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The 3-D Numerical Simulation of a Walking Beam Type Slab Heating Furnace with Regenerative Burners

Jiin-Yuh Jang, Chien-Nan Lin, Sheng-Chih Chang, Chao-Hua Wang

Abstract: ***This study investigates the furnace thermal efficiency for a walking-beam type slab heating furnace with regenerative burners. The walking-beam type heating furnace is composed of five zones, namely, flameless, preheating, first heating, second heating and soaking zones with regenerator efficiency 90 %. The furnace uses a mixture of coke oven gas as a fuel to reheat the slabs. The numerical model considers turbulent combustion reactive flow coupled with radiative heat transfer in the furnace. It is shown that with regenerator burners, the furnace thermal efficiency is 72%, which is significantly higher than that of a furnace using the conventional burner without regenerator. Comparison with the in-situ experimental data from steel company in Taiwan shows that the present heat transfer model works well for the prediction of thermal behavior of the slab in the reheating furnace with regenerator burners.***

Keywords: Reheating Furnace, Combustion, Radiative Heat Transfer, Regenerative burner

I. INTRODUCTION

In steel factories, the reheating furnace is used to reheat the steel slabs before the hot-rolling process. The walking beam type furnace comprises flameless zone, preheating zone, first heating zone, second heating zone, and soaking zones. The heat energy is released via the combustion reaction of the COG injected into the heating and soaking zones. The regenerative furnace burners are installed pairs at opposite side of the furnace wall. The fuel and fresh air are injected into the furnace via one-half the total of burners for combustion. About 80 percent flue gas is absorbed to heat the spherical regenerator by the other one-half regenerative burners at the opposite side. The remains of 20 percent flue gas flow directly to the furnace outlet. The burners change its function from being an injector to being an absorber periodically; the switching time is about 30-120 second. The heat energy of flue gas is stored in the spherical regenerator in the absorbed period, and released in the injection period. Accordingly, the regenerative type of reheating furnace is expected to improve the thermal efficiency of the furnace by increasing the temperature of inlet air to achieve the goal of carbon emission reduction and green production.

Many studies of heat transfer performance and temperature distribution of slab in a reheating furnace with regenerator were discussed in recent years. Ishii et al. [1] indicated that the heating efficiency can be over than 70%, and the low NOx emission in the furnace can be achieved, even the inlet air is preheated to 1573 K. It is found that the air/fuel injection velocity ratio affect significantly on the NOx production rate in the furnace. Suzukawa et al. [2] revealed that the heat storage capacity of the honeycomb regenerator is higher than that of the spherical regenerator, and its size and weight is smaller. Compared to the reheating furnace without heat recovery device, the reheating furnace with regenerative burner saves the fuel about 40 percent. It is 10% to 15% while compared to the reheating furnace with recuperative device. Kim et al. [3] adopted the software FLUENT to simulate heat transfer performance in a reheating furnace. They revealed that the heat energy impinged on the slab surface is dominated by the radiation heat transfer, estimated to be about 95 percent, while the remains is by the convection heat transfer. Ishii et al. [4] discussed the temperature distribution of slab in a reheating furnace with regenerator. They depicted that the flue gas temperature is uniform and the thermal efficiency is promotive in the regenerative furnace. Rafidi et al. [5] utilized the effectiveness-NTU method to calculate the thermal efficiency and design of optimum size with honeycomb regenerator, the results indicated the fuel usage is saved for the regenerator burners. Ou et al. [6] discussed three switching time mode of the burner nozzle in a three-dimensional transient model for reheating furnace. They are partial same side switching mode, same side switching mode, and cross switching mode, respectively. The simulation results showed the best outlet temperature of steel slabs was achieved by adopting the cross-switching mode. Han et al. [7] utilized the software FLUENT combined with a user defined functions to simulate the periodically transient movement of the slabs, and descripted the heat characteristics of the slabs in their unsteady calculation. Han et al. [8] indicated that the injected fuel at the soaking zone must be less than 20% of total fuel mass flow rate to achieve uniformity of temperature of the slab. Morgado et al. [9] studied numerically to simulate periodically transient movement of the slabs, predicted the temperature distribution of slab in furnace. Both the explore combustion calculation method and radiation heat transfer with constant furnace wall temperature method were examined.

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The error between simulated results and measurement values is within 3% for the explore combustion calculation method. By contrast, the radiation heat transfer with constant furnace wall temperature method saved about 5% computation time. Casal et al. [10] also used the software FLUENT combined with a user defined functions to simulate heat conduction phenomenon of the slabs, and used source terms to simulate periodically movement of the slabs in their calculation.

In this study, a three-dimensional numerical transient model is developed to simulate the characteristics of heat transfer and flue gas flow. The temperature distribution of flue gas and slab in the reheating furnace with regenerative burners and conventional type burners are examined with the in-situ data of a five-zone reheating furnace operated at China Steel Corporation (CSC), in Taiwan.

II. THEORETICAL ANALYSIS

A. *Theoretical Model*

The reheating furnace used in CSC has dimensions of 50.6 m in length, 10.8 m in width, 4.8 m in height, and the furnace wall thickness of 0.52 m. There are 38 slabs in the reheating furnace simultaneously; every slab stayed about 240 minutes in the furnace. It has dimensions of 9.6 m in length, 1.25 m in width, and 0.25 m in height. The slabs are supported by the stationary beams and transported to a forward position on the moving beams during every moving period. The schematic diagram of the reheating furnace is shown in Figure 1. In order to reduce huge computational time consumption, the physical model of the walking beam type reheating furnace is simplified as a three-dimensional transient model to simulate the full size furnace. The length of the furnace is considered as 10.2 m, which contained seven slabs in this numerical model as shown in Figure 2. This numerical model considered the heating process for the five heating zone individually. Accordingly, the final temperatures of slabs calculated in each heating zone are transferred to the next heating zone as an initial condition; thus, five boundary conditions are raised in the calculation. Meanwhile, the resident time of each slab in every furnace zone must be consistence with the length of each furnace as listed in the Table 1.

Table 1: The corresponding heating time and the furnace length for each heating zone

	Time (min)	Length (m)
Flameless zone	60	12.5
Preheating zone	54	11.3
First heating zone	54	11.3
Second heating	40	8.5
Soaking zone	32	7
Total	240	50.6

B. *Governing Equations*

This study considers the chemical reaction of gases combustion coupled with the three-dimensional transient turbulent flow in the reheating furnace. The continuity equation, momentum equation, energy equation, and turbulent equations are described as follows：

Continuity equation：

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho \bar{u}_j}{\partial x_j}=0 \qquad (1)$$

Momentum equation：

$$\frac{\partial \rho \overline{u_i}}{\partial t}+\frac{\partial \rho \overline{u_i}\,\overline{u_j}}{\partial x_j}$$

$$=-\frac{\partial \overline{p}}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial \overline{u_i}}{\partial x_j}+\frac{\partial \overline{u_j}}{\partial x_i}-\frac{2}{3}\frac{\partial \overline{u_k}}{\partial x_k}\delta_{ij}\right)-\rho\overline{u_i{}'u_j{}'}\right] \qquad (2)$$

Energy equation：

$$\frac{\partial \rho c_p \overline{T}}{\partial t}+\frac{\partial \rho c_p \overline{u_j}\,\overline{T}}{\partial x_j}=\frac{\partial \overline{p}}{\partial t}+\overline{u_j}\frac{\partial \overline{p}}{\partial x_j}+\overline{u_j{}'\frac{\partial p'}{\partial x_j}}$$

$$+\frac{\partial}{\partial x_j}\left(k\frac{\partial \overline{T}}{\partial x_j}-\rho c_p\overline{u_j{}'T'}-\sum_j h_j\vec{J}_j\right)-\nabla\cdot\vec{q}_{rad} \qquad (3)$$

The high Reynolds $\kappa-\varepsilon_i$ model is employed for combustion gas flow：

$$\frac{\partial \rho\kappa}{\partial t}+\frac{\partial \rho\kappa\overline{u_j}}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\kappa}\right)\frac{\partial \kappa}{\partial x_j}\right]+\rho\left(P_r-\varepsilon\right) \qquad (4)$$

$$\frac{\partial \rho\varepsilon}{\partial t}+\frac{\partial \rho\varepsilon\overline{u_j}}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+\rho\frac{\varepsilon}{\kappa}\left(c_1P_r-c_2\varepsilon\right)$$

(5)

Since the radiation heat transfer dominates the temperature distribution of the slabs and the gases within the furnace, the radiation transfer equations are described as：

$$\left(\vec{s}\cdot\nabla\right)I_r\left(\vec{r},\vec{s}\right)=-\varepsilon_e I_r\left(\vec{r},\vec{s}\right)+\sigma_a I_{r,b}\left(\vec{r}\right)$$

$$+\frac{\sigma_s}{4\pi}\int_0^{4\pi} I_r\left(\vec{r},\vec{s}\right)\Phi\left(\vec{s},\vec{s}\,'\right)d\Omega' \qquad (6)$$

The three-dimensional transient model considers the non-premix combustion for fuel and preheated air in this simulation. The heat energy is generated by the chemical reactions of coke oven gas (COG) combustion, which are described as follows：

$$H_2+\frac{1}{2}O_2\rightarrow H_2O \qquad (7)$$

$$CH_4+2O_2\rightarrow CO_2+2H_2O \qquad (8)$$

$$CO+\frac{1}{2}O_2\rightarrow CO_2 \qquad (9)$$

$$C_2H_4+3O_2\rightarrow 2CO_2+2H_2O \qquad (10)$$

The three-dimensional transient heat conduction governing equation for the temperature field of the steel slab is

$$\rho c_p\frac{\partial T}{\partial t}=\frac{\partial}{\partial x_j}\left(k\frac{\partial T}{\partial x_j}\right) \qquad (11)$$

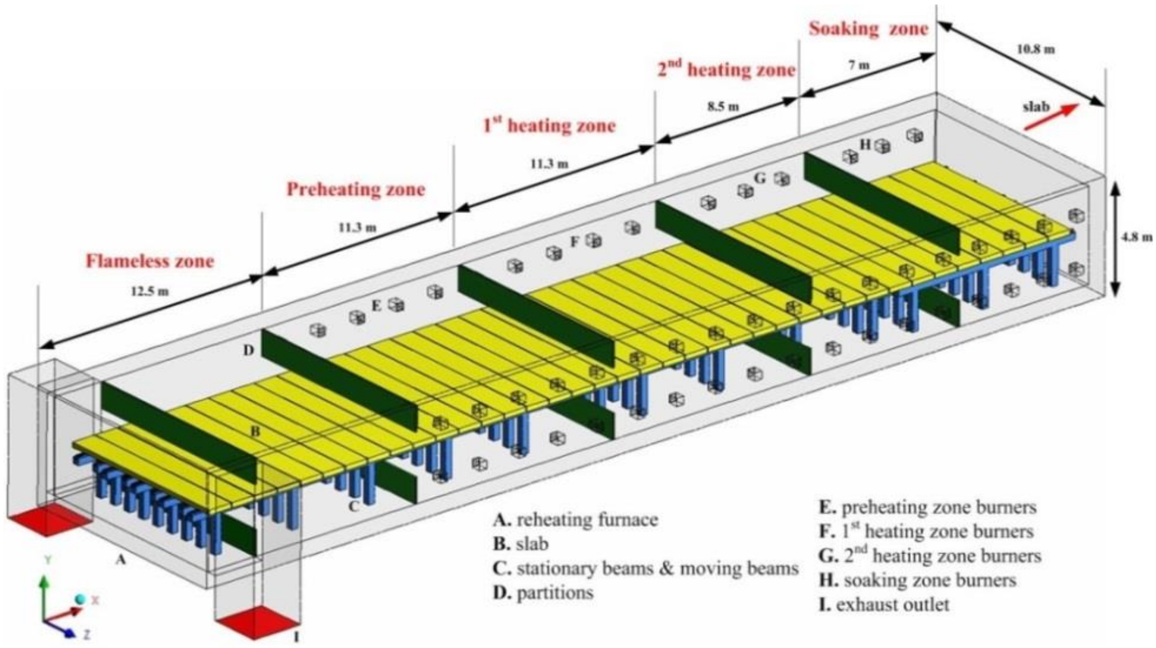


Fig. 1: Schematic diagram of the reheating furnace

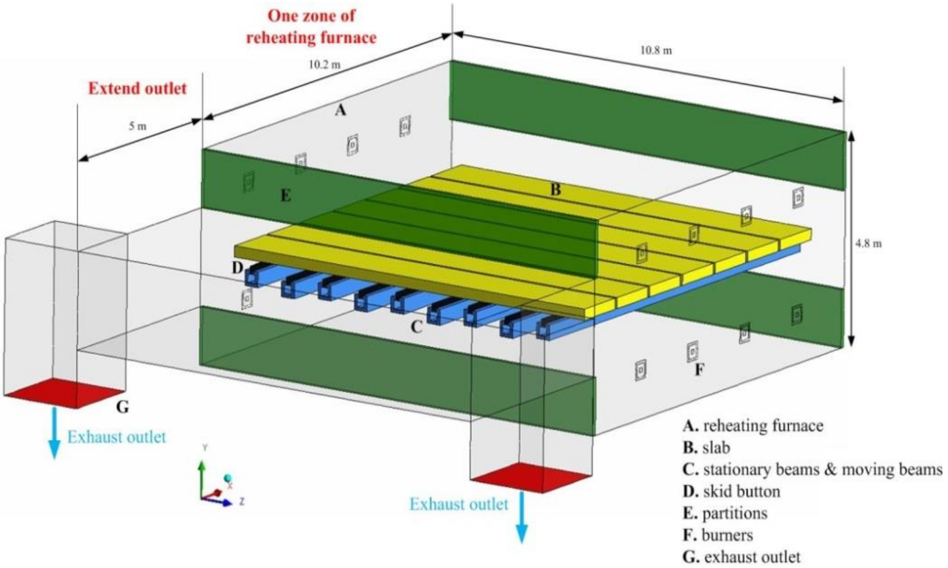


Fig. 2: The simplified three-dimensional physical model

C. Boundary Condition

There are sixteen burners in the preheating zone, first heating zone, second heating zone, and soaking zone, individually. The insulated boundary condition is assumed at the walls, owing to less heat dissipated from the wall [3]. By contrast, the constant furnace wall temperature, 1000 K, is assumed to heat steel slab via radiation heat transfer in the flameless zone. Besides, the stationary and moving beams are considered as heat convection boundary condition, with convective heat transfer coefficient 1000 W/m2-K and water temperature 308K.

(1) Regenerative type of burners：

The inlet temperature of COG and the temperature of outside fresh air are 300K. While the air gains the heat from the regenerating spheres, the temperature is getting higher, and calculated by Eq. (12) as a dynamic boundary condition.

$$T_a^{n+1} = T_a + \varepsilon\left(T_g^n - T_a\right) \qquad (12)$$

Noting that the heat energy stored in the regenerating spheres is come from the 80% of the flue gas as mentioned above. The required fuel and air mass flow rates at each heating zone of furnace are shown in Table 2. Where ε is the thermal efficiency of regenerative burner, T_a is the outside air temperature, it is 300 K, the $T_g^{\,n}$ is the current furnace temperature, and the $T_a^{\,n+1}$ is the corrected temperature of air absorbed the regenerating heat at the entry of furnace.

(2) Conventional type of burners：

The inlet temperature of COG and air are 300 K and 850 K, respectively, at the inlet of 16 burners for the conventional type furnace. Note that the flue gas flows directly to the furnace outlet. The required fuel and air mass flow rates at each heating zone of furnace are shown in Table 3.

Table 2: Total mass flow rate of regenerative type of furnace

	$\dot{m}_f$ (kg/s)	$\dot{m}_a$ (kg/s)
Preheating zone	0.7559	8.4272
1st heating zone	0.5879	6.5545
2nd heating zone	0.2940	3.2773
Soaking zone	0.1176	1.3109

Table 3: Total mass flow rate of conventional type of furnace

conventional	$\dot{m}_f$ (kg/s)	$\dot{m}_a$ (kg/s)
Preheating zone	0.9165	10.210
1st heating zone	0.6499	7.2404
2nd heating zone	0.4271	4.7576
Soaking zone	0.1384	1.5415
Total fuel mass (kg)	6366.03	

III. NUMERICAL ANALYSIS

A. *Mathematics Model*

The governing equations (1)-(3) are coupled with the turbulent equation, species transport combustion equation. The radiation mode adopts the discrete ordinates radiation model, and the weighted-sum-gray-gases model (WSGGM) in the energy equation. The commercial software ANSYS-FLUENT is utilized to solve the above coupled equations. Figure 3 shows the computational grids of the three-dimensional model, which is composed of 1,200,220 cells. The simulations are performed in parallel calculation with sixteen core CPUs, the computer consummation time is around 120 hours. The convergence criterion is defined as:

$$R_{\phi} = \frac{\sum_{cells\ p} \left| \sum_{nb} a_{nb}\phi_{nb} + b - a_p\phi_p \right|}{\sum_{cells\ p} \left| a_p\phi_p \right|} \qquad (13)$$

$$\sum \left| R_{\phi} \right| < 10^{-3}, \phi = u, v, w, \kappa, \varepsilon, P$$
$$\sum \left| R_{\phi} \right| < 10^{-6}, \phi = T$$

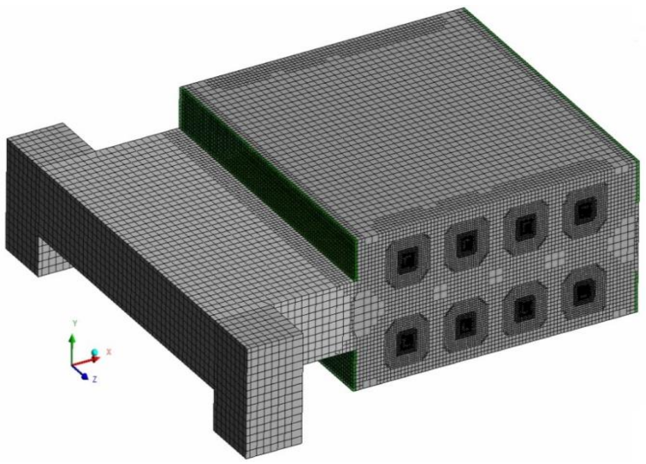


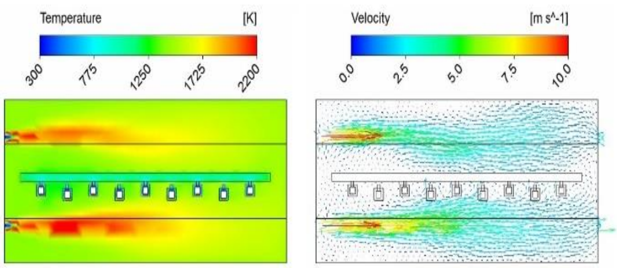
Fig. 3: Computational grid systems for the three-dimensional model

B. *User-Defined Function*

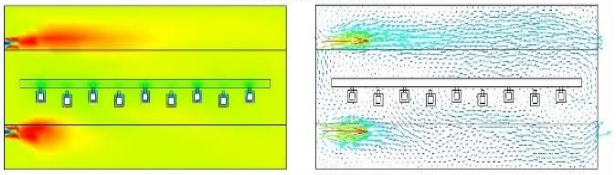
The boundary conditions used in the injection burners of regenerating furnace change periodically; therefore, a user-defined function is utilized to alternate the burners as inlet or outlet boundary condition, the switch time is considered as 60 seconds in this study. Meanwhile, another user-defined function is utilized to calculate the flue gas temperature at every switch time and set the varied air inlet temperature.

IV. RESULTS AND DISCUSSION

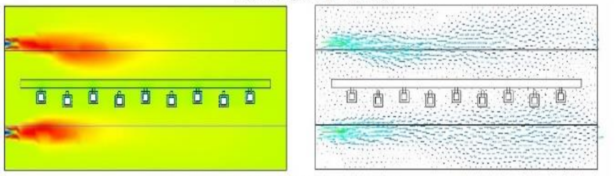
Figure 4 displays the temperature contours and velocity vector at the section plane of first and fourth burners. The fuel and air flow rates are shown in Table 2, and the thermal recovery efficiency of the regenerative burners is considered as 90%. Inspect the vector distribution, a 10m/s of velocity of flue gas is observed in the preheating zone, owing to the greater fuel and air mass flow rates are supplied in the zone. In contrast, the minimum fuel and air mass flow rates result in minimum velocity distribution in the soaking zone. By contrast, the differences of the temperature distributions around the burners are insignificant for all zones, owing to the combustion temperature are all the same about 2200K for every heating zone. The flue gas flow in reverse direction around the first and the fourth burner, as shown in Figure 4 (a) and (b) due to the burners changed periodically function at every switch time.



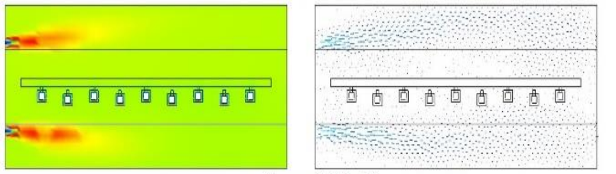
preheating zone (t=114 min)



first heating zone (t=168 min)



second heating zone (t=208 min)



soaking zone (t=240 min)

(a)

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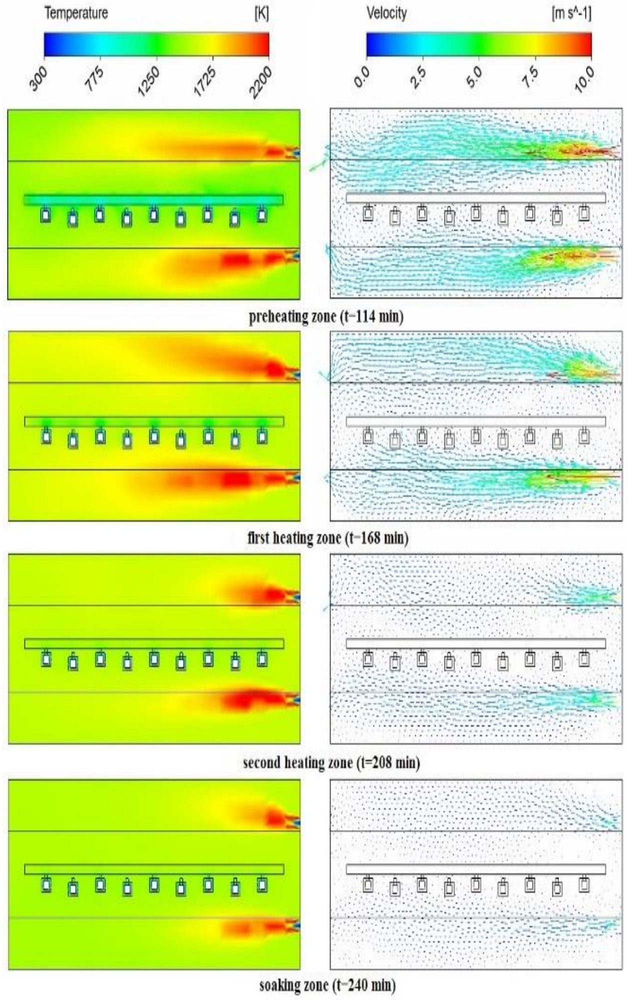
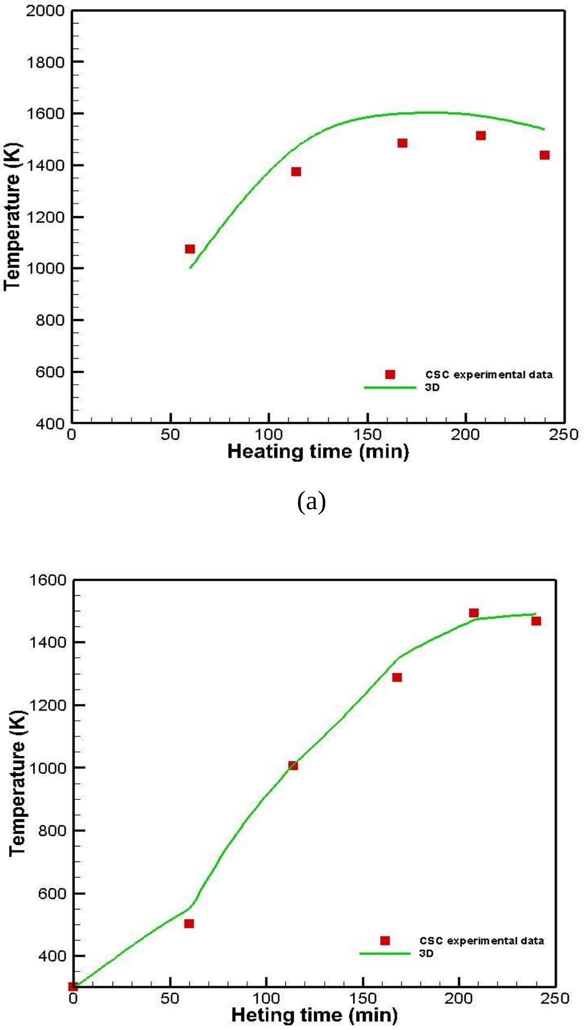


(b)

Fig. 4: Temperature and velocity distribution diagram of regenerative type of reheating furnace with (a) first burner (b) fourth burner

The calculated temperature of flue gas and slabs are examined with the measured data from the CSC. Figure 5(a) revealed the calculated flue gas temperatures are higher than the experimental temperature for the four heating zones except the flameless zone. The deviations are within 5-8% in this simulation, as listed in Table 4, the overall average error of flue gas temperature is 6.76%. Figure 5(b) shows the temperature variation of the slabs, which enter the furnace at the temperature of 300K, and gradually absorb the heat energy from the flue gas and leave the furnace at the temperature of 1490K. This simulation underestimates 47K and 60K of temperature of slabs in the flameless zone and first heating zone, respectively. The corresponding errors are 9.34% and 4.58%, respectively, as shown in Table 5, results in an average error of 3.47% for the slabs temperature. The thermal efficiency of the furnace is defined as the ratio of the total energy absorbed by the slab to the total heat energy of the fuel input in the furnace. Accordingly, the thermal efficiency of the three-dimensional model is 72.07%.The energy dissipation compound of two parts; the convection from stationary and moving beams, and the flue exhausted from furnace outlet. Based on this simulation, they are 14.06% and 13.87%, respectively.



(a)

(b)

Fig. 5: (a) Flue gas temperature curve and (b) slab heating curve of regenerative type of reheating furnace

Table 4: Flue gas temperature table

	Flue gas temperature		
zone	Simulation result (K)	Experimental value (K)	Error (%)
Flameless zone (60 min)	1000	1073	6.80
Preheating zone (114 min)	1470	1373	7.06
1st heating zone (168 min)	1599	1483	7.82
2nd heating zone (208 min)	1590	1513	5.09
Soaking zone (240 min)	1539	1438	7.02

Table 5: Slab temperature table

	Slab temperature		
zone	Simulation result (K)	Experimental value (K)	Error (%)
Flameless zone (60 min)	550	503	9.34
Preheating zone (114 min)	1010	1006	0.40
1st heating zone (168 min)	1346	1287	4.58
2nd heating zone (208 min)	1471	1492	1.41
Soaking zone (240 min)	1490	1466	1.64

Figure 6 displayed the temperature variation with the heating time in the furnace; the error between the two heating curve is insignificant. Noting that the comparison is based on the demanded temperature, 1490K, of the slabs when they leave the furnace, thus the fuel and air flow rates are different as shown in Table 6. It shows that the conventional furnace needs more fuel to heat the slabs to the demanded temperature, which yields a low thermal efficiency of 59%. The high thermal efficient for the regenerating burners is owing to the higher temperature of inlet air. The temperature differences of the two burners are shown in the Figure 7. The inlet air temperature is remaining constant at 850 K for the conventional burners. The deviation between the curves increases with an increase of the heating time, but the deviation turn down at around 180 minute, this is corresponding to the second heating zone, owing to the fuel and air flow rate decrease in the soaking zone. The temperature curve of the regenerating curve is similar to the temperature of flue gas curve shown in Figure 5(a), due to the heat energy absorbed by the regenerating burner come from the flue gas.

Table 6: Regenerative burner and conventional burner table

	Regenerative burner (ε=90%)	**Conventional burner**
Total fuel mass (kg)	5285.4	6366.03
Furnace efficiency (%)	72.07	59.33
Compared to the conventional burner total fuel ratio	0.83	1

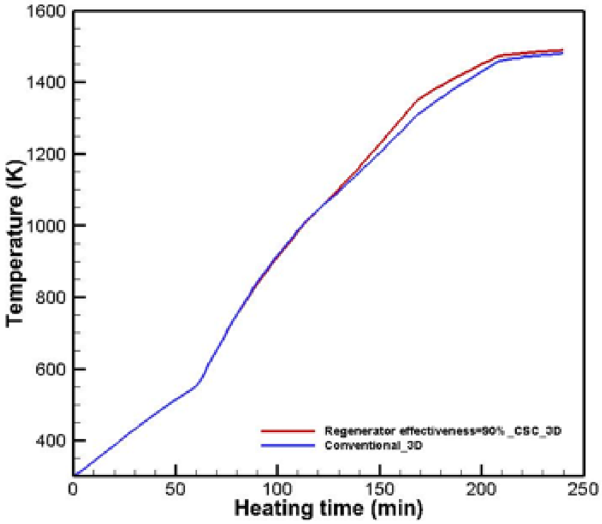


Fig. 6: Slab heating curve diagram of Regenerative burner and conventional burner

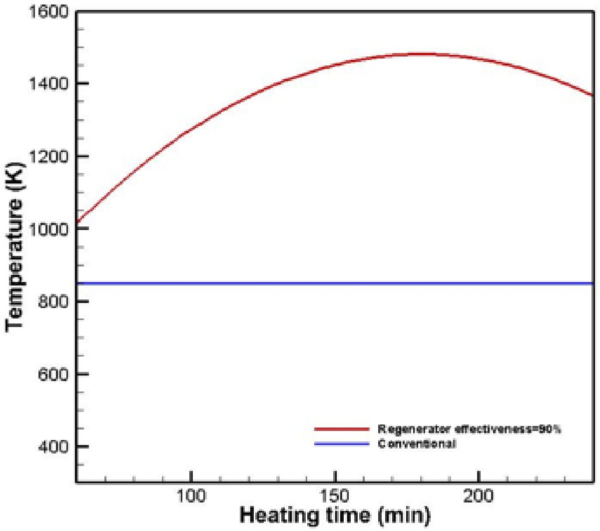


Fig. 7: Inlet air temperature of Regenerative burner and conventional burner

V. CONCLUSION

A three-dimensional transient simplified model coupled with periodically changed inlet air temperature has been developed to predict the temperature distribution of the flue gas and the slabs. The numerical results indicated that the furnace thermal efficiency is 72 % and a good agreement with the in-situ experimental data from China Steel Corporation. The average deviations for the flue gas temperature and the slab temperature are 6.8% and 3.8%, respectively. Compared with a conventional furnace without regenerator, the quantity of fuel reduction rate is up to 15% when the regenerator burners are used in a reheating furnace.

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