fig. 8.



Fig. 8. Two-dimensional model of the combine burner and rotary kiln.

The temperature is relatively high which close to the end of burner when the rotary kiln is burning, and the temperature gradient changes greatly, so take the reasonable mesh density, which not only can show the temperature field of the flame, also want to minimize the number of mesh, and improve calculation efficiency. It is to achieve this goal by the function of mesh in Gambit Software, first meshing of the gas inlet/outlet, outer wall of burner and each boundary, then dividing surface mesh for the entire computational domain. In order to see the mesh density distribution of the computational domain, Fig. 9 shows only a portion of the combustion computational domain.

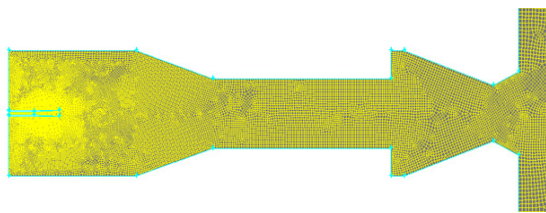


Fig. 9. The finite element mesh of the combustion calculation domain.

#### 4. The flame field analysis with different type of fuel and velocity of gas inlet.

In order to analyze the effects of flame field with the different type of fuel and velocity of gas inlet, for combustion analysis with different kinds of inlet velocity of fuel and air when the coal gas as fuel and ensure the fuel gas can be fully burned; then take the methane as fuel for the combustion simulation, compared the flame field that produced by two different kind of fuel, and analysis of their characteristics.

Take the coal gas as fuel, only changing the velocity of fuel inlet for analysis and other conditions remain. Take the two-dimensional finite element model into the fluent, the gas inlet velocity was set 100m/s, 80 m/s and 60m/s to simulate the calculation [13]. Obtained the flame temperature contours respectively as shown in Fig. 10, Fig. 11 and Fig. 12.

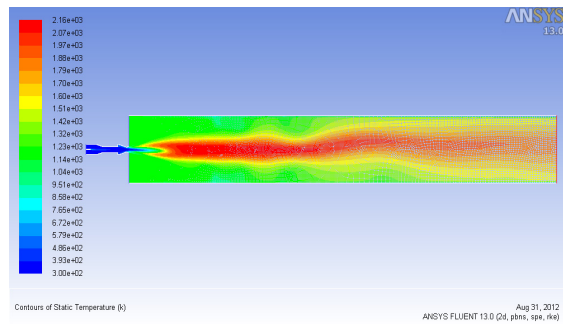


Fig. 10. Flame images of coal gas in inlet velocity of 100 m/s.

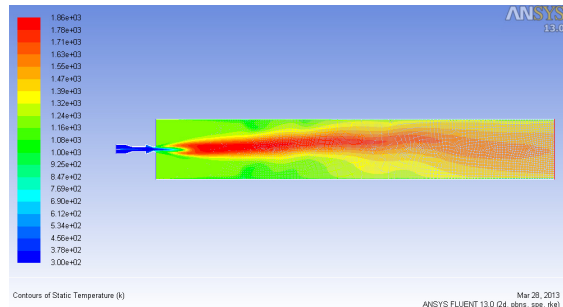


Fig. 11. Flame images of coal gas in inlet velocity of 80 m/s.

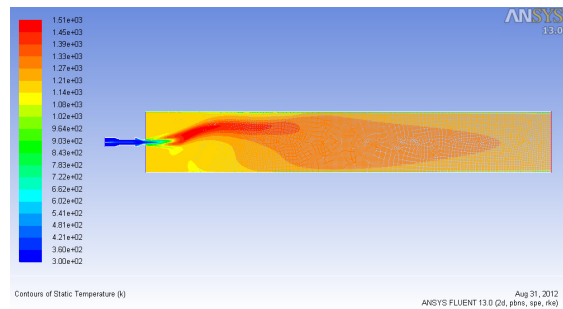


Fig. 12. Flame images of coal gas in inlet velocity of 60 m/s.

In order to make the result of analysis is more convincing, in the premise of the normal combustion, selected more of fuel inlet velocity to simulate, then reading the obtained data into the Matlab Software to process [14], the curve of relationship of fuel inlet velocity and flame temperature as shown in Fig. 13.

As can be seen from Fig. 10 combustion flame temperature is up to 2160 K, the flame shape is more slender and relatively stable; As can be seen from Fig. 11 combustion flame temperature is up to 1860 K, the flame shape is more slender and relatively stable; As can be seen from Fig. 12 maximum flame temperature is 1510 K, the flame shape is short and the flame deviation from center. Comparative the result of analysis that we can say the velocity of gas inlet is larger, the shape of flame is more stable, and

is not easy to deviate. We can see from the Fig. 13 that the velocity of fuel inlet is greater and the temperature of flame is higher in the condition of fully burn [16]. It is also found that we cannot get the desired flame form which means abnormal combustion when the velocity of fuel inlet more than 160 m/s or less than 40 m/s in the simulation experiment.

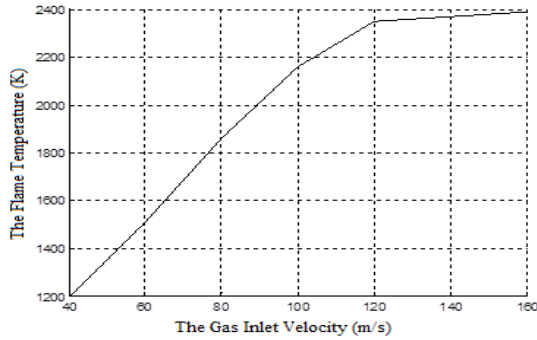


Fig. 13. The curve of relationship of fuel inlet velocity and flame temperature.

The gas inlet velocity 100 m/s unchanged, only to change the air inlet velocity with respectively set 16 m/s, 18 m/s, 20 m/s to simulation analysis [17], the flame temperature images of three speeds are shown in Fig. 14, Fig. 15 and Fig. 16.

In the premise of the normal combustion, selected more of fuel inlet velocity to simulate, then reading the obtained data into the Matlab Software to process, the curve of relationship of gas inlet velocity and flame temperature as shown in Fig. 17.

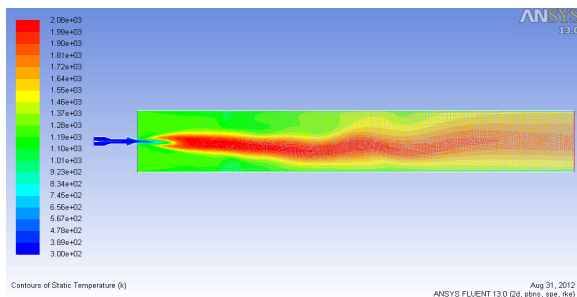


Fig. 14. Flame images in air inlet velocity of 16 m/s.

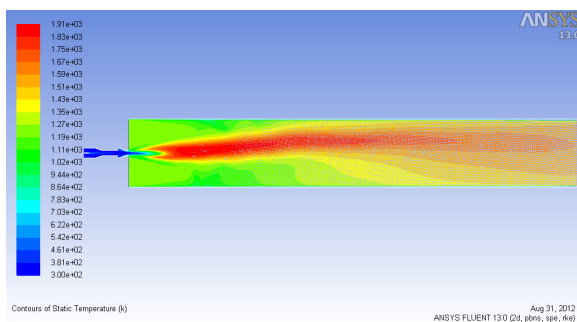


Fig. 15. Flame images in air inlet velocity of 18 m/s.

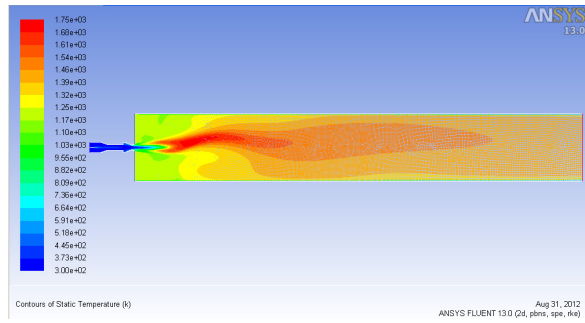


Fig. 16. Flame images in air inlet velocity of 20 m/s.

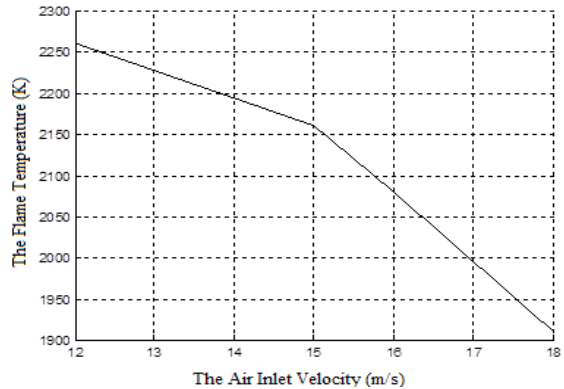
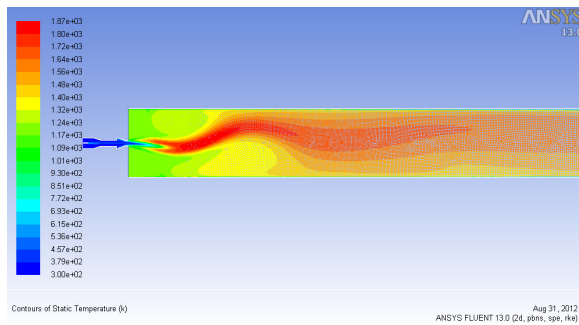


Fig. 17. The curve of relationship of gas inlet velocity and flame temperature.

As can be seen from Fig. 14, the maximum flame temperature is 2080 K, the flame shape is slender and slightly distorted; as can be seen from Fig. 15, the maximum flame temperature is 1910 K, the flame shape is slender; as can be seen from Fig. 16, the maximum flame temperature is 1750 K, and flame shape is shorter. Comparative Figs. 14 to 16, we can found that the flame length gradually shortened with the air inlet velocity increases when the fuel inlet velocity is constant, in the premise of the normal combustion. As you can see from Fig. 17, the velocity of air inlet is greater and the temperature of flame is lower, but the air inlet velocity is too large or too small can't get ideal flame form.

Using methane as a fuel, the velocity of methane inlet has been set 100 m/s to simulate for guarantee the energy consumption does not change, obtained the flame images as shown in Fig. 18 when the air inlet velocity of 20 m/s. As can be seen from the figure, the maximum flame temperature is 1870 K, the flame shape is shorter, and there is a greater distortion.

Comparing Fig. 16 and Fig. 18, we can see the difference with coal gas and methane as fuel for combustion. The flame temperature of methane combustion is relatively slightly higher, and the flame shape is more slender, but the high temperature flow generated by the two kinds of fuel is not very different. So we can substitute the methane for gas as fuel in the combustion condition is not very strict requirements.



**Fig. 18.** The flame cloud of air inlet velocity is 20 m/s when methane as fuel.

## 5. Conclusions

Through simulate the inlet velocity of different fuel and different air of the rotary kiln cylindrical burner, it is found that the gas inlet velocity is greater the temperature is higher, and the velocity of air inlet is greater and the temperature of flame is lower, it indicate that reasonable selection of fuel inlet velocity and the inlet velocity is very important influence on the flame temperature and the heat flow in the combustion condition; in not strict requirements, we can use the gas instead of coal gas as fuel. At the same time, make a theoretical guidance for the actual production.

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