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A CFD Study on the Energy Saving in Reheating Furnace with Oxygen-Enriched Air Conditions

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Abstract. In this study, the full-scale model of reheating furnace of an example steel plant, Bangkok Steel Industry PCL, was simulated to investigate the heat characteristics and energy consumption by using computational fluid dynamic (CFD) software, ANSYS Fluent. In hot rolling mills, reheating furnace process consumes the highest energy cost compared to that of the other processes. The improvement of the key process parameters such as fuel flow rate and oxygen enrichment result in the reduction of energy consumption and production costs. The purpose of this study is to predict the effect of oxygen enrichment in the combustion air on the specific energy consumption and billet temperature. The study consists of two parts: (1) the effect of oxygen enrichment on the billet exit temperature under the same fuel rate condition; (2) the effect of oxygen enrichment on the fuel saving under the same billet exit temperature condition. The simulation was carried out by using species transport model. The eddy dissipation model with fuel-oil mixture were selected as the combustion model. The results show that oxygen enrichment system has a potential to perform the energy saving for more than 6% in the reheating furnace.

INTRODUCTION

Reheating furnace is one of the largest energy consumers in hot rolling mill. In hot rolling process, billets at room temperature up to 1,160 ^{o}C are reheated and being rolled in the reheating furnace. The main energy for this process is usually provided by fossil fuels. [1] High temperature experiments require high-cost equipment to conduct experiments. However, numerical methods can be used for investigating heating characteristics in the reheating furnace nowadays. [2] Currently, the cost of production has been increasingly high due to the energy price. It is therefore significantly important to concern the energy efficiency in hot rolling steel industry. Oxygen enrichment is one of the useful energy-saving methods in reheating furnace. [3] Previous research studies [4] adopted conventional air and fuel burners to carry out oxygen-enriched combustion. The experimental results indicated that air/fuel burners could be adapted to lower than 28% oxygen concentration with no modifications. In addition, K. Qiu et. al. [5] investigated oxygen-enriched combustion of natural gas in porous ceramic radiant burners, at oxygen concentrations varying between 21% and 28%. The nitrogen proportion in the combustion air was decreased by an increase of oxygen percentage resulting in the lower thermal energy for nitrogen heating during the reheating furnace operation. It was found that the natural gas could be saved about 22% when oxygen concentration was increased to 28%. Obviously, the specific energy consumption during the process plays an important role in the production cost. In this current study, a computational fluid dynamic (CFD) is performed to investigate the effect of oxygen enrichment in combustion air fed into the reheating furnace of the example plant, Bangkok Steel Industry PCL. Eddy-dissipation concept model has been widely used to simulate oxy-fuel combustions [11] and used as a benchmark to determine the time saving potential of other models [6]. The Eddy-dissipation model was therefore used to simulate the combustion phenomena in simulation. To determine the billet temperature distribution that represents the heating characteristics, numerical simulations were performed by ANSYS Fluent software. A schematic of the reheating process used in this study is shown in Fig. 1.

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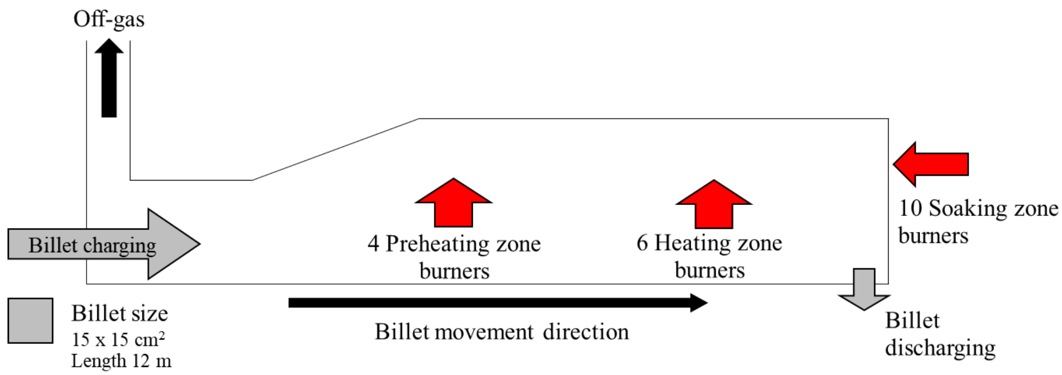

FIGURE 1. Schematic of reheating furnace operating in the example steel plant, Bangkok Steel Industry PCL

NUMERICAL SIMULATION METHODOLOGY

Governing Equation and Modelling

The calculation of fluid flow in this study were carried out on the basis of Reynolds-Averaged Navier-Stokes modelling as shown in equations (1) and (2) which consist of the mass and momentum conservation. The governing equations are solved based on pressure-based solver. The turbulent flow within the reheating furnace was calculated by realizable k-ε turbulence model. Two equations for realizable k-ε turbulence model are shown in equations (3) and (4). Recent investigations [2, 6, 7] show that the realizable k-ε model is useful in the simulation of reheating furnace burners. The pressure velocity coupling in this study was calculated with the SIMPLEC scheme and the gradient was calculated with the Green-Gauss node-based method. The model parameters are shown in Equation (5)-(8), where S, u and ν are the modulus of the mean strain rate tensor, the velocity components in vertical and the velocity components in gravitational directions. [6]

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_j} - \frac{2}{3}\delta_{ij}\frac{\partial u_1}{\partial x_1}\right)\right] + \frac{\partial}{\partial x_j}(-\rho u_i' u_j') \tag{2}$$

$$\frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon \tag{3}$$

$$\frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial y}{\partial x}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \rho C_1 S\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{v\varepsilon}} + C_{1\varepsilon} \times \frac{\varepsilon}{k} C_{3\varepsilon} G_b \tag{4}$$

$$C_1 = \max\left[0.43, \frac{\eta}{\eta + 5}\right] \tag{5}$$

$$\eta = S\frac{k}{\varepsilon}, S = \sqrt{2S_{ij}S_{ij}} \tag{6}$$

$$C_{3\varepsilon} = \tan\mathrm{h}\left|\frac{v}{u}\right| \tag{7}$$

$$C_{1\varepsilon} = 1.44,\ C_2 = 1.9,\ \sigma_k = 1,\ \sigma_\varepsilon = 1.2 \tag{8}$$

Numerical models of chemical reaction, turbulence-chemistry and radiation are significantly important to predict the combustion simulation with precise results and optimal computational time. B.F. Magnussen et. al. [8, 9] were the first two researchers to propose the Eddy-dissipation model for the simulation of combustion. It was assumed in this model that the chemical reaction rate is dominated by large-eddy mixing time scale [10]. In this study, the species transport with Eddy-dissipation model was used to calculate fuel-air combustion in the simulation. The radiative heat transfer between wall, gas and billet surface were simulated by the surface to surface model (S2S).

Reheating Furnace Model, Meshing and Boundary Conditions

The geometry of a full-scaled reheating furnace model of the example plant is 19 m long, 14 m wide and 2 m in height. The billets have a dimension of 15 x 15 cm^2 in square and 13 m long. The 3D model of reheating furnace for the simulation is presented in Fig. 2.

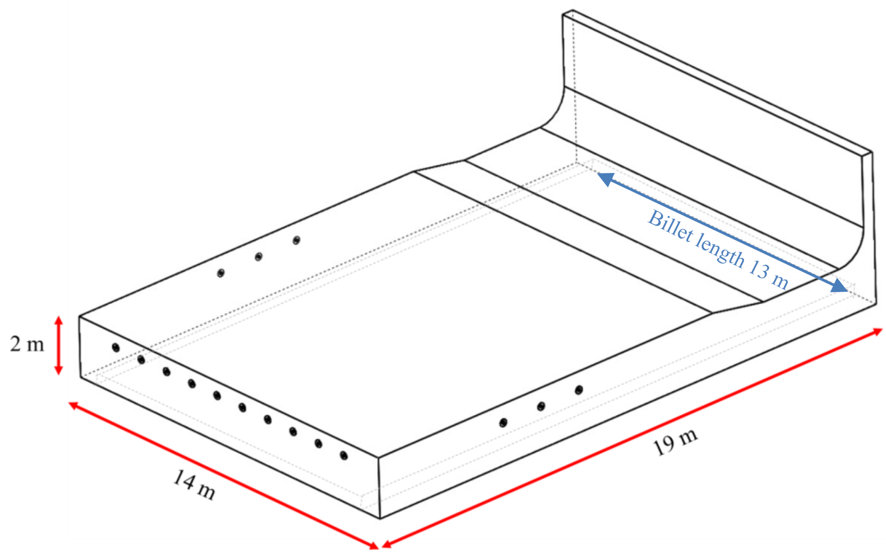

FIGURE 2. The 3D CAD model of reheating furnace

Meshing technique is very important to simulation results with an acceptable level of accuracy. Mesh sensitivity test is the mesh technique to avoid the simulation error and optimal computational time. Computational mesh from 8 million cells to 32 million cells were tested to find out the proper set up in the simulation. Finally, the computational mesh of 16 million cells was found the most proper number for the reheating furnace model in the current study.

The simulations were performed with the assumption of 3D steady state, pressure-based solver and absolute velocity formulation. Constant flow rate and pressure conditions were applied as the boundary conditions at inlet and outlet. Due to the fuel oil is used as energy source in example plant, fuel oil ($C_{19}H_{30}$) is performed as combusted material in the simulation at fuel inlet. All inlet of fuel and air were set by mass flow inlet with 5% turbulence intensity. Gas outlet of the furnace model was set as pressure outlet. The outlet boundary was defined with backflow of 6.6 % O_2 and 14.4 % CO_2 and backflow temperature of 1,273 K. Billet is moved from billet inlet to billet outlet in the furnace. The billet properties used in the simulation were defined as steel, but the state of material was set to high viscosity steel fluid (100,000 k/ms) with 0.0007 m/s velocity which is equivalent to the productivity of 37 t/h. The other properties of steel fluid are defined as same as of steel such as density, specific heat, thermal conductivity, standard enthalpy and standard entropy. The reheating furnace wall was set as no heat loss to outer ambient. The boundary conditions of the reheating furnace are shown in Fig. 3. Heating zones consist of 3 fuel and air inlets on each side of reheating furnace. Additionally, 10 fuel and air inlets are set at the soaking zone.

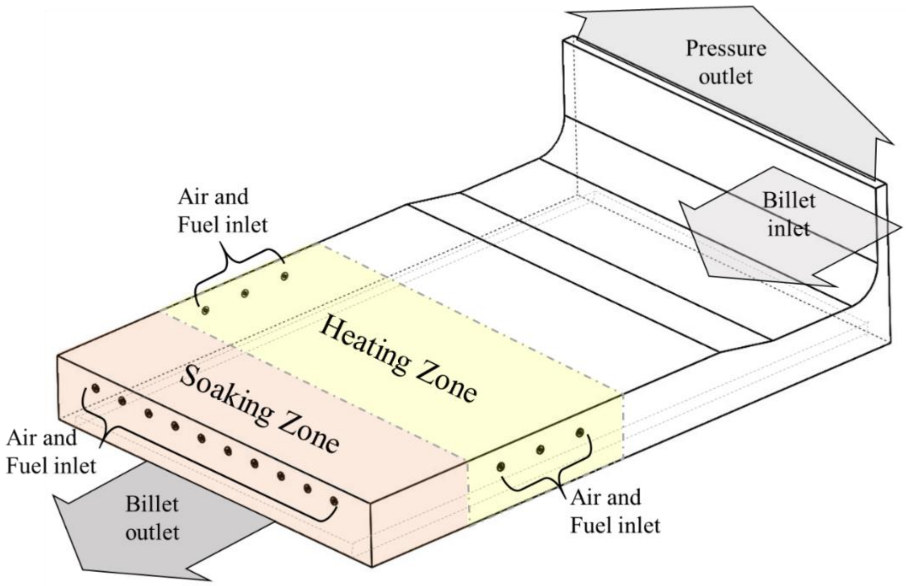

FIGURE 3. Boundary conditions of the reheating furnace

Simulation Conditions

The simulation cases were designed to study the effect of oxygen enrichment on energy saving potential. An air and fuel ratio of 11:1 of the example plant was employed in the simulation. For the example steel plant, there are two different sizes of available oxygen pipe line system that can be invested. Due to the limitation of oxygen supply system, the maximum percentage of oxygen enrichment that can be used in simulation are 2% and 4%. The study can be divided into five cases. The first case that has 21% of oxygen composition in combustion air is baseline from the example plant. In case 2 and 3, 2% and 4% of oxygen enrichment percentage were added, making the oxygen composition in combustion air 23% and 25%, respectively. Different oxygen compositions were performed to predict the billet temperature in the reheating furnace. In addition, the prediction of specific energy consumption was further studied in the last two cases by reducing fuel flow rates to show the opportunity of specific energy consumption reduction. Flow rates in heating zone and soaking zone for case 1 to 3 was collected from real process parameters. For case 4 and 5 the fuel flow rates were selected from trial and error in the simulation to get the equal billet output temperature as the example plant (case 1). Air and fuel flow rates of each burner in soaking zone and heating zone were set in the simulation with different percentages of oxygen enrichment as shown in the Table 1.

TABLE 1. The simulation conditions

		Baseline	**O_2 enrichment and fixing fuel flow rate**		**O_2 enrichment, fixing billet outlet temperature**	
		Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Oxygen in combustion air (%)		21%	23%	25%	23%	25%
Flow rate (kg/s) in heating zone	Air	0.4400	0.4400	0.4400	0.4372	0.4279
	Fuel	0.0280	0.0280	0.0280	0.0267	0.0261
Flow rate (kg/s) in soaking zone	Air	0.2590	0.2590	0.2590	0.2536	0.2478
	Fuel	0.0170	0.0170	0.0170	0.0162	0.0158

RESULTS AND DISCUSSION

Furnace temperature was obtained by using the computational simulation under steady-state condition which represents the actual temperature during a continuous reheating process. The results showed that realizable k-ε turbulence model is able to calculate the phenomena in reheating furnace. The numerical simulation can predict energy saving with different input of oxygen enrichment percentages in the combustion air with the high temperatures of the actual reheating process.

Effect of Oxygen Enrichment on Billet Temperatures

In the first case of the study, the computational simulation without oxygen enrichment was conducted to validate the billet output temperature between the simulation model and actual process of the example plant. The simulation of reheating furnace shows the heating characteristics of the billet in the furnace. The simulation results show that the average billet output temperature is in an agreement with the actual process temperature (about 1,177 ^{o}C). The results of heating characteristics and maximum temperature of the reheating furnace (a) and the billet (b) are illustrated in Fig. 4.

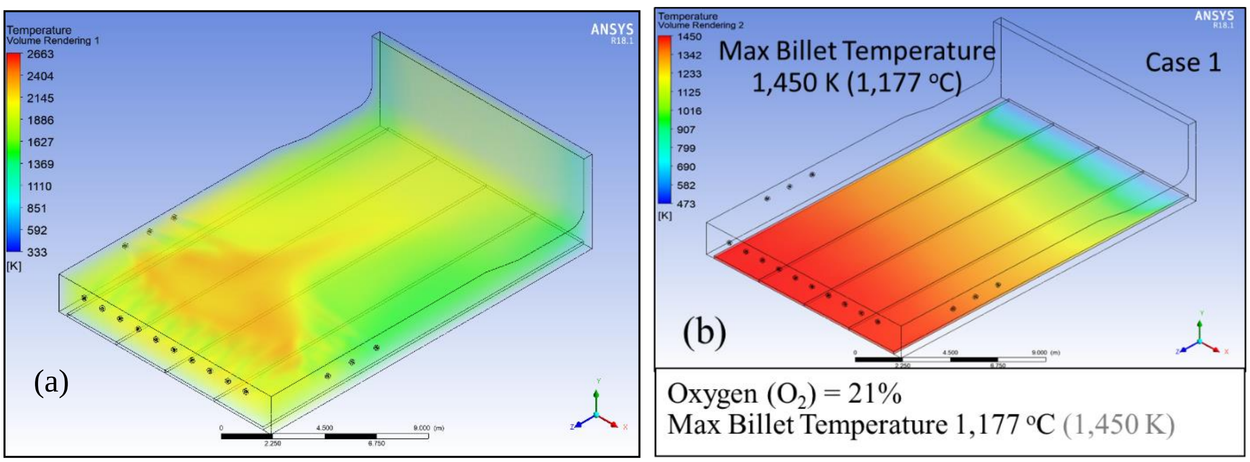

FIGURE 4. The simulation results of: (a) the reheating furnace and (b) the billet in case 1

Case 2 and 3 show the results of oxygen enrichment from 21% to 23% and 25%. The billet output temperatures with fixed fuel flow rates were increased to 1,197 ^{o}C and 1,225 ^{o}C respectively as shown in Table 2.

TABLE 2. The simulation result when fuel flow rate fixed

	Baseline	O_2 enrichment and fixing fuel flow rate	
	Case 1	**Case 2**	**Case 3**
Oxygen in combustion air (%)	21%	23%	25%
Max Billet Temperature increased	1,177	1,197	1,225

Due to the increasing of oxygen, the efficiency of combustion air was increased. This is the result of more oxygen atom can combine with the carbon atom in fuel oil and provide more energy. The temperature of billet that received more energy when oxygen increased can be shown as max billet temperature in the result as shown in the Fig. 5.

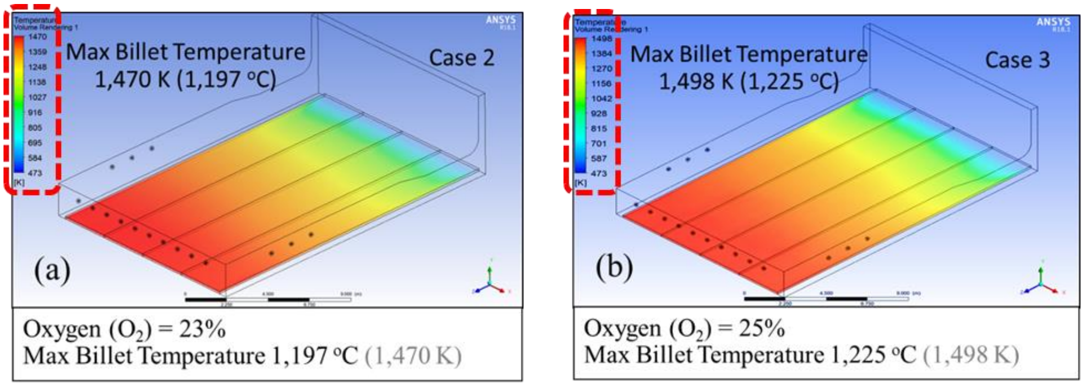

FIGURE 5. The simulation results of billet temperature: (a) 23% oxygen enrichment and (b) 25% oxygen enrichment

Energy Saving by Oxygen-Enriched Air Conditions

The fuel flow rates have direct effects on energy in reheating furnace and billet temperature. The operation temperature required in the reheating furnace of the example plant is around 1,177 ^{o}C. It was found that the oxygen enrichment is able to increase the combustion the efficiency. The fuel flow rates could be reduced when energy in the billet is enough to make its temperature equal to the example plant operating temperature. Various rates of fuel flow rates at different oxygen concentrations were tested until the billet temperature at around 1,170 - 1,190 ^{o}C as shown in Table 3.

TABLE 3. The simulation result when reduce fuel flow rate

	Baseline	**O_2 enrichment and fixing fuel flow rate**	
	Case 1	**Case 2**	**Case 3**
Fuel flow rate in Heating zone (kg/s)	0.0280	0.0267	0.0261
Fuel flow rate in Soaking zone (kg/s)	0.0170	0.0162	0.0158
Billet Temperature (^{o}C)	1,177	1,176	1,188

The simulation results show that 23% and 25% oxygen enrichment in combustion air can reduce total fuel flow rate as shown in Fig. 6.

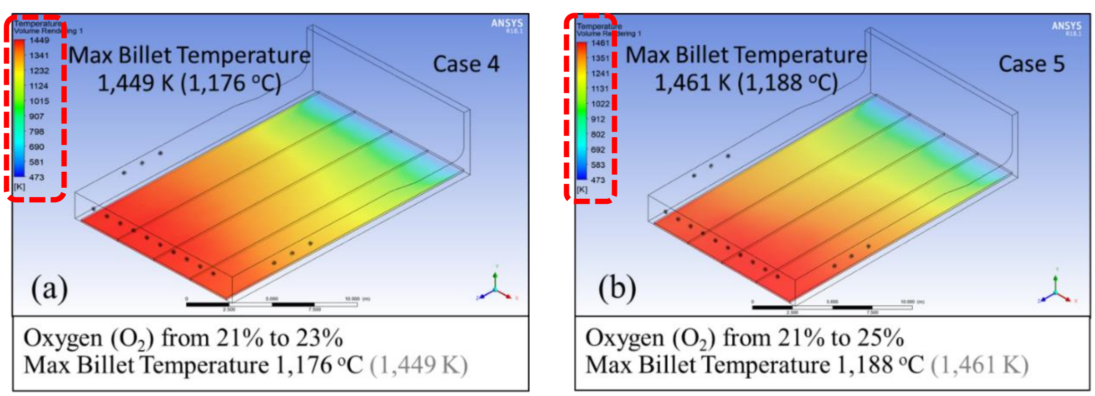

FIGURE 6. The simulation results of oxygen enrichment:

(a) 23% oxygen in combustion air and (b) 25% oxygen in combustion air

In case 1 to 3, the fuel flow rates in simulation were fixed at 0.0280 kg/s and 0.0170 kg/s at each inlet of heating zone and soaking zone. There are 6 inlets in heating zone and 10 inlets in soaking zone. Therefore, the fuel flow rates at the heating zone and the soaking zone were converted into the fuel consumption around 605 kg/h and 612 kg/h respectively. After combining heating zone and soaking zone fuel consumption, the total fuel consumption is equal to 1,217 kg/h. Case 4 and 5 were calculated as the first three cases. The total fuel consumption in the following cases are 1,160 kg/h and 1,133 kg/h respectively as shown in Table 4.

TABLE 4. The simulation conditions

	Baseline	**O_2 enrichment and fixing fuel flow rate**		**O_2 enrichment, fixing billet outlet temperature**	
	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Fuel Flow rate (kg/s) in heating zone	0.0280	0.0280	0.0280	0.0267	0.0261
Fuel Flow rate (kg/s) in soaking zone	0.0170	0.0170	0.0170	0.0162	0.0158
Total fuel consumption (kg/h)	1,217	1,217	1,217	1,160	1,133

The graph in Figure 7 shows that the increasing of oxygen proportion in combustion air has significant effect on the fuel consumption rate in the reheating furnace operation. With the increasing of oxygen enrichment from 21% to 23%, the fuel consumption rate is reduced for 4.6% from 1,217 kg/h to 1,160 kg/h (from 32.9 kg/t to 31.35 kg/t in term of specific fuel consumptions). In case of increasing oxygen enrichment from 23% to 25%, the fuel consumption rate is reduced for 2.4% from 1,160 kg/h to 1,133 kg/h (from 31.35 kg/t to 30.62 kg/t in term of specific fuel consumptions). With the increasing of oxygen enrichment from 21% to 25%, the fuel consumption rate is reduced for 6.9% from 1,217 kg/h to 1,133 kg/h (from 32.9 kg/t to 30.62 kg/t in term of specific fuel consumptions). This shows that oxygen enrichment system reduces the specific fuel consumption by 4.6% - 6.9%.

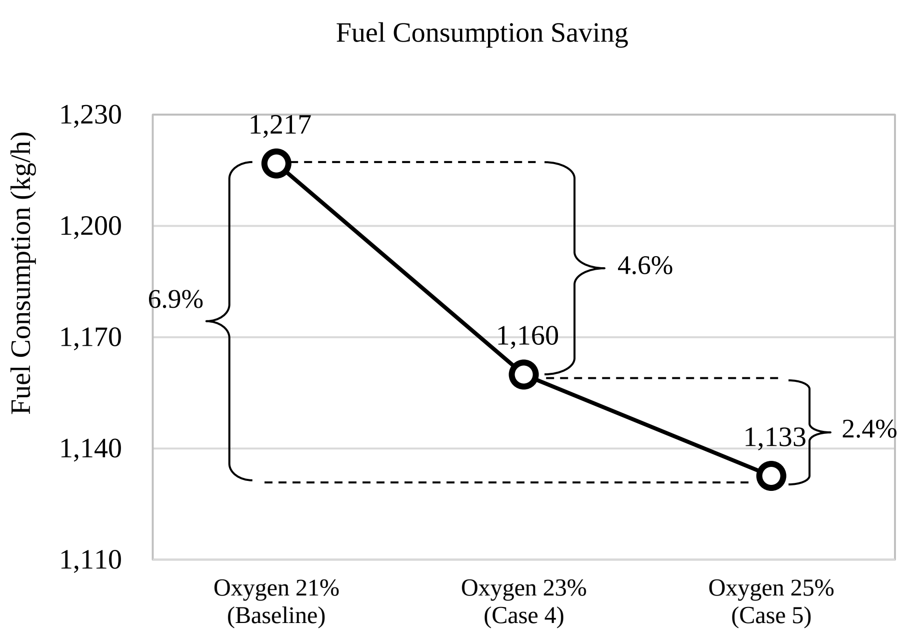

FIGURE 7. The fuel consumption rate compared to the percentage of oxygen enrichment

CONCLUSION

In this study, the heating characteristics of reheating furnace and billet temperature using the example plant parameters were predicted through the computational fluid dynamic simulation. In this study, S2S radiation model is applicable to use in reheating furnace simulation with optimal computational time and lower chance of simulation error compared with the other radiation models. The simulation revealed an asymmetric temperature distribution in the billets along their length due to the asymmetric flow in the furnace. The simulation cases with fixed billet temperature at 1,177 ^{o}C were applied to investigate the effects of 23% and 25% oxygen enrichment on the energy saving of reheating process. In case of adding 2%, and 4% of oxygen enrichment, the specific energy consumption is decreased from 32.90 kg/t to 31.35 kg/t and 30.62 kg/t respectively. The potential of oxygen enrichment to reduce the specific energy consumption is slightly decreased when oxygen enrichment percentage in the combustion air is increased. By maintaining the same billet temperature while reducing the fuel consumption, the simulation results in this current study show that oxygen enrichment system has a potential to perform the energy saving for more than 4.6% in the reheating furnace.

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