THE ANNALS OF "DUNAREA DE JOS" UNIVERSITY OF GALATI
FASCICLE IX. METALLURGY AND MATERIALS SCIENCE
N°. 4 – 2014, ISSN 1453 – 083X

METAL HEATING FURNACE WITH FLUE GAS CONDENSATION. A THERMOECONOMIC ANALYSIS

Daniela PANĂ[a], Ion V. ION[b], Marcel DRĂGAN[b]
"Dunarea de Jos" University of Galati, Romania
[a]Department of Engineering Sciences and Management
[b]Department of Thermal Systems and Environmental Engineering
e-mail: daniela.pana@ugal.ro

ABSTRACT

The heat treating furnaces are one of the largest energy consumers in the manufacturing sector and therefore many techniques to improve their energy efficiency have been developed. One of them focuses on the recovery of the heat contained in exhaust gases and its use to preheat combustion air/charge or to generate steam. The maximum amount of recovered heat is obtained when the flue gases are cooled down below dew point temperature in order to recover the latent heat of water vapor in flue gases. The use of a condensing economizer in a 70 t/h heat treating furnace allows the decrease of the cost of heated metal bars by 0.32%, which means a cost saving of 158 lei/h.

KEYWORDS: furnace, exergy, efficiency, heat recovery

1. Introduction

The heat treating furnaces operate with low efficiency due to the high temperature at which the flue gases have to leave the furnace (higher than the load temperature). That is why the largest amount of the heat supplied in the heating process is wasted in the form of sensible and latent heat contained by the exhaust gases.

This wasted heat by exhaust gases depends mainly on the design and operation of the heating equipment. A significant reduction of this waste can be obtained by heat recovery in order to preheat the load or combustion air or to generate steam. The amount of heat to be recovered from exhaust gases depends on the temperature at which the flue gases are cooled down. After the preheating of load or combustion air, or the steam generation, the exhaust gases usually have a temperature of about 200 °C. At this temperature the exhaust gases still contain a large amount of heat which can be recovered by cooling them down below the dew point in order to recover both the sensible and the latent heat of water contained in flue gases.

The dependence of the enthalpy of flue gases on temperature is almost linear when the temperature is above the dew pint temperature and has a parabolic profile for temperatures below the dew point (Fig. 1).

In this paper the thermoeconomic analysis of a 70 t/h heat treating furnace with flue gases condensation for steam generation is performed.

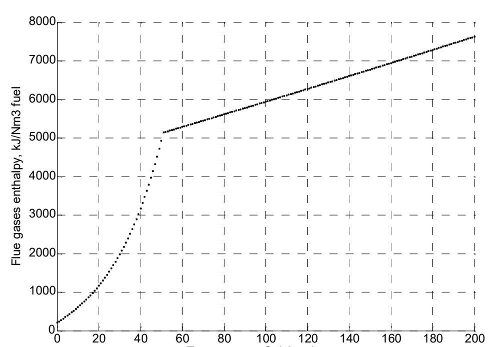

Fig. 1. *Enthalpy of flue gases vs temperature (natural gas, stack air excess λ=1.4)*

2. Enthalpy of flue gases

The enthalpy of flue gases is calculated with the following equations:

- for temperatures above dew point: eq. (1);
- for temperatures below dew point: eq. (2);

$$h_{fg}(T) = m_{CO_2}h_{CO_2}(T) + m_{N_2}h_{N_2}(T) + m_{O_2}h_{O_2}(T) + m_{SO_2}h_{SO_2}(T) + m_{H_2O}\left[h_{H_2O}(T) + h_l\right] \text{ [kJ/Nm}^3\text{ fuel]} \quad (1)$$

$$h_{fg}(T) = m_{CO_2}h_{CO_2}(T) + m_{N_2}h_{N_2}(T) + m_{O_2}h_{O_2}(T) + m_{SO_2}h_{SO_2}(T) + m_{H_2Osat}\left[h_{H_2O}(T) + h_l\right] + \left(m_{H_2O} - m_{H_2Osat}\right)c_{pW} \cdot T \text{ [kJ/Nm}^3\text{ fuel]} \quad (2)$$

where:

$m_{CO_2}, m_{H_2O}, m_{N_2}, m_{O_2}, m_{SO_2}$ - mass of CO_2, H_2O, N_2, O_2 and SO_2 in flue gases;

$h_{CO2}(T)$, $h_{SO2}(T)$, $h_{H2O}(T)$, $h_{N2}(T)$, $h_{O2}(T)$ – enthalpy of CO_2, SO_2, H_2O, N_2 and O_2 corresponding to temperature *t*, [kJ/kg];

h_l– latent heat of water vapour, [kJ/kg]; h_l = 2502 kJ/kg.

m_{H_2Osat} - mass of water vapour in flue gases at saturation temperature T_s:

$$m_{H_2Osat} = x_{fgs} \cdot m_{fgd} \text{ [kg water/ Nm}^3\text{ fuel]} \quad (3)$$

$$m_{fgd} = m_{CO_2} + m_{O_2} + m_{N_2} + m_{SO_2} \text{ [kg dfg/Nm}^3\text{ fuel]} \quad (4)$$

x_{fgs} – absolute humidity of flue gases at saturation:

$$x_{fgs} = 0.622\frac{p_s}{p_{dfg}} \quad (5)$$

$$p_{dfg} = 1.013 \cdot 10^5 \frac{V_{CO2} + V_{O2} + V_{N2} + V_{SO2}}{V_{ga}} \quad (6)$$

$$p_s = 610.78 \cdot e^{17.2694\frac{t}{(t+238.3)}} \quad (7)$$

c_{pw}– specific heat of liquid water, [kJ/kg·K]

$$c_{pw} = 2820 + 11.82 \cdot T - 0.03502 \cdot T^2 + 0.00003599 \cdot T^3 \quad (8)$$

The dew temperature of flue gases can be calculated by the following equation [1]:

$$T_d = 1000/\left[2.20732 - 2.117187 \cdot 10^{-1}\ln m - 2.166605 \cdot 10^{-3}(\ln m)^2 + 1.619692 \cdot 10^{-4}(\ln m)^3 + 4.8998 \cdot 10^{-5}(\ln m)^4 + 3.691725 \cdot 10^{-6}(\ln m)^5 + 1.619692 \cdot 10^{-4}(\ln m)^3 + 4.8998 \cdot 10^{-5}(\ln m)^4 + 3.691725 \cdot 10^{-6}(\ln m)^5\right] \text{ [K]} \quad (9)$$

$$m = \frac{p_{H_2O}}{10};\ p_{H_2O} = 1.013 \cdot 10^5\frac{V_{H_2O}}{V_{ga}} \quad (10)$$

The heat recovered from the flue gases is given by the following equation:

$$\dot{Q}_r = B\left[h_{fg}(T_1) - h_{fg}(T_2)\right],\text{ [kW]} \quad (10)$$

where:

B – fuel flow rate, Nm³/s; $h_{fg}(T_1)$, $h_{fg}(T_2)$ – enthalpy of flue gases corresponding to temperature t_1 at condenser inlet, and to temperature t_2 at condenser outlet, respectively, kJ/Nm³ fuel.

3. Description of heat treating furnace

The furnace is schematically shown in Fig. 2. It comprises the combustion chamber, air preheater, heat-recovery steam generator, condensing economizer, air fan, feed water pump and exhauster.

The fuel used is natural gas with the following composition:

CH_4=97.7%, C_2H_6=0.5%, C_3H_8=0.35, C_4H_{10} =0.15, N_2=0.8%, H_2S =0.35, CO_2=0.15% and the lower heating value of 35888 kJ/Nm³. The furnace heating capacity is 70 t/h. Its operation parameters are shown in Table 1.

Table 1. *Operation data of the furnace*

Parameter	Value
Natural gas flow rate	0.412 Nm³/s
Combustion air flow rate	4.13 Nm³/s
Air fan power	250 W
Exhauster power	100 W
Feed water pump power	10 W
Saturated team pressure	12 bar
Excess air coefficient at stack	1.54
Dew point of flue gases	51 °C
Temperature of flue gases before condensing economizer	157 °C
Temperature of exhaust gases	40 °C

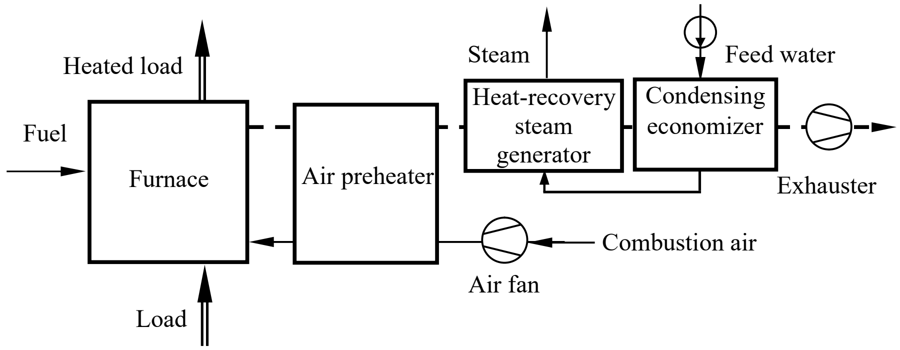

Fig. 2. *Schematic diagram of the furnace*

4. Thermoeconomic analysis

The exergetic cost of the products heated into the furnace is calculated using the following exergetic cost balance equations written for steady state operation, lei/s:

$$\dot{C}_{sf,e} = \dot{C}_f + \dot{C}_{sf,i} + \dot{C}_{el} + \dot{C}_w - \dot{C}_{steam} + \dot{C}_{environ} + \dot{Z}^{CI}_{furnace} + \dot{Z}^{OM}_{furnace} \quad (11)$$

where:
$\dot{C}_f$ - fuel cost rate: $\dot{C}_f = c_{e,f} \cdot \dot{E}_f$, lei/s;
$c_{e,f}$ - exergetic cost of fuel, lei/kJ (Tab. 2);
$\dot{E}_f$ - fuel exergy flow rate, kJ/s;
$\dot{C}_{sf,i}$ - cost rate of metal bars at furnace inlet;
$\dot{C}_w$ - feed water cost rate: $\dot{C}_w = c_{e,w} \cdot \dot{E}_w$;
$c_{e,w}$ - exergetic cost of feed water (Tab. 2);
$\dot{E}_w$ - feed water cost rate;
$\dot{C}_{el}$ - electricity cost rate: $\dot{C}_{el} = (W_w + W_{Ex} + W_{ac})c_{el}$;
W_w, W_{Ex}, W_{ac} - power of feed water pump, exhauster, and combustion air fan;
c_{el} - electricity specific cost;
$\dot{C}_{st}$ - steam cost rate: $\dot{C}_{st} = G_{st} \cdot c_{e,st} \cdot e_{st}$;
G_{st} - steam flow rate;
$c_{e,f}$ - exergetic cost of steam, (Tab. 2);
e_{st} - steam exergy;
$\dot{Z}^{CI}_{furnace}$ - cost rate associated with capital investment calculated according to [2].

The purchase cost of the heat-recovery steam generator is calculated using the following equation [3]:

$$Z_{HRSG} = C_1\left[\left(\frac{\Phi_E}{(\Delta TLM)_E}\right)^{0.8} + \left(\frac{\Phi_{EV}}{(\Delta TLM)_{EV}}\right)^{0.8}\right] + C_2\dot{m}_{st} + C_3\dot{m}_g^{1.2} \quad (12)$$

$\dot{m}_g$, $\dot{m}_{st}$ - steam and flue gas mass flow rate, kg/s;
ΔTLM - log mean temperature difference;
Φ_E, Φ_{EV} – heat flow rate transferred in economiser and evaporator respectively;
C_1 = 12712 lei/(kW/K)$^{0.8}$; C_2 = 41165 lei/(kg/s); C_3 = 2292 lei/(kg/s)$^{1.2}$;
$\dot{Z}^{OM}_{furnace}$ - cost rate associated with operation and maintenance of the furnace;
$\dot{C}_{env}$ - cost rate due to environmental pollution and energy taxes;

Table 2. *Costs associated with furnace operation*

Cost rate of cold metal bars	14.088 lei/s
Exergetic cost of fuel	$2.440 \cdot 10^{-5}$ lei/kJ
Exergetic cost of feed water	$1.170 \cdot 10^{-3}$ lei/kJ
Electricity specific cost	$7.970 \cdot 10^{-5}$ lei/kJ
Exergetic cost of steam	$5.820 \cdot 10^{-5}$ lei/kJ
Cost rate associated with capital investment without condensing economizer	$1.580 \cdot 10^{-3}$ lei/s
Cost rate associated with capital investment with condensing economizer	$1.583 \cdot 10^{-3}$ lei/s
Cost rate associated with operation and maintenance of furnace	$4.88 \cdot 10^{-3}$lei/s

The purchase cost of condensing, calculated by equation (11) leads to a slight increase of the cost rate associated with capital investment from $1.580 \cdot 10^{3}$ lei/s to $1.583 \cdot 10^{-3}$ lei/s.

By using the condensing economizer, the recovered heat from flue gases is equal to 1562.21 kW. The temperature of exhaust gases decreases in this way from 157 °C to 40 °C.

The flue gas condensation allows for the increase of the steam flow rate from 1.94 kg/s to 2.49 kg/s. The steam cost rate increases from 0.186 lei/s to 0.233 lei/s leading to the decrease of exergetic cost of the heated metal bars from 0.002856 lei/kJ to 0.002847 lei/kJ.

The cost of the heated metal bars decreases from 0.8387 lei/kg to 0.8360 lei/kg, which means a cost saving of 158 lei/h.

4. Conclusions

Condensing heat exchangers to recover the heat contained in flue gases generated especially by the natural gas burners are widely used.

Combustion type furnaces used to heat treat metal have low energy efficiency because of heat losses in different areas and forms, especially with exhaust gases.

In the studied case, the use of a condensing economizer allowed for the recovery of 1562.21 kW from flue gases which led to the increase of the steam flow rate from 1.94 kg/s to 2.49 kg/s and therefore the increase of the steam cost rate from 0.186 lei/s to 0.233 lei/s. In this way the cost of heated metal bars decreases from 0.8387 lei/kg to 0.8362 lei/kg. The achieved cost saving is 158 lei/h.

Acknowledgement

This work has been funded by the TEMPUS Programme of the European Union through the project „Development of Training Network for Improving Education in Energy Efficiency – ENERGY" (530379-TEMPUS-1-2012-1-LV-TEMPUS-JPCR).

References

[1]. Pop G. M., ş.a., *Îndrumar. Tabele, nomograme şi formule termotehnice*, Ed. Tehnică, Bucureşti, 1987.

[2]. Bejan A., Tsatsaronis G., Moran M., *Thermal Design and Optimization*, Wiley, New York, 1996.

[3]. Kotas I. J., *The exergy method of thermal plant analysis*, Exergon Publishing Company UK Ltd., London, 2012.

[4]. Iliev I., *Heat exchangers*, Ruse, Academic publishing centre of Ruse University, 2013.

[5]. Iliev I., *Heat waste recovery from corrosive flue gas streams*, Proceedings of the 2nd International Conference of Thermal *Equipment,* Renewable Energy and Rural Development - TE-RE-RD 2013, 20-22 June, Romania, PRINTECH, p. 61-66, 2013.

[6]. Iliev I., Kaloyanov N., Gramatikov P., Kamburova V., Terziev A., Palov I., Stefanov S., Sirakov K., *Energy Efficiency and Energy Management Handbook*, Bulgaria Energy Efficiency for Competitive Industry Financing Facility (BEECIFF): Project Preparation, Capacity Building and Implementation Support. Sofia, Ministry of Economy, Energy and Tourism ("MoEET"), 2012.

[7]. Mullinger P., Jenkins B., *Industrial and Process Furnaces. Principles, Design and Operation*, Butterworth-Heinemann, 2008.

[8]. Trinks W., Mawhinney M. H., Shannon R. A., Reed R. J., Garvey J. R., *Industrial Furnaces,* Sixth Edition, John Wiley & Sons, 2004.

[9]. Hasanuzzaman M., Rahim N. A., Hosenuzzaman M., Saidur R., Mahbubul I. M., Rashid M. M., *Energy savings in the combustion based process heating in industrial sector*, Renewable and Sustainable Energy Reviews, Vol. 16, Issue 7, p. 4527-4536, 2012.