Cogeneration and Heat Recovery in the Industrial Process

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Related to energy requirements for non-cellulose i. e. polyester production as an energy-intensive process, potential saving options are proposed. From the process data, it is evident that unit operations need electric and thermal energy in significant amounts. At the same time, improved energy management could be realized by applying a combined heat and power system (CHP) instead of the usually used process with separate heat and power production. In addition, the boiler flue gases with a sufficiently high outlet temperature could be used for combustion air preheating. Considering industrial process data, a calculation and comparison between the primary energy demand for conventional, CHP system and flue-gas heat recovery is presented. Comparison between separate heat and electricity production i.e. the conventional system with an overall efficiency of 55.6 % and CHP with efficiency of 85 %, shows an absolute efficiency increase of 29.4 %. Using an air preheater for combustion air temperature increasing saves 5.6 % of the fuel and at the same time diminishes thermal pollution because the exhaust flue-gas temperature becomes 77.3 °C instead of 204 °C. Conclusively, cogeneration and flue-gas heat recovery presents fuel savings, which also implies economic and environmental benefits.

Key words: *Energy consumption, cogeneration, flue gases, fuel savings*

Introduction

Non-cellulose i. e. polyester production is one of the most energy-intensive industrial processes. In this continuous polymerization, the most widely used purified terephthalic acid (TPA) process is based on cobalt catalyzed air oxidation of p-xylene in nitric acid.[1] The industrial process operation (Fig. 1.) uses electrical and heat energy in the form of dry saturated steam. The electrical energy is provided for filtration, esterification, crystallization, rolling, transesterification, tow drawing, crimping and cutting, usually from the grid. The steam is supplied to the autoclave reactor and dryers.[2,3] In terms of energy utilization, 33.5 % electric and 66.5 % thermal energy is supplied. Because of the significant amount of electric and thermal energy in the process chain, some conservation options are proposed and derived. Regarding the amount of electric energy, the configuration based on co-production of heat and electricity (CHP) is a feasible alternative since it saves large amounts of primary energy input.[4–6] An enhanced secondary source i.e. flue-gas heat recovery is also a significant measure for energy optimal solution. Therefore, the reuse of boiler exhaust gases supplied to the air preheater is also presented as an option for energy conservation and environmental protection.

Preliminary calculation from process data

The heat and power supply is derived from actual process data. For polyester production, the electricity input is 33.5 % while thermal energy is 66.5 %, meaning N_e = 2.7 MWe ($Q_e = 9.7 \cdot 10^6$ kJ h^{-1}) and N_t = 5.35 MW$_t$ ($Q_t = 19.3 \cdot 10^6$ kJ h^{-1}). The conventional scheme consists of an oil-fuelled boiler with efficiency η_B = 85 %. The produced heat is transferred to the autoclave reactor as dry saturated steam. None of the necessary heat becomes available as stored energy in the finished product, and according to the first law of thermodynamics, it must be removed as heat. The lower heating value is determined from the fuel oil composition by mass 85.3 % C; 11.6 % H; 0.6 % N; 2.5 % S_v.[7]

$$H_L = 340C + 1035H + 104S_v = 340 \cdot 85.3 + 1035 \cdot 11.6 + 104 \cdot 2.5 = 41268 \text{ kJ kg}^{-1}. \quad (1)$$

The dry saturated steam (3 bar, 132 °C) produced in the boiler is transferred to the autoclave reactor and after processing rejected as condensate at 132 °C. The mass rate of dry saturated steam calculated from the thermal energy requirement is:

$$D_S(h'' - h') = Q_t \quad (2)$$

$$D_S = Q_t/(h'' - h') = 19.3 \cdot 10^6/(2724 - 560) = 8918.7 \text{ kg h}^{-1}$$

where *h'' and h'* are dry saturated steam and boiling water enthalpies.[7]

This conventional system with a standard boiler satisfied the total amount of thermal energy while the power is supplied from the grid.

Separate heat and power production

Assuming such a conventional scheme, the process operations are supplied with heat from the boiler, while power is

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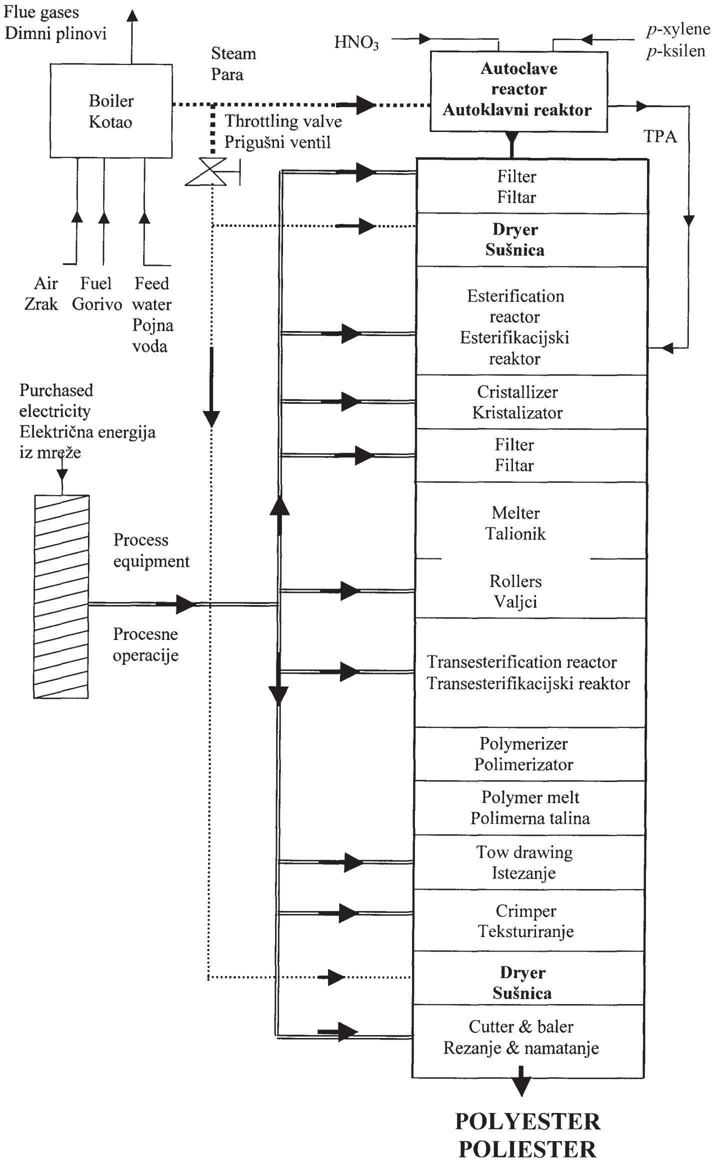


F i g. 1 – *Process and energy flow*
S l i k a 1 – *Procesni i energetski tokovi*

purchased from the grid. In this case, the fuel oil consumption (kW, kg h^{-1}) is:

$$F_t(kW) = N_t/\eta_B = 5350/0.85 = 6294.1 \tag{3}$$

$$F_t(\text{kg h}^{-1}) = F_t(\text{kW}) \cdot 3600/H_L = 6294.1 \cdot 3600/41268 = 549.1. \tag{4}$$

With a plant utilization factor of β = 84.9 % i. e. τ = 7440 hours per year, the fuel requirement is:

$$F_{ta}(\text{kg a}^{-1}) = F_t(\text{kg h}^{-1}) \cdot \tau = 549.1 \cdot 7440 = 4.09 \cdot 10^6. \tag{5}$$

This separate heat and power production satisfies the heat demand while power is produced in the power plant with efficiency η_e = 33 %. Now, the fuel consumption calculated from (3–5) is:

$$F_e(\text{kW}) = N_e/\eta_e = 2700/0.33 = 8182$$

$$F_e(\text{kg h}^{-1}) = [F_e(\text{kW}) \cdot 3600]/H_L = (8182 \cdot 3600)/41268 = 713.7$$

$$F_{ea}(\text{kg a}^{-1}) = F_e(\text{kg a}^{-1}) \cdot \tau = 713.7 \cdot 7440 = 5.31 \cdot 10^6.$$

The overall efficiency for the mentioned heat and electrical energy (all values are expressed in kW) is:

$$\eta_{oC} = (N_e + N_t)/(F_e + F_t) = (2700 + 5350)/(8182 + 6294.1) = 0.556 \text{ or } 55.6\ \%. \tag{6}$$

Energy conservation

Polyester production is one of the most energy-intensive industrial processes. At the same time, however, the specific energy consumption can be lowered by using cogeneration, i. e. combined heat and power production (CHP).[8–10] Also, significantly improved performances may be obtained if the secondary source in the form of combustion gas is used in an air preheater (AP) for combustion air preheating.[11] To prove this significant potential for energy conservation, the CHP and flue-gas heat recovery have been carried out.

Combined heat and power production

Currently, the development of combined heat and power production (CHP) plays a significant role in energy strategies aimed at saving primary sources and reducing CO_2.[12] This system is less energy-intensive and more environmentally friendly than the conventional system.[13] A solution is proposed to replace the conventional plant with a boiler supplying steam to the prime mover i.e. back pressure turbine coupled with an electric generator (Fig. 2).

In the proposed process, the superheated steam with the previously calculated mass from (2) is generated in the boiler at 40 bar, 487 °C and expanded to pressure of 3 bar with power production. In this case, CHP satisfied the entire heat demand of the process (Q_t = 19.3 · 10^6 kJ h^{-1} or 5350 kWt). Now, the electrical power output is:

$$N_{eCHP} = D_S(h_{487} - h'')/3600 = 8918.7(3400 - 2724)/3600 = 1675 \text{ kW}_e \text{ or } Q_{eCHP} = 6.03 \cdot 10^6 \text{ kJ h}^{-1}, \tag{7}$$

and fuel oil consumption:

$$F_{eCHP} = N_{eCHP}/\eta_B = 1675/0.85 = 1971 \text{ kW}_e. \tag{8}$$

Yearly fuel consumption is:

$$F_{eCHPa} = F_{eCHP}(\text{kW}) \cdot 3600 \cdot \tau/H_L = 1971 \cdot 3600 \cdot 7440/41268 = 1.3 \cdot 10^6 \text{ kJ}. \tag{9}$$

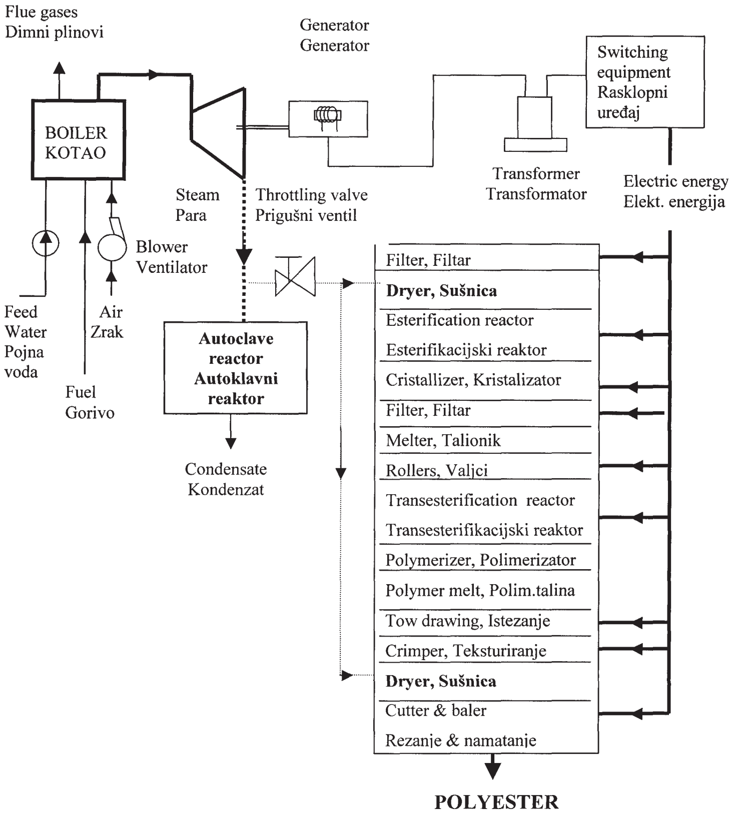
The savings in purchased electrical energy compared to the conventional process is:

$$S_{CHP} = N_e - N_{eCHP} = 2700 - 1675 = 1025 \text{ kW or } 38\ \%. \tag{10}$$

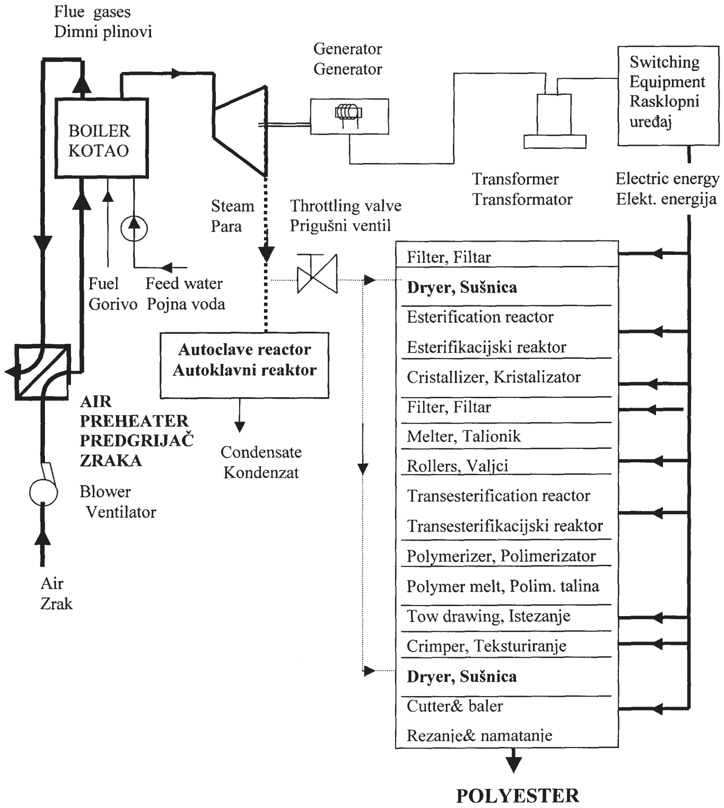
In the presented option, the fuel oil rate is:

$$F_{CHP}(\text{kW}) = F_{eCHP} + F_t = 1971 + 6294.1 = 8265.1 \tag{11}$$

$$\text{or } F_{CHP}(\text{kg h}^{-1}) = 721.$$



F i g. 2 – *Combined heat and power production (CHP)*
S l i k a 2 – *Kogeneracija*



F i g. 3 – *Flue gas heat recovery with cogeneration*
S l i k a 3 – *Povrat topline dimnih plinova s kogeneracijom*

The cogeneration system in this example has an overall efficiency of:

$$\begin{aligned}\eta_{CHP} &= (N_{eCHP} + N_t)/F_{CHP} \\ &= (1675 + 5350)/8265.1 = 0.85 \text{ or } 85\ \%.\end{aligned} \tag{12}$$

Compared to the conventional system, the absolute efficiency increase is:

$$\eta_{CHP} - \eta_{oC} = 85 - 55.6 = 29.4\ \%.$$

Combustion air preheating

Additional progress can be achieved when the flue gas heat is recovered and reused for combustion air preheating. In this presented case (Fig. 3), the flue gas from the boiler with t_{oFG} = 204 °C is transferred into an air preheater (η_{AP} = 80 %) where the ambient temperature (t_{ai} = 25 °C) is preheated before entering the boiler. The flue gases volume is calculated using the common relations as follows:[14]

Theoretical or stoihiometric air volume:

$$V^S_{\ a} = (1.867\text{C} + 5.6\text{H} + 0.7\text{S}_\text{v})/0.21 \tag{13}$$

$$\begin{aligned}V^S_{\ a} &= (1.867 \cdot 0.853 + 5.6 \cdot 0.116 \\ &+ 0.7 \cdot 0.025)/0.21 = 10.8\ \text{m}^3\ \text{kg}_\text{F}^{-1}.\end{aligned}$$

Actual volume with excess air α = 1.15:

$$\begin{aligned}V_a &= V^S_{\ a} \cdot \alpha \cdot F_{CHP} = 10.8 \cdot 1.15 \cdot 721 \\ &= 8953.8\ \text{m}^3\ \text{h}^{-1}.\end{aligned} \tag{14}$$

Theoretical volume of combustion products with excess air is:

$$\begin{aligned}V^S_{\ FG} &= 1.867\text{C} + 0.7\text{S}_\text{v} + 0.79\ V^S_{\ a} + 0.8\text{N} \\ &+ 11.2\text{H} + 1.0161\ V^S_{\ a}(\alpha - 1) = 13.1\ \text{m}^3\ \text{kg}_\text{F}^{-1},\end{aligned} \tag{15}$$

while the total volume becomes:

$$V_{FG} = V^S_{\ FG} \cdot F_{CHP} = 13.1 \cdot 721 = 9445.1\ \text{m}^3\ \text{h}^{-1}. \tag{16}$$

The air outlet temperature t_{ao} and flue gas outlet temperature t_{FGo} with specific heat for air c_{pa} = 1.29 kJ m^{-3} deg^{-1}, and flue gas c_{pFG} = 1.382 kJ m^{-3} deg^{-1} estimated from air preheater balance:[15]

$$\begin{aligned}V_a \cdot c_{pa}\ (\boldsymbol{t_{ao}} - t_{ai}) &= V_a \cdot c_{pa}\ (t_{FGi} - t_{ai})\ \eta_{AP} \\ &= V_{FG} \cdot c_{pFG}\ (t_{FGi} - \boldsymbol{t_{FGo}})\end{aligned} \tag{17}$$

gives t_{ao} = 168 °C and t_{FGo} = 77.3 °C.

The flue-gas heat recovery is:

$$\begin{aligned}Q_{FG} &= V_{FG} \cdot c_{pFG}\ (t_{FGi} - \boldsymbol{t_{FGo}}) \\ &= 9445.1 \cdot 1.382\ (204 - 77.3) = 1.65 \cdot 10^6\ \text{kJ h}^{-1}\end{aligned} \tag{18}$$

or expressed as fuel savings:

$$F_S = Q_{FG}/H_L = 1.65 \cdot 10^6/41268 = 40.1\ \text{kg h}^{-1} \tag{19}$$

or yearly:

$$S_{Fa} = F_S \cdot \tau = 40.1 \cdot 7440 = 0.3 \cdot 10^6\ \text{kg}.$$

Achieved savings:

$$S = F_S/F_{CHP} = 40.1/721 = 0.056 \text{ i.e. } 5.6\ \%.$$

Conclusion

Energy conservation is seen increasingly as a promising way for attaining simultaneously the goals of energy security, environmental protection and economic growth. Therefore, this article outlines some significant opportunities for improving energy efficiency. By researching the heat and power demands of polyester production, possible conservation solutions are suggested. Overall efficiency and environmental quality can be enhanced through widespread and increased use of cogeneration in the industrial sector. From the presented analyses, the cogeneration system achieves an overall efficiency of 85 %. The obtained efficiency is 29 % higher than if power and heat were provided by separate conventional energy-conversion systems. Regarding sustainable development, improving energy management also includes the use of secondary sources i.e. waste heat recovery. Flue gases from the boiler, in the medium temperature range, could be utilized economically for combustion air preheating. This valuable energy conservation technique with savings of 5.6 %, reduces specific energy consumption and environmental pollution.

Conclusively, these environmental and economic benefits indicat that the implementation of the proposed valuable conservation options should be important for any, especially energy-intensive industrial process.

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List of symbols*
Popis simbola

AP – air preheater
– predgrijač zraka

CHP – combined heat and power
– kogeneracija

C_{pa} – specific heat of air at constant pressure, kJ m^{-3} deg^{-1}
– specifična toplina zraka uz konstantni tlak, kJ m^{-3} deg^{-1}

C_{pFG} – flue gas specific heat, RJ m^{-3} deg^{-1}
– specifična toplina dimnih plinova, RJ m^{-3} deg^{-1}

D_S – steam mass flow rate, kg h^{-1}
– masa pare, kg h^{-1}

F_{CHP} – CHP fuel rate, kg h^{-1}
– potrošnja goriva u kogeneracijskom sustavu, kg h^{-1}

F_e – fuel consumption, kWe
– potrošnja goriva, kWe

F_{eCHP} – CHP fuel rate, kWe
– potrošnja goriva u kogeneracijskom sustavu, kWe

F_{eCHPa} – annual CHP fuel rate, kWe
– godišnja potrošnja goriva u kogeneracijskom sustavu, kWe

F_{ea} – annual fuel consumption, kWe
– godišnja potrošnja goriva, kWe

F_S – fuel savings, kg h^{-1}
– ušteda goriva, kg h^{-1}

F_t – conventional fuel input, kg h^{-1}
– potrošnja goriva u konvencionalnom procesu, kg h^{-1}

F_{ty} – annual fuel input, kg
– godišnja potrošnja goriva, kg

h' – enthalpy of boiling water, kJ kg^{-1}
– entalpija vrele vode, kJ kg^{-1}

h'' – enthalpy of dry saturated steam, kJ kg^{-1}
– entalpija suhozasićene pare, kJ kg^{-1}

H_L – lower heating value, kJ kg^{-1}
– donja toplinska vrijednost goriva, kJ kg^{-1}

N_e – output power, kW$_e$
– izlazna snaga, kW$_e$

N_{eCHP} – CHP output power, kW$_e$
– CHP izlazna snaga, kW$_e$

N_t – thermal output rate, kW$_t$
– toplinska energija, kW$_t$

Q_e – process power requirement, kJ h^{-1}
– električna energija u procesu, kJ h^{-1}

Q_{eCHP} – CHP power output, kJ h^{-1}
– CHP električna energija, kJ h^{-1}

Q_{FG} – flue gas heat recovery, kJ h^{-1}
– povratna toplina dimnih plinova, kJ h^{-1}

Q_t – process heat, kJ h^{-1}
– procesna toplina, kJ h^{-1}

S – savings, %
– ušteda, %

S_{CHP} – CHP savings, %
– CHP ušteda, %

S_{Fa} – annual fuel savings, kg h^{-1}
– godišnja ušteda goriva, kg h^{-1}

S_v – sulphur volatile
– hlapivi sumpor

t_{ai} – air inlet temperature, °C
– temperatura ulaznog zraka, °C

t_{ao} – air outlet temperature, °C
– izlazna temperqatura zraka, °C

t_{FGi} – flue gas inlet temperature, °C
– ulazna temperatura dimnih plinova, °C

t_{FGo} – flue gas outlet temperature, °C
– izlazna temperatura dimnih plinova, °C

T_{PA} – terephthalic acid
– tereftalna kiselina

V_{FG} – total flue gas volume, $m^3\ h^{-1}$
– ukupni volumen dimnih plinova, $m^3\ h^{-1}$

V^S_a – stoihiometric air volume, $m^3\ kg_F^{-1}$
– stehiometrijski volumen zraka, $m^3\ kg_F^{-1}$

V^S_{FG} – theoretical volume of combustion products, $m^3\ kg_F^{-1}$
– teoretski volumen produkata izgaranja, $m^3\ kg_F^{-1}$

α – excess air
– koeficijent suviška zraka

β – plant utilization factor, %
– stupanj iskorištenja postrojenja, %

η_B – boiler efficiency, %
– iskorištenje kotla, %

η_e – power plant efficiency, %
– iskorištenje postrojenja, %

η_{oC} – overall efficiency, %
– ukupno iskorištenje, %

η_{CHP} – CHP efficiency, %
– CHP iskorištenje, %

η_{AP} – air preheater efficiency, %
– iskorištenje predgrijača zraka, %

τ – plant use factor, $h\ a^{-1}$
– stupanj iskorištenja postrojenja, $h\ a^{-1}$

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* Autori nisu prihvatili sve primjedbe metrologa.

SAŽETAK

Kogeneracija i povrat topline u industrijskom postupku

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Predložene su mogućnosti uštede energije u industrijskoj proizvodnji poliestera kao energetski intenzivnom procesu. Iz procesnih podataka proizlazi značajna potrošnja električne i toplinske energije u procesnim operacijama. Istodobno, poboljšanje gospodarenja energijom moguće je ostvariti primjenom kogeneracije, tj. zajedničke proizvodnje toplinske i električne energije kao zamjene za uobičajenu odvojenu proizvodnju istih. Nadalje, plinovi izgaranja sa zadovoljavajućom temperaturnom razinom mogu se upotrebljavati radi predgrijavanja zraka za izgaranje. U skladu s procesnim podacima provedeni su proračuni i usporedba potrošnje energije za konvencionalni i kogeneracijski sustav kao i povrat topline dimnih plinova. Komparacija odvojene proizvodnje toplinske i električne energije s učinkovitošću od 55,6 % i kogeneracije s 85 % ukazuje na porast apsolutnog iskorištenja od 29,4 %. Primjenom predgrijača radi povišenja temperature zraka za izgaranje ušteda goriva je 5,6 %. Time se istodobno smanjuje toplinsko opterećenje okoliša što rezultira iz sniženja izlazne temperature dimnih plinova od oko 127 °C. Zaključno, kogeneracija i povrat topline dimnih plinova osim sniženja specifične potrošnje energije rezultira ekološkim i gospodarstvenim prednostima.

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