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Optimization of Binary Co-generative Thermal Power Plants with SOFC on Solid Fuel

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The purpose of this paper is to gain insight in the optimization problem of binary co-generative power plant with high temperature solid oxide fuel cells on solid fuel with a higher power. Thus conceived power plant belongs to the category of high efficiency modern power systems composed of modular fuel cells, gas turbine and steam turbine co-generation power plant. Main emphasis is placed on the lignite, mostly represented fuel in Macedonia.
For this type of power plants it was developed software package, used for optimization of the complex functions (composed of many variables) and the optimization criteria is maximum exergy efficiency. The optimization procedure of this combined plant provides many technical, environmental and economy benefits. Verification of the software package is made by comparison of the simulation results and the already performed and analyzed similar plants from literary sources. Another comparison is made between binary co-generation power plant with and without fuel cell, in relation of the efficiency and environmental benefits.

1. Introduction

Tendency of world energetic is to guide its policy towards the development of power plants with high efficiency. Many scientific institutions declare that power plants with fuel cells are the future of energetic. The main advantage of fuel cell power plant regarding the future is that they can use classic fuels (solid, liquid and gas), fuel gas rich with hydrogen obtained in different ways and pure hydrogen.
In the world there are many installed small power plants with fuel cells on gas fuels, Maru et al. (2010). In known literary sources, Hirschenhofer et al. (1998), can be found information’s of power plant with high power on solid fuels (with fuel cells and without co-generation) which are still in research phase. In this paper has been developed optimization method implemented in a software package which results contributes to the increase of efficiency of power plant with high power fuel cells and co-generation. Energy method for determining the overall efficiency is replaced by exergy method, also used by other researchers like Kotas (2010), which gives an insight of the level of efficiency.

2. Binary co-generative power plants with high temperature SOFC

Binary co-generative power plant with high temperature solid oxide fuel cells (BCFC) are combined plants consisting of three thermal power plants: high temperature solid oxide fuel cell (SOFC), gas turbine and steam turbine co-generation plant (Hirschenhofer et al., 1998). In this kind of plants electricity is produced in three ways: from the inverter at the fuel cell and from the generators of the gas and steam turbine, and also produced heat in the co-generation steam turbine power plant. Functional scheme of high power BCFC on lignite is shown in Figure 1 (Tashevski, 2004).

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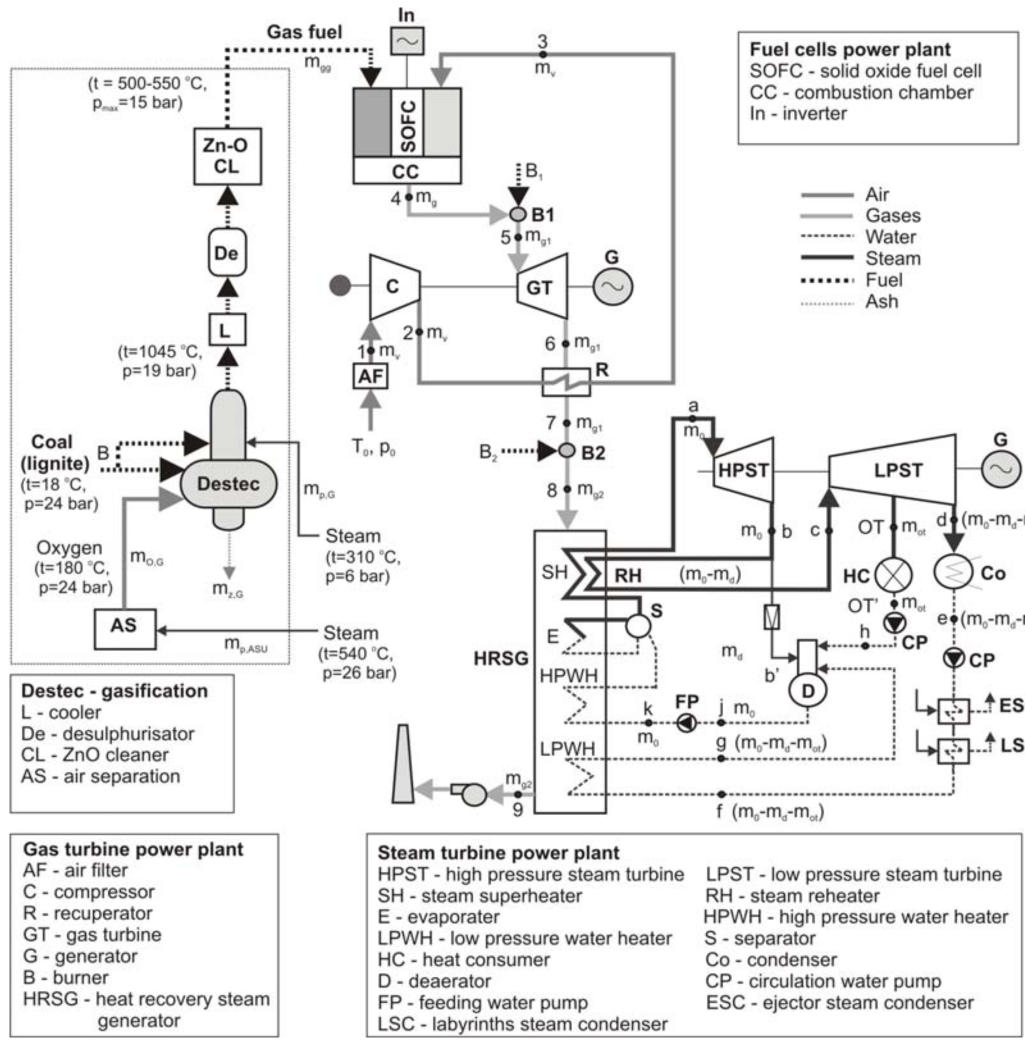

Figure 1: Functional scheme of binary co-generative power plant with SOFC on lignite

Coal (lignite) is reformed in the fuel reformer (Destec gasifier). As a product of the reformer is gas fuel rich in hydrogen (primary fuel in the high temperature fuel cells). Compressed air heated to the required temperature in the recuperator (R) could be used to heat the exhaust gases from the gas turbine (GT). A small percentage of uncombusted fuel and carbon monoxide continues to burn in the additional combustion chamber (CC), causing increase in the fuel cell outlet gas temperature (900-1100 °C). The heat of the flue gases from the fuel cell is used in the gas turbine. To achieve the high parameters at the inlet of gas turbine it is required to install burner for additional combustion (B1). Second burner for additional combustion (B2) is placed ahead the heat recovery steam generator (HRSG), in order to achieve the required steam parameters. The co-generation power plant has condensing steam turbine with regulated steam extraction used for heat consumers, also as an option can be applied back-pressure steam turbine (several variants).

2.1 Coal-lignite gasification (fuel reforming)

When a fuel in the fuel cell is coal (lignite) or liquid fuels it is obligatory to use fuel reformers (gasifiers), where as a product is gas fuel with high percentage of hydrogen. In Macedonia there are significant reserves of lignite in composition and lower heating value (LHV) shown in Table 1 (Tashevski, 2004).

Table 1: Macedonian lignite composition (%) and lower heating value (LHV)

Carbon	Hydrogen	Oxygen	Sulphur	Nitrogen	Ash	Wet	LHV kJ/kg
23.3-29.1	2.2-3.0	9.3-16.0	0.55-0.56	0.72-1.1	14.2-18.3	32.3-49.4	7,946-10,361

Shelton and Lyons (2000) have reported that Destec gasifiers during the process of gasification produces 1.1-1.4 kg of gas fuel from 1 kg of lignite, whereby in the reformer is using 0.5-0.55 kg of oxygen (95 %) and 0.3-0.35 kg steam. The additional heat for providing steam used in the process of gasification has negative impact to the overall power plant efficiency.
Composition of gas fuel rich in hydrogen, which is a product from the gasification of lignite is given in Table 2. Due to lack of gasification facility in Macedonia, for our lignite are used informations obtained from lignite gasification in various types of gasifiers in USA, reported by Dorminey et al. (2009).

2.2 High temperature SOFC applied in power plant

The BCFC uses high temperature SOFC which operates at a temperature level about 1000 °C and pressure up to 15 bar. This type of fuel cell is a product of Siemens-Westinghouse Company, specialized in manufacturing of tubular fuel cells. Their model of individual fuel cell, analysed by George (1996) and Veyo (1999) designed with standard components: diameter 0.4 m, height 2 m, power of individual cell 315 W, power of a module 1.7 MW, number of individual cells in a module 5,600. In fuel cells calculations are used well known chemical equations for the processes which occurs at the SOFC anode, cathode and overall reaction in SOFC, Hirschenhofer et al. (1998).

3. Optimization and calculation of BCFC

Optimization of the BCFC with SOFC is a complex problem, since there are many systems, components and functions needed for their operation, which should be considered. Regarding the large number of requirements that need to be fulfilled in these plants, it is necessary to make many compromises during their optimization, Pakalapati et al. (2007). For this purpose at the Department of Thermal Engineering, Faculty of Mechanical Engineering in Skopje, was developed software package for optimization and calculation of BCFC.
A criteria for the optimization is the maximum total exergy efficiency of BCFC, which is indicator for the overall efficiency of the BCFC. For determining the electrical and overall efficiency of the BCFC an exergy (entropic) method is applied which gives a more realistic insight for the efficiency:

$$\eta_{exBCFC} = \frac{\Delta ex_{eBCFC} + \Delta ex_{tBCFC}}{exQ_d + \Delta ex_{REF}} = \frac{P_{eBCFC} + \Delta ex_{tBCFC}}{B_t \cdot e_d + \Delta ex_{REF}} \tag{1}$$

Where is: exergy change during electrical energy generation Δex_{eBCFC} kW (values are very near to the electrical power P_{eBCFC} kW), exergy change during thermal energy generation Δex_{tBCFC} kW, exergy brought with fuel exQ_d kW, specific exergy of the fuel e_d kJ/kg, total fuel consumption B_t kg/s, exergy change of the steam for fuel reforming Δex_{REF} kW.
The following general equation is used to determine the exergy change Δex kW:

$$\Delta ex = m(\Delta h - T_o \cdot \Delta s) \tag{2}$$

Where is: flow m kg/s, change of specific enthalpy Δh kJ/kg, environment temperature T_o K, change of specific entropy Δs kJ/kgK.

Table 2: Lignite gas compositions and LHV/specific exergy of the fuel for oxygen-blown gasifiers

	Gas compositions % - Gasification process/producer				
	Moving-bed	Fluidized-bed	Entrained-bed		
	Lurgi	Winkler	Shell	Texaco	Destec
CH_4/Ar	3.3/-	4.6/0.7	-/1.1	0.1/0.9	0.6/0.8
C_2H_4/C_2H_6	0.1/0.2	-	-	-	-
CO/CO_2	5.8/11.8	33.1/15.5	63.1/1.5	39.6/10.8	45.2/8.0
H_2/ H_2O	16.1/61.8	28.3/16.8	26.7/2.0	30.3/16.5	33.9/9.8
H_2S/N_2	0.5/0.1	0.2/0.6	1.3/4.1	1.0/0.7	0.9/0.6
LHV kJ/m^3	3,960.0	8,930.0	11,170.0	8,550.0	9,800.0
Specific exergy e_d kJ/kg	4,875.0	-	-	-	12,350.0

Overall efficiency is obtained by simple summarization of the electrical and thermal energy and dividing by the total energy input (according to the energy method), which gives unrealistically high values (80-90 %). Applying the exergy method in the calculations, gives values for exergy change during electrical energy generation which are very close to the electrical power calculated according to the energy method (due to the small change of entropy). Significant differences appear in exergy change during thermal energy generation and the exergy change of the steam (used for fuel reforming), compared with values obtained by energy method (due to the significant change of entropy in this case). The values of the specific exergy of the gaseous fuels are very close to the LHV. This approach is supported by many authors, such as Kotas (2010), who works on the problem of modelling and calculation of modern energy systems.

Table 3: Variables, input data and results from optimization process of BCFC on lignite

Variables/Input data values/level			Results from optimization			
			Destec without B1/B2	Destec with B1/B2	Lurgi without B1/B2	Lurgi with B1/B2
SOFC power	P_{AC} MW	100 (choice)	100	100	100	100
Fuel cells voltage	V_{FC} V	0.6-0.7 (step 0.1)	0.7	0.7	0.7	0.7
Fuel utilization	U_g %	93-98 (step 1)	98	98	98	98
Oxidant utilization	U_o %	10-18 (step 1)	18	18	18	18
SOFC fuel inlet temp.	T_{gv} K	773-823 (step 10)	823	823	823	823
SOFC oxidant inlet temp.	T_{ov} K	973-1023 (step10)	973	973	973	973
Gasified fuel composition		average	(Table 2)			
Oxidant composition (air)		standard/choice	O_2=20,8 %; N_2=78,2 %; H_2O=1 %			
Compressor pressure ratio	Π_C	1-15 (step 1)	5	10	5	10
Compressor air inlet temp.	t_1 °C	15 (average)	15	15	15	15
Gas turbine inlet temp.	T_{iGT} K	1770 (max)	1770	1700	1770	1770
HRSG steam outlet press.	p_I MPa	1-14 (step 1)	5	14	5	14
HSRG steam outlet temp.	t_I °C	560 (max/stand.)	560	560	560	560
Steam extraction pressure	p_{HC} MPa	0.5 (choice)	0.5	0.5	0.5	0.5
Deaerator pressure	p_D MPa	0.7 (standard)	0.7	0.7	0.7	0.7
Condenser pressure	p_{CO} MPa	0.006 (standard)	0.006	0.006	0.006	0.006
Specific steam extraction	α_{OT} kg/kg	0.3 (choice)	0.3	0.3	0.3	0.3
BCFC overall ex. efficiency	η_{exBCFC}	Optimiz. criteria	0.665	0.642	0.628	0.619

Table 4: Results from calculation of BCFC on lignite

Results for BCFC (without or with additional burners B1 and B2)			Destec without B1/B2	Destec with B1/B2	Lurgi without B1/B2
FC fuel consumption	B_{FC}	kg/s	26.651	26.651	53.157
FC gases outlet flow	m_g	kg/s	186.007	186.007	209.908
FC electrical power (change of exergy)	P_{eFC}	kW	100,000.0	100,000.0	100,000.0
FC electrical exergy efficiency	η_{FC}	-	0.290	0.290	0.342
Burners B1/B2 fuel consumption	B_1/B_2	kg/s	-	2.94/0.63	-
GT electrical power	P_{eGTP}	kW	82,305.27	100,249.6	58,375.1
GT and FC exergy efficiency	η_{eGTP}	-	0.529	0.581	0.542
Condensed steam turbine (ST) with steam extraction					
ST steam flow	m_o	kg/s	29.443	29.315	24.226
Heath consumer steam flow	m_{OT}	kg/s	8.833	8.794	7.268
ST electrical power (exergy change)	P_{ePTP}	kW	38,634.16	37,604.27	19,999.4
ST electrical exergy efficiency	η_{ePTP}	-	0.366	0.366	0.312
Change of exergy (thermal power)	Δex_{tBCFC}	kW	8,517.49	12,007.37	5,126.83
Change of exergy (fuel reforming)	Δex_{REF}	kW	15,622.19	15,622.19	32,895.93
BCFC total fuel consumption	B_t	kg/s	26.651	30.221	53.157
Coal (lignite) consumption	$B_{lignite}$	kg/s	23.986	27.199	47.841
BCFC electrical power (exergy change)	P_{eBCFC}	kW	220,939.4	237,853.9	178,374.5
BCFC electrical exergy efficiency	η_{eBCFC}	-	0.641	0.612	0.611
BCFC overall exergy efficiency	η_{exBCFC}	-	0.665	0.642	0.628
Back-pressure steam turbine (ST)					
BCFC electrical exergy efficiency	η_{eBCFC}	-	0.608	0.591	
BCFC overall exergy efficiency	η_{exBCFC}	-	0.722	0.664	

Many variables in the gas and steam turbine co-generation plant mainly depend on the fuel cell parameters. It must be noted that during the optimization process, the important variables for the gas and steam turbines cannot be neglected, Mu L. (2010).
According the Kavrakoglu (1981), in many cases of practical variable (Table 3) calculations it is necessary to optimize function that depends on many variables:

$$\eta = \eta\left(V_{FC}, U_g, U_o, T_{gv}, T_{ov}, \Pi_C, p_I\right) \tag{3}$$

An overview of two types of data is given in Table 3. The first group of data represents the software input parameters and second ones are the variables, which are subject of the optimization process (Eq. 3). According to the recommendations of the producers of fuel cells, given by George (1996) and Veyo (1999), and with the performed detailed analysis of the variable impact on the BCFC performance, narrowed intervals and steps of variables variation are determined. Also in the same table are presented the optimal values of the variables (results from the optimization process, given in Eq. 3) under which maximum overall exergy efficiency is achieved (optimization criteria).
The optimization is done for SOFC with power of 100 MW, without and with additional burners, for two types of lignite gasification process. Results from BCFC calculation are shown in Table 4. The software package is composed of a number of sub-programmes for calculation of various combinations of power plants and other different types of the BCFC.

4. Verification and comparison the results from the software

Comparison and verification of the results obtained from the software are done by using data's from a 500 MW power plant on lignite, with Destec entrained-bed gasifier and SOFC, without co-generation, which is still under investigation, proposed by Department Energy's of the USA, reported by Hirschenhofer et al. (1998). The presented results from the investigated power plant are identical with results from the simulation process (Table 5), Tashevski (2004). To be able to present the perspective of the BCFC, comparison is made between BCFC with a binary co-generation plant without fuel cell (for the same fuel consumption). BCFC achieved a 15 % higher overall exergy efficiency and 30 % lower emissions of CO_2 and NO_X.

Table 5: Input data and results from comparison between investigated power plant (DOE USA) and simulation process

Input data			
SOFC electrical power/voltage	MW/V	301.6/0.69	
Fuel/oxidant utilization	%	90/21.4	
SOFC fuel/oxidant inlet temperature	K/K	673/853	
Gas fuel compos. $CH_4/H_2/CO/CO_2/H_2O/N_2$	%	0.3/35.8/42.3/9.5/10.3/1.8	
Oxidant composition $O_2/N_2/H_2O$	%	20.8/78.1/1.1	
Compressor inlet air temp./pressure ratio	°C/-	17/3.33	
Gas turbine inlet temperature	K	1,500	
HRSG steam outlet pressure/temperature	MPa /°C	12/560	
Results		Investigated BCFC	Simulation process
Consumption of gaseous fuel	kg/s	70.0	69.427
Lignite consumption	kg/s	42.0	41.656
Oxidant flow (air)	kg/s	370.0	376.793
SOFC outlet gas flow	kg/s	500.0	497,434
SOFC efficiency	-	0.35	0.367
Gas turbine electrical power	kW	125,000.0	125,460.0
Steam flow	kg/s	75	74.669
Steam turbine electrical power	kW	110,000.0	109,895.77
BCFC electrical power	kW	536,600.0	536,955.75
BCFC electrical efficiency	-	0.64	0.649

5. Conclusion

From this paper can be concluded that BCFC achieve high efficiency ranges up to 60-70 %, one of the highest efficiency in actual combined power plants.

The high efficiency is verified by an exergy method which gives more realistic results compared to the unrealistically high values obtained by the classical energy method. The value of the exergy efficiency of these power plants depends from:

- Type and characteristics of selected fuel cells, i.e. the selected SOFC are characterized by excellent features for multiple combinations.
- The type of gasification process. Greater efficiency is obtained when using gas fuels with higher quality, i.e. fuels with higher hydrogen content (rich in H_2).
- The type of gas turbine, i.e. the process uses gas turbines with high efficiency and high inlet temperature at the gas turbine (Mitsubishi - G series gas turbine), reported by MHI (2012).
- The type of steam turbine, two types of condensing steam turbine with steam extraction and back-pressure steam turbine are considered. The higher overall efficiency of BCFC is achieved by back-pressure steam turbine thanks to greater thermal power.
- The application of additional burners at BCFC, achieve slightly lower overall efficiency due to greater fuel consumption, but also better features and allocation of electrical and thermal energy.

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