APPLICATION AND DESIGN OF AN ECONOMIZER FOR WASTE HEAT RECOVERYIN A CO-GENERATION PLANT

by

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Energy increase cost has required its more effective use. However, many industrial heating processes generate waste energy. Use of waste-heat recovery systems decreases energy consumption. This paper presents case study of waste heat recovering of the exhaust flue gas in a 1415 kWe co-generation plant. This waste heat can be recovered by installing an economizer to heat the condensed and fresh water in thermal degasification unit and reduce steam use for maintaining the temperature of 105 °C for oxygen removal. Design methodology of economizer is presented.

Key words: *economizer, exhaust flue gas, energy saving, waste heat recovery, co-generation plant*

Introduction

Co-generation or combined heat and power (CHP) is defined as sequential generation of two different forms of useful energy from a single primary energy source, typically mechanical and thermal energy. Mechanical energy may be used either to drive an alternator for producing electricity, or rotating equipment such as motor, compressor, pump or fan for delivering various services. Thermal energy can be used either for direct process applications or for indirectly producing steam, hot water, hot air for dryer or chilled water for process cooling. The principal technical advantage of co-generation systems is their ability to improve the efficiency of fuel use in the production of electrical and thermal energy. Less fuel is required to produce a given amount of electrical and thermal energy in a single co-generation unit than is needed to generate the same quantities of both types of energy with separate, conventional technologies [1]. Co-generation is used in large and small locations where power and another form of energy is required. It has found application in the largest industrial locations such as integrated paper mills and petrochemical plants and in locations as small as fast food restaurants and even homes. The range of fuels used in co-generation plant includes natural gas, diesel or heavy fuel oil, propane, coal, waste liquids or gasses from industrial process, and renewables in low power applications. Today, there are several available co-generation technologies (steam turbine co-generation system, gas turbine co-generation sys-

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tem, combined cycle gas turbine co-generation system, internal combustion engine co-generation system…).Which of these technologies will be used depends on the fuel type, sector of use, and nominal electricity power of plant. Technology recommendations are shown in tab. 1. With new developments in reliable technology, the concept of co-generation has become a staple in any new plant design. The process is highly efficient, predictable and reliable, with failure rates lower than those of most pieces of process equipment. The total useable output of co-generation project can be double that of traditional power generator such as a fossil fuel steam generation plant. With such benefits, it is natural to ask why co-generation is not used in every application where power is produced. There are several requirements for a co-generation project which will pay for itself in a reasonable amount of time:

- there has to be a need for large amounts of thermal (heat, process and/or cooling) energy nearby to the co-generation plant,
- co-generation has high initial cost relative to traditional power generation technologies,
- it requires a significant amount of valuable plant space with interconnections for electricity and thermal energy, and
- it requires higher trained operators than a simple power plant.

Table 1. Selection of co-generation technologies [1]

Sector	Plant size [MW]	Coal	Gas	Heavy fuel oil	Light fuel oil	Biomass	Wastes	Biogas
Domestic	< 0.015	–	GE	–	GE	–	–	GE
Commercial	0.015-0.1	–	GE	–	GE	ST	ST	GE
	0.1-1	–	GE	–	GE	ST	ST	GE
	1-5	ST	GT/GE	ST	GT/GE	ST	ST	GT/GE
Industry	1-5	ST	GT/GE	ST	GT/GE	ST	ST	GT/GE
	5-50	ST	OCGT	ST	OCGT	ST	ST	OCGT
	> 50	ST	OCGT	ST	OCGT	ST	ST	CCGT

Notes: CCGT – combined cycle gas turbine, GE – gas engine, GT – gas turbine, OCGT – open cycle gas turbine, ST – steam turbine

Before any equipment is installed, cost benefit thorough analysis must also be performed. The savings from reduced electricity and fuel purchases must offset the increased costs of labor, maintenance, taxes and capital financing. Each of these costs can be managed individually [10].

The goal of this paper is to present technical and economical analysis of one small co-generation plant, which is built to provide heat energy (hot water and steam) for nearby milk products plant in Serbia. Also, this paper analyzed possibility to increase energy efficiency with installation of additional heat exchanger in the existing CHP plant.

Economizer (ECO) in this study is gas-water heat exchanger, design by [2] with respect of [3]. Other types of heat exchangers can be used, depends of application [11, 12]. For shell and tube type, instructions are also given in [2], while optimal design is presented in [4]. For plate type, optimal design is presented in [5].

Experimental study on waste heat recovery from an internal combustion engine using thermoelectric technology is presented in [6]. Heat recovery from a natural gas powered internal combustion engine by CO_2 transcritical power cycle is presented in [7]. Thermodynamic analysis of heat recovery steam generator in combined cycle power plant is presented in [8].

Crucial integral part of CHP plant is turbine. A lot of experimental study has been done on further improvement of turbine. Optimization of micro CHP gas turbine is presented in [9].

Description of co-generation plant

The CHP plant is installed in milk products plant production 2011, in order to reduce energy production costs. The CHP is functioning as separate economic unit. Figure 1 shows the CHP flow diagram in its basic form. Exhaust flue gas (EFG) is formed in natural gas combustion process (average: CH_4 = 95%vol and H_d = 34 MJ/kg) in the gas engine.

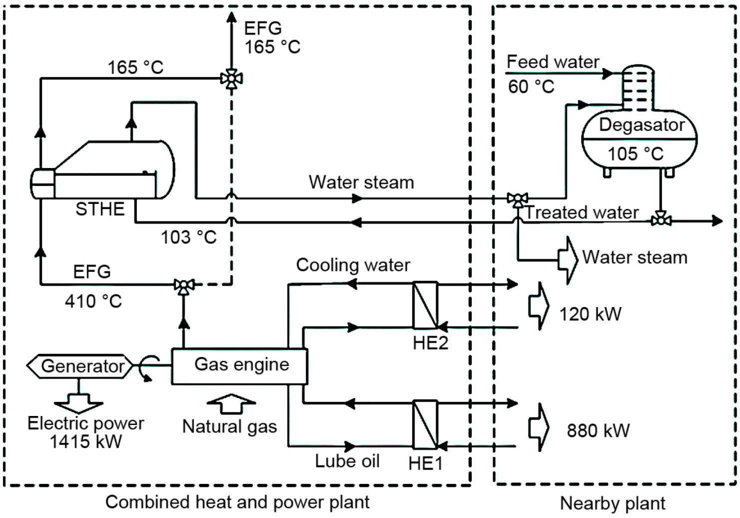

Figure 1. Co-generation plant (without ECO)

Constant temperature of the gas engine is held by cooling water. Amount of energy transferred to cooling water per time unit is 880 kW. This heat transfer takes place in plate heat exchanger (HE1). Lube oil is also cooled with water in plate heat exchanger (HE2) which heat power is 120 kW. Electric generator is powered by the engine in order to produce 1415 kW of electrical power which is sold by the factory. Average natural gas consumption is 360 m_S^3/h (where S refers to t = 0 °C, and p = 1 barA), and average EFG flow rate is 8100 kg/h. About 6.8% (550 kg/h) of this flow rate is water steam and non-condensing gasses are rest. Currently, EFG enters the shell and tube heat exchanger (STHE) which is used for steam production. The EFG enters STHE tube side at 410 °C, and exits at 165 °C. The EFG which leaves STHE is removed from the process. Water treated from degasification unit enters the shell side of STHE at 103 °C and steam is produced. Nominal heat power that is consumed in steam production is 660 kW. The total nominal energy output of CHP is 1660 kW of thermal power and 1415 kW of electric power. It should be noted that these values are nominal (projected). Measured values are slightly different because nearby milk factory does not always have the same energy needs. Measured values are presented in tab. 2.

In order to achieve maximum CHP plant capacity, EFG at 165 °C is considered for heating. Two possibilities were discussed:

- the ECO installation to reduce EFG temperature to 120 °C (there is no condensation of water vapor in EFG) – case 1, and
- the ECO installation to reduce EFG temperature to 90 °C (there is condensation of water vapor in EFG) – case 2.

Table 2. The result of one-year monitoring on the co-generation plant (year 2012)

Measured value	Nominal	Amount	Unit
Gas consumption	2851200	2851879	m^3 per year
Electricity produced (brutto)	11206800	11289013	kWh per year
Own consumption	–	162711	kWh per year
Electricity produced (netto)	–	11126302	kWh per year
Feed water	–	7152	m^3 per year
Feed water, kWh per year	–	775500	kWh per year
Heat exchanger HE1 (1)	6969600	3257868	kWh per year
Heat exchanger HE2 (2)	950400	253947	kWh per year
Evaporator STHE (3)	5227200	5249686	kWh per year
Sum of transfer heat (1, 2, 3)	–	8761501	kWh per year

Water vapor condensation can be done as exhausted gasses practically do not produce any sulfuric acid, hence there would be no harm to equipment by water. Position of ECO in the existing CHP plant is shown in fig. 2. Of course, ECO design and consequently price is depending on its purpose and thermal performance (heat power).

Two cases have been analyzed, without and with condensation of water vapor in EFG. In the first case, when ECO serves as a simply heat exchanger which heat power is 120 kW it is necessary to invest approximately 18000 €. Taking into account the purchase price of heat 0.0458 €/kWh, payback time for this investment is around five months. Investment in condenser with nominal heat power of 460 kW would be 35000 €, but this investment will return for two and a half months.

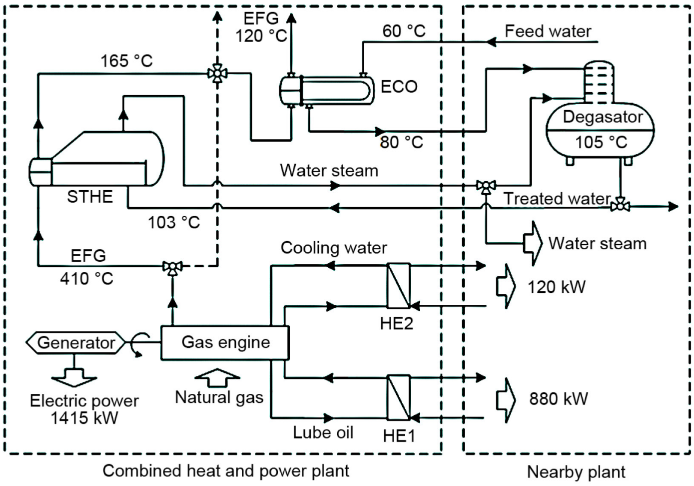

Figure 2. Co-generation plant (with ECO)

Due to thermal energy needs, board of directors has chosen option without condensation – case 1. The ECO will heat the feed water. Feed water will enter ECO at 60 °C and exit at 80 °C. The EFG will enter ECO at 165 °C and exit at 120 °C. Amount of feed water in degasator is 5000 kg/h.

Produced steam from STHE is saturated at 6 bar (gauge). Due to 120 kW in EFG, degasator will use less steam to heat feed water. Production of steam in STHE is identical with and without ECO. Amount of steam to other consumers will be increased, and to degasator, decreased. Amount of steam without and with ECO are shown in tab. 3. Heat energy of steam are shown in tab. 4.

Table 3. Amount of steam without and with ECO

Amount of steam [kgh^{-1}]	Without ECO	With ECO
Total production from STHE	1150	1150
Degasator	457	248
Other consumers	693	902

Table 4. Heat energy of steam without and with ECO

Heat energy of steam [kW]	Without ECO	With ECO
Total production from STHE	660	660
Degasator	262	142
Other consumers	398	518

Design detail of ECO

The ECO is designed according to *Heat Exchanger Design Handbook*, [2]. Basic sketch of ECO is given in fig. 3, and some of basic equations are:

– Heat transfer coefficient from outside flow, EFG side:

$$\mathrm{Nu}=0.134\,\mathrm{Re}^{0.681}\,\mathrm{Pr}^{1/3}\left(\frac{s_r}{h_r}\right)^{0.2}\left(\frac{s_r}{\delta_r}\right)^{0.1134}\psi_{Nr} \quad (1)$$

where Re is the Reynolds number for EFG, and Pr – the Prandtl number for EFG.

– Correction factor concerning number of pipes row, ψ_{Nr} is:

$$\psi_{Nr}=\left(1+\frac{w}{Nr}\right)^{-0.14} \quad (2)$$

when $Nr < 6$, if $Nr \geq 6$, $\psi_{Nr} = 1$.

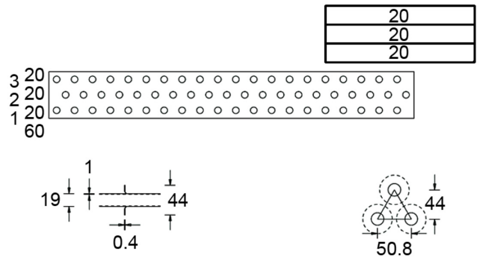

Figure 3. Basic sketch of ECO (3 tube rows, 20 pipes per row, 3 water passes, 60 pipes, pipe 19 × 1 mm, fin 44 × 0.4 mm, pitch triangular 50.8 × 44 mm)

– Heat transfer coefficient from inside flow, water side:

$$\mathrm{Nu}=\frac{\frac{\varepsilon}{8}(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7\sqrt{\frac{\varepsilon}{8}}\left(\mathrm{Pr}^{2/3}-1\right)}\left[1+\left(\frac{d_u}{L_c}\right)^{2/3}\right]\varphi_t \quad (3)$$

where Re is the Reynolds number for water, Pr – the Prandtl number for water, $\varphi_t = 1$ for our case – recuperation of EGF, using equations from [2].

– Overall heat transfer coefficient for ECO with fins pipes for outside flow is:

$$\frac{1}{k}=\left(\frac{1}{\alpha_1}+R_1\right)\frac{1}{\eta_1}+\frac{S_1}{2\pi L_c\lambda_z}\ln\frac{d_s}{d_u}+\left(\frac{1}{\alpha_2}+R_2\right)\frac{S_1}{S_2} \quad (4)$$

where α_1 is the heat transfer coefficient at outside surface, α_2 – the heat transfer coefficient at inside surface, R_1 [m^{2}KW^{-1}] – the fouling resistance for EFG, R_2 [m^{2}KW^{-1}] – the fouling resistance for water, S_1 [m^2] – the surface for outside flow, both bare pipes and fins, and S_2 [m^2] – the surface for inside flow.

– Efficiency coefficient of finned surface η_1 is:

$$\eta_1=1-\frac{S_{1,r}}{S_1}(1-\theta_1) \quad (5)$$

where S_{1r} [m^2] is the fin surface, and θ_1 – the fin efficiency.

$$\theta_1 = \frac{\tanh\left(\sqrt{\mathrm{Bi}}\right)}{\sqrt{\mathrm{Bi}}} \tag{6}$$

$$\mathrm{Bi} = \frac{1}{\dfrac{1}{\alpha_1} + R_1} \frac{l_r}{\lambda_r} \tag{7}$$

– Overall heat transfer rate:

$$Q = k\,S_1 \Delta t_{\mathrm{MDT}} \tag{8}$$

where Δt_{MDT} [°C] is the logarithmic mean temperature difference.

$$\Delta t_{\mathrm{MDT}} = \frac{\Delta t_a - \Delta t_b}{\ln \dfrac{\Delta t_a}{\Delta t_b}} \tag{9}$$

$$\Delta t_a = t_{1i} - t_{2o} \tag{10}$$

$$\Delta t_b = t_{1o} - t_{2i} \tag{11}$$

where t_{1i} [°C] is the EFG inlet temperature, t_{1o} [°C] – the EFG outlet temperature, t_{2i} [°C] – the water inlet temperature, and t_{2o} [°C] – the water outlet temperature.

Specification sheet with all details of ECO are presented in accordance to API 661 in Appendix in this paper [3].

Conclusions

Process of using waste heat is familiar from decades ago, hence unlimited number of plants in the world do not utilize waste heat. Presented ECO in study or similar economizer design can be installed in every kind of plant: power plant, oil&gas plant, heating plant, various production plant, *etc.* Benefit for society are reduced consumption for fossil fuels and reduced greenhouse effect, due lower heating atmosphere.

The primary aim of this study is to use waste thermal energy from EFG at 165 °C and lower its temperature to 120 °C before leaving to the atmosphere. Energy is used for heating fees water in degasator from 60 °C until 80 °C. Achieved heat power utilization is 120 kW, due to plant is producing 209 kg/h less steam in boiler for degasator needs. With ECO, overall efficiency of CHP plant is upgraded from currently 74.5% to 78%.

Due to tendency of increasing energy prices, this kind of investment will have smaller payback time period, and we can expect in near future intensive implementation of economizer in plants.

Nomenclature

Bi – Biot number
CH_4 – volumetric percent of methan in natural gas, [%]
c_p – specific heat, [$\mathrm{Jkg^{-1}K^{-1}}$]
d_s – outer diameter of the pipe for EFG, [m]
d_u – inner diameter of the pipe for water, [m]
H_d – lower heating power of natural gas, [$\mathrm{MJkgK^{-1}}$]
k – overall heat transfer, [$\mathrm{Wm^{-2}K^{-1}}$]
L_c – length of the pipe, [m]
l_r – geometric characteristics of fin, [m]
Nr – number of tube rows
Nu – Nusselt number
P – pressure, [bar]
Pr – Prandtl number (= $c_p\mu/\lambda$)
R – fouling resistance, [$\mathrm{m^2KW^{-1}}$]
Re – Reynolds number (= $wd\rho/\mu$)
S – surface, [m]
S_r – fin step, [m]

T – temperature, [°C]
$t_{1\mathrm{i}}$ – EFG inlet temperature, [°C]
$t_{1\mathrm{o}}$ – EFG outlet temperature, [°C]
$t_{2\mathrm{i}}$ – water inlet temperature, [°C]
$t_{2\mathrm{o}}$ – water outlet temperature, [°C]
w – EFG velocity, [ms^{-1}]

Greek symbols

α – heat transfer coefficient (= Nuλ/d), [Wm^{-2}K^{-1}]
γ_{Nr} – correction factor concerning number of pipes row
Δt_{MDT} – logarithmic mean temperature difference, [°C]
η_1 – efficiency coefficient of finned surface
θ_1 – fin efficiency
λ – thermal conductivity of fluid, [Wm^{-1}K^{-1}]
λ_r – thermal conductivity of fin's material, [Wm^{-1}K^{-1}]
λ_z – thermal conductivity of pipe's material, [Wm^{-1}K^{-1}]
μ – EFG dynamic viscosity, [Pa·s]
ξ – friction factor
ρ – EFG density [kgm^{-3}]
φ_r – fin thickness, [m]
ϕ_t – the correction factor

Acronyms

CCGT – combined cycle gas turbine
CHP – co-generation plant
EFG – exhaust flue gas
ECO – economizer
GE – gas engine
GT – gas turbine
HE – heat exchanger
OCGT – open cycle gas turbine
OD – outside diameter
ST – steam turbine
STHE – shell and tube heat exchanger

Acknowledgment

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Appendix

API 661 Specification sheet			Number 1/1
Company: NN Plant		Location: Serbia	
Type	ECO	Size [mm]	1143 × 1138
Number of units in serial	1	Number of units in parallel	1
Overall heat transfer rate [kW]	120	Surface – bare/finned tube [m^2]	3.5/63.3

Performance date

Parameter	Shell side		Tube side	
	In	Out	In	Out
Fluid	EFG		Feed water	
Mass flow rate [kgs^{-1}]	2.25		1.389	
Liquid [kgs^{-1}]	0	0	1.389	1.389
Gas [kgs^{-1}]	2.25	2.25	0	0
Temperature [°C]	165	120	60	80
Bubble point/dew point [°C]	105	105	–	162
Pressure [barA]	1.03170	1.03123	3.00000	2.99379
Molecular weight, liquid [kgkmol^{-1}]	–	–	4.185	4.188
Density – gas [kgm^3]	0.72	0.81	–	–
Density – liquid [kgm^3]	–	–	985.57	972.87
Viscosity – gas [mPa·s]	0.0215	0.0199	–	–
Viscosity – liquid [mPa·s]	-	-	0.4743	0.3520
Specific heat – gas [kJkg^{-1}K^{-1}]	1.194	1.182	–	–
Specific heat – liquid [kJkg^{-1}K^{-1}]	–	–	4.185	4.188
Thermal conductivity – gas [Wm^{-1}K^{-1}]	0.0340	0.0304	–	–
Thermal conductivity – liquid [Wm^{-1}K^{-1}]	–	–	0.6432	0.6632
Fluid passes	1		3	
Fluid velocity [ms^{-1}]	3.08		0.25	
Pressure drop – allowable/calculate [Pa]	–	47	–	621
Fouling resistance [m^{2}KW^{-1}]	0.00175		0.00009	
Middle temperature difference [°C]	71.24			
Overall heat transfer coefficient for tube side – bare [Wm^{-2}K^{-1}]	Service		475.8	
	Clean		680.4	
Overall heat transfer coefficient for shell side – finned [Wm^{-2}K^{-1}]	Service		26.7	

Design – Materials – Construction

Design pressure 3 barA	Design temperature 165	Tube
Tube bundle	Header	Material copper
Size 1143	Type Plug	Specifications welded
Tube rows 3	Material P265GH	OD 19 Min thk. 1 mm
Arrangement mixed or horiz.	Passes 3	Number 60 lng 1m
Bundles 1 par 1 ser	Gasket mat. comp. fibber	Pitch 50.85/40.04 staggered
Bundle frame galv. steel	Inlet nozzle (1) 50.8 mm	Fin L-type weld OD 44.5 tks 0.43 mm
	Outlet nozzle (1) 50.8 mm	Number 390#/m

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