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Energy efficiency assessment by process heating assessment and survey tool (PHAST) and feasibility analysis of waste heat recovery in the reheat furnace at a steel company

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ABSTRACT

The steel industry is one of the most energy intensive industries, contributing greenhouse gas (GHG) emissions. This research analyzes the feasibility of waste heat recovery and assesses energy efficiency at a steel company, Gerdau Ameristeel in Selkirk, Manitoba. The process heating assessment and survey tool (PHAST) determined that the overall efficiency in the reheat furnace is 60%. Flue gas losses are the biggest energy losses in the reheat furnace, accounting for 29.5% of the total energy losses during full production. Heat losses from wall, hearth and roof are also significant, being 7,139,170 kJ/h during full production. To reduce energy inefficiencies, it is recommended that billets be preheated to 315 °C in the reheat furnace. This requires 1.48 h to capture waste heat with a preheating section length of 1691.64 cm. The annual energy savings are estimated to be $215,086.12 requiring a 3.03 years payback period. This study was the first to determine the required size of a preheating box and the rate of heat transfer through billets in the preheating section.

Contents

1. Introduction

Improving energy efficiency of all industries, including the steel industry, will reduce greenhouse gases [GHG]. Energy efficiency is considered the most cost-effective way to reduce energy consumption and increase production [1,2]. Edenhofer and Stern [3] recommend energy efficiency as the number one priority for the

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most developed countries (e.g., Global 20 top national economies) which would create a green global recovery. Current energy efficiency achievements are insufficient to stabilize atmospheric concentrations of GHG that will prevent dangerous anthropogenic interference with the climate system [4,5]. The International Energy Agency [6] reports that industry is half as energy efficient as it could be: "*The energy intensity of most industrial processes is at least 50% higher than the theoretical minimum determined by the laws of thermodynamics*". Industries are often not willing to implement energy efficiency due to: limited access to capital, its disruption of production, inappropriate technologies interfere with production and lack of capacity in efficiency assessment [7,8].

As the steel industry accounts for approximately 7% of global anthropogenic emissions of greenhouse gas equivalents [9], improving energy efficiency industry is particularly important. Steel production is estimated to emit 1500–1600 Mt CO_2 per year, including process related emissions and energy related emissions [9]. In the iron and steel sector, there are many opportunities to improve energy efficiency and reduce GHG emissions, including enhancing continuous production processes, waste energy recovery, and changing from primary to secondary production routes [10,11]. Worrell et al. [12] provided a detailed report of potential energy saving and CO_2 reduction from steelmaking in the US, proposing 47 energy efficiency practices and technologies. De Beer et al. [13] estimated that the global energy efficiency in the steel sector would be improved by 29% by 2020 using existing technologies, such as smelt reduction and near net shape casting. Iron and steel industries were pioneers of energy recovery. In the 19th century, iron and steel industries developed and installed techniques of waste energy recovery [14], which was widely implemented around the world, producing significant economical and environmental benefits. Energy efficiency in the steel industry continues to be innovative. North Star Steel's Wilton Iowa (which was acquired by Gerdau Ameristeel) plant completed a number of heat recovery projects in 2004 that included: (1) changing the reheat discharge skid base, which produced $122,950 energy saving per year, with a pay back period of 10 months; (2) modifying temperature combustion air for the reheat furnace produced $278,369 annual energy saving with a pay back period of 6.47 months [15]. A feasibility study of preheating billets was also conducted [15], but the size of the preheating box and the rate of heat transfer in the preheating box were not determined.

This study evaluates the energy efficiency of several operations at a Gerdau Ameristeel special sections steel making mill in Selkirk, Manitoba, Canada. Gerdau Ameristeel is the second largest mini-mill steel producer in North America, with an annual manufacturing capacity of over ten million metric tons of crude steel production in 2009 tons [16]. It is one of the largest consumers of energy in Manitoba using natural gas and electricity. Gerdau Ameristeel Manitoba (GAM) is a scrap-based electric arc furnace steel producer. In the first step of the GAM process scrap metal is melted into liquid steel in the electric arc furnace (EAF) at 1600 °C, then the liquid steel is sent to the ladle furnace where steel is homogenized, desulphurized and dephosphorized. The deoxidized, clean molten steel is then delivered to the tundish where the liquid steel supplies the continuous casting machine. The steel is casted directly into semi-finished shapes (slabs and billets). The semi-finished products are then stored at ambient outdoor temperature (2.7 °C) [17] at the billet bay before being transported to a reheat furnace where they are heated to 1200 °C. The temperature of billets in the preheating box needs to be spatially uniform in order to meet steel production requirement. As a sector initiative, steel companies explore the feasibility of capturing the reheat furnace's flue gas, averaging 815 °C, to preheat billets from ambient to 315 °C (600 F). The reheat furnace is 2286 cm long and currently individual billets need to be reheated in the furnace for approximately 2 h. Finally, semi-finished products are transported to the rolling mill and rolled into the finished products [18] (Fig. 1).

An analysis of the GAM operation found two areas that had high potential for energy efficiency namely: (1) recovering waste heat to preheat billets; and (2) assessing energy efficiency in the reheat furnace. Currently, the billet temperature drops from 1200 °C to ambient outdoor temperature, where the billets are stored after casting and then reheated to 1200 °C again. This study looks at preheating billets to 315 °C (600 F) using flue gas captured from the reheat furnace.

Energy efficiency was examined using the process heating and assessment survey tool (PHAST). PHAST was developed by the U.S. Department of Energy. Industries can survey heating equipment that consumes steam, electricity, or natural gas by this tool and identify the energy losses and energy efficiency potential.

The process heating assessment and survey tool (PHAST) worked well to analyze energy efficiency of reheat furnace considering all the necessary factors including: (1) heat absorbed by cooling water; (2) heat transmission through wall, hearth and roof; (3) heat radiation through opening areas (charge end and discharge end); (4) heat losses by flue gas and atmosphere infiltration; (5) atmosphere losses by air leaking into furnace. The rate and amount of heat losses in each category could be analyzed by inputting the following factors:

- Water losses: water flow rate, temperature difference between water in and out, etc.
- Wall, hearth and roof losses: outside area of furnace, thickness and thermal properties of refractories and insulation, surface temperature, etc.
- Opening losses: area of opening and by furnace inside temperature.
- Flue gas losses: flue gas temperature, combustion air temperature and oxygen in flue gas.
- Atmosphere losses: temperature difference between in and out atmosphere and atmosphere flow rate.

PHAST provides different scenarios of preliminary projections for energy efficiency projects. This study uses PHAST to consider efficiency in a reheat furnace in the steel sector. In addition, this study is the first to determine the size requirements of a preheating box and the rate of heat transfer through billets in the preheating box [15].

2. Methods

One of the semi-finished billet products was used to analyze energy efficiency in the reheat furnace and the rate of heat transfer in the preheating box. Analysis of this billet shape should be applicable to all products. The following steps were taken in this study:

Step 1: Measured structural data for reheat furnace including its dimensions, layer information, opening areas and wall information.

Step 2: Collected production data for the dates of April 9th 2010 (7:00–16:00), June 13th 2010 (20:15–23:50) and July 27th 2010 (2:30–7:00) including flue gas temperature, waste gas temperature, furnace temperature, water temperature, discharge temperature, inside temperature and opening cycle and time of charge and discharge ends at full production (85 ton/h), partial production (65 ton/h) and idling (0 ton/h). The temperatures for different variables were read every 5 min and averaged over the three days for this analysis.

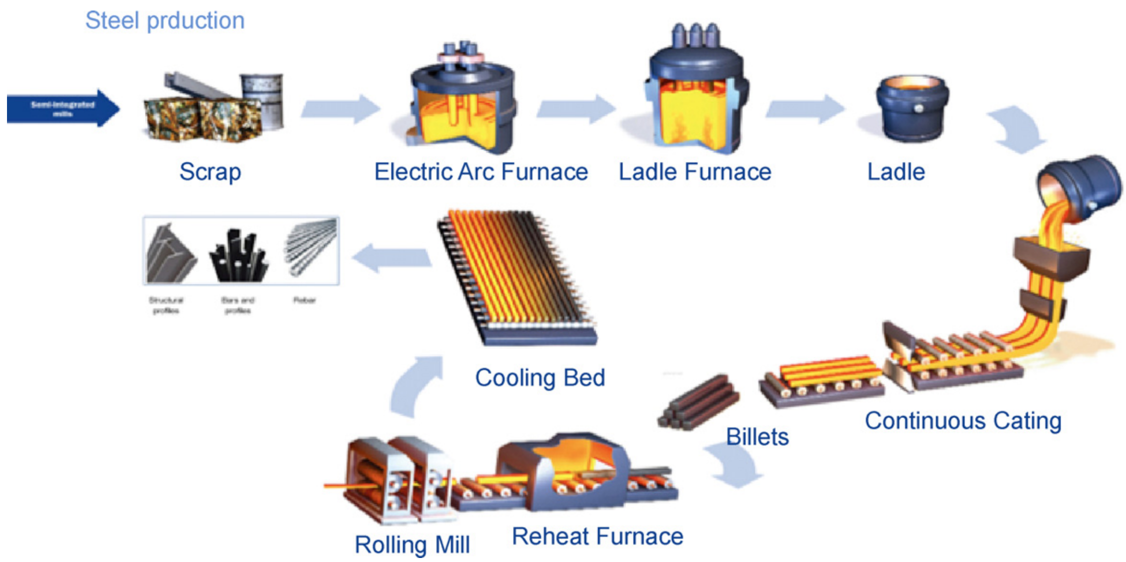

Fig. 1. Production process of an electric arc furnace (EAF) steel making operation, adapted from Gerdau Ameristeel [18].

Step 3: Calculated energy efficiency and energy losses into PHAST the full production, partial production and idling data.
Step 4: Determined heat transfer by the lumped capacitance method to determine billet heating time (from ambient to 315 °C) in the preheating box.

The heating time is calculated by Eq. (1):

$$\frac{\theta}{\theta_i} = \frac{T_{(t)} - T_a}{T_i - T_a} = \exp\left[-\left(\frac{hA_s}{\rho V c}\right)t\right] \quad (1)$$

where $T_{(t)}$: reached temperature, 315 °C (600 F); T_a: surrounding temperature, 815 °C (1500 F); T_i: body temperature, 2.7 °C (36 F); ρ: density, 7800 kg/m^3; c: heat capacity of steel, 440/JK; t: the heat time (s).

Biot number is used to validate the approach of the lumped capacitance method. The Biot number is calculated by Eq. (2)

$$Bi = \frac{hL_c}{k} \quad (2)$$

where B_i: Biot number; V: volume, 0.2 m (0.64 ft., width) × 0.2 m (0.64 ft., height) × 7.01 m (23 ft., length); A_s: area exposed to hot air, 0.2 m (0.64 ft.) × 0.2 m (0.64 ft.) × 2 + 3 × 0.2 m (0.64 ft.) × 7.01 m (23 ft.); L_C: characteristic length = V/A; h: convection coefficient, 20 W/m^2 K; k: thermal conductivity, 43 W/m K.

3. Results

The reheat furnace is 22.86 m (75 ft.) long, 1.22 m (4 ft.) high and 6.40 m (21 ft.) wide. The charge end has a curtain with a fixed opening area of 1.86 m^2. The discharge end has a variable opening area of 3.34 m^2. Billets are dropped out of the furnace every 10 s from the discharge end door. The main differences among full operation, partial operation and idling are furnace temperature, wall temperature, roof and hearth temperature, combustion air temperature and flue gas temperature. See Table 1.

3.1. Energy losses in the reheat furnace

3.1.1. Energy losses during peak production rate

Full production occurred approximately 50% of the time. The overall efficiency of the reheat furnace was 60.4% at full production rate. Although the reheat furnace has a recouperator for improving the combustion air temperature, the flue gas losses are still the largest area of heat loss in the reheat furnace. Flue gas losses accounted for 30% of energy lost amounting to 26,436,368 kJ/h (Table 2 and Fig. 2). Hearth and roof losses were the biggest energy loss in the net heat distribution, accounting for 9.5% of energy lost or 6,000,814 kJ/h. Water is used for cooling products at the discharge end in the reheat furnace. The temperature of water is measured by a temperature gauge, the water losses only accounted for 0.2% in the net heat distribution. The amount of atmosphere losses was 1,376,892 kJ/h. GAM does not have any fixture, basket or tray for materials handling, so there are no material handling losses in the reheat furnace.

Table 1
Differences of production parameters among full operation, partial operation, and idling.

	Full operation	Idling	Partial operation
Feed rate (kg/h)	77110.70	0	58967.0
Furnace inside temperature (°C)	1276.11	1196.67	1278.89
Wall surface temperature (°C)	232.78	141.11	232.78
Roof and hearth temperature (°C)	245	185.55	245
Combustion air temperature (°C)	396.11	321.11	401.11
Flue gas temperature (°C)	799.44	463.89	813.33

3.1.2. Energy losses during idling

Approximately 30% of the time the production line was idle with the flue gas temperatures dropping to 426.67 °C, which reduces flue gas losses by 95%, compared to losses at full production. However, the reheat furnace was not shut down maintaining temperatures of 1196 °C. Heat transmission from hearth and roof was the largest energy loss at 3,657,238 kJ/h (Fig. 2). The atmosphere losses during idling account for 22.1%, which was 20% higher than the losses in

Table 2
Gross heat distribution in the reheat furnace during 85 ton/h at MRM.

Area of heat consumption	kJ/h
Net load weight	54,155,711
Flue gas losses	26,436,368
Other losses (roof and hearth)	6,000,814
Atmosphere losses	1,376,892
Wall losses	1,138,356
Opening losses	396,768
Water losses	109,898
Fixture losses	0

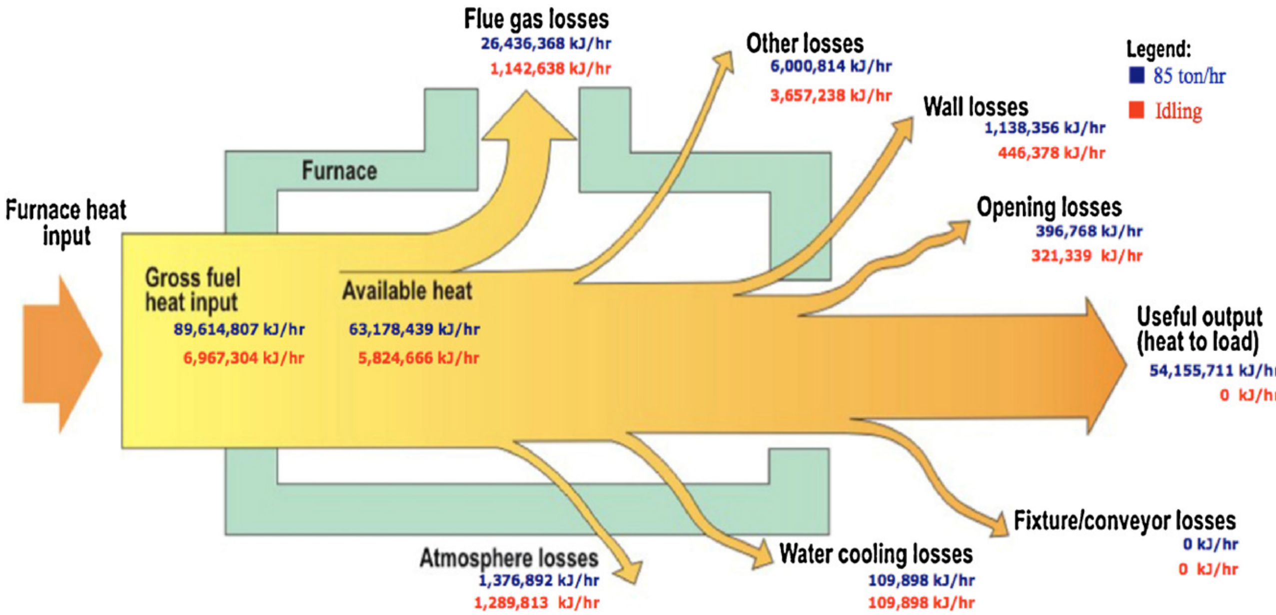

Fig. 2. Energy losses in the reheat furnace at GAM during 85 ton/h and idling production.

full production. The percentage of opening losses during idling was increased as well to 5.5% in the net heat distribution in contrast to 0.6% during peak production.

3.1.3. Energy losses during partial production

Approximately 20% of the time the production line was at partial production. The overall efficiency in the reheat furnace decreased to 57.5% during partial production. The energy intensity increased by 5%, compared with the energy intensity in the peak production. Flue gas temperature, combustion air temperature and atmosphere air temperature were slightly higher than the temperatures in the peak production, which resulted in the reduction of flue gas losses by 18% and the increase in atmosphere losses by 0.2%.

3.2. Heat transfer

As the Biot number of the billet is 0.03 (<0.1), the lump capacitance method can be used in the heat transfer calculation. The lump capacitance method predicts that preheating billets from ambient temperature to 315 °C needs 1.48 h with 815 °C flue gas. In order to keep the same velocity (19.05 cm/min) in the reheat furnace, the preheating section was calculated as requiring a length of 1691.64 cm.

4. Discussion

4.1. Energy efficiency improvement

This analysis of energy efficiency found four areas that improvements could be made.

4.1.1. Waste heat recovery

Waste heat from the reheat furnace can be reused for preheating billets, incoming water, etc., for which energy efficiencies can be calculated by PHAST. The heat required (kJ/h) in the reheat furnace will be reduced by 23.6% and the energy intensity (kJ/kg) will be reduced by 278.12 kJ/kg. Preheating billets to 315 °C will save $215,086.12 annually. Based on a $500,000 initial cost, $50,000 of annual maintenance cost and $6.48/GJ, a payback period of 3.03 years was calculated by cumulative cash flow. In addition, the length of the preheating box depends on the preheating temperature and flue gas temperature. The larger the difference between the preheating temperature and the flue gas temperature, the shorter preheating time is required. The waste heat from the reheat furnace can either go through a heat exchange system or be charged into billets directly. Waste heat directly contacting the billets will minimize the preheating time and reduce the heat losses in the exchange system.

4.1.2. Upgrading the charge end to improve energy efficiency

The charge end in the reheat furnace is a 100% fixed opening area. This opening area leaks cold air into the furnace, which must be heated before exiting through the flue system, wasting energy. The opening losses caused a 396,768 kJ/h energy loss, accounting for 14.5% and 2.1% energy loss during full production and idling, respectively. The discharge end has a door from which billets are dropped out of the furnace every ten seconds, so this opening cycle is variable. Upgrading the charge end to a variable opening end similar to the discharge end is proposed. PHAST estimates that this upgrade would reduce 83% of losses. The upgrading project will have $46,463 energy saving per year with a payback period of 4.2 years.

4.1.3. Control system to improve energy efficiency

In the reheating process, furnace pressure and temperature control have significant effects on energy efficiency improvement. Empirical research stated that keeping furnace temperature and pressure at an optimal level will increase the combustion efficiency and reduce flue gas losses [19–22]. The negative pressure inside a reheat furnace can cause ambient air to enter into the reheat furnace, which needs extra energy to heat the leakage air to flue gas temperature. In this study, the atmosphere losses accounted for 2.2% with 1,376,892 kJ/h during peak production. When operation is at partial production, the atmospheric pressure is slightly increased by 0.2%. Furnace pressure controller can keep a positive pressure in the furnace chamber to reduce atmosphere losses.

4.1.4. Maximize furnace operation capacity

Keeping furnace operation at its peak capacity can maximize energy used per unit of production. By contrast, idle and partial operations in the reheat furnace are much less efficient. In this study, during partial production, the overall efficiency dropped to 56.4% compared with 60.43% at full production, and the energy intensity increased by 6%. Due to partial operation 268 GJ was wasted directly in 2009. Therefore, better scheduling and loading of the furnace should be taken into consideration by production planners to increase energy saving.

5. Conclusions

There are many opportunities for energy efficiency that are feasible. Preheating billets by waste heat to 315 °C will need 1.48 h, and result in approximately $215 thousand in annual energy saving with a three year payback period. Preheating will significantly reduce flue gas losses, heat required and energy intensity in the reheat furnace. This study shows that preheating billets is feasible. The heat needs to be used directly on the billets without requiring heat exchangers. As the reheat process is an essential process in steel manufacturing, requiring lots of energy, this finding regarding preheating can be used to reduce energy and GHG widely in the steel sector.

The overall efficiency of the reheat furnace is about 60% according to PHAST at full production. Flue gas losses are the biggest energy losses. Minimizing flue gas losses will maximize the energy efficiency in the reheat furnace by heat recovery. Upgrading the charge end from a fixed opening to a variable opening is also feasible, which would reduce opening losses by 83% and result in $46 thousands in energy saving. Finally, adding insulation to wall, roof and hearth should be considered.

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