Exergoeconomic Analysis of a 70t/h Metal Heating Furnace

Ion V. Ion, Florin Popescu, Simona Paraschiv, Spiru Paraschiv

Exergoeconomic Analysis of a 70t/h Metal Heating Furnace: *Fuel-fired furnaces for metal heating are energy intensive plants with one of the lowest energy efficiencies. For this reason, measures to increase the efficiency are welcome, given the rising cost of fuel and increasingly restrictive legislation regarding pollutant emissions. The most available powerful method used to identify the less efficient processes and components of an energy system is the exergoeconomic method. In this paper the exergoeconomic analysis of a continuous furnace with heating capacity of 70t billets/h is performed.*

Key words: *Metal Heating Furnace, Exergy, Exergoeconomy.*

INTRODUCTION

The ways to increase the efficiency of energy systems are well established by the thermodynamics, but not the ways to increase the economic efficiency. One of methodologies to assess the effectiveness of an energy system became known as thermoeconomy or exergoeconomy [1, 2, 3]. Exergoeconomy offers to designers or users of energy systems information which are crucial in the economically efficient design and operation of system. Knowing the real cost of each energy and material stream in system is useful in identifying less economic efficient processes and to choose technical solutions to improve system efficiency. In this paper the exergoeconomic analysis is applied to a metal heating furnace in order to determine factors that influence the cost of heated billets and to find the ways of improving.

PLANT DESCRIPTION

The 70t/h furnace with mechanical pushers is used to heat billets before being rolled. The furnace is equipped with 24 natural gas burners (9 burners of 150 Nm^3/h, 6 burners of 200 Nm^3/h and 9 burners of 100 Nm^3/h). The combustion gases are evacuated from furnace through underground channels and driven through heat recovery boiler and air preheater by using an exhauster. Pressure adjustment inside the furnace is made with a rotating register placed in flue gas channel after the air preheater. The main furnace parameters are given in Table 1.

Table 1. Operating parameters

Ambient air: 15°C, 1.013 bar, 60% relative humidity		
Mass rate of billets entering the furnace	kg/s	17.61
Mass rate of billets exiting the furnace	kg/s	17.33
Mass rate of burnt metal in furnace	kg/s	0.26
Fuel flow rate	m^3_N/s	0.412
Combustion air flow rate (λ_f = 1.05)	m^3_N/s	4.13
Billet temperature at furnace entrance	°C	230
Billet temperature at furnace exit	°C	1200
Preheated air temperature	°C	475
Flue gas temperature at furnace exit	°C	1400
Flue gas temperature at air preheater exit	°C	433
Flue gas temperature at stack	°C	157
Cooling water temperatures	°C	22/45
Cooling water flow rate	m^3_N/s	0.05
Cooling water pressure	bar	3
Saturated steam generated		
- temperature	°C	188
- pressure	bar	12
- flow rate	kg/s	1.94
Excess air coefficient		

- at furnace exit	-	1.15
- at air preheater exit	-	1.35
- at heat recovery steam boiler exit	-	1.54
Fuel: Natural gas		
Low heating value	kJ/Nm^3	35888
CH_4	(% mas)	97.7
C_2H_6	(% mas)	0.5
C_3H_8	(% mas)	0.35
C_4H_{10}	(% mas)	0.15
H_2S	(% mas)	0.35
N_2	(% mas)	0.8
CO_2	(% mas)	0.15

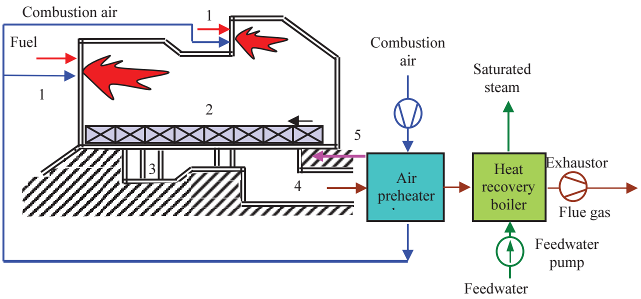

Fig.1. Sketch of 70t/h metal heating furnace: 1- natural gas burners; 2 - billets; 3 - support gliders; 4 – flue gas channel; 5 – gliders cooling water

ENERGY AND EXERGY ANALYSES

The energy and exergy analyses are performed at the furnace component level. The data used in analyses are given in Table 2.

Table 2. Used data

Air specific heat	*1.004 kJ/(kg·K)*
Flue gas specific heat	*1.17 kJ/(kg·K)*
Specific heat of billets	*0.711 kJ/(kg·K) at 230°C* *0.4 kJ/(kg·K) at 1200°C*
Generated heat by metal oxidation	*5694.2 kJ/kg*
Absobed heat during phase change from gamma-Fe to alpha-Fe	*50.22 kJ/kg*
Furnace flame emissivity	*0.90*
Emissivity of furnace opennings (opennings area = 5.5 m^2)	*0.65*
Heat flow rate lost through furnace wall	*6.61 kW/m^2*
Heat lost through steam boiler wall and air preheater wall	*2580 $kJ/(m^2·h)$*

In Figure 2 are presented as a percentage the outgoing heat flows from furnace plant, and in Figure 3 is shown the furnce Sankey diagram. It can be seen that the useful heat flow (heat contained in billets and generated steam) represents 73.14% of the total input heat flow, the remaining 26.86% being thermal losses of the plant. The largest losses are produced by the evacuation of flue gas stack (10.78%) and are followed by losses through endothermic reactions (4.71%) and losses through the furnace walls (4.53%). The smallest losses are caused by cooling water (0.03%) and those that occur through openings (0.01%).

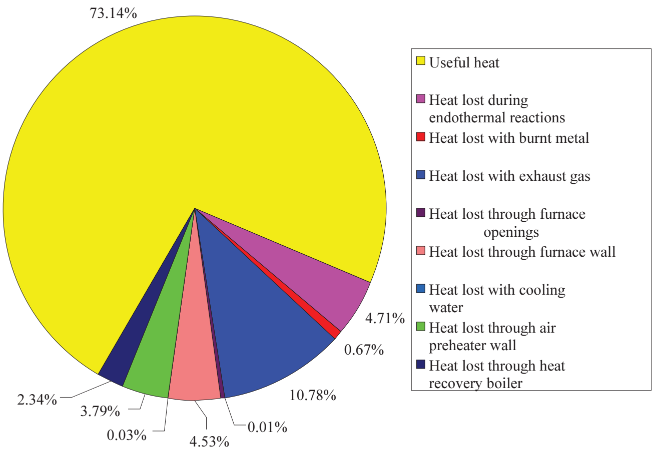

Fig.2. Furnace heat output

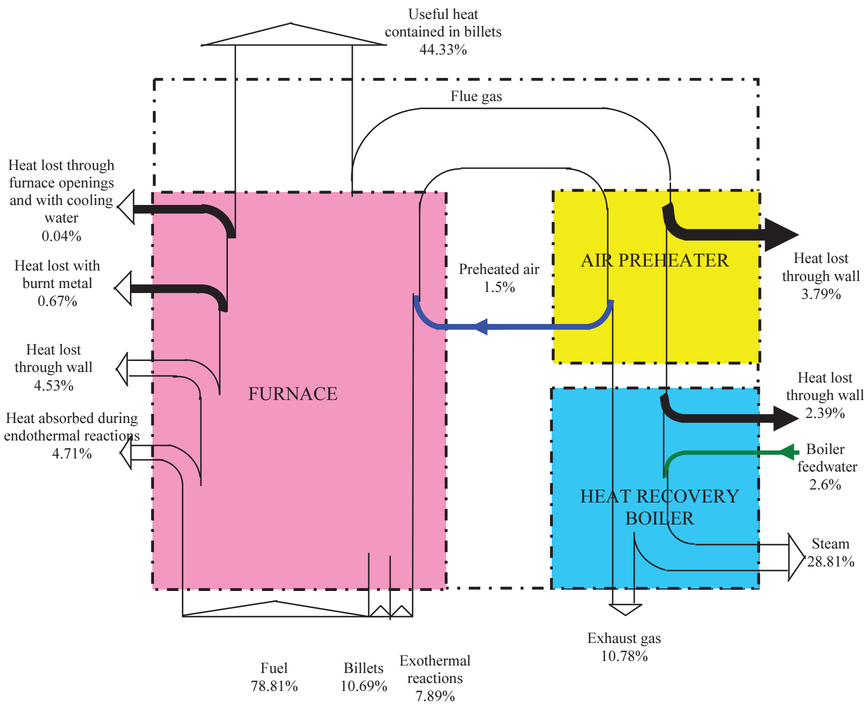

Fig.3. Sankey diagram of furnace plant

Exergy analysis is divided into two parts: the first part analyses the adiabatic combustion process and the second the heat transfer process in the furnace, air preheater and heat recovery boiler respectively. The main sources of exergy destruction in the furnace are: fuel combustion (reactants diffusion, oxidation reaction, heat exchange between chemical species, mixing of reaction products); heat exchange at finite temperature difference between flue gas and metal, combustion air and water; flow of flue gas, air and water with pressure loss. Compared to thermal efficiency, exergy efficiency is much lower (32% vs 58.81%). This is explained by the fact that unlike energy, exergy is not conserved, it can be destroyed and lost. The percentage values of exergy loss and destroy that occur in the plant components are: 23.91% in combustion chamber; 4.8% in furnace 4.22% in heat recovery boiler and 2.83% in air preheater.

In Figure 4 the furnace exergy balance is represented as Grassmann diagram. For thermodynamic performance analysis (flows of lost and destroyed exergy through fuel combustion and heat exchange in plant components) was done the graphic representation in Figure 5.

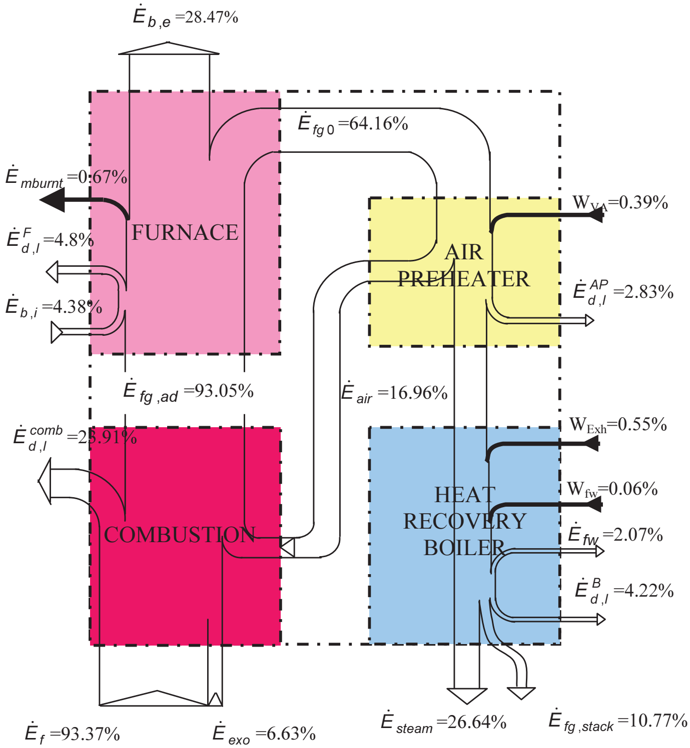

Fig.4. Grassmann diagram of furnace plant

In the combustion process occurs the largest exergy destruction, followed by the heat exchange process in heat recovery boiler, air preheater and furnace.

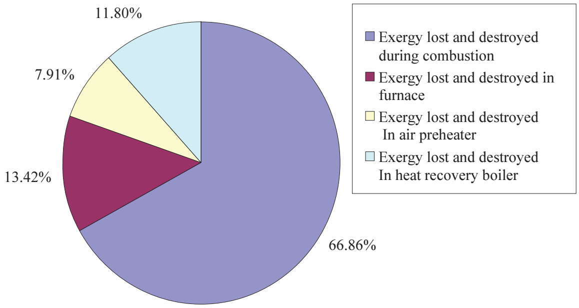

Fig.5. Exergy destroyed and lost in furnace plant

THERMOECONOMIC ANALYSIS

The exergetic cost of heated billets leaving the furnace is calculated using the following balance equation, written for steady state operation [1]:

$$\dot{C}_{b,e} = \dot{C}_f + \dot{C}_{b,i} + \dot{C}_{el} + \dot{C}_{fw} - \dot{C}_{steam} + \dot{Z} \quad [€/s] \tag{1}$$

where: $\dot{C}_f$ - cost rate associated with fuel exergy:

$$\dot{C}_f = c_{e,f} \cdot \dot{E}_f$$

$c_{e,f}$ – cost per unit of fuel exergy ($5.54 \cdot 10^{-6}$ €/kJ);

$\dot{E}_f$ – fuel exergy flow calculated from the exergy analysis;

$\dot{C}_{fw}$ - cost rate associated with feedwater exergy:

$$\dot{C}_{fw} = c_{e,fw} \cdot \dot{E}_{fw}$$

$c_{e,f}$ – cost per unit of feedwater exergy ($4.02 \cdot 10^{-4}$ €/kJ [6]);

$\dot{C}_{el}$ - cost rate associated with electrical power driving the air fan, exhauter and feedwater pump:

$$\dot{C}_{el} = c_{el}\left(W_{fw} + W_{af} + W_{exh}\right)$$

c_{el} – cost per unit of electricity ($1.82 \cdot 10^{-5}$ €/kJ);

$\dot{C}_{steam}$ - cost rate associated with generated steam:

$$\dot{C}_{steam} = c_{e,steam} \cdot \dot{E}_{steam}$$

$c_{e,steam}$ - cost per unit of steam exergy ($c_{e,steam} = 1.33 \cdot 10^{-5}$€/kJ [6])

$\dot{Z}$ - cost rate associated with capital investment and maintenance costs [3]:

$$\dot{Z} = \frac{Z \cdot CRF \cdot \varphi}{N \cdot 3600} \quad [€/s]$$

Z – purchase cost of plant (84650 € [6]);

CRF – annual capital recovery factor (CRF = 18.2% [3])

φ – maintenance factor (φ = 1)

N - number of hours of plant operation (N = 7000 h/an)

$\dot{C}_{b,i}$ - rate cost associated with billets exergy entered into furnace:

$$\dot{C}_{b,i} = c_{e-b,i} \cdot \dot{E}_{b,i} \quad [€/s]$$

$c_{e\text{-}b,i}$ – specific exergy cost of billets enetered into furnace ($1.17 \cdot 10^{-2}$ €/kJ).

From equation (1) results the specific exergy cost of billets leaving the furnace $c_{e\text{-}b,e} = 2.3 \cdot 10^{-3}$ €/kJ. The specific billets cost increases from 0,488 €/kg to 0,661 €/kg.

The cost rate associated with exergy destroy and loss is:

$$\dot{C}_{ex,d,l} = c_{e,f} \sum_k \dot{E}^k_{d,l} = 0.036 \text{ €/s}$$

where $\sum_k \dot{E}^k_{d,l}$ is the sum of destroyed and lost exergy flows in plant.

In Figure 6 it can be seen contribution of various cost categories in formation of heated billets cost. The highest contribution has the cost of steel stock (96.68%), followed by cost of fuel (2.84%) and capital investment and maintenance cost (0.35%).

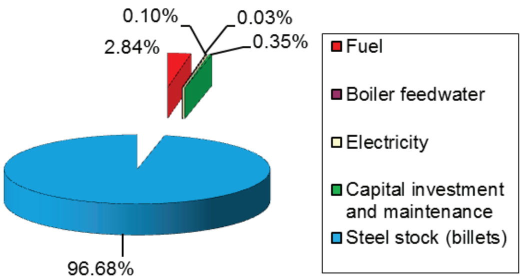

Fig.6. Contribution of different costs to cost formation of heated billets

CONCLUSIONS

Energy analysis revealed that heat loss with exhaust gas to stack has the highest percentage (10.78%). As energy analysis, exergy analysis revealed that exergy flow of exhaust gas to stack has the highest value of exergetic losses of the plant. Exergoeconomic analysis revealed that for constant costs of fuel, electricity, feedwater and steel stock, the key functional parameters determining the cost of heated billets are:

- heated material flow. For this reason, the furnace load should be as close to the nominal one, which is characterized by minimum fuel consumption;
- fuel flow, which depends on combustion exergy efficiency;
- power used by air fan, exhauster and feedwater pump;
- coefficient of excess air in the furnace, which determines the temperature inside the furnace;
- temperature of exhaust gas to stack.

The exergoeconomic analysis reveals that the highest contribution to cost formation of heated billets has the cost of steel stock (96.68%), followed by cost of fuel (2.84%) and capital investment and maintenance cost (0.35%). Therefore, the solutions to reduce the cost of heated billets are: increasing the exergy efficiency of furnace (combustion improvement, recovery of heat contained in billets and cooling water) and optimal control of air fan and exhauster to reduce electricity consumption.

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About the authors:

Assoc. Prof. Ion V. Ion, PhD, Department of Thermal Systems and Environmental Engineering, “Dunarea de Jos” University of Galati, E-mail: iion@ugal.ro

Prof. Florin Popescu, PhD, Department of Thermal Systems and Environmental Engineering, “Dunarea de Jos” University of Galati, E-mail: florin.popescu@ugal.ro

Assist. Prof. Simona Paraschiv, PhD, Department of Thermal Systems and Environmental Engineering, “Dunarea de Jos” University of Galati, E-mail: Simona.Craciun@ugal.ro

Assist. Prof. Spiru Paraschiv, PhD, Department of Thermal Systems and Environmental Engineering, “Dunarea de Jos” University of Galati, E-mail: sparaschiv@ugal.ro

This paper has been reviewed.