The Study of Energy Efficiency and Development of Energy Balance Model in the Reheating Furnace

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Abstract

One of the high energy consumption industries in Thailand is the hot rolling steel plant. In the rolling mill, a specific energy consumption in reheating furnace plays the most important role in reduction of total energy cost which is the main operation cost in hot rolling steel production. Several hot rolling steel plants in Thailand use fuel oil as a reheating furnace energy source. The purpose of this study is to develop a model that can calculate the specific energy consumption in hot rolling process using fuel oil as an energy source and to study effects of parameters in reheating furnace. The furnace and fuel data from the example steel company, Bangkok Steel Industry PCL were used in this study. The energy balance model of reheating furnace was developed and billet temperature profile can be derived from this model. The investigation shows that, the oxygen enrichment is able to reduce the specific fuel consumption in the example plant. The hot charge temperature is able to reduce the specific fuel consumption significantly depend on temperature of billet and the effect is increased at the high hot charge temperature.

Keywords: *Reheating furnace, Combustion efficiency, Energy balance model, Specific energy consumption*

Introduction

In steel rolling mill, specific energy consumption in reheating furnace plays the important role in reduction of total energy cost which is the main operation cost in steel production [1]. In hot rolling process, steel bar and rebar are produced from billet that is heated up to 1,100 – 1,200 oC in reheating furnace before being rolled. Generally, furnace-operating parameters of rolling mill plants such as an air-fuel ratio, an oxygen proportion in combustion air and hot charge temperature can be improved to reduce the energy consumption, thereby leading to the reduction of the energy cost.

Over the past decades, reheating furnace efficiency evaluation has been determined in numerical simulation. The numerical simulation requires a long computational time for an accurate result [1] - [3]. However, the reheating furnace efficiency that rolling steel plants need for the energy consumption analysis can be calculated from an energy balance model which requires less computational time and resources. One of the energy balance models of natural gas reheating furnace has been developed by Pfeifer [4], by which the heat conduction in the billet is transient and the related Fourier's differential equation is solved by an explicit difference equation scheme.

In the current study, the energy balance model of fuel oil reheating furnace was developed based on energy balance theories [4], [5]. The furnace geometry and operation conditions from the example steel plant, Bangkok Steel Industry PCL were use in this study. The specific energy consumption is calculated from the process production rate and the actual energy used in reheating furnace. The parameters of actual energy can be determined by the sum of reheating furnace energy efficiency. In this energy balance model, the total efficiency in the furnace system is calculated in order to find the specific energy consumption. The total efficiency consists of combustion efficiency and reactor efficiency. These parameters are calculated from input and output of reheating furnace [5]. In addition, enthalpy from the preheat air and charged billet must be considered to calculate the energy input and output. Reheating furnace energy input and output of the example plant are shown in Figure 1.

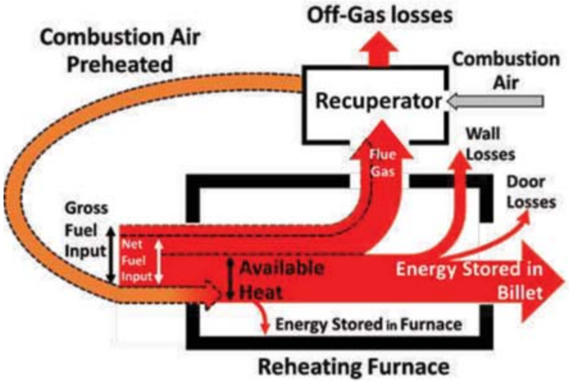

Figure 1 Energy system in reheating furnace

The results of this study can be used to support the hot rolling mill plant to evaluate the suitable parameters in reheating furnace specific energy consumption such as ratio of oxygen enrichment, billet hot charge temperature and the production rate of process.

Methodology

Reheating Furnace Data

The furnace of the example steel plant is walking heart type with a capacity of 38 t/h. It includes 3 zones, namely Preheating zone, Heating zone and Soaking zone. The burners in preheating zone was closed. The heating zone equipped with 6 burners: 3 burners on the left wall and 3 burners on the right wall which arranged in inclined position. The soaking zone equipped with 10 burners. The size of billet is 150 mm x 150 mm x 6000 mm, with two pieces along the width of the furnace. Each piece is about 1000 kg in weight. The diagram of the reheating furnace is shown in Figure 2.

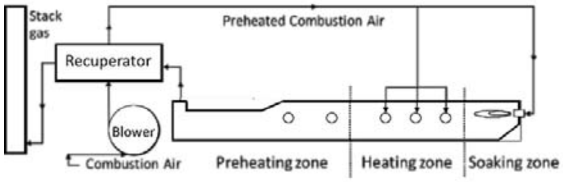

Figure 2 Reheating furnace systems

Fuel Oil Data

Compositions of fuel oil in this research from example plant are shown in Table 1

Table 1 Fuel oil compositions

Compositions	Percent by Mass (%)
Carbon	88.79
Hydrogen	11.17
Nitrogen	0.31
Sulfur	1.82
Water and Sediment	0.05

The temperature of fuel oil in reheating furnace operation is preheated at 50-70 °C. The gross calorific value from the certificate is 43,484 kJ/kg.

Energy Balance Model Development

The energy balance in reheating furnace consists of energy input and energy output. In this current study, energy input is thermal energy from reaction between fuel oil and air, billet preheating (hot charge), fuel oil preheating and combustion air preheating from recuperator. Energy output consists of heat in billet, radiation from door opened and heat loss from furnace walls. The specific energy consumption can be solved from the energy balance between energy input and energy output. The energy balance of reheating furnace can be expressed as equation (1)

$$\dot{H}_{fuel} + \dot{H}_{air} - \dot{H}_{off-gas} + \dot{H}_{steel,in} - \dot{H}_{steel,out} - \dot{Q}_f - \dot{Q}_r = 0 \quad (1)$$

where $\dot{H}_{fuel}$ is energy from fuel enthalpy, $\dot{H}_{air}$ is energy from combustion air preheated enthalpy, $\dot{H}_{off-gas}$ is energy loss from off-gas enthalpy, $\dot{H}_{steel,in}$ is energy from billet hot charge temperature, $\dot{H}_{steel,out}$ is energy in billet out, $\dot{Q}_f$ is wall heat loss and $\dot{Q}_r$ is doors heat loss from radiation. The remaining energy of billet can be described as $\dot{E}_{Load}$ as shown in equation (2)

$$\dot{E}_{Load} = \dot{H}_{steel,out} - \dot{H}_{steel,in} \quad (2)$$

The specific energy consumption of reheating furnace is calculated from the efficient energy. This energy has to calculated from Total efficiency of furnace energy system and the energy balance of reheating furnace. Total efficiency can be calculated from equation (3)

$$\eta_{tot} = \eta_c \eta_r \quad (3)$$

where η_r is Reactor efficiency and η_c is Combustion efficiency. Reactor efficiency and Combustion efficiency can be calculated as shown in equation (4) and (5) respectively.

$$\eta_r = \frac{\dot{E}_{Load}}{\dot{E}_{Load}+\dot{Q}_{Wall}+\dot{Q}_{Rad}} = \frac{\dot{E}_{Load}}{\dot{H}_{Fuel}+\dot{H}_{Air}-\dot{H}_{Off-gas}} \quad (4)$$

$$\eta_c = 1 - \frac{\dot{H}_{Off-gas}}{\dot{H}_{Fuel}+\dot{H}_{Air}} = \frac{\dot{H}_{Fuel}+\dot{H}_{Air}-\dot{H}_{Off-gas}}{\dot{H}_{Fuel}+\dot{H}_{Air}} \quad (5)$$

Heat Loss

Heat loss in walking heart furnace is separated into wall heat loss (Q_{wall}) and door heat loss (Q_{rad}). The wall heat loss is heat conduction from inside to surfaces of furnace and heat convection from surfaces to environment. The door heat loss is radiation when the furnace doors are opened. The wall heat losses and door heat losses are calculated from heat transfer equations shown in equation (6) and (7)

$$\dot{Q}_{wall} = \frac{T_1 - T_{env.}}{\frac{s_1}{\lambda_1} + \frac{s_2}{\lambda_1} + \frac{1}{\alpha_{env.}}} A_{wall} \quad (6)$$

$$\dot{Q}_{rad} = \sigma \varepsilon A_{door} \left(T^4_{entry,exit} - T^4_{env.}\right) \times t \quad (7)$$

where T_1 is temperature inside the furnace, $T_{env.}$ is temperature of environment around furnace, $T_{entry,exit}$ are temperature at entry and exit door of furnace, $s_{1,2}$ is wall insulator thickness layer 1 and layer 2, $\lambda_{1,2}$ are insulator thermal conductivity in layer 1 and layer 2, $\alpha_{env.}$is heat transfer coefficient of environment ,$A_{wall,door}$ are total area of wall and open doors respectively, σ is Stefan-Boltzmann constant, ε is emissivity and t is door opened time. These calculation results are used to calculate the reactor efficiency as shown in equation (4).

Billet Temperature

The heat transfer from the furnace to the load is assumed to be transient, one-dimensional and symmetrical from the top and the bottom. Explicit (Euler) finite-difference method and Fourier number were applied to calculate the temperature of billet in the furnace. The furnace parameters, e.g. temperature of each zone and billet initial temperature, which are required for the calculation of the billet temperature along the furnace were obtained from the example steel plant. The equation which is expressed as a function of Fourier-number shown in equation (8)

$$Fo = \frac{\lambda}{\rho c}\frac{\Delta t}{(\Delta x)^2} \tag{8}$$

The relation between known temperature T_i^{ρ} and the unknown temperature of the moving billet at next time step, $T_i^{\rho+1}$, can be expressed by 3 equations. The first one describes the temperature at the billet surface as shown in the equation (9)

$$T_i^{p+1} = 2\dot{q}_i'' \frac{\Delta t}{\rho c \Delta x} + 2F_o\left[T_{i+1}^p + T_i^p\right] + T_i^p \tag{9}$$

where $\dot{q}_i''$ is the heat flux density from the furnace to the billet and it can be calculated from equation (10).

$$\dot{q}_i'' = \alpha\left(T_{env.} - T_1^p\right) + \varepsilon F_{ij}\sigma(T_{env.}^4 - T_1^4) \tag{10}$$

The parameters Δt is time step size, ρ is steel density, c is steel specific heat capacity, Δx is distance between time step and F_{ij} is view factor (F=1). The second one equation describes the temperature at the billet surface, as shown in (11).

$$T_i^{p+1} = T_i^p + F_o[T_{i-1}^p - 2T_i^p + T_{i+1}^p] \tag{11}$$

The last equation which is expressed as the billet temperature at the middle elements (symmetry) shown in equation (12)

$$T_i^{p+1} = T_i^p - 2F_o(T_i^p - T_{i-1}^p) \tag{12}$$

Combustion Air and Off -gas Enthalpy

For the application of combustion in reheating furnace, a complete combustion without excess air is normally targeted in order to make full use of the chemical energy stored in the fuel. Air proportion using in base case without oxygen enrichment contains 23.2% oxygen and 76.8% nitrogen by mass. The most stable oxidized product of carbon, hydrogen and sulphur are CO2, H2O and SO2 respectively. The formation reactions of CO2, H2O and SO2 are used to calculate the stoichiometric reaction of fuel oil. These equations can be expressed as equation (13)-(15)

$$C + O_2 \rightarrow CO_2 \tag{13}$$

$$2H_2 + O_2 \rightarrow 2H_2O \tag{14}$$

$$S + O_2 \rightarrow SO_2 \tag{15}$$

From the stoichiometric of equation (13), 32 kg of oxygen combines with 12 kg carbon to form 44 kg of carbon dioxide. So, 1 kg of carbon requires 2.667 kg of oxygen. In the same way, 1 kg of hydrogen requires 8 kg of oxygen and 1 kg of sulphur requires 1 kg of oxygen from equations (14) and (15) respectively. The equation is expressed as (16)

$$\tilde{O}_{2,min} = 2.677\, C + 8.0\, H + 1.0\, S - 1.0\, O_2 \tag{16}$$

The minimum air ratio ($l_{o\,min}$) for the stoichiometric combustion can be expressed as (17)

$$l_{o\,min} = \frac{\tilde{O}_{min}}{0.232} \tag{17}$$

Practically, combustion providing an excess air in order to achieve complete combustion by adding air proportion more than the stoichiometric air ratio. The air proportion used in this case is described as (18)

$$l_o = \lambda\, l_{o,min} \tag{18}$$

From these reactions, product of combustion in the furnace can be defined by fuel input and the heat capacity of the product reaction is used to calculate the enthalpy in off- gas. Finally, combustion efficiency of reheating furnace can be calculated from the relationship between enthalpy of fuel, combustion air and the remaining off-gas as shown in equation (4).

Fuel Oil Enthalpy

The specific enthalpy of fuel oil can be calculated from the specific heat capacity of fuel oil which is expressed as a function of specific gravity and temperature shown in equation (19). [6], [7]

$$\begin{aligned} C_p &= (2 \times 10^{-3} \times T - 1.429) \times S.G. \\ &\quad +(2.67 \times 10^{-3}) \times T + 3.049 \end{aligned} \tag{19}$$

where C_p is specific heat capacity (kJ/kg·°C), T is temperature (°C) and S.G. is specific gravity (unitless).

Specific Energy Consumption

The specific energy consumption (SEC) in this study can be calculated from the equation (20)

$$SEC = \frac{Fuel\ energy\ consumption\ rate, \dot{M}_{Fuel}\ (MW/t)}{Productivity\ (t/h)} \tag{20}$$

From equation (1) - (5), the total efficiency is can be described as shown in equation (21)

$$\eta_{tot} = \eta_c \eta_r = \frac{\dot{E}_{Load}}{\dot{H}_{Fuel} + \dot{H}_{Air}} \tag{21}$$

where $\dot{H}_{Fuel}$ and $\dot{H}_{Air}$ can be calculated from equation (22) and (23) respectively.

$$\dot{H}_{Fuel} = \dot{M}_{Fuel} \cdot \Delta h_{Fuel\ Calorific\ Value} \qquad (22)$$

$$\dot{H}_{Air} = (\dot{M}_{Air/1\ kgFuel} \cdot \dot{M}_{Fuel}) \cdot \Delta h_{Air} \qquad (23)$$

From equation (21) - (23), the fuel energy consumption rate can be calculated as shown in equation (24)

$$\dot{M}_{Fuel} = \frac{1}{\eta_{tot}} \cdot \frac{\dot{E}_{Load}}{\Delta h_{Fuel\ Calorific\ Value} + \dot{M}_{Air/1\ kgFuel} \cdot \Delta h_{Air}} \qquad (24)$$

Calculation Scenarios

The fixed parameters from the example plant that is used for the calculation specific energy consumption are shown in Table 2

Table 2 Parameters from the example plant

Final billet temperature	1150	°C
Excess Air ratio	1.1	
Air Preheating	350	°C
Oil Calorific value	43.48	MJ/k
Oil Preheating	60	°C
Room Temperature	27	°C
Preheating zone Temperature	720	°C
Heating zone Temperature	1100	°C
Soaking zone Temperature	1150	°C
Billet cross section area	0.13 x 0.13	m
Billet length	6 x 2	m
Production Rate	37	t/h

Several calculation cases were performed in energy balance model to evaluate the suitable parameters of example plant**.** The main testing parameters in this study are oxygen fraction in combustion air and hot charge temperature as described in Table 3

Table 3 The process parameters which is used in calculation

		Hot charge Temperature (°C)		
		27	200	400
Oxygen Proportion (%)	21	21% Oxygen, 27 °C	21% Oxygen, 200 °C Hot charge	21% Oxygen, 400 °C Hot charge
	23	23% Oxygen, 27 °C	23% Oxygen, 200 °C Hot charge	23% Oxygen, 400 °C Hot charge
	25	25% Oxygen, 27 °C	25% Oxygen, 200 °C Hot charge	25% Oxygen, 400 °C Hot charge

Results and discussion

Due to furnace zone temperature are fixed, the results of billet temperature calculation when the hot charge temperature was changed are shown in Figure 4 and Figure 5

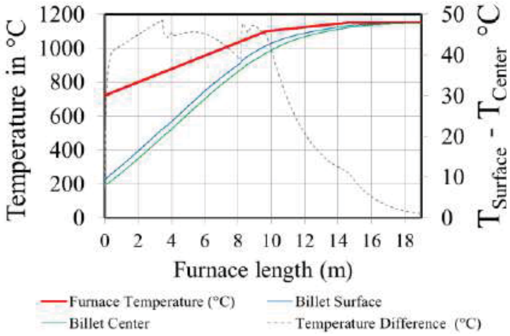

Figure 4 Result from the case with hot charge at 200 °C

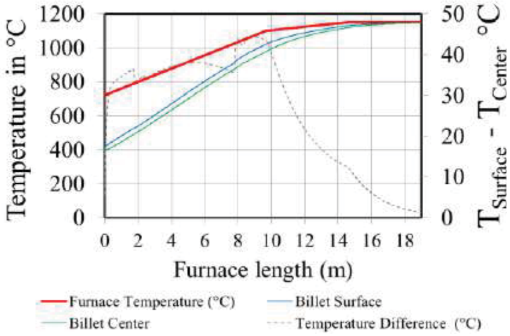

Figure 5 Result from the case with hot charge at 400 °C

The higher hot charge temperature shows the higher starting point of billet temperature and the lower temperature difference between surface and center of billet in preheating zone. The calculated specific fuel consumption results from energy balance model with different testing parameters are shown in Figure 6.

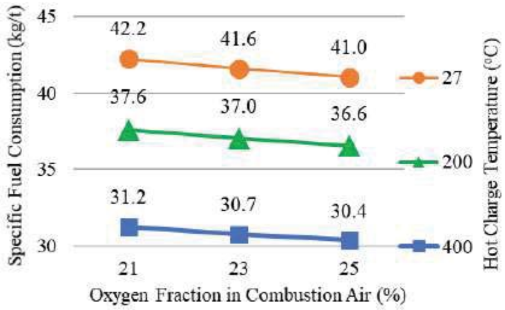

Figure 6 The results from the Energy Balance Model

From the results, different testing process parameters provide different specific fuel consumption as shown in Figure 6. It illustrates that at the same hot charge temperature, the higher oxygen proportion in combustion air can reduce the fuel oil consumption for a certain amount. For example, with billet charging temperature at

27 ºC, the specific fuel consumption was decreased from 42.5 kg/ t to 41.9 kg/ t with an increase in oxygen enrichment from 21% to 23%.

In this study, the hot charge temperature at 27 ºC (room temperature), 200 ºC and 400 ºC show that the increasing of hot charge temperature can reduces the fuel consumption significantly. For example, the specific fuel consumption was decreased from 42.5 kg/t to 37.8 kg/t with an increase in hot charge temperature from 27 ºC to 200 ºC.

From the Figure 9, the reduction rate of specific fuel consumption (the slope of the line) is higher when the temperature of hot charged billet is increased, since the steel enthalpy value in the hot charge billet has non-linear relationship to the temperature.

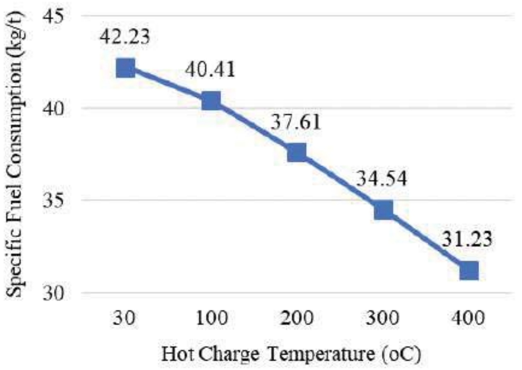

Figure 9 Specific fuel consumption reduction

Conclusion

Model of specific energy consumption with using of fuel oil as energy source has been developed in this study. The effects of oxygen enrichment and hot charge temperature were investigated by this energy balance model. The different oxygen proportion in the combustion air is able to reduce the specific fuel oil consumption to a certain extent. It has been shown that hot charge temperature has a significant effect in reheating furnace specific fuel consumption.

From the results, increasing of the hot charge temperature and oxygen proportion in reheating furnace process are able to reduce the specific fuel consumption. The results from the study will be useful for the cost analysis in the further improvement plan.

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