NUMERICAL STUDY ON LADLE BAKING PROCESS OF OXY-FUEL COMBUSTION

by

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Ladle baking technology is a widely adopted method in the iron and steel industry. For reducing defects such as centre segregation of billet, it is crucial to minimize the heat loss of molten steel; maintaining a high drawing speed and low superheat during the continuous casting process. Nevertheless, it is well known that the traditional air combustion ladle baking technology suffers from high energy consumption and severe pollution problems. On the other hand, the oxy-fuel combustion technology where fuel combustion is supported by pure oxygen offers many attractive advantages, including high theoretical combustion temperature, low flue gas emission, and enhanced heat transfer of gas radiation. Unfortunately, up to date, limited researches have been carried to understand the potential of the technology. In the present study, a 3-D mathematical model has been established considering the details of turbulent combustion behaviour and its coupling effects on the heat transfer phenomenon during ladle baking process. Considering the difference between gas radiation in oxygen-enriched combustion and the traditional air-assisted combustion, a modified weighted sum of gray gases model were introduced and compared with the conventional model. Based on the established mathematical model, the operation efficiency of the oxy-fuel combustion and air combustion technologies were studied in details. Numerical results show that the oxy-fuel combustion is more efficient and achieves a potential fuel savings of 41.6%.

Keywords: *energy consumption, oxy-fuel combustion, ladle baking, mathematical model, heat transfer*

Introduction

With the acceleration of China's urbanization and the adjustment of industrial energy demand structure, China's energy consumption shows a rapid growth. Energy efficiency, emission reduction and green development have become the main goals of all aspects in China. The energy consumption of China's iron and steel industry accounts for about 10% of China's total energy demand, while the steel industry alone accounts for 17% emissions and 10.75% of effluent [1]. Therefore, the metallurgical industry has put forward higher requirements for energy conservation and emission reduction.

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Process optimization and energy consumption minimization became the research focus of China's iron and steel industry. Ladles are used to transport the molten steel refined outside the furnace to the continuous casting process. Ladles need to be baked before use, which not only makes the temperature of molten steel stable, but also enables continuous casting at low superheat. Continuous casting under low superheat not only improves drawing speed and reduces accidents, but also increases slab quality, eliminates the cavity shrinkage at the centre and reduces segregation [2]. The development of ladle baking technology took place through four stages. In the first stage, the casing ladle baking device was adopted. The combustion in the bushing ladle baking unit was assisted by air, which had problems such as uneven heating and incomplete combustion. In the second stage, the self-preheating ladle baking machine could save 15% fuel, but the recovery of waste heat is incomplete. In the third stage, the high-speed burner ladle baking machine greatly improved the baking efficiency, but the burners' life was short and produced a lot of noise pollution. In the fourth stage, regenerative ladle baking machine was adopted, which is currently embraced by most steel mills in China. This method improves waste heat recovery, but has low baking efficiency, high crushing rate of heat accumulator, and high construction and maintenance costs [3-6]. In view of existing problems, some engineers highlight the use of oxy-fuel combustion method for ladle baking. Theoretical temperature of oxy-fuel combustion flame is higher, while the flue gas volume is smaller and carries away less heat. Combustion products are mainly CO_2 and H_2O, which enhances radiation heat transfer along with heat dissipation [7-10]. However, in oxy-fuel combustion, high combustion temperature leads to the high temperature of the burner, which in turn shortens the life of burner and causes safety problems [11]. Meanwhile, the efficiency of oxygen fuel combustion has yet to be proven.

Since the beginning of the 20th century, the research on ladle has focused on the temperature change of molten steel and refractories. Anurag *et al.* [12] established a CFD mathematical model for ladle temperature prediction and verified the reliability of the model with the data collected from the factory. Gaston *et al.* [13] developed TEMPCU, a software for temperature field and thermal stress field analysis of ladles. The software uses finite element method to establish a 2-D model of ladles, which can analyse the temperature field and stress field of ladles in the stages of preheating, steel loading, refining, transportation, pouring and cooling. With the attention of ladle baking in the later period, the burning way of ladle baking has been constantly updated, people have done more research on the baking process of ladle. Krishnamurthy and Blasiak [14] carried out an oxy-fuel combustion experiments for REBOX-W burners, and their research showed that, under the condition of oxy-fuel combustion, relatively high flame extreme temperature could be obtained, and the increase of flame temperature level also caused the problem of high NO_x emissions, which was mutually verified with Dias *et al.* [15] research results.

In the present study, a 3-D mathematical model has been built considering the combustion and fluid-flow coupled with heat transfer of the ladle baking process. Based on this model, oxy-fuel combustion and air combustion ladle baking technology were compared. The obtained results are of great significance to the application and further development of the oxy-fuel ladle baking process.

Mathematical model

Heating process of ladle baking is composed of three stages, namely small fire stage, medium fire stage and fire stage. According to the characteristics of refractory, each stage corresponds to different fuel consumption and different heating rate. Generally, the final temperature of ladle baking is about 1500 K. The complex physicochemical process occurs in ladle baking device, where combustion is coupled with fluid-flow, heat transfer, mass transfer, chemical reactions and their interactions. This study aims to compare the energy efficiency and advantages of oxy-fuel combustion with air combustion ladle baking processes by numerical simulation. The numerical model was developed based on the commercial CFD package ANSYS FLUENT.

Fluid-flow and heat transfer during the baking process is modelled using conservation equations of mass eq. (1), momentum eq. (2), and energy eq. (3). Stability, economy and accuracy of the standard k-ε model make it suitable for simulation of wide range of turbulent phenomena in industrial flow and heat transfer. Therefore, the standard k-ε turbulence model was used to simulate the turbulent flow in this study. Turbulent kinetic energy and dissipation rate transport equations are given in eqs. (4) and (5):

$$\frac{\partial \rho}{\partial t} + \nabla\left(\rho \vec{\mathrm{v}}\right) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}\left(\rho \vec{\mathrm{v}}\right) + \nabla\left(\rho \vec{\mathrm{v}}\vec{\mathrm{v}}\right) = -\nabla p + \nabla\left[\mu\left(\nabla \vec{\mathrm{v}} + \nabla \vec{\mathrm{v}}^{T}\right)\right] + \rho \vec{\mathrm{g}} \tag{2}$$

$$\frac{\partial}{\partial t}\left(\rho E\right) + \nabla\left[\vec{\mathrm{v}}\left(\rho E + p\right)\right] = \nabla\left(k_{\mathrm{eff}} \nabla T - \sum\nolimits_i h_i \vec{\mathrm{J}}\right) \tag{3}$$

$$\frac{\partial}{\partial t}\left(\rho k\right) + \nabla\left(\rho k \vec{\mathrm{v}}\right) = \nabla\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\nabla k\right] + G_k - \rho\varepsilon \tag{4}$$

$$\frac{\partial}{\partial t}\left(\rho \varepsilon\right) + \nabla\left(\rho \varepsilon \vec{\mathrm{v}}\right) = \nabla\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\nabla \varepsilon\right] + C_1 \frac{\varepsilon}{k} G_k - c_2 \rho \frac{\varepsilon^2}{k} \tag{5}$$

where $E = h - (p/\rho) + (v^2/2)$ is specific heat capacity, h – the enthalpy, $h = \Sigma_i Y_i h_{\mathrm{i}}$.

The one-step reaction mechanism is adopted for the combustion process. Considering that the reaction rate of the eddy-dissipation model is controlled by the turbulent mixing, the eddy-dissipation model is used in present study. The P-1 model is chosen for the radiation modelling because it consumes less computational resources, takes scattering into account, and is more stable for combustion model with larger optical thickness:

$$\frac{\mathrm{d}I\left(\vec{\mathrm{r}},\vec{\mathrm{s}}\right)}{\mathrm{d}x} + \left(a + \sigma_s\right) I\left(\vec{\mathrm{r}},\vec{\mathrm{s}}\right) = a n'^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi}\int_0^{4\pi} I\left(\vec{\mathrm{r}},\vec{\mathrm{s}}'\right)\Phi\left(\vec{\mathrm{s}},\vec{\mathrm{s}}'\right)\mathrm{d}\Omega' \tag{6}$$

The combustion in ladle baking process is non-premixed combustion, and the gaseous fuel and combustion gas enter the combustion zone, respectively. Heat transfer in the baking process mainly depends on radiation and convection, while radiation heat transfer takes up the main part. The basic radiation parameters in this study, namely the gas absorption coefficient, were calculated by the weighted sum of gray gases model (WSGGM) of radiation characteristics [16, 17]:

$$a = -\frac{1}{L}\ln\left(1 - m\right) \tag{7}$$

$$m = \sum_{i=0}^{I} a_i\left(T\right)\left(1 - \mathrm{e}^{-f_i PL}\right) \tag{8}$$

$$a_i(T) = \sum_{j=1}^{J} b_{i,j}\left(\frac{T}{T_{\text{ref}}}\right)^{j-1} \qquad i = 1,\ldots,I$$
$$I = 4, \quad J = 4, \quad T_{\text{ref}} = 1200\ \text{K} \tag{9}$$
$$f_0 = 0: \text{represents windows in the spectrum; } a_0 = 1 - \sum_{i=1}^{I} a_i > 0$$
$$P: \text{sum of the partial pressures of all of the participating gases } [\text{atm}]$$

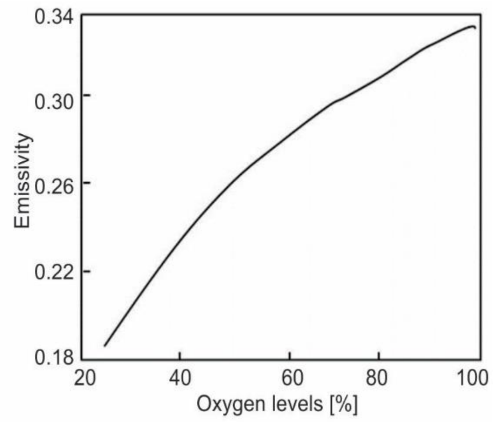


Figure 1. The relation curve of flue gas emissivity and combustion oxygen concentration

The WSGGM can be easily combined with the solution method of any form of radiation transfer equation, while pertaining high calculation efficiency. As oxy-fuel combustion is adopted, the combustion products are mainly CO_2 and H_2O, and the concentration has a certain impact on the absorption coefficient. Figure 1 shows the change trend of emissivity with the oxygen concentration. The emissivity increases with the oxygen concentration, and the rising rate decreases gradually, but the overall value increases. Oxy-fuel combustion is different from the traditional combustion mode, and the concentration of combustion products has a significant impact on the radiation and heat transfer process in the whole baking area.

The calculation accuracy of the traditional WSGGM model can only be maintained under the condition of $CO_2 + H_2O < 30\ \%$ [18]. The calculation error is relatively large under the conditions of oxy-fuel combustion, meaning high share of CO_2 and H_2O, and their pressure ratio. Thus, a modified WSGGM has been developed by UDF based on recent literature data [19]. The specific steps of modifying WSGGM model are shown in fig. 2.

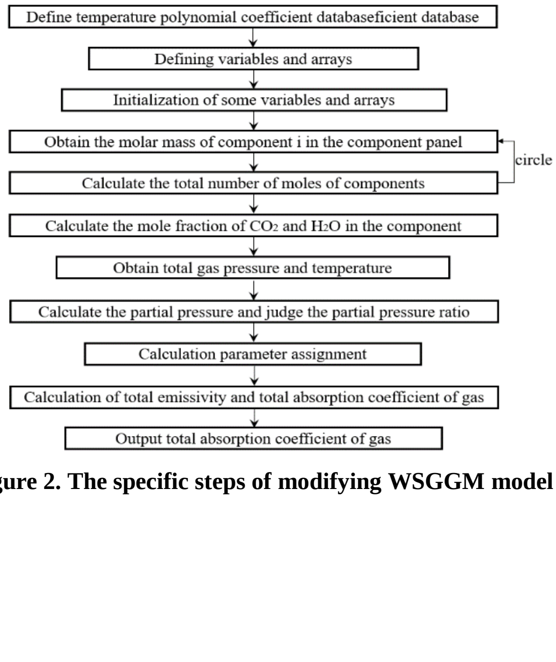
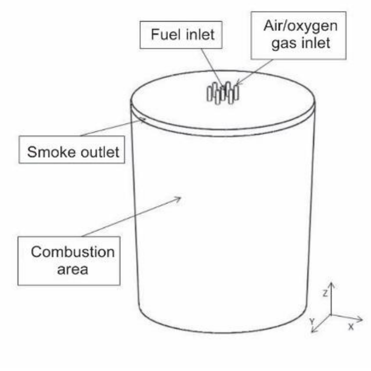
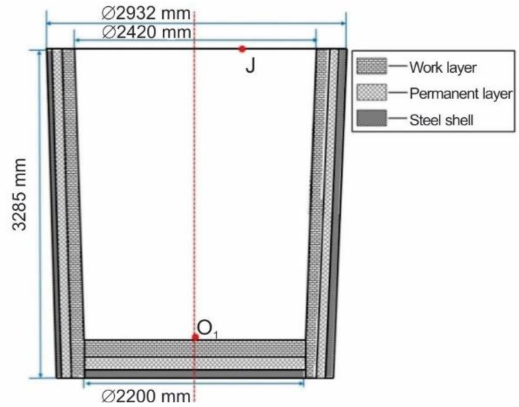


Figure 2. The specific steps of modifying WSGGM model

Computational domain and mesh generation

Figure 3(a) represents a schematic diagram of the whole ladle baking device. The upper part is the burner, the lower part is the combustion area. The burner is composed of seven round nozzles with diameter of 40 mm, of which the nozzle in the middle is the fuel channel, while others are the combustion-supporting gas channels. The flue gas outlet is located in the upper half of the ladle and is a ring area with a height of 100 mm. The overall size of the ladle is shown in fig. 3(b). The co-ordinates of temperature monitoring point J and O_1 are (450, 0, 2900) and (0, 0, 385). The ladle wall is composed of working layer, permanent layer and steel shell. The materials and dimensions of each layer are shown in tab. 1.





(a) **(b)**

Figure 3. Schematic diagram of ladle baking device; (a) the overall structure and (b) insulation structure drawing

Table 1. Materials and thicknesses at all layers

Layers	Material	Ladle wall position thickness [mm]	Ladle bottom position thickness [mm]
Work layer	Magnesium carbon brick	135	180
Permanent layer	High alumina brick	85	130
Steel shell	SM490B	36	75

The computational grid is shown in fig. 4. The upper burner adopts non-structural grid and the lower burner adopts structural grid. Through grid independence study it has been shown that the most appropriate mesh is the one consisting of 680 000 volumes, and the following numerical simulation is carried out based on this grid.

Operation parameters and boundary conditions

All operating parameters in the numerical simulation process are set according to the field data. The whole baking process is divided into three stages according to the heating system, and each stage includes heating and holding process, as shown in fig. 5. Fuel is natural gas with the composition shown in tab. 2. The whole simulation process is carried out in strict accordance with the temperature curve shown in fig. 5. The combustion gas flow rate defined according to the temperature requirements of different heating stages. The corresponding flow rates of fuel, oxygen and air are shown in tab. 3.

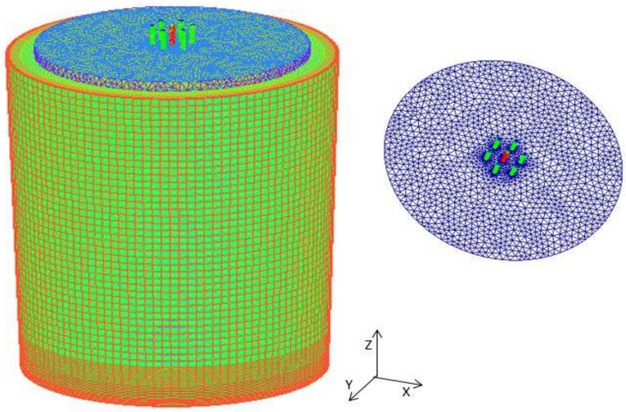


Figure 4. Grid of computational domain

Due to the fluid-solid coupling method for simulation, the corresponding refractory material properties need to be set accurately as shown in tab. 4. According to the field test, in the ladle baking process, the final temperature of the rigid ladle wall is higher, so the heat transfer between the ladle wall and the external environment needs to be taken into account. The radiation heat transfer between ladle and environment is converted into natural convection heat transfer by empirical formula [20].

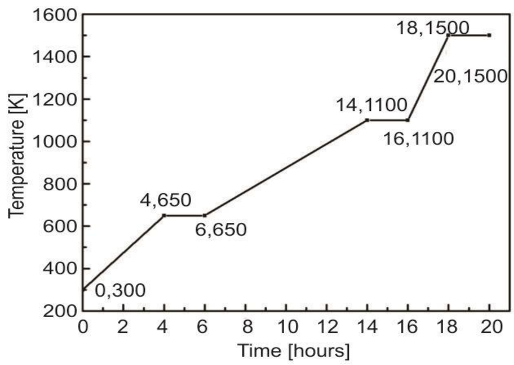


Figure 5. Heating curve of the baking process

Table 2. Composition of natural gas

Species	CH_4	CnHm	CO	H_2	O_2	N_2	H_2S	CO_2
Fraction	85	8.5	0.3	0.7	0.2	4	0.3	1

Table 3. Fuel and combustion gas flow rate

Fuel and gas	Fuel flow rate [Nm^3h^{-1}]	Oxygen flow rate [Nm^3h^{-1}]	Air-flow rate [Nm^3h^{-1}]
The first stage	14.2	31.2	153.3
The second stage	28.5	62.4	305.8
The third stage	57	124.8	611.8

Table 4. The Material size and properties

Material	Density [kgm^{-3}]	Specific heat capacity [$Jkg^{-1}K^{-1}$]	Coefficient of thermal conductivity [$Wm^{-1}K^{-1}$]
Magnesium carbon brick	2900	750	2.1
High alumina brick	2380	857	1.22
SM490B	7830	480	56

Results and discussions

Model validation

In this paper, the on-site monitoring data in literature [21, 22] were used to validate the model. The test conditions in the literature were coke oven gas baking under air combustion. The fuel gas flow rate is 430 m^3/h and air temperature equal to 300 K. The temperature along the inner side of the envelope wall is tested, and the detection points are A, B, C, D. The comparison of simulated temperature and the actual measured temperature at the monitoring points is shown in tab. 5. It can be seen that the temperature decreases gradually along the bottom of the ladle, and the relative error at monitoring point A is large. Since this monitoring point is located at the centre of the ladle bottom, the flame may have random deviation in the actual combustion process. The comprehensive analysis shows that the calculation error is within a reasonable range, which proves the accuracy of the mathematical model. So, the model can be used for the subsequent calculation in this study.

Table 5. The measured values and the simulated values

Temperature measuring points	A	B	C	D
Measured values [K]	1558	1485	1432	1383
Simulation values [K]	1659	1427	1372	1325
Relative error [%]	6.5	–3.9	–4.1	–4.2

Modified comparison of WSGGM

Oxy-fuel combustion strongly promote radiation heat transfer, as a result of the much higher content of CO_2, H_2O, and in-flame soot, as well as the different CO_2/H_2O ratio compared to air combustion [19]. In order to accurately simulate the radiative heat transfer of the gas, gas absorption coefficient should be known. For the traditional WSGGM model, when the concentration of H_2O and CO_2 is greater than 30%, the predicted absorption coefficient will have a large error. Therefore, the absorption coefficient in present model was calculated by a modified WSGGM model based on a relevant literature, in which the accuracy of the model was verified. The simulation results of the modified WSGGM model and the traditional WSGGM model were compared. fig. 6 shows the temperature rising curve at the monitoring point J in the second stage of baking. Because the modified WSGGM model refines the partial pressure ratio of CO_2 and H_2O, it can accurately predict the gas absorption coefficient under the condition of high concentration of CO_2 and H_2O. The simulation results show that the temperature calculated by the modified model is higher than that of the traditional one, and the fluctuation range is 12-14 K.

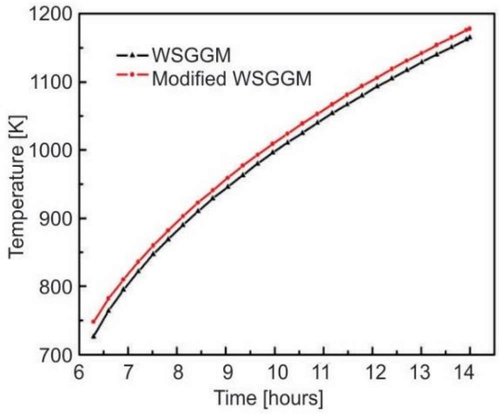


Figure 6. Temperature rise curve of the monitoring point J under two WSGGM models

Comparison of oxy-fuel combustion and air combustion

The oxy-fuel combustion and air combustion baking methods are carried out with the same baking time, and the results are compared and analysed. The whole baking process is divided into three stages, and the temperature distributions at the end of each stage are shown in figs. 7 and 8.

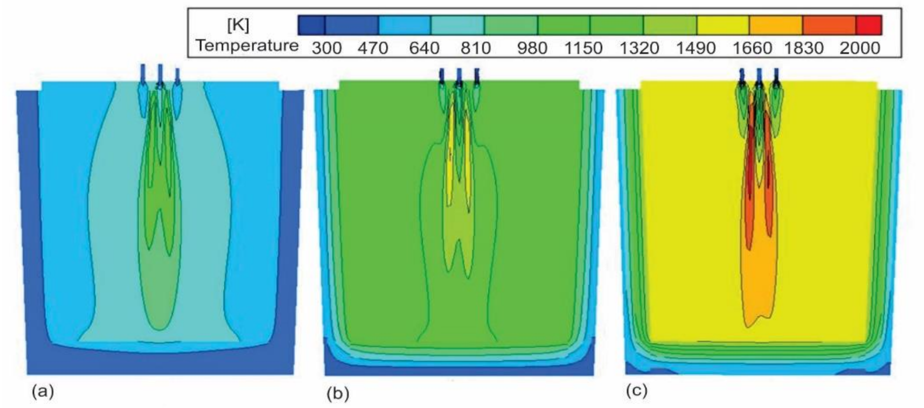


Figure 7. The temperature distribution of oxy-fuel combustion: (a) first stage, (b) second stage, and (c) third stage

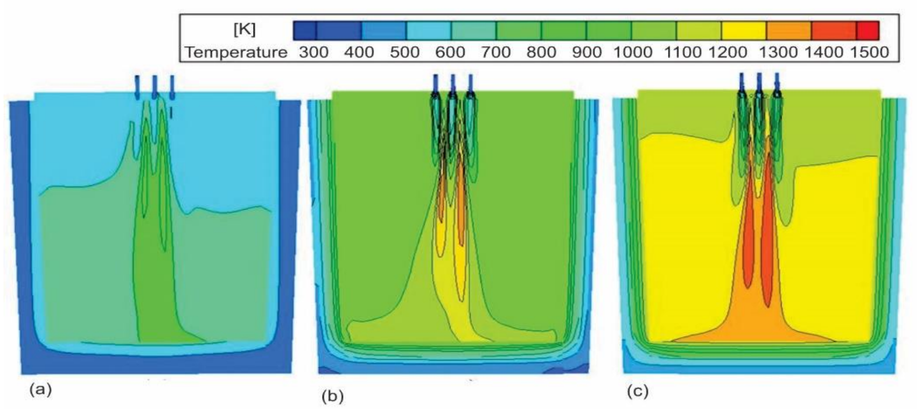


Figure 8. The temperature distribution of air combustion: (a) first stage, (b) second stage, and (c) third stage

By comparing those figures, it can be seen that oxy-fuel combustion flame temperature is higher, and flame length is shorter. According to the heating curve of monitoring point J in fig. 9, It can be observed that the temperature of oxy-fuel combustion at each stage is higher than that of air combustion with the same amount of fuel and the same heating time. At the first stage, the temperature of oxy-fuel combustion is 96 K higher than that of air combustion, 200 K higher at the second stage, and 351 K higher at the third stage. By calculation, the oxy-fuel combustion can save 41.6% of fuel compared with air combustion. Depending on the slope of the curve of the first stage, it can be found that the heating rate of the two combustion modes is almost the same, but at the second stage, the heating rate of the oxy-fuel combustion mode is higher than that of air combustion. Therefore, the oxy-fuel combustion is more suitable for the requirement of rapid heating.

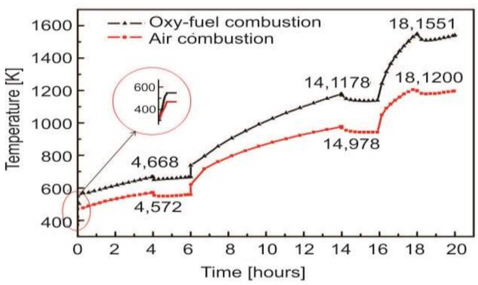


Figure 9. Temperature curves of combustion zone at the monitoring point J

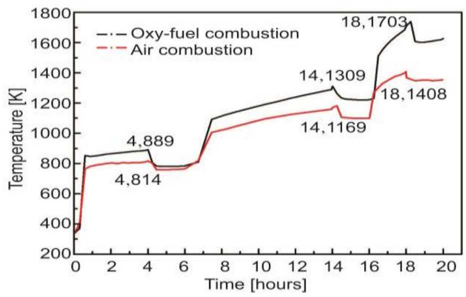


Figure 10. Temperature curve at the monitoring point O_1

Figure 10 is the temperature curve at the monitoring point O_1. Monitoring point O_1 is located at the centre of working layer at the bottom of the ladle. The temperature at this point is important for the safety of the whole baking process because it's directly impacted by the high temperature flame. The temperature is always higher in oxy-fuel combustion compared to that of air combustion. At the end of baking, the temperature is 1703 K for oxy-fuel combustion and 1408 K for air combustion. Therefore, it is necessary to control the length of the flame when burning with oxy-fuel to avoid the harm caused by high temperature at the bottom of the ladle.

Conclusion

In this study, a 3-D mathematical model has been built considering combustion and fluid-flow coupled with heat transfer of the ladle baking process. A modified WSGGM was applied to simulate the absorption coefficient of radiation model when the oxygen content in the auxiliary gas is more than 30%. The oxy-fuel combustion enhanced the heat transfer of gas radiation and it is suitable for rapid heating ladle. The temperature field simulated by the modified WSGGM model is 12~14 K higher than that simulated by traditional WSGGM model. To achieve the same baking effect, using pure oxygen combustion can effectively reduce fuel consumption, and the fuel saving rate is up to 41.6%. Oxy-fuel combustion ladle baking is an energy-saving burning method, but special attention should be paid to control the length of the flame to achieve the best baking efficiency.

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Nomenclature

$b_{i,j}$	– new parameters for mod. WSGGM model	L	– beam length
C_1, C_2	– constants in the k-ε two-eq. turbulent model	m	– total emissivity
E	– specific heat capacity	n	– refractive index
f_i	– new WSGGM parameter	p	– pressure
G_k	– turbulence kinetic energy produced by mean velocity gradient	$\vec{r}$	– position vector
		$\vec{s}$	– direction vector
$\vec{g}$	– gravitational vector	$\vec{s}'$	– scattering direction vector
h	– enthalpy	T	– temperature
I, i, J, j	– data-fitting parameter	t	– time
$\vec{J}$	– diffusion flux of species	$\vec{v}$	– velocity vector
k	– turbulent kinetic energy	v	– velocity
k_{eff}	– effective conductivity		

Greek symbols

α – absorption coefficient
μ – viscosity
μ_t – turbulent viscosity
Ω' – solid angle
ρ – density
σ – Stefan-Boltzmann constant
σ_S – scattering coefficient
$\sigma_k, \sigma_\varepsilon$ – Schmidt number for k and ε

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