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Technical Note

Numerical analysis of heating characteristics of a slab in a bench scale reheating furnace

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1. Introduction

The heat transfer to a slab in a reheating furnace depends on various factors such as the shape of furnace, type of burners, arrangement of burners, burner operating conditions, type of fuel, location of the slab, and the slab's thermal property. The furnace geometry as well as installation of burners has decisive role in determining the flow and temperature fields which have direct influence on the heat transfer. A slab is heated by conduction, convection and radiation. Conduction and convection are incurred by combustion gas, while radiation heat comes from furnace wall as well as product gases. However, conduction and convection exert only a little contribution, as a slab is mostly heated by the radiation. Radiation heat transfer is largely affected by the composition of combustion gas and flame temperature which are determined by the characteristics of turbulent combustion.

A few numerical researches have been conducted to simulate a reheating furnace and heating slabs. Li et al. calculated radiative heating of slabs in a furnace chamber using zone method [1]. Chapman et al. performed numerical modeling and parametric studies for a direct fired continuous reheating furnace [2]. Zhang et al. tried to predict the thermal performance of a regenerative reheating furnace by using FLUENT [3]. They used P1 method for radiation model and PDF model for turbulent combustion. The prediction of transient slab temperature was carried out in a walking-beam type reheating furnace by Kim and Huh [4]. They calculated steady state heat transfer to slabs using FLUENT and performed separate calculation of the temperature distribution in slab with finite difference method. Chen et al. analyzed energy consumption and performance of reheating furnaces in a hot strip mill by means of both numerical and experimental method [5].

The present work is to simulate the transient heating characteristics of a slab inside bench scale reheating furnace installed in POSCO Corporation. The bench scale reheating furnace is a test facility for investigating the slab heating characteristics. Its operation makes it possible to overcome many limitations existing in the experiment with full scale reheating furnace. Experimentally, a slab is inserted into the furnace and its temperature variation is measured in both the gas field and the slab with thermocouples. The numerical analysis is performed here by developing its own code. A detailed numerical calculation of heating characteristics of slab is carried out with the developed code and its results are validated in comparison with experiments.

2. Theoretical model

The developed code adopts the SIMPLE algorithm [6–8], the structured curvilinear grids, the standard k–ε model for turbulence [9], the eddy–dissipation model for combustion [10,11], and FVM method for radiation [12–14]. The weight sum of gray gas model is applied to the radiation solving procedure for better accurate solution [15,16].

Fuel is assumed to be a mixture of CO, H_2, CH_4, C_2H_6. Fuel is injected into the furnace through a burner in a premixed state. Chemical reactions of fuel are governed by simple two step reaction. While CH_4 and C_2H_6 are initially oxidized to the mixture of CO and H_2O, H_2 is directly oxidized to H_2O by one step reaction.

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Nomenclature

k	turbulent kinetic energy, m^2s^2
T	temperature, K
W_k	molecular weight, kg/mol
Y_k	mass fraction of species k

Greek symbols

ε	turbulent dissipation
ε_s	emissivity of a slab
ρ	density of mixture, kg/m^3
λ	thermal conductivity, W/m/K

Subscripts

fu	fuel
g, s	gas field and slab
pr	product

$$C_{x_k}H_{y_k} + \left(\frac{x_k}{2}+\frac{y_k}{4}\right)O_2 \rightarrow x_k CO + \frac{y_k}{2}H_2O,\quad k = H_2, CH_4, C_2H_6 \tag{1}$$

$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \tag{2}$$

Eddy dissipation model, proposed by Magnussen and Hjertager [10], is used to simulate turbulent combustion in the code. It is an extended model of eddy-break-up [EBU] model to be applied to both premixed and non-premixed flame, whereas EBU was intended only for premixed flame. According to this model, the reaction rate R_{fu} is defined as

$$R_{fu} = \rho\frac{\varepsilon}{k}\min\left\{aY_{fu}, a\frac{Y_{O_2}}{s_1}, b\frac{Y_p}{1+s_1}\right\},\quad \text{where } s_1 = \frac{0.5\,W_{O_2}}{W_{fu}} \tag{3}$$

Here ε/k is the reciprocal of turbulent mixing time τ_t and s_1 is the stoichiometric mass ratio of oxygen to fuel. Empirical constants a and b, used in the above equation, are 4 and 2, respectively.

On the surface of the slab, the incoming heat flux from gas field is balanced with conductive heat flux into the slab. The incoming heat flux to the slab consists of conductive and radiative heat fluxes.

$$-\lambda_g\frac{\partial T}{\partial n}\bigg|_g - \varepsilon_s\sigma T_s^4 + \varepsilon_s q_{in}^R = -\lambda_s\frac{\partial T}{\partial n}\bigg|_s \tag{4}$$

where the subscripts g, s, and n denote gas, solid, and normal direction, respectively. q_{in}^R is the incoming radiative heat flux and $-\varepsilon_s T_s^4$ is the radiative emission from the slab surface to gas field. The slab surface temperature T_s is calculated by transformation of Eq. (4). T_s is obtained through a linearization to get more stable convergence.

$$T_s = -\frac{-\lambda_g\frac{T}{\Delta s}\big|_g + \varepsilon_s q_{in}^r + 3\varepsilon_s\sigma T_s^{*4} + \lambda_s\frac{T}{\Delta s}\big|_s}{-\frac{\lambda}{\Delta s}\big|_g + 4\varepsilon_s\sigma T_s^{*3} + \frac{\lambda}{\Delta s}\big|_s} \tag{5}$$

Asterisk $*$ denotes previous iteration step and Δs means the spacing between two neighboring nodes. T_s is updated at the end of each iteration and it is used for boundary condition in later iteration step.

3. Results and discussion

Fig. 1 shows an overall feature of the bench scale reheating furnace which has the dimension of 6.0 m × 1.6 m × 1.6 m. There exists a single burner at the center of left end of the furnace and its port is simplified to be a simple circle with diameter of 0.182 m. Exhaust gas exits the furnace through the right-hand side wall. One slab of 0.07 m × 0.4 m × 0.85 m is located at the height of 0.21 m from the furnace bottom and the slab is tested at two different axial locations of 0.5 and 4.0 m from the burner wall.

Temperature is measured at three locations in the gas field. The locations of the thermocouple, which measures gas temperature, are plotted in Fig. 2a. The figure is the top view located at $z = 1.3$ m. Their locations vary along x-coordinate, whereas their y and z coordinates are fixed to 0.5 m and 1.3 m. Three temperature measurement positions inside the slab are shown in Fig. 2b. It is a central cross section of a slab which is perpendicular to x-direction. The thermocouples are located along the z-directional center line of the cross section.

Figs. 3 and 4 show a variation of experimental and computational slab temperature at three location S_1, S_2 and S_3 inside the slab as shown in Fig. 2. The computational results in Fig. 3 for axial slab location of 0.5 m show more deviation from the experimental ones than those for 4.0 m in Fig. 4. This is due to the fact that the slab heating is more intense and the thermo-fluid mechanical characteristics

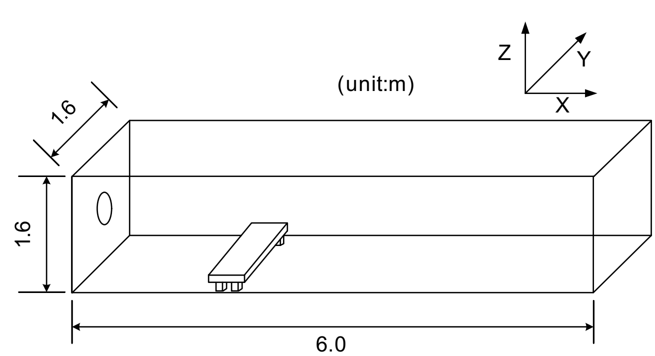

Fig. 1. Geometrical model of the bench scale furnace.

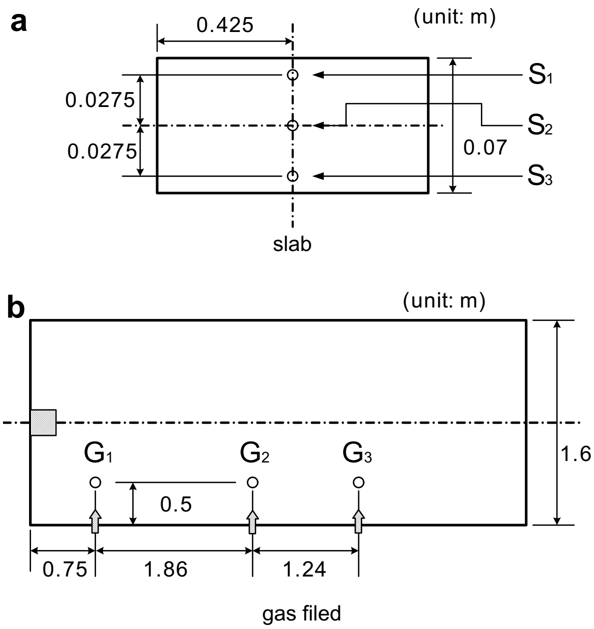

Fig. 2. Location of the thermocouples.

are more complex for axial slab location of 0.5 m. Therefore, the slab at 0.5 m is heated up faster than that at 4.0 m location. For the case of 4.0 m location, a very good agreement between computational and experimental ones is observed. The slope in temperature variation is important because it is correlated to the rate of heating of a slab. The heating rate can be used for designing reheating furnace. The slope in a temperature profile is largely affected by radiative heat transfer because it is more dominant than convection. The mass average temperature of a slab is raised to 925 °C at the time of 3600 s for the 0.5 m location while it is 690 °C for the 4.0 m location.

Fig. 5 represents a transient variation of gas temperature at three locations. At the upstream location, G_1 the gas temperature is the lowest due to the effect of intake of fresh air during the insertion of a slab. At the mid-location, G_2 the gas temperature reaches the highest temperature and then it decreases going downstream at the location, G_3. This trend is also well observed by computations, which is similar regardless of the slab location. But the gas temperature for slab location of 4.0 m is observed to be lower than that for 0.5 m, since the fuel flow rate is lower as listed in Table 1. Experimentally, the measurements show an unsteady behavior owing to its inherent burner characteristics. On the other hand, the computational prediction

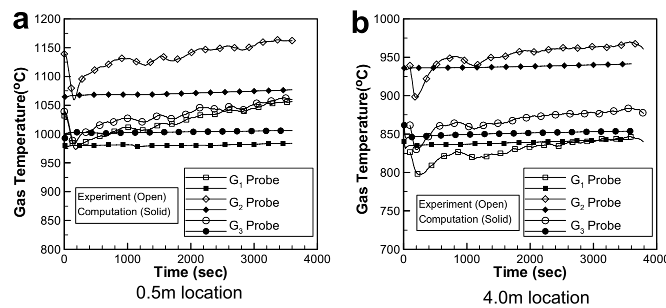

Fig. 5. Transient temperature plot for the gas field.

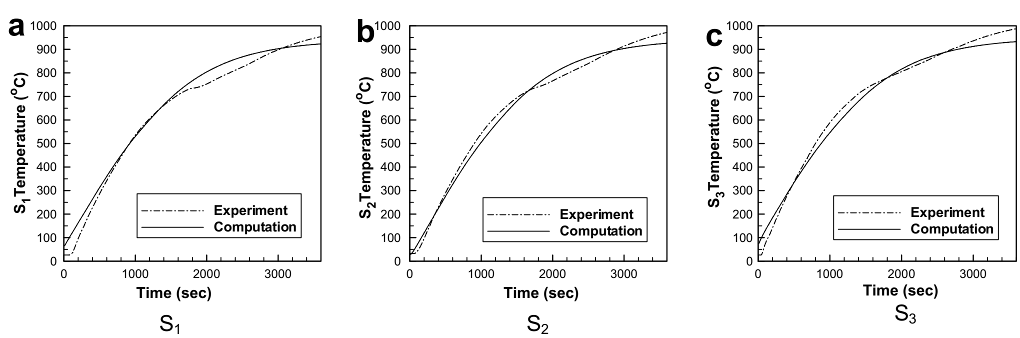

Fig. 3. Variation of temperature for three locations inside slab for the slab location of 0.5 m.

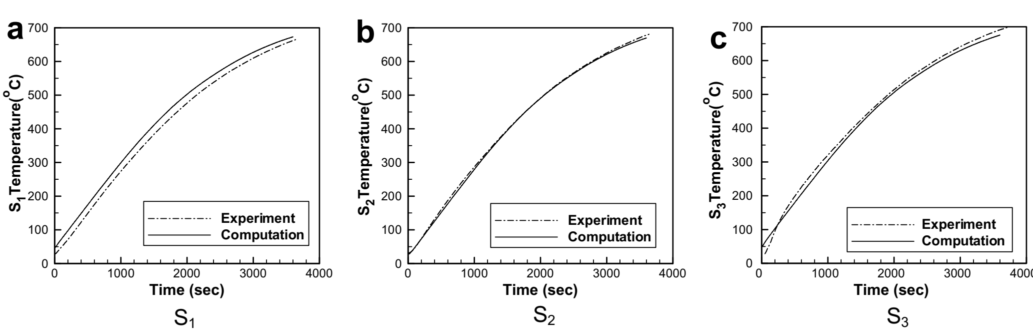

Fig. 4. Variation of temperature for three locations inside slab for the slab location of 4.0 m.

Table 1
Burner inlet conditions

Location (m)	Fuel flow rate (m^3/h)	Air flow rate (m^3/h)
0.5	245	1206
4.0	203	999

exhibits an almost steady behavior in gas temperature variation. Experimental gas temperature is seen to slowly rise because a heat loss from hot gas to a slab decreases with time on account of increase in the slab temperature.

When a slab is heated up, its corners are heated faster than any other region. A corner has larger thermal resistivity than the other regions, because heat penetrates into the slab from three adjoining surfaces. The temperature of a corner is raised up to 241 °C in only 10 s, while inner region inside the slab remains at 41 °C. In case of edges, the number of heat penetration directions is two. So the slab also experiences larger temperature build-up on edges than on flat plain surfaces. Fig. 6 illustrates variations of the temperature difference between inner slab point and three other points – corner, edge and flat surface on the upper surface of the slab. Corner temperature is taken from the corner point of $x = 0.5$ and $y = 0.375$, while the edge temperature is from the middle point of $y = 0.375$ line. Plain surface temperature is taken from the center point of the upper surface. Maximum temperature difference between corner and inner slab is 419 °C at 210 s for 0.5 m slab location and 264 °C at 550 s for 4.0 m slab location. Maximum temperature difference between edge and inner slab is 255 °C at 320 s for 0.5 m slab location and 155 °C at 700 s for 4.0 m slab location so that the maximum temperature difference occurs earlier for the corner than for the edge. This is due to quicker heating of the corners than the edges. The flat surface reaches the maximum temperature difference earlier than any other region. It is because the heat transfer from the center point of flat surface to inner slab travels the shortest distance among others.

Fig. 7 represents a transient variation of various heat fluxes from hot gas to the slab. It is seen that over 90% of heat flux comes from the radiation. Heat flux continues to decrease with time because of the rise in the slab temperature. It is also observed that heat fluxes for two different locations are reversed at certain time. This is because the slab temperature for slab location of 0.5 m is raised more quickly than that for the 4.0 m location on account of larger heat transfer rate in the early stage.

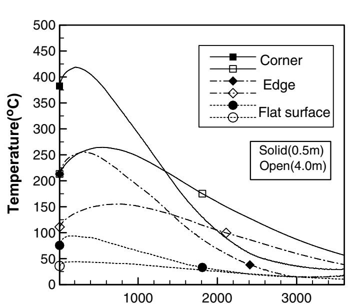

Fig. 6. Variation of temperature difference between respective point and inner slab.

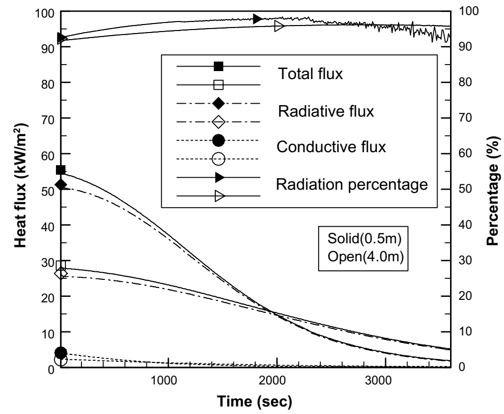

Fig. 7. Transient variation of various heat fluxes.

4. Conclusions

A numerical program has been developed and applied to investigate the heating characteristics of the slab in a bench scale reheating furnace. Its numerical results were validated by comparison with the experimental data obtained in the test facility installed in POSCO company.

1. The corners of the slab are heated faster than any other regions because they have larger thermal resistivity than the other regions – edges and flat plain surfaces. The temperature difference between a corner point considered and inner slab point increase until a certain instant, but after then it continuously decrease by action of inward conduction. Maximum temperature difference between the corner point and inner slab is 419 °C at 210 s for 0.5 m slab location and 264 °C at 550 s for 4.0 m slab location.
2. It was found that over 90% of the total heat transfer from the gas to the slab occurred by radiation. Therefore, a very accurate method would be necessary in solving the radiative transfer equation. Numerical method for radiation has to be able to treat gas emission as well as wall emission with appropriate accuracy. In this respects, the finite volume method for radiation was turned out to be very suitable for the simulation of a reheating furnace through the comparison of prediction with experimental results.
3. The premixed assumption combined with eddy–dissipation model made some difference in predicting gas phase temperature, but it worked out a pretty favorable prediction of slab temperature. This is because a slab is mostly heated by radiation of which quantity is not critically dependent on the location of flame but on the size and temperature of the flame. So, premixed combustion model is thought to be the appropriate assumption for the simulation of slab-heating characteristics of a real

scale reheating furnace. The burners can be more simplified with the premixed assumption than with the non-premixed assumption and it can make full scale calculation, which requires huge computing power, more probable.

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