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SECOND LAW ANALYSIS OF A FURNACE FOR METAL HEATING

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ABSTRACT

The industry represents an important sector of the final energy consumption and despite the effort made so far, energy saving potential still remains in this sector. This paper presents an example of energy efficiency improvement in a furnace for metal heating by adjustment of burners and recovery of heat. The useful concept of exergy is used to investigate the exergy efficiencies of the furnace operating in different situations: with air preheating using the waste heat contained in exhaust gases and with different air excess. The overall exergy efficiency of the furnace decreases with the increase of air excess and increases from 29.65% to 52% by using air preheating. The exergy efficiency of combustion is higher (70%) than the exergy efficiency of heat transfer from flue gas to metal (36.4%).

KEYWORDS: furnace, exergy, efficiency, heat recovery

1. Introduction

Energy efficiency improvement is one of major concerns in all EU countries as the main objective of the EU 20-20-20 directive is to reach the following climate targets by 2020: a 20% reduction in greenhouse gas emissions, a 20% improvement in energy efficiency, and a 20% share for renewable in the EU energy mix.

Furnaces are the most common and important facilities in metal industries. The product heating in furnace is accompanied by heat losses in different areas and forms such as: stored heat in furnace structure; heat losses through furnace walls; material handling losses; cooling media losses; radiation (opening) losses; loss due to air infiltration and wasted heat in exhaust gases. Thermal efficiency of furnaces used as heating equipments is low due to the heat losses mainly by heat in exhaust gases. The energy efficiency improvement can be achieved by implementation of energy management, optimisation of energy flows and improving the existing facilities by optimisation of thermal insulation, adjustment of burners, use of efficient burners, recovery of heat, installation of variable speeds on engines. Implementation of the above mentioned improvements is well analysed using exergetic approaches which take into account the quality of the energy used.

This paper presents an example of energy efficiency improvement in a furnace for metal heating by adjustment of burners and recovery of heat. The improvements are analysed using the exergy approach.

Energy analysis cannot offer information on the location, cause, and true magnitude of waste and loss. Energy can neither be produced nor consumed; it is always conserved-a first law concept. The second law of thermodynamics that is exergy analysis provides better understanding of the process, to quantify sources of inefficiency, to distinguish quality of energy used [1]. For real processes, that are irreversible processes, exergy is not in balance, it is partly consumed due to irreversibilities. This exergy consumption is called exergy destruction. The exergy output consists of the utilized output and non-utilized output, i.e. exergy of waste output. This latter part is entitled exergy waste. It is very important to distinguish between exergy destruction caused by irreversibilities and exergy waste due to unused exergy, i.e. exergy flow to the environment. Both represent exergy losses, but irreversibilities have, by definition, no exergy and no environment effects [2].

2. Description of furnace for forging

The furnace for forging is schematically shown in Figure 1. The fuel used is natural gas with the following composition: CH_4=97.9%, C_2H_4=0.8%, N_2=1.2%, CO_2=0.1% and the lower heating value of 35420 kJ/Nm^3.

The furnace heating capacity is 315 kg per charge and the total time of heating is 1.7 hours. The furnace operation parameters are shown in Table 1.

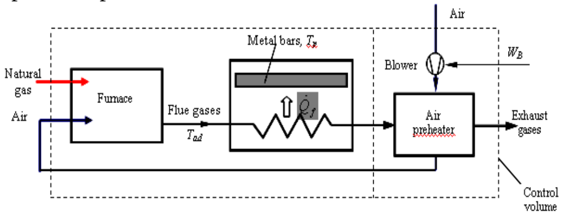

Figure. 1. Schematic diagram of the furnace for forging

Tab 1. Operation data for forging furnace (metal bars heating)

Parameter	Without combustion air preheating	With combustion air preheating
Capacity (kg of metal parts) (steel with 0.5% carbon)	315 kg	315 kg
Total time for heating	1.7 hours	1.7 hours
Natural gas flow rate, *B*	20.14 Nm^3/h	13.68 Nm^3/h
Combustion air flow rate	227 Nm^3/h	154.17 Nm^3/h
Air fan power, W_A	250W	
Initial temperature of metal parts	20°C	
Final temperature of metal parts	850°C	
Specific heat of steel	c_p(20°C) = 0.42 kJ/(kg·grd) c_p(850°C) = 0.685 kJ/(kg·grd)	
Initial temperature of combustion air	20°C	
Temperature of preheated air	-	772.7°C
Exhaust gases temperature	1054°C	120°C

3. Second law analysis

The adiabatic temperature results from energy balance of combustor:

$$\eta_c \cdot LHV + m_{ca} \cdot c_{p,a}(T_a) \cdot T_a = c_{p,cp}(T_{ad}) \cdot T_{ad} \quad (3.1)$$

where: η_c=0.99, combustor efficiency;

LHV=49610 kJ/kg (lower heating value of natural gas);

m_{ca} – mass of combustion air, kg air/(kg fuel)

$c_{p,a}(T)$ - air specific heat, kJ/(kg air·K).

Specific heat as a function of temperature (temperature range: 273-1800 K) is calculated for the different gases as it is shown in Table 2 [5];

$c_{p,cp}(T)$ – specific heat of combustion products, kJ/(kg·fuel·K):

$$c_{p,cp}(T) = c_{p,CO_2}(T) \cdot m_{CO_2} + c_{p,O_2}(T) \cdot m_{O_2} + c_{p,H_2O}(T) \cdot m_{H_2O} + c_{p,N_2}(T) \cdot m_{N_2} + c_{p,SO_2}(T) \cdot m_{SO_2} \quad (3.2)$$

Tab 2. Ideal-gas specific heats of various gases

$c_p(T) = A_0 + B_0 T + C_0 T^2 + D_0 T^3$				
Substance	A_0	B_0	C_0	D_0
Air	0.97034	$0.6789 \cdot 10^{-4}$	$1.657 \cdot 10^{-7}$	$-6.786 \cdot 10^{-11}$
Nitrogen	1.0316	$-0.5608 \cdot 10^{-4}$	$2.884 \cdot 10^{-7}$	$-1.0256 \cdot 10^{-10}$
Oxygen	0.7962	$4.75 \cdot 10^{-4}$	$-2.235 \cdot 10^{-7}$	$4.1 \cdot 10^{-11}$
Water vapor	1.789	$0.106 \cdot 10^{-4}$	$5.856 \cdot 10^{-7}$	$1.995 \cdot 10^{-10}$
Carbon dioxide	0.505	$1.359 \cdot 10^{-3}$	$-7.955 \cdot 10^{-7}$	$-1.697 \cdot 10^{-10}$
Sulfur dioxide	0.4028	$9.0547 \cdot 10^{-4}$	$-5.9562 \cdot 10^{-7}$	$1.3456 \cdot 10^{-10}$

The exergy balance for combustor (the exergy associated with the entering matter is equal to the exergy of the exiting matter plus the irreversible destruction of exergy associated with the combustion) is:

$$E_f + E_a = E_{fg} + I \text{ [kJ/(kg fuel)]} \quad (3.3)$$

where: E_f - chemical exergy of natural gas. It is evaluated according to Kotas [3]:

$$E_{uo} = \varphi \cdot LHV = 1.04 \cdot 49610 = 51594 \quad (3.4)$$

kJ/(kg fuel)

E_a - exergy of combustion air:

$$E_{ca} = m_{ca}\left(\int_{T_0}^{T_{ca}} c_{p,a}(T)\left(1 - \frac{T_0}{T}\right)dt + R_a T_0 \ln\frac{p}{p_0}\right) \quad (3.5)$$

[kJ/(kg fuel)]

R_a=0.2868 kJ/(kg·K) – air gas constant;

E_{fg} - exergy of flue gases:

$$E_{fg} = \underbrace{E_{cp}^{TM}}_{\text{thermomechanical exergy}} + \underbrace{E_{cp}^{ch}}_{\text{chemical exergy}} = \int_{T_0}^{T_{ad}} c_{p,cfg}(T)\left(1 - \frac{T_0}{T}\right)dT + \left(\sum_k n_k \varepsilon_k^0 + 8.314\, T_0 \sum_k n_k \ln x_k\right) \quad (3.6)$$

(1) ε_k^0 - molar standard chemical exergy, kJ/kmol (Table 3) [3];

Tab 2. Molar standard chemical exergy [3]

Substance	Molar mass M, kg/kmol	Molar standard chemical exergy ε^0, kJ/kmol
Air	28.97	0
Nitrogen	28.013	720
Oxygen	31.999	3970
Water vapor	18.015	11710
Carbon dioxide	44.01	20140
Sulfur dioxide	64.062	303 500

The exergy destruction can also be expressed as:

$$I = T_0 S = T_0\left[\sum_i (n_i s_i)_{out} - \sum_i (n_i s_i)_{in}\right] = S_{in} - S_{out} \quad (3.7)$$

where: S_{in}, S_{out} - entropy flow corresponding to reactants (air and fuel) and combustion products, respectively:

$$S_{in} = m_{ca} s_a(T_{ca}, p_0) + s_f(T_0, p_0)$$
$$S_{out} = \sum_k m_k s_k(T_{ad}, p_0) \quad (3.8)$$

s_a - air entropy;
s_f - fuel entropy;
S_{out} - exhaust gases entropy.

The exergy efficiency of combustion, defined as the ratio of energy outputs to exergy inputs is:

$$\eta_{comb} = \frac{E_{fg}}{E_a + E_f} \tag{3.9}$$

The exergy efficiency of heat transfer from hot flue gases to metal is given by the following equation:

$$\eta_{hex} = \frac{E_{metal}}{E_{fg} - E_{fg,exh}} \tag{3.10}$$

where: E_{metal} - exergy of metal parts: $E_{metal} = m \cdot e_t$;
m – metal mass inside the furnace, kg;
e_t – specific exergy of metal [3]:

$$e_t = e_t^{ph} + e_t^{ch} = c_p\left(T - T_0 - T_0 \ln\frac{T}{T_0}\right) + e_t^{ch} \text{ [kJ/kg]} \tag{3.11}$$

c_p – specific heat at constant pressure of metal, kJ/(kg·K);
e_t^{ch} - chemical exergy of steel [3]:
e_t^{ch} = 6763.84 kJ/kg;
$E_{fg,exh}$ - exergy of flue gases at furnace outlet.

Variations of exergy efficiency of combustion, heat transfer inside the furnace and adiabatic temperature with variation of excess air for two cases with and without air preheating are given in Figures 2, 3 and 4.

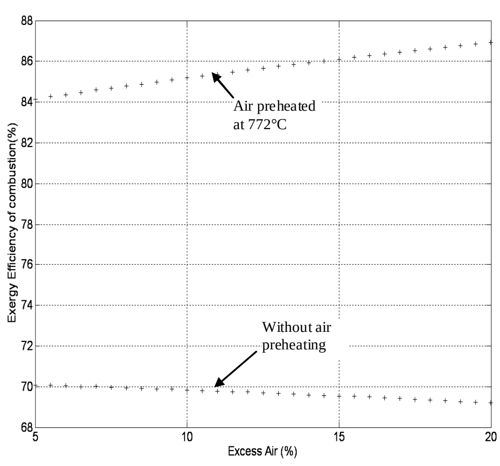

Fig. 2. Exergy efficiency of combustion with and without air preheating

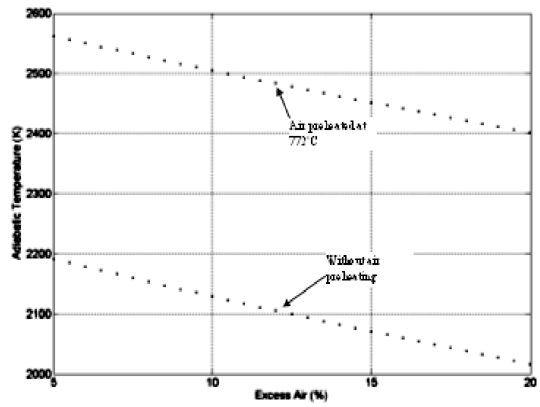

Fig.3. Adiabatic temperature with and without air preheating

(7)

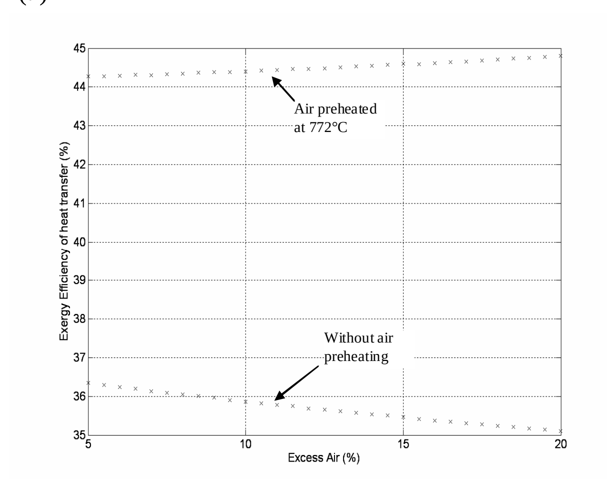

Fig. 4. Exergy efficiency of heat transfer from flue gas to metal with and without air preheating

The exergy efficiency of furnace in both cases of operation with and without air preheating as function of air excess is given in Figures 5 and 6.

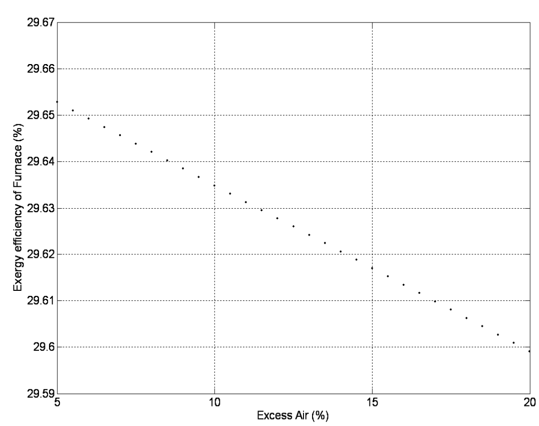

Fig. 5. Exergy efficiency of furnace

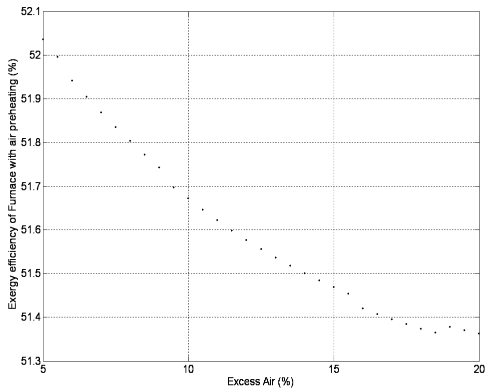

Fig. 6. Exergy efficiency of furnace with heat recovery for air preheating.

4. Conclusions

The adiabatic temperature inside the furnace decreases with the increase of air excess. The increase of adiabatic temperature due to air preheating is about 370K from 2200K.

Exergy efficiency of combustion and exergy efficiency of heat transfer in the case without air preheating decreases slightly with the increase of excess air and increases with excess air in the case of air preheating.

The exergy efficiency of combustion is higher than exergy efficiency of heat transfer (70% compared to 36.4%).

The exergy efficiency of furnace increases from 29.65% to 52% when the waste heat in exhaust gases is recovered to preheat combustion air.

In both cases of furnace operation, with and without air preheating, the exergy efficiency of furnace decreases with increasing of excess air.

The second law analysis of a furnace highlighted the directions of energy improvements: enhancement of heat transfer from flue gases to metal parts, recovery of heat waste contained in exhaust gases and burner adjustment.

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