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Three-generation Power Plant with High-temperature Fuel Cells for Complex Buildings

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Abstract:– The paper analyses the application of three-generation power plants with high-temperature fuel cells in complex buildings. Optimization and calculation for these power plants is done using software package developed in the Faculty for mechanical engineering Skopje. Software package is composed of several subprograms for calculation of power plants with or without fuel cells. Variables are optimized by the method of successive approaches and as criteria for optimization is used the maximum overall exergy efficiency. The software package is verified by comparing the results with the collected parameters of existing power plants or power plants which are still in the research phase. Economy and ecology analysis is provided for this type of power plants.

Keywords:– Three-generation, Fuel Cell, Software Package, Optimization, Calculation, Exergy Efficiency

I. INTRODUCTION

The world energy situation requires significant progress to be made in the rational energy usage i.e energy efficiency regarding the building sector and energy power plants energy cycles. Energy efficiency definition and philosophy clearly defines the directions – doing more with less in same time considering the environment impact. Also, energy efficiency is a way to save energy while meeting current and future energy needs without changing requirements (conditions) to the consumer. Energy efficiency is a number of measures to save energy and one of them is to find new effective ways to produce energy [1].

Cogeneration and three-generation fuel cells power plant are characterized with its high efficiency in the process for production of electrical (electricity) and thermal (heat) power [2], [3]. Because of its high efficiency they are subject of research of many researchers engaged in modelling of modern power systems [4]-[11]. These plants regarding the fuel type utilization can use classic fuels (solid, liquid and gas), hydrogen-rich gaseous fuels derived in different ways and pure hydrogen [12]-[14]. Therefore, these power plants are among the group's most promising for the process of production of energy. Mostly applied are high-temperature solid oxide fuel cells (SOFC) in which despite receiving electricity gets a considerable amount of heat output from the fuel cell [15]-[18].

Building sector in most countries is responsible for at least 40 % of the energy use, therefore the potential for energy savings is significant [19]. Complex buildings are buildings that need electricity and thermal energy for various needs such as heating/cooling, steam (sterilization, laundry, etc.), and domestic (sanitary) hot water.

Application of the three-generation power plants with fuel cells depends on their profitability. Limitation of installing these facilities is relatively high price of fuel cells, which in the near future is expected to be equal the price of other power plants. For this purpose, is made an economic analysis of these power plants [20]-[26].

Emissions of harmful substances in the air are rising especially worrying trend have CO_2 emissions caused by excessive consumption of fossil fuels. Therefore, the term energy efficiency in buildings involves a wide range of measures to reduce consumption of all types of fuels [27], [28].

For these reasons the right choice of efficient power plants to supply the complex building is very important and as a result the worldwide are installed and analyzed a number of these combined power plants.

II. THREE-GENERATION POWER PLANT WITH HIGH-TEMPERATURE SOFC

Three-generation power plants with high-temperature solid oxide fuel cells (TPFC) are a combined power plants for production of electrical and thermal (heat) energy, which in summer is used in absorption chillers for cooling. That means TPFC fully satisfy the energy needs of complex buildings, i.e. in addition to the production of electrical energy they produce thermal energy required for heating/cooling, steam for various purposes, and sanitary hot water.

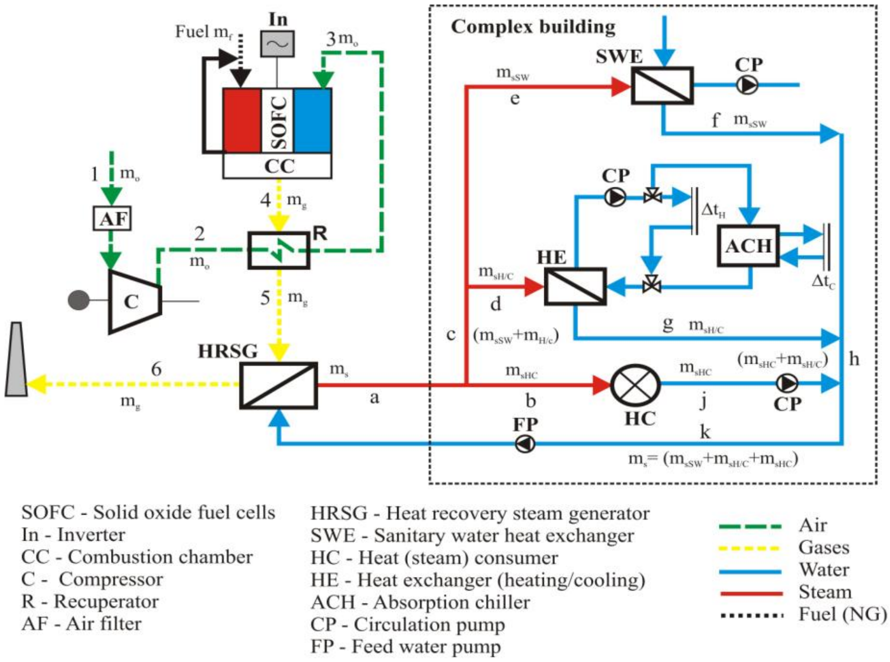

Fig.1: Three-generation pover plant with high-temperature SOFC

Scheme of selected TPFC with the characteristic points is shown Fig. 1. These plants consist of high-temperature solid oxide fuel cell (SOFC), air compressor (C), heat recovery steam generator (HRSG), heat exchangers and absorption chiller.

Required compressed air temperature level is reached in the recuperator (R) which utilizes the heat of the flue gases from the fuel cell. Small percentage of unburned fuel and carbon monoxide additionally burns to a combustion chamber (CC), located at the exit of the fuel cell, which causes an increase in the output of the fuel cell temperature above 1000 °C (for this power plant 1041 °C).

Flue gas leaves with high temperature (about 570 °C), which is utilized in the HRSG. If the HRSG requires higher parameters there is a possibility of installation (before HRSG) channel burner for additional combustion, which is not provided in the specific case of the selected building.

The steam generated in the HRSG is used for heat consumers (machines for drying and processing, sterilization, laundry, etc.). Part of the steam is used to heating and cooling the building (HE and ACH) and rest for domestic hot water (SWE). Energy demand for selected building is shown in Table I.

A. Characteristics of SOFC

TPFC apply SOFC which operates at a temperature about 1000 °C and pressure of 0.3 MPa. This type of fuel cell is the product of the Siemens-Westinghouse, specializing in the production of tubular (cylindrical) SOFC. Last their individual fuel cell is a model with the following characteristics [3], [15]-[18]:

- Diameter 0.4 m, height 2 m
- Power of an individual cell 315 W
- Power of a module 1.5-2.0 MW
- Number of individual cells in a module 4760-6400

The plant runs on natural gas which is desirable fuel for combustion in fuel cells and also ecology favorable fuel. Modular SOFC are with internal reforming of natural gas (99 % methane) into hydrogen which is the primary fuel for combustion in fuel cells. Internal reforming of natural gas needs additional heat provided by heat recirculation of the anode, which causes a drop in temperature before combustion chamber of the fuel cell. Fuel brings the anode and cathode air (oxidant) [3].

Taбle I: Energy demand of complex building

Energy	**Power kW**	**Flow kg/s**		**Parameters**
Electrical energy (electricity)	100	-	-	
Heat consumer (thermal energy)	500	Steam/m_{sHC}	0.24	0.4 MPa and 150 °C
Heating (thermal energy)	700	Water/m_{wH}	8.35	90/70 °C
Cooling (thermal energy)	700	Water/m_{wC}	33.4	88/83 °C
Domestic hot water (thermal energy)	50	Water/m_{wSW}	0.3	50 °C

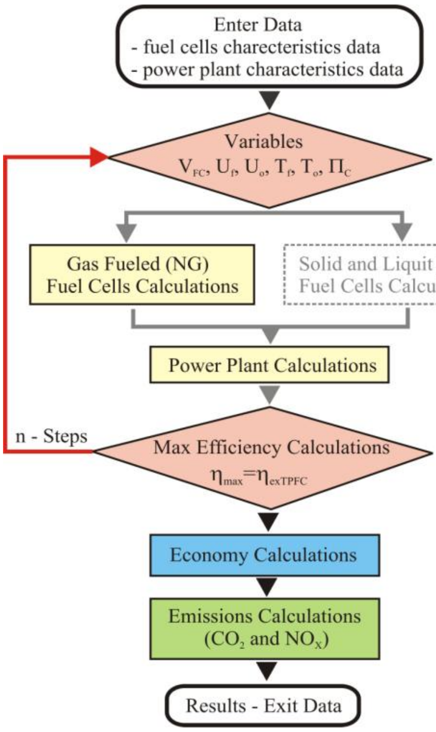

Fig.2: Block diagram of model for optimization and calculation of TPFC (software package)

B. Model for optimization and calculation of TCFC

Optimization and calculation of TPFC is done with the software package developed in our faculty. Software package is composed of several subprograms for calculation of power plant with and without fuel cells. Input data (variables) for the fuel cell are optimized by the method of successive approaches and as optimization criteria is the maximum overall exergy efficiency [6]. Other input data for calculation of TPFC included as standard or maximum values, characteristic of a particular plant (Table II).

Assessment of the validity of the results obtained with the mathematical model is done by comparing the data of gas fuel power plant collected from the literature sources [3]-[10]. Comparison is done on the results obtained with the used model of the TPFC on gas fuels and existing plant with a power of 4 MW on natural gas, product one of the leading companies in this field Siemens-Westinghouse with assistance from the U.S. company Heron [3]. Obtained results (parameters) from the model are very close to the parameters of the selected power plant. It must be noted that the considered power plant is a combination of modular fuel cell and gas-turbine. However, it does not diminish the reliability of the obtained results, because all the characteristic variables of this plant are covered by the optimization and calculation [6].

Optimization and calculation of electric and overall power plant efficiency apply exergy (entropic) method which gives a more realistic overview of the size of the efficiency. Applying classical method gives unrealistically high values of the efficiency which is result of simply summary of electrical and thermal energy. For this purpose the entire system is analyzed and calculated with using exergy method. Classical thermal method is used for comparing the obtained results [4], [11].

Table II: Input data and results from optimization of TPFC:

Enter data/Results	**Value/Field/Step**			**Procedure (*)**
Voltage of individual fuel cell	V_{FC}	V	0.7/0.5-0.7/0.1	O
Fuel utilization	U_f	%	93/93-98/1	O
Oxidant utilization	U_o	%	85/75-85/1	O
Fuel inlet temperature	T_f	K	823/783-823/1	O
Oxidant inlet temperature	T_o	K	973/973-1023/1	O
Compressor inlet temperature	T_1	K	288	S
Compressor pressure ratio	$\square_C$	-	3/1-15/1	O
HRSG steam outlet pressure	p_a	MPa	0.4/0.1-14/0.1	O
HRSG steam outlet pressure	t_a	°C	150	S
Maximum exergy overall efficiency	η_{exTPFC}	-	0.667	Optimization criteria
(*) S-standard (maksimum) values O-values obtained by optimization				

For determining the electrical and overall efficiency of the TPFC an exergy method is applied:

$$\eta_{exBCFC} = \frac{\Delta ex_{eTPFC} + \Delta ex_{tTPFC}}{exQ_d} = \frac{P_{eTPFC} + \Delta ex_{tTPFC}}{B_f \cdot e_d} \quad (1)$$

Where: change of exergy during the production of electrical energy Δex_{eTPFC} kW (values are very near to the electrical power P_{eTPFC} kW), change of exergy during the production of thermal power (heat) Δex_{tTPFC} kW, brought (inlet) exergy with the fuel exQ_d kW, specific exergy of the fuel e_d kJ/kg (for natural gas is equal to the LHV), total fuel consumption B_f kg/s.

The following general equation is used for determination the change of exergy Δex kW:

$$\Delta ex = m \cdot \left(\Delta h - T_o \cdot \Delta s\right) \quad (2)$$

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

Applying the exergy method in the calculations, results with values for change of exergy during the production of electrical energy which are very near with electrical power according the thermal method (low change of entropy). Significant differences appear in change exergy during the production of thermal energy (heat) compared with values obtained by thermal method (significant change of entropy). Values of the specific exergy of the gas fuels are very close to the LHV values.

Natural gas characteristics used in these power plants such as: composition, density and lower heat value (LHV) are equal to the applied in Macedonia (NG density 0.7 kg/m^3 and LHV = 33500 kJ/m^3) [12]-[14].

This approach is supported by many authors, such as Kotas [11], who works on the problem of modelling and calculation of modern energy systems.

C. Results from optimization and calculation of TCFC

Results (output data) obtained from the software package are shown in Table III. From the table III we can see that the electrical power of 4000 kW are receive in a modular SOFC with efficiency of 59.5 %. Part of that power of 300 kW is spent in the air compressor and the net electricity produced from TPFC is 3700 kW. Thermal power of HRSG from the gas side is 1500 kW and useful energy required for the building is 1250 kW.

Accordingly electrical efficiency is 59.5 % and the overall exergy efficiency of TCPFC is 66.7 %. Must say that the efficiency is remarkably high. The applications of these plants that achieve high overall efficiency 66.7% is a challenge for many authors and do in order approximation of efficiency to efficiency of fantastic Carnot cycle about 78 %.

Table III: Results – output data obtained from the calculation of TPFC:

Parameter	**Value**		
Fuel cells (SOFC)			
Air flow	m_a	kg/s	2.48
Gases flow	m_g	kg/s	2.61
Fuel consumption	B	kg/s	0.13
Fuel cells electrical power	P_{eFC}	kW	4000
Fuel cells electrical efficiency	η_{eFC}	-	0.595
Number of individual fuel cells/modules	$n_{iFC/}$ n_{mFC}	-	13092/2
Fuel cells area	A_{FC}	m^2	5.95
Fuel cells dimension	a/b/c	m/m/m	2/3/2.5
Fuel cells gases outlet temperature	t_4	°C	1041
Air compressor (C), HRSG and heat exchangers (HE)			
Air compressor power	P_C	kW	300
HRSG thermal power	Q_{tHRSG}	kW	1500
HRSG gases inlet temperature	t_5	°C	570
HRSG outlet (total) steam flow	m_s	kg/s	0.61
Heat consumer (HC) steam flow	m_{sHC}	kg/s	0.24
HE steam flow for heating/cooling (steam/water)	$m_{sH/C}$	kg/s	0.34
HE steam flow for sanitary hot water (steam/water)	m_{sSW}	kg/s	0,03
Three-generation power plant with SOFC (TPFC)			
TPFC electrical power	P_{eTPFC}	kW	3700
TPFC thermal power (thermal method)	Q_{tTPFC}	kW	1250
TPFC change of exergy during the production of heat	η_{exTPFC}	kW	450.4
TPFC overall exergy efficiency	η_{exTPFC}	-	0.667

Table IV: Comparison with TPFC and classic boiler on natural gas

Parameters			**TPFC**	**Boiler (NG)**
Fuel consumption	B_f	kg/s	0.13	0.03
Electrical power	P_e	kW	4000	-
Surplus of electrical power	P_{es}	kW	3600	-
Thermal power (HRSG/boiler)	Q_t	kW	1500	1500
Electrical efficiency	η_e	-	0.595	-
Overall exergy efficiency	η_{ex}	-	0.667	0.310/thermal 0.870

III. COMPARISON TPFC WITH CLASIC BOILER ON NATURAL GAS

To be able to present the perspective of TPFC comparison is made between TPFC and classic boiler on natural gas. Boiler facility have characteristics to meet thermal requirements of the building. Electrical energy provides by other sources of energy (electricity grid, diesel generator or others.). Results from a comparison are shown in Table IV.

From the table we can see that the required 1500 kW thermal power should be installed TPFC with total electric power of 4000 kW. Subtracting from the total electric power: 100 kW electrical power for the building and 300 kW for the air compressor results with 3600 kW net electrical power.

The natural gas boiler can only meet the heating load requirements but for the electrical power it is necessary to allocate funds.

IV. ECONOMIC ANALISYS – PROFITABILITY CALCULATION

Economic analysis is performed for this power plant which results are presented in the Table V. Can be concluded that the feasibility of installing these plants primarily depends on the price of natural gas, the specific cost of the plant, as well as interest rates and inflation.

By the end of the 2015-20 year the cost of fuel cells is expected to equal the price of other power plants, which states that the calculation of profitability would be more favorable [20]-[26].

Table V: Profitability calculation

	Variant 1: **With profit derived from heat**		**Variant 2:** **Without profit derived from heat**	
Hours	7000	h/god	7000	h/god
Price of electricity	0.137	$/kWh	0.137	$/kWh
Price of heat	0.144	$/kWh	0.144	$/kWh
Price of natural gas	0.88	$/kg	0.88	$/kg
Electrical power	4000	kW	4000	kW
Net electrical power (electricity)	3600	kW	3600	kW
Thermal power (heat)	1250	kW	0	kW
Fuel consumption	0,13	kg/s	0..13	kg/s
Power plant specific investment	2000	$/kW	2000	$/kW
Power plant investment	8000000	$	8000000	$
Total investment	20000000	$	20000000	$
Real interest	4.45	%	4.45	%
Profit (electricity)	3452400	$/god	3452400	$/god
Profit (heat)	1008000	$/god	0	$/god
Total profit	4460400	$/god	3452400	$/god
Fuel costs	2882880	$/god	2882880	$/god
Wage costs	14400	$/god	14400	$/god
Amortization	400000	$/god	400000	$/god
O&M costs	312228	$/god	241668	$/god
Other costs	120000	$/god	120000	$/god
Total costs	3729508	$/god	3658948	$/god
Simple payback	5.32	god	6.85	god
IRR	16.11	%	11.97	%

Considered are two variants of the calculation of profitability. The first variant is with the profits derived from thermal energy, i.e. in the case of requirement of thermal energy (heat) of the building would be purchased from another producer. The second variant is without the profits derived from thermal energy (heat), i.e. in the case of thermal energy building requirements would be generated in classic boiler on natural gas.

Simple payback period for first variant would have been 5.32 years and second variant 6.85 years. TPFC both variants makes a profit from the sale of surplus electricity, unlike use the classic boiler for thermal energy requirements of the building makes the only cost for buying fuel.

V. ECOLOGICAL ANALYSIS - ECOLOGICAL BENEFITS

For the determination of the emission of pollutants from TPFC will be used standard emission factors of different pollutants for different types of fuel. In Macedonia used emission factors per unit of burnt fuel. Emission factors used in our country in accordance with the EU emission factors proposed by the EPA [27], [28].

These emission factors for natural gas are shown in Table VI. For this purpose, a comparison is made with natural gas boiler that is used for thermal energy production and electricity is provided from the power grid. From the diagram in Fig. 3 can be seen that TPFC achieves 2.3 times less emissions of CO_2 and NO_x.

Table VI: TPFC emissions and specific emissions of CO_2 и NO_x

			CO_2	**NO_x**
Emission factor	E_f	g/MJ	55.9	0.06
Emission	E	g/s	347.78	0.37
Specific emission	e	g/kWh	313.00	0.34

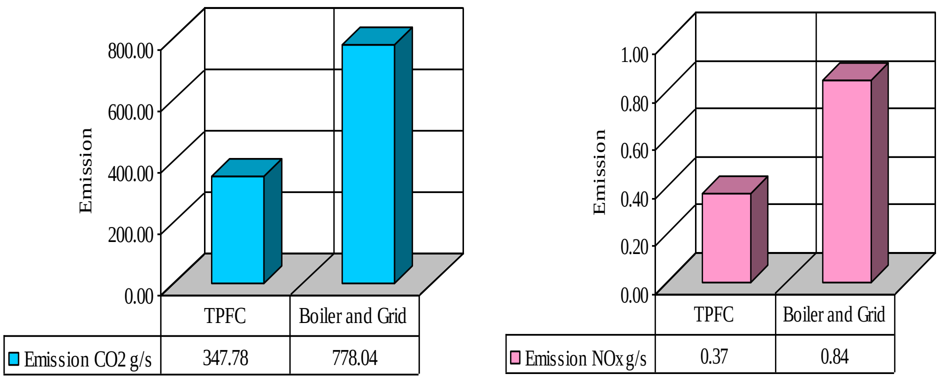

Fig.3: Comparison between TPFC and boiler on natural gas for production of thermal (heat) energy

VI. CONCLUSIONS

Based on what has been done it can be concluded that TPFC very practical can meet the electrical and thermal needs of a building, and always exists a chance of getting profit from the sale of surplus of electricity (presented example). These plants have a series of advantages:

- Three-generation power plant with high-temperature fuel cells achieve very high efficiency about 67 %
- Able to use any kind of fuel, and hydrogen
- Able to install for different power and be used as an independent source for production of electrical and thermal energy for complex building
- Fuel cells operate at constant parameters and uninterrupted supply the building with constant amount of electricity and heat
- The current status of fuel cells provides a relatively long lifetime up to 70 000 h.
- Emissions of pollutants is low, that they are environmentally friendly
- Fuel cell works completely silently, because there are no rotation parts.

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