Boiler Flue Gases as Secondary Source in Polyester Production

A. Mihelić-Bogdanić [a,*], R. Budin [b]

[a] University of Zagreb, Faculty of Textile Technology, Department of fundamental natural and technical sciences, 10000 Zagreb, Savska 16, Croatia

[b] University of Zagreb, Faculty of Chemical Engineering and Technology, Department of thermodynamics, mechanical engineering and energetics, 10000 Zagreb, Savska 16, Croatia

[a] amihel@fkit.hr [b] rbudin@fkit.hr

***Abstract*- Energy efficiency improvement in polyester production by applying boiler flue gases heat recovery was investigated. This study presented increasing process efficiency and at the same time the thermal pollution reduced. The implementation of the economizer for feed water preheating with heat contained in the exhaust flue gases reduced natural gas consumption by 9.2 % and also flue gases exhaust temperature diminished from 204 ^{0}C to 51.8 ^{0}C. When an air preheater using for combustion air preheating was applied, the natural gas savings became 7%. Simultaneously, the air pollution was also lowered and the outlet flue gases temperature diminished from 204 ^{0}C to 64.4^{0}C. The utilization of the economizer and the air preheater resulted in a maximum fuel saving of 10.15% and a minimum thermal pollution with flue gases exhaust temperature of 31.15^{0}C.**

Keywords: Polyester; Flue gases heat recovery, Natural gas savings; Environmental protection

[*] Corresponding author. Tel.:+385 1 4597138.
E-mail address:amihel@fkit.hr(A. Mihelić-Bogdanić)

I. INTRODUCTION

Polyesters, i.e. synthetics polymers or non-cellulose organic fibres, are heterochain macromoleculer marked by the appearance of carboxylate ester groups in the repeating units of their main chains [1,2]. They were historically the first family of synthetic condensation polymers, which comprises all polymers with ester functional groups in the backbone. Previously, polyester production was based on dimethyl ester polymerization. At present, the most commonly used terephtalic acid process is based on cobalt catalyzed air oxidation of paraxylene in nitric acid [3,4].

The widely applied linear polyester prepared from terephthalic acid and ethylene glycol is poly ethylene terephthalate (PET), which is a synthetic polymer that takes a central position under engineering plastics with commercial use. That could be easily explained by its excellent properties, heat stability and resistance to wrinkling, which make it superior to cotton and wool [5]. Polyesters are used to produce fibres and films. They are light-weight and shatter-resistant, and possess high tensile strength. Also, there are various methods for recycling polyester and wide acceptance of the products [6].

The continuous polymerization, as an energy intensive process, includes many procedures where significant percentages of thermal and electrical energy as well as water are applied [7,8]. The large amount of fuel consumption results in indicative amount of flue gases rejected to the surrounding. This waste heat, as a secondary source, causes energy efficiency increase as well as environment protection. One method for improving the technological process is the implementation of flue gases heat recovery by combustion air preheating, feed water preheating as well as the combination of both. The mentioned three options will be represented and discussed.

II. ENERGY CONSUMPTION

This research presents the energy consumption in polyester (PET) production. The analyzed plant is designed to produce polyester at the rate of D_{PET}=45000 kg/day i.e.D_{PET}=1875 kg/h. The plant use factor is β=83%, meaning a yearly operating time of τ=7271 h since the equipment is shut down for two months yearly [9]. The manufacturing cycle (Fig. 1), which includes operations of autoclave reactor, filters, dryers, esterification reactor, crystallizer, melter, rollers, transesterification reactor, polymerizer, polymer melt, tow drawing, crimper, cutter and baler, requires a large amount of thermal and electrical energy together with water. Electrical energy provided by the grid in whole amount of e_e=1.433 kWhe/kg$_{PET}$ is distributed to the ten process units as follows: filters (21.06%); reactor esterification (2.63%); cristallizer (5.26%); rollers (15.79%); transesterification reactor (2.63%); polimyzer (7.89); tow drawing (15.80 %); crimper (13.16%) and cutter & baler (15.78%). This process needs cold water in the amount of d_{H_2O} =54 t_{H_2O}/kg$_{PET}$ be used in the autoclave reactor (83.3%) and cristallizer (16.7%). The thermal energy produced in a natural gas fueled boiler is used as dry saturated steam (p_S=2.9 bar) in the amount of d_S=2.3 kg$_S$/kg$_{PET}$. The saturated steam at the temperature of t_S=132 ^{0}C generated by the boiler with efficiency η_B =82% is used in the autoclave reactor. The feed water enters the boiler at the temperature of t_B=25 ^{0}C and the air, which is essential for natural gas combustion, enters the fire box at the temperature of t_a=25 ^{0}C. The temperature of the flue gases is t_{FG}=204 ^{0}C (Fig .2) [9].

The composition of the natural gas by volume is $CH_4:C_2H_6:C_3H_8:C_4H_{10}:C_5H_{12}:CO_2:N_2$ = 98,05:0,36:0,12:0,05:0,01:0,85:0,56, while the fuel is burned with excess air coefficient α=1.24 [10]. The lower heating value of the natural gas based on gas fuel constituents is calculated by the following equation [11]:

$$H_L=358CH_4+636C_2H_6+913C_3H_8+1158C_4H_{10}+1465C_5H_{12}=35513 \text{ kJ/m}^3{}_F \text{ .} \tag{1}$$

The hourly steam production is:

$$D_S=d_S \times D_{PET}=2.3\times45000=103500\text{kg}_S\text{/day}=4312.5 \text{ kg}_S\text{/h,} \tag{2}$$

and the heat transferred to the steam generator becomes:

$$Q_B=D_S(h_S-h_B)=4312.5(2723-104.7)=11.29\times10^6\text{kJ/h,} \tag{3}$$

$$Q_B =270.96\times10^6 \text{ kJ/day}=82.1\times10^9\text{kJ/year,}$$

where h_S and h_B are the steam and water enthalpies [12].

From the heat balance, the natural gas demand is assembeled as:

$$V_F=Q_B/\eta_B \times H_L=11.29\times10^6 /0.82 \times35513= 387.7 \text{ m}^3{}_F\text{/h}=9304.8\text{m}^3{}_F\text{/day.} \tag{4}$$

The fuel consumption with yearly operating time is calculated as:

$$V_{F\ Y}=V_F\times \tau=387.7\times7271=2.82\times10^6\text{m}^3{}_F\text{/year.} \tag{5}$$

The mass of condensate $D_C=D_S$=4312.5 kg/h with exhaust temperature t_C=82^{0}C is withdrawn to the surrounding and the responding heat is:

$$Q_C=D_C\times h_{82}{}^o=4312.5\times343.3=1.48\times10^6\text{kJ/h}=10.76\times10^9\text{kJ/year.} \tag{6}$$

III. FUEL COMBUSTION PRODUCTS

Natural gas combustion is attained when fuel is burned with a stoichiometric supply of air and when combustion is complete [13]. The minimum air volume for this combustion can be expressed as [14]:

$$V_a= 1/21[\ 2CH_4+\Sigma(x+y/4)\ C_XH_Y]=9.45 \text{ m}^3{}_a\text{/kg}_F, \tag{7}$$

where X, Y are numbers of C and H atoms, respectively.

The excess air coefficient α=1.24 is taken to ensure the complete combustion of natural gas and the actual volume of air becomes:

$$V_{a\alpha}= V_a\times\alpha= 9.45 \times1.24=11.72 \text{ m}^3{}_a\text{/ m}^3{}_F \tag{8}$$

The flue gases volume consists of carbon dioxide, water vapour, nitrogen and oxygen:

$$V_{FG}= V_{CO_2}+ V_{H_2O} + V_{N_2}+ V_{O_2}. \tag{9}$$

The volume of each gas constituent is estimated by the next formulae [14]:

$$V_{CO_2} = 0,01(CO_2 + \Sigma xC_xH_y)=1.00 \text{ m}^3{}_{CO_2}\text{/m}^3{}_F, \tag{10}$$

$$V_{H_2O} = 0,005\ \Sigma yC_xH_y + V_a(\alpha-1)d/\rho=2.02 \text{ m}^3{}_{H_2O}\text{/m}^3{}_F, \tag{11}$$

where air moisture d=0.013 kg/m^3 and steam density ρ=0.805 kg/m^3 are taken from [12].

$$V_{N_2}=\alpha(0,79\ V_a + N/100) = 9.26 \text{ m}^3{}_{N_2}\text{/m}^3{}_F, \tag{12}$$

$$V_{O_2} = 0,21\ (\alpha-1)V_a=0,21(1,25-1)9.3571 = 0.48 \text{ m}^3{}_{O_2}\text{/m}^3{}_{F.} \tag{13}$$

The whole flue gases volume with excess air is:V_{FG}=12.76 m$^3{}_{FG}$/m$^3{}_F$.

The distribution of individual component uttered as a percentage of the whole wet products is: V_{CO_2} 7.84%; V_{H_2O} 15.83%; V_{N_2} 72.57%; V_{O_2}3.76%.

The specific heat of flue gases at the temperature of t_{FG}=204 ^{0}C and the preliminarily calculated percentage by volume of products together with the specific heat of each gas product should be recognized [15].

$$c_{pFG} = c_{pCO_2} \times \%V_{CO_2} + c_{pH_2O} \times \%V_{H_2O} + c_{pN_2} \times \%V_{N_2} + c_{pO_2} \times \%V_{O_2}, \tag{14}$$

$$c_{pFG} = 1.384\ kJ_{FG}/m^3\ deg.$$

The energy regarding to the actual combustion relying on total flue gases volume (V_{FG}), specific heat (c_{pFG}) and flue gases temperature (t_{FG}):

$$Q_{FG} = V_{FG} \times c_{pFG} \times t_{FG} = 12.76 \times 1.384 \times 204 = 3602.61\ kJ_{FG}/m^3{}_{F,} \tag{15}$$

$$Q_{FG\ PET} = Q_{FG} \times V_F = 3602.61 \times 387.7 = 1.396 \times 10^6\ kJ_{FG}/h = 10.16 \times 10^9\ kJ_{FG}/year. \tag{16}$$

In this inefficient process, flue gases at the temperature of t_{FG}=204^{0}C in amount of

$$V_{FG\ PET} = V_{FG} \times V_F = 12.76 \times 387.7 = 4947.1\ m^3{}_{FG}/h = 35.97 \times 10^6\ m^3{}_{FG}/year \tag{17}$$

are discharged to the environment.

IV. BOILER FEED WATER PREHEATING BY APPLYING AN ECONOMIZER

In order to reduce natural gas consumption simultaneously while increasing the process efficiency, the exhaust flue gases should be reused [16,17,18]. Low or medium temperature of flue gases that leave the boiler can be used to preheat the boiler feed water using economizers which are simply gas to liquid water heat exchangers. An economizer is a separately finned tube bundle, with gas flowing outside normal to the finned tubes and water inside the tubes. Finned tubes are rugged, heavy, usually made up of steel, and able to withstand flue gas temperature up to 900 ^{0}C [10].

To calculate flue gases heat recovery, the essential parameters should be known. Feed water at the temperature of $t_{Ei}=t_B=25^0$C passes the economizer with efficiency η_E=85%. Cold water is heated with exhaust flue gases at the inlet temperature of $t_{FG\ Ei}$=204^{0}C in the amount of V_{FG}= 12.76 $m^3{}_{FG}/m^3{}_{F.}$ The water specific heat is c_{pH_2O} = 4.187 kJ/kg deg and flue gases c_{pFG} = 1.384 kJ $_{FG}$/m^3 deg. The steam production is D_S=4312.5 kg$_S$/h and the natural gas consumption V_F=387.7 $m^3{}_F$/h.

The economizer water outlet temperature t_{Eo} calculated by applying energy balance [15]:

$$V_{FG} \times c_{pFG}\ (t_{FG\ Ei} - t_{Ei})\ \eta_E = D_S/V_F \times c_{pH_2O}(\mathbf{t_{Eo}} - t_{Ei}) \tag{18}$$

is t_{Eo}=82.7 ^{0}C.

Obtained from the next relation the flue gases outlet temperature:

$$V_{FG} \times c_{pFG}\ (t_{FG\ Ei} - \mathbf{t_{FG\ Eo}}) = D_S/V_F \times c_{pH_2O}(t_{Eo} - t_{Ei}) \tag{19}$$

is $t_{FG\ Eo}$=51.8 ^{0}C.

The natural gas consumption for feed water preheating is now:

$$V_{F\ E} = D_S(h_S - h_{Eo})/H_L \times \eta_B = 4312.5 \times (2723 - 346.3)/35513 \times 0.82, \tag{20}$$

$V_{F\ E}$ =351.96$m^3{}_F$/h=8447.21$m^3{}_F$/day.

The fuel consumption with yearly operating time τ =7271 h is calculated:

$$V_{F\ E\ Y} = V_{F\ E} \times \tau = 351.96 \times 7271 = 2.56 \times 10^6 m^3{}_F/year. \tag{21}$$

Comparing with process without flue gases, the heat recovery shows energy savings of:

$$Q = (V_F\text{-}V_{F\,E})\, H_L\times\eta_B = (\,387.7\text{-}351.96)\, 35513\times0.82 = 1.04\times10^6 \text{ kJ/h}, \tag{22}$$

or in term of fuel savings:

$$S_1 = (V_F - V_{F\,E})/V_F = (387.7\text{-}351.96)/387.7=0.092 \quad \text{i.e.}9.2\ \% \tag{23}$$

The fuel consumption lowering results in flue gases exhaust reduction of:

$$V_{FG\,E\,PET} = V_{FG}\times V_{F\,E}=12.76\times351.96=4491.0\ m^3{}_{FG}/h=32.65\times10^6\ m^3{}_{FG}/\text{year}\ . \tag{24}$$

The volume of flue gases is lowered from 4947.1 $m^3{}_{FG}/h$ to 4491.0 $m^3{}_{FG}/h$ or for 9.2%, and at the same time the gases are cooled from 204^0C to 51.8^0C.

V. COMBUSTION AIR PREHEATING BY APPLYING AIR PREHEATER

The high temperature of boiler exhaust flue gases shows a problem of clean energy generation. An alternative method of reducing the combustion gases temperature is known as air preheating [19]. Flue gases temperature of natural gas fired boiler can be lowered using an air preheater system, resulting in less fuel consumption and lower flue gases outlet temperature. The heat of flue gases will be transferred to preheat the incoming ambient air that is essential for fuel combustion [7,8]. The flue gases at the temperature of $t_{FG\ Ai}$=204 ^{0}C enter the air preheater with efficiency η_A = 90%. The ambient air with volume $V_{a\alpha}$=11.72 $m^3{}_a/m^3{}_F$ and at the temperature of $t_{a\ Ai}$= t_a=25^{0}C passes through air preheater, where it is heated by flue gases in the amount of V_{FG}= 12.76 $m^3{}_{FG}/m^3{}_{F.}$ The specific heat of air is c_{pa} = 1.29 kJ/m^3 deg [12] and for flue gases, as calculated previously, it is c_{pFG} = 1.384 kJ/m^3 deg. Taking into account these data, the outlet air temperature computed by [15]:

$$V_{a\alpha}\times c_{pa}(\mathbf{t_{a\,Ao}}\text{-}t_{a\,Ai}) = V_{a\alpha}\times c_{pa}(t_{FG\,Ai}\text{-}t_{a\,Ai})\eta_A \tag{25}$$

is $t_{a\ Ao}$ =187 ^{0}C,

while the flue gases outlet temperature calculated from formula:

$$V_{a\alpha}\times c_{pa}(t_{FG\,Ai}\text{-}t_{a\,Ai})\eta_A=V_{FG}\times c_{pFG}(t_{FG\,Ai}\text{-}\mathbf{t_{FG\,Ao}}) \tag{26}$$

becomes $t_{FG\ Ao}$ =64.4 ^{0}C.

The heat of flue gases transferred to the air preheater is:

$$Q_{FG\,A\,PET}= V_F\times V_{FG}\times c_{pFG}(t_{FG\,Ai}\text{-}t_{FG\,Ao})= 955.8\times10^3 \text{ kJ/h}, \tag{27}$$

or expressed as natural gas savings:

$$V_{F\,S} =Q_{FG\,A\,PET}/H_L=959.8\times10^3)/35513=27.03\ m^3{}_F/h \tag{28}$$

The fuel consumption is now:

$$V_{F\,A}=V_F - V_{F\,S}= 387.7\text{-}27.03=360.67\ m^3{}_F/h =8656.08\ m^3/\text{day}, \tag{29}$$

and the natural gas consumption with yearly operating time τ =7271 h is given by:

$$V_{F\,A\,Y} = V_{F\,A}\times \tau=360.67\times7271=2.62\times10^6\ m^3{}_F/\text{year}. \tag{30}$$

The heat consumption for dry saturated steam production is:

$$Q_{B\,A}= V_{F\,A}\times\eta_B\times H_L=360.67\times0.82\times35513=10.5\times10^6 \text{ kJ/h}=252\times10^6 \text{ kJ/day}. \tag{31}$$

The natural gas savings in comparison with the process without flue gases heat recovery is:

$$S_2=(V_F\text{-}V_{F\,A})/V_F=(387.7\text{-}360.67)/387.7=0.0697 \sim0.07 \text{ i.e. } 7\%. \tag{32}$$

The volume of flue gases that will be rejected to the atmosphere is:

$$V_{FG\,A\,PET}=V_{FG}\times V_{F\,A}=12.76\times360.67=4602.15\ m^3{}_{FG}/h=33.46\times10^6\ m^3{}_{FG}/\text{year}. \tag{33}$$

The volume of flue gases is diminished from 4947.1$m^3{}_{FG}/h$ to 4602.15$m^3{}_{FG}/h$ or for 7 % while the exhaust gases are cooled for 139.96 ^{0}C.

VI. IMPLEMENTATION OF THE ECONOMIZER AND AIR PREHEATER

Heat interchanging cycle combinations are those where a heat exchanger or similar device is used to transfer waste heat from a higher temperature as input to a lower temperature [10,15]. An alternative method for reducing the temperature of combustion flue gases is the use of an economizer in conjunction with an air preheater (Fig. 3). The combustion gases are cooled while the temperature of air prior to combustion as well as boiler feed water increased. These approaches with feed water and combustion air preheating by applying heat of flue gases appear to be attractive to industrial users, especially in polyester production. Earlier estimated process data point out that V_{FG}=12.76 m^3_{FG}/m^3_F of flue gases have an economizer outlet temperature of $t_{FG\,Eo}=t_{FG\,EA\,Eo}$=51.8 ^{0}C, which is simultaneously flue gas air preheater inlet temperature $t_{FG\,EA\,Ai}$. Surrounding air with volume $V_{a\alpha}$=11.72 m^3_a/m^3_F and at the temperature of $t_{a\,Ai}=t_{a\,EA\,Ai}=25^0$C enters the air preheater.

The temperature of outlet air $t_{a\,EA\,Ao}$ is estimated with following energy balance:

$$V_{a\alpha}\times c_{pa}(\mathbf{t_{a\,EA\,Ao}} - t_{a\,EA\,Ai}) = V_{a\alpha}\times c_{pa}(t_{FG\,EA\,Ai} - t_{a\,EA\,Ai})\eta_{A}, \tag{34}$$

and becomes $t_{a\,EA\,Ao}$ =49.12 ^{0}C.

The outlet temperature of flue gases $t_{FG\,EA\,Ao}$ obtained from relation:

$$V_{a\alpha}\times c_{pa}(t_{FG\,EA\,Ai} - t_{a\,EA\,Ai})\eta_A = V_{FG}\times c_{pFG}(t_{FG\,EA\,Ai} - \mathbf{t_{FG\,EA\,Ao}}), \tag{35}$$

is $t_{FG\,EA\,Ao}$ = 31.15 ^{0}C.

According to the volume of natural gas consumption $V_{F\,E}$=351.96 m^3_F/h in the process with economizer as estimated formerly, the flue gases heat recovery in this case is:

$$Q_{FG\,EA\,PET} = V_{F\,E}\times V_{FG}\times c_{pFG}(t_{FG\,EA\,Ai} - t_{FG\,EA\,Ao}), \tag{36}$$

$$Q_{FG\,EA\,PET} = 128.35\times10^3\ \text{kJ/h} = 3.08\times10^6\text{kJ/day} = 933.23\times10^6\ \text{kJ/year},$$

or expressed as fuel savings:

$$V_{F\,EA\,S} = Q_{FG\,EA\,PET}/H_L = 128.35\times10^3/35513 = 3.61\ m^3_F/h. \tag{37}$$

Natural gas consumption is:

$$V_{F\,EA} = V_{F\,E} - V_{F\,EA\,S} = 351.96-3.61 = 348.35\ m^3_F/h = 8360.4\ m^3_F/\text{day}, \tag{38}$$

and with yearly operating time τ =7271 h:

$$V_{F\,EA\,Y} = V_{F\,EA}\times\tau = 348.35\times7271 = 2.53\times10^6\ m^3_F/\text{year}. \tag{39}$$

Comparing with the process without flue gases, the recovery shows energy reduction of:

$$Q_{EA\,S} = (V_F - V_{F\,EA})H_L = (387.7-348.35)35513 = 1.397\times10^6\ \text{kJ/h}, \tag{40}$$

or in term of natural gas savings:

$$S_3 = (V_F - V_{F\,EA})/V_F = (387.7-348.35)/387.7 = 0.1015\ \text{i.e.}10.15\%. \tag{41}$$

In this process where economizer and air preheater are incorporated, the volume of flue gases that will be rejected to the atmosphere is:

$$V_{FG\,EA\,PET} = V_{FG}\times V_{F\,EA} = 12.76\times348.35 = 4444.95\ m^3_{FG}/h = 32.32\times10^6 m^3_{FG}/\text{year}. \tag{42}$$

Considering the foregoing analyses regarding the emission of flue gases to the atmosphere, the volume of flue gases is reduced from 4947.1 m^3_{FG}/h to 4444.95 m^3_{FG}/h or for 10.15% while the flue gases outlet temperature decreases from 204^{0}C to 31.15^{0}C.

VII. CONCLUSIONS

The aim of the presented study was to obtain insight into the characteristics and possibilities for energy efficiency improvements in industrial polyester production. Energy investigation showed decrease of specific fuel consumption, reduction of environment impacts and diminishing of natural gas consumption. The significant amount of thermal energy available in boiler flue gases provides very good heat recovery possibility in polyester production. The presented analyses showed utilizations of flue gases heat for feed water and combustion air preheating as well as both.

The application of an economizer for feed water preheating with heat contained in exhaust flue gases gained natural gas savings of 9.2% and thermal pollution decrease while the flue gases outlet temperature became 51.8 ^{0}C instead of 204^{0}C in an inefficient process.

For applying an air preheater for combustion air preheating, the natural gas savings was estimated to be 7%, while the exhaust gases temperature diminished from 204^{0}C to 64.04^{0}C.

Finally, in the presented process where an economizer and an air preheater were used, feed water and combustion air were preheated with boiler exhaust flue gases. This combination produced fuel savings of about 10.15 % and at the same time the outlet flue gases temperature was lowered from 204^{0}C to 31,15^{0}C.

REFERENCES

[1] Rodriguez F, Cohen C, Ober C, Archer L, Archer A. Principles of polymer systems. 5th ed. USA: CRC Press; 2003.

[2] Budin R, Mihelić-Bogdanić A. Energy effective polyester production. Chapter 9 in DAAAM International Scientific Book. Katalinić B. ed. Vienna: DAAAM International; 2006.

[3] Stevens M P. Polymer chemistry. Oxford: University Press; 1999.

[4] Edlund U, Albertsson AC. Polyesters based on diacid monomers. Advanced Drug Delivery Reviews.2003;55(6): 585-609.

[5] Budin R, Mihelić-Bogdanić A, Vujasinović E. Cogeneration and heat recovery in the industrial process. Kem. Ind.2007:56(11):551-555.

[6] Paszun D, Spychaj T. Chemical Recycling of Poly(ethylene terephthalate). Industrial and Engineering Chemistry Research 1997:36(4):1373-1383.

[7] Budin R, Mihelić-Bogdanić A, Sutlovic I, Filipan V. Advanced polymerization process with cogeneration and heat recovery. Appl. Thermal Eng. 2006:26(16): 998-2004.

[8] Mihelić-Bogdanić A, Budin R.Heat recovery in thermoplastic production. Energy Convers Mgmt 2002;43(8):1079-1089.

[9] Production plant data – private communication, 2011.

[10] Eastop TD, McConkey A. Applied thermodynamics for engineering technologists.5th ed. New York: Longman Scientific and Technical, Wiley; 1994.

[11] Požar H. Fundamentals of energetics.Zagreb:Školska knjiga; 1992[in Croatian].

[12] Budin R, Mihelić-Bogdanić A. Fundamentals of technical thermodynamics. 3rd ed.Zagreb: Školska knjiga; 2012 [in Croatian].

[13] Eastop TD, Croft DR. Energy efficiency. Essex; Longman group; 1995.

[14] Budin R, Mihelić-Bogdanić A. Sources and industrial energy management. Zagreb: Element; 2013 [in Croatian].

[15] Bošnjaković F. Technische Thermodynamik. Dresden: Verlag T Steinkopff; 1982.

[16] Stijepovic M, Linke P. Optimal waste heat recovery and reuse in industrial zones. Energy 2011;36(8) :4019-4031.

[17] Song HC, Sang HK, Sang GY, Sunwon P. Optimization of a waste heat utilization network in an eco-industrial park. Applied Energy 2010; 87 (6):1978-1988.

[18] Műnster M, Meivorn P. Optimization of use of waste in the future energy system. Energy 2011; 36 (3):1612-1622.

[19] Pavlas M, Touš M, Bébar L. Energy efficient processing of waste. Chem Eng Trans 2010;21(2): 841-846.