

Performance comparison of two combined SOFC–gas turbine systems

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Abstract

A necessary step in the use of natural gas (methane) in solid oxide fuel cells (SOFCs) is its preliminary conversion to hydrogen and carbon monoxide. To perform methane conversion within fuel cells and avoid catalyst carbonization the molar ratio between methane and steam (or steam with carbon dioxide) should be 1:2 or higher at the SOFC inlet. In this article two possible technological approaches to provide this desirable ratio in a combined SOFC–gas turbine system are compared. The first approach involves generation of the required steam in the coupled gas turbine cycle. The second (which is more traditional) involves recycling some part of the exhaust gases around the anodes of the SOFC stack.

Exergy and energy analyses for the two SOFC–gas turbine systems are conducted to determine their efficiencies and capabilities to generate power at different rates of oxygen conductivity through the SOFC electrolyte (ion conductive membrane), as well as various efficiencies for natural gas conversion to electricity in the SOFC stack. It is determined that with a fixed SOFC stack the scheme with recycling has higher exergy and energy efficiencies (requiring less natural gas for a fixed electricity output) and the scheme with steam generation is associated with a higher capability for power generation. The question of which scheme permits a higher reduction in natural gas consumption (per unit of time), in the case of its implementation instead of a contemporary combined gas turbine–steam power cycle is considered. The greater capability of power generation while retaining high efficiency of fuel consumption in the scheme with steam generation makes its implementation more favorable. This scheme provides a better relative reduction in natural gas consumption (relative to the scheme with exhaust gas recycling) calculated per unit of time which reaches values of about 20%. At higher values of oxygen conductivity and efficiency of natural gas conversion to electricity in the SOFC stack this relative reduction becomes less significant, remaining in the range of 3–8%.

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1. Introduction

Despite the ability of solid oxide fuel cells (SOFCs) to generate electricity, their implementation in industry is more effective in combination with traditional gas turbines cycles [1]. In coupled gas turbine cycles, the exhaust gases from SOFCs are utilized, making the completeness of fuel conversion in the SOFC stack less essential. This coupling increases the power of the combined unit and decreases the size and the cost of the SOFC stack, which is a significant advantage today [2,3]. Dokiya [2] has reviewed the materials and fabrication methods used for the different cell components, discussed the performance of cells

fabricated using these materials, and surveyed the materials and processing efforts to reduce cell cost. Fontel et al. [3] show that the SOFC stack, system controls and power electronics are the major cost factors while the remaining equipment constitutes a minor share of the manufacturing cost. Many studies have investigated an optimal structure of SOFC–gas turbine systems employing an SOFC stack with a maximum efficiency. A performance analysis of a tubular SOFC–gas turbine system based on a quasi-two dimensional model is reported by Song et al. [4], who conclude that different system arrangements can influence significantly system performance. Kuchonthara et al. [5,6] investigate power generation systems using hydrogen and consisting of SOFCs and a gas turbine with steam and heat recuperation. The integration of steam recuperation is found to improve the overall efficiency and specific power of a SOFC–gas turbine combined system with a relatively compact SOFC component. Campanari [7] presents a mathematical model and detailed parametric

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Nomenclature

$\dot{a}, \dot{c}, \dot{n}$	molar flow rates (mol s^{-1})
\dot{E}_x	exergy flow rate (kJ s^{-1})
ex	specific exergy (kJ mol^{-1})
F	Faraday constant (C mol^{-1})
\dot{G}	natural gas consumption rate (mol s^{-1})
g	gas
h	specific enthalpy (kJ mol^{-1})
\dot{H}	enthalpy flow rate (kJ s^{-1})
N	number
P	pressure (atm)
q	specific heat (kJ mol^{-1})
s	specific entropy ($\text{kJ mol}^{-1}\text{K}^{-1}$)
\dot{S}	entropy flow rate ($\text{kJ s}^{-1}\text{K}^{-1}$)
SOFC	solid oxide fuel cell
T	temperature (K)
V	voltage (Volt)
w	specific work ($\text{kJ mol}^{-1} \text{CH}_4$)
\dot{W}	power (kW)

Greek symbols

α	molar fraction of recycled exhaust gases
β	relative reduction in natural gas consumption (%)
γ	fraction of oxygen which oxidizes the fuel yielding energy which is directly converted into electricity (%)
η	efficiency

Subscripts

Air	air
cmp	compressor
cmb	combustion products
D	exergy destruction
e	electrons
el	electrical
ex	exergy
i	index
in	input
j	index
max	maximum
min	minimum
out	output
Q	heat
t	turbine
0	reference environment

Superscripts

a	scheme a
Air	air
b	scheme b
cmb	combustion products
ex	exhaust gases
gt	gas turbine
i	index

in	input
j	index
LHV	lower heating value
out	output
r	recycle gases
0	reference environment

analysis of a SOFC stack with internal reforming of methane and discusses its design and integration with gas turbine cycles.

A necessary step when using natural gas (mainly methane) in SOFCs is its preliminary conversion to hydrogen and carbon monoxide. State-of-the-art Ni-YSZ (yttria-stabilized zirconia) anodes permit methane conversion directly on the anode surfaces (internal reforming), so that the electrochemical and reforming processes proceed simultaneously. Hengyong and Stimming [8] report that to perform methane conversion and avoid catalyst carbonization the molar ratio between methane and steam (or steam with carbon dioxide) should be 1:2 or higher at the SOFC inlet [8]. One way to provide this ratio involves recycling the exhaust gases around the anodes of the SOFC stack [1,3,4,7]. Another approach, proposed by the authors [9], is to produce the required steam in the coupled gas turbine cycle. The objective of this article is to conduct a numerical thermodynamic comparison of these two technical approaches for providing the appropriate methane to steam ratio taking into account the following criteria: exergy and energy efficiencies (η_{ex} , η) (electrical work produced per unit of exergy or energy of fuel supplied) and power \dot{W} (electrical work generated per unit of time). In the analysis the considered technical approaches are compared for fixed SOFC stacks with the equal exergy and energy efficiencies and electrical work generation capacities.

1.1. Description of systems

Two SOFC–gas turbine systems are presented in Fig. 1a and b. The initial stream of natural gas, after compression in device 5, heating in device 7 and mixing with steam in device 14 for scheme (a) or with exhaust gases for scheme (b), is directed to the anodes of the SOFC stack (device 1). There, two processes occur simultaneously: conversion of methane into a mixture of carbon monoxide and hydrogen on the surface of the anodes and electrochemical oxidation of the resultant mixture with oxygen. The oxidation reaction is accompanied by electricity generation in the SOFCs. The anode exhaust gaseous flow is directed to the combustion chamber (device 2), where the remainder of the conversion products combust with air.

For scheme (a) the water after pumping (device 11) is evaporated in device 9, superheated in a heat exchanger (device 8), mixed with methane in device 14 and directed to the anodes of the SOFC stack (device 1).

For scheme (b) the exhaust gaseous flow, which still contains fuel, from the anodes of the SOFC stack is divided by

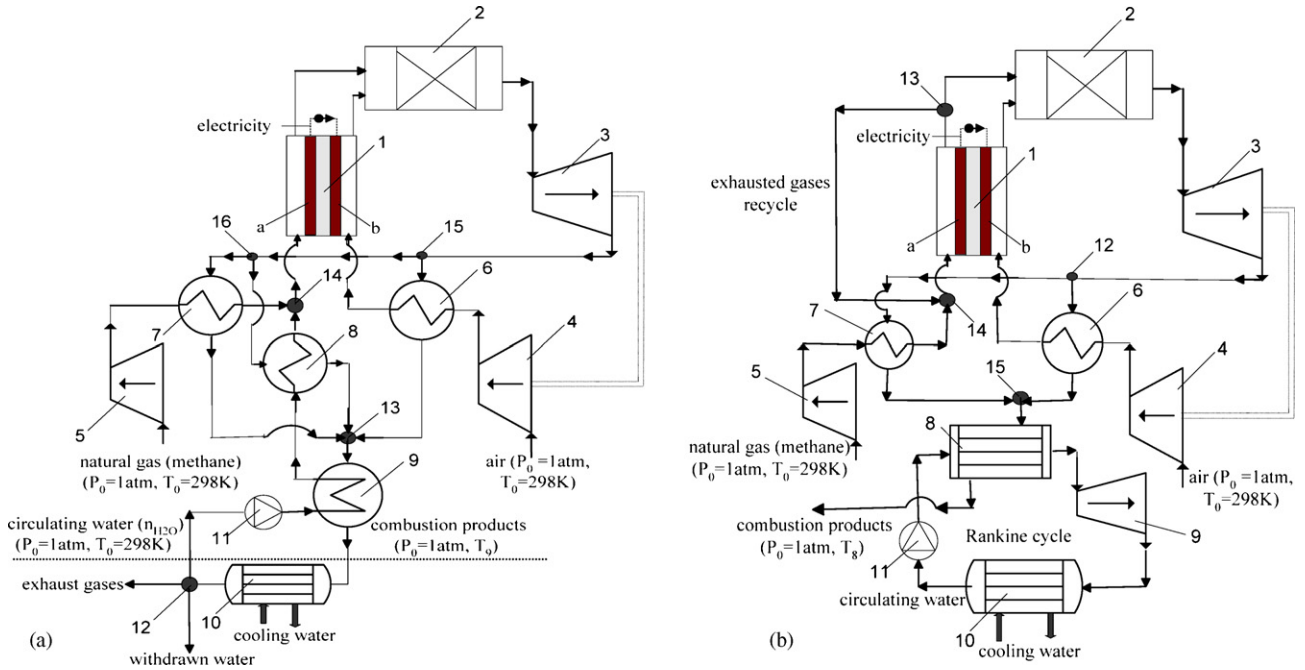


Fig. 1. Two combined SOFC–gas turbine systems: (a) with steam generation in the gas turbine cycle; (b) with a recycle of the exhaust gases around anodes of the SOFC stack. Numbers indicate devices, as follows: 1—SOFC stack; 2—combustion chamber; 3—turbine; 4 and 5—compressors; 6—recuperator; 7—fuel pre-heater; 8(a*)—steam superheater, 8(b)—water evaporator and superheater; 9(a)—evaporator; 9(b)—steam turbine; 10—condenser; 11—pump; 12(a)—separator; 12(b), 13(b), 15(a), 16(a)—flow divider valves; 13(a), 14(a and b), 15(b)—mixers; a and b—anode and cathode of SOFC stack, respectively. *Indexes in parentheses denote scheme a or b. The numbers without indexes in parentheses denote the same devices in both schemes.

a flow divider valve (device 13) into two flows. The first flow is directed to the combustion chamber (device 2) and the second is recycled and mixed with the input methane in device 14 and directed back to the anodes of the SOFC stack (device 1).

Air is compressed in device 4, heated in a recuperator (device 6), and directed to the cathodes of the SOFCs (device 1). In the SOFCs, oxygen is utilized, and oxygen-depleted air is heated, mixes with the remainder of the conversion products from the SOFC anodes and enters the combustion chamber (device 2). The combustion products expand in a turbine (device 3), and are divided for scheme (a) by the flow divider valves (devices 15 and 16) into three flows, and for scheme (b) into two flows (device 12). Then the flows are directed into three heat exchangers (devices 6, 7 and 8) for scheme (a) or into two heat exchangers (6 and 7) for scheme (b) where they heat the input flows of air, methane and water (scheme (a)) and air and methane (scheme (b)). Subsequently, all flows of combustion products are mixed again in device 13 (scheme (a)) or in device 15 (scheme (b)). Then the heat of the combined flow is employed to evaporate circulation water in device 9 (scheme (a)) or to produce electricity in the bottoming Rankine cycle (scheme (b)). The bottoming Rankine cycle consists of a water evaporator and superheater (device 8), steam turbine (device 9), condenser (device 10), and water pump (device 11).

For scheme (a) after the evaporator (device 9), the combustion products are cooled in a condenser (device 10) and then divided into the three parts in a separator (device 12): recycled and withdrawn water and exhaust gases.

1.2. Exergy analysis

A general schematic of the SOFC with internal reforming and recycling of part of the exhaust gases is presented in Fig. 2. During operation, a neutral molecule of oxygen takes four electrons from the porous cathode of the SOFC, depletes into negative charged ions, conducts through the electrolyte (ion-conductive membrane), returns electrons to the external circuit, and oxidizes the products of methane conversion (H_2 and CO) on the

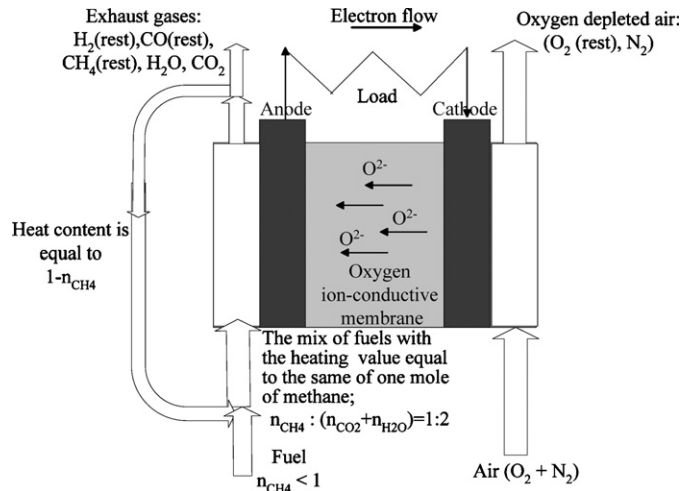


Fig. 2. Operation of a SOFC with recycle of exhaust gases and with internal methane reforming to hydrogen and carbon monoxide. The SOFC is drawn for a fuel load of 1 mol of methane.

anode surface. The recycle of the combustion products provides the necessary molar ratio of methane to the sum of steam and carbon dioxide at the inlets of the fuel cells, which is not lower than 1:2. This experimentally demonstrated minimum ratio [8] is required for reforming methane into hydrogen and carbon monoxide and avoiding carbon deposition on the porous anodes surfaces.

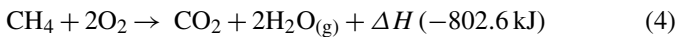
To compare the two schemes (Fig. 1a and b) the efficiencies of the SOFC stack are taken to be the same, meaning that at equal energy content of the inlet flows the same power is generated. The necessity to recycle some part of the combustion product flow for scheme Fig. 1b, normally containing a significant amount of combustible components, decreases the input methane flow. The input flow of methane for scheme Fig. 1b is determined by (i) the energy content of the recycled exhaust gases and (ii) the concentrations of steam and carbon dioxide in the total flow of exhaust gases. Then in line with Fig. 2 for scheme Fig. 1b the molar fraction of recycled exhausted gases α and the molar methane input flow rate $\dot{n}_{\text{CH}_4}^{\text{b}}$ are determined as follows:

$$\dot{n}_i^{\text{r}} = \alpha \dot{n}_i^{\text{ex}} \quad (1)$$

$$\frac{\dot{n}_{\text{CH}_4}^{\text{b}} + \dot{n}_{\text{CH}_4}^{\text{r}}}{\dot{n}_{\text{CO}_2}^{\text{r}} + \dot{n}_{\text{H}_2\text{O}}^{\text{r}}} = \frac{1}{2} \quad (2)$$

$$\dot{n}_{\text{CH}_4}^{\text{r}} q_{\text{CH}_4}^{\text{LHV}} + \dot{n}_{\text{CO}}^{\text{r}} q_{\text{CO}}^{\text{LHV}} + \dot{n}_{\text{H}_2}^{\text{r}} q_{\text{H}_2}^{\text{LHV}} + \dot{n}_{\text{CH}_4}^{\text{b}} q_{\text{CH}_4}^{\text{LHV}} = \dot{n}_{\text{CH}_4}^{\text{a}} q_{\text{CH}_4}^{\text{LHV}} \quad (3)$$

where $\dot{n}_{\text{CH}_4}^{\text{a}}$ is the molar methane input flow rate for scheme Fig. 1a; \dot{n}_i^{r} and \dot{n}_i^{ex} are the molar flow rates of components in the recycled and exhaust flows, respectively; and q_i^{LHV} is the lower heating value of the i -th component in the flows considered. The left side of Eq. (3) represents the sum of lower heating values of the combustible components in the recycled and input flows. The first and second equations account for the requirement for a specific ratio of methane to steam plus carbon dioxide in the SOFC inlet flow and the third equation is introduced to ensure the two presented schemes are compared for equal energy contents of the inlet flows. The lower heating value of methane is $q_{\text{CH}_4}^{\text{LHV}} = 802.6 \text{ kJ mol}^{-1}$, as defined by the oxidation reaction:



Analogously the lower heating values of hydrogen and carbon monoxide, respectively, are $q_{\text{H}_2}^{\text{LHV}} = 241.8 \text{ kJ mol}^{-1}$ and $q_{\text{CO}}^{\text{LHV}} = 283.0 \text{ kJ mol}^{-1}$.

The assumptions applied in the exergy analyses of the designs in Fig. 1 follow: (i) gases are modeled as ideal; (ii) energy losses due to mechanical friction are negligible; (iii) the work of the water pump is negligible compared to the work of the turbines and compressors; (iv) thermodynamic and chemical equilibria are achieved at the outlet of the SOFC stack; and (v) all combustible components are combusted completely in the combustion chamber. The fourth assumption is based on the fact that the catalytic conversion of methane to hydrogen and carbon

Table 1

Parameter values for the SOFC–gas turbine power generation systems

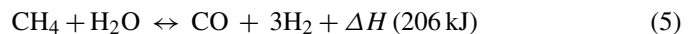
Parameter	Value
Isentropic efficiency of turbines η_t	0.93
Isentropic efficiency of compressors η_{cmp}	0.85
Minimum pressure in the gas turbine cycle P_{min} (atm)	1
Temperature at the turbine outlet T_3^{out} (K)	1023
Temperature of SOFC inlet streams T_1^{in} (K)	973
Standard temperature T_0 (K)	298
Standard pressure P_0 (atm)	1
Ratio of 1 mol of methane (scheme in Fig. 1a) or the combustible mixture with the heat content equal to that of 1 mol of methane (scheme in Fig. 1b) at the SOFC inlet to the moles of air	1:20
Air composition (volume percentage)	21% O ₂ , 79% N ₂

monoxide is faster than the electrochemical processes inside a fuel cell [10] and, therefore, the composition of the mixture at the anode outlet is close to the equilibrium one.

The parameters that characterize the combined power generation cycle and their values are listed in Table 1. Typical values of η_t and η_{cmp} are considered [11] and the temperature of gases at the SOFC inlet, based on values often cited in the literature, is taken to be 700 °C ($T_1^{\text{in}} = 973 \text{ K}$) [12]. The outlets temperature for the turbines (device 3 in Fig. 1) (T_3^{out}) are taken to be 1023 K to provide a temperature difference between the input and output flows in the heat exchangers (devices 6a, 7a, 8a, 6b and 7b) of 50 °C, which is generally acceptable for such heat exchange processes [13]. Since the temperature of the gaseous mixture decreases as it expands in the turbines, the temperatures at the turbine outlets define the pressure drop ($P_{\text{max}}/P_{\text{min}}$) in the gas turbine cycle.

1.3. Thermodynamic model of the SOFC stack

The efficiency of the SOFC stack can be defined by the following two parameters (related to the heat content of 1 mol of methane): the total molar flow rate of oxygen \dot{n}_{O_2} conducted through the electrolyte (ion-conductive membrane) and the fraction of the conducted oxygen flow γ which oxidizes the fuel yielding energy which is directly converted to electricity. The remainder is the oxygen flow which oxidizes the fuel, but where the released energy provides heating of the input flows of methane and air and drives the endothermic reforming of methane to hydrogen and carbon monoxide. This heat is related to the activation, ohmic and concentration losses. If the SOFC stack is included in the combined SOFC–gas turbine system these losses do not directly corresponded to the exergy losses (the loss in ability to produce electrical work) because this heat is employed in the gas turbine cycle and used to heat the input flows of fuel and air and drive the endothermic reactions of methane conversion to carbon monoxide and hydrogen:



For an adiabatic SOFC stack, the following energy balance can be written:

$$\Delta \dot{H} + \dot{W}_{el} = 0 \quad (7)$$

where \dot{W}_{el} denotes electrical power and $\Delta \dot{H}$ is the rate of the enthalpy change in the SOFC stack. The calculations are made for an input methane flow rate $\dot{n}_{CH_4}^a$ of 1 mol s^{-1} for the scheme in Fig. 1a. Since the efficiencies of the SOFC stack application are taken to be the same, the input flow rate of methane $\dot{n}_{CH_4}^b$ for the scheme in Fig. 1b is obtained by solving Eqs. (1)–(3). The electrical power \dot{W}_{el} is determined as a percentage of the energy flow rate equal to the flow rate of 1 mol of methane with lower heating value $q_{CH_4}^{LHV}$ in line with reaction (4) and by using the given values of \dot{n}_{O_2} and γ .

The enthalpy change is a function of temperatures T_1^{in} and T_1^{out} and the compositions of all the flows at the inlet and outlet of the SOFC stack:

$$\Delta \dot{H} = f(T_1^{in}, T_1^{out}, \text{composition}^{in}, \text{composition}^{out}) \quad (8)$$

Temperature T_1^{out} defines the composition of the methane conversion products (according to assumption (iv)), so that the solution of Eq. (8) gives the temperature at the SOFC outlet. Details on the thermodynamic calculations for the SOFC stack and the overall system are described in our previous papers [9,14]. The electrical power produced is related to the operational-circuit fuel cell voltage V_s as follows:

$$V_s = \frac{\dot{W}_{el}}{\dot{n}_{O_2} N_e F} \quad (9)$$

where \dot{n}_{O_2} is the molar flow rate of oxygen conducted through the electrolyte of the fuel cell, N_e the number of moles of electrons transmitted into a circuit chain by 1 mol of oxygen (which is 4), and F the Faraday constant (the charge of 1 mol of electrons).

1.4. Exergy balance of the overall systems

An exergy balance of a system permits the evaluation of the efficiency with which input fuel is utilized. For the power generation scheme with steam generation presented in Fig. 1a the exergy balance is considered for the part of the system above the dashed line, i.e., excluding the condenser and the separator (devices 10 and 12). This division implies that the thermal exergy of the combustion products transmitted to the cooling water in the condenser is not utilized in this system. For the scheme with the recycle (Fig. 1b) the temperature of the combustion products leaving the Rankine cycle is taken as equal to 100°C ($T_{cmb}^{out} = T_8 = 373 \text{ K}$) (this condition favors this scheme) and the efficiency of their exergy transformation into mechanical work to be 40% [15].

The exergy balance in the case when only mechanical and electrical works are produced is expressible for both cases as follows:

$$\Delta \dot{E}x = \sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \sum_j \dot{W}_j + \sum_j \dot{E}x_{D_j} \quad (10)$$

where $\sum \dot{E}x_{in}$ is the sum of the input exergy flow rates of methane, air and water for the scheme in Fig. 1a and methane and air for the scheme in Fig. 1b, at standard conditions (T_0, P_0). That is,

$$\dot{E}x_{in}^{CH_4} = \dot{n}_{CH_4}(h_{CH_4}(T_0) - T_0 s_{CH_4}(T_0, P_0)) \quad (11)$$

$$\dot{E}x_{in}^{Air} = \sum_i \dot{a}_i^{Air}(h_i^{Air}(T_0) - T_0 s_i^{Air}(T_0, P_i)) \quad (12)$$

$$\dot{E}x_{in}^{H_2O} = \dot{n}_{H_2O}(h_{H_2O}(T_0) - T_0 s_{H_2O}(T_0, P_0)) \quad (13)$$

Here, $\sum \dot{E}x_{out}$ is the exergy flow rate of the combustion products directed to the condenser (Fig. 1a) or leaving the Rankine cycle (Fig. 1b):

$$\sum \dot{E}x_{out} = \sum_i \dot{c}_i^{cmb}(h_i^{cmb}(T_{cmb}^{out}) - T_0 s_i^{cmb}(T_{cmb}^{out}, P_i)) \quad (14)$$

Also, $\sum_j \dot{W}_j$ is the sum of the power generated in the turbines and SOFCs, and consumed in the compressors (with a negative sign), and $\sum_j \dot{E}x_{D_j}$ denotes the rate of the exergy destruction in the system which is calculated as the sum of the rates of the exergy destructions in each of the system devices:

$$\dot{E}x_{D_j} = T_0 \Delta \dot{S}_j \quad (15)$$

Here, $\Delta \dot{S}_j$ is the entropy generation rate in the j -th device of the schemes considered, and \dot{a}_i^{Air} and \dot{c}_i^{cmb} denote the molar flow rates of the components constituting the flows of air (oxygen and nitrogen) and combustion products, P_i denote partial pressure, and h_i and s_i denote their specific enthalpies and entropies, respectively.

The two schemes are considered in order to compare their electrical work generation capacities (the efficiency of mechanical work conversion into electrical is higher than 97%) and exergy and energy efficiencies. It is seen from Eq. (10) that the power generated $\sum_j \dot{W}_j$ increases with increasing rate of the exergy change $\Delta \dot{E}x$ and with decreasing rate of the exergy destruction $\sum_j \dot{E}x_{D_j}$ in the system. The rate of the exergy change $\Delta \dot{E}x$ in the system at fixed input and output temperatures and pressures increases with increasing flow rate of methane \dot{n}_{CH_4} and, related to it, flow rates of air, water and combustion products (Eqs. (11)–(14)).

2. Results and discussion

The results of modeling the two considered systems are listed in Tables 2a and 2b. The input data are presented in Table 1 and in the first two columns in Tables 2a and 2b. The first column provides the molar flow rate of oxygen \dot{n}_{O_2} conducted through the electrolyte of the SOFC stack per mole of methane (Fig. 1a, Table 2a) or per the mixture of the combustible components with an energy content equal to that of 1 mol of methane (Fig. 1b, Table 2b). According to the basic principles of SOFC performance all oxygen conducted through the electrolyte is completely combusted in the anode compartments. Therefore, the total fuel energy or exergy consumed in the SOFC stack can be defined by the flow of oxygen conducted through the electrolyte \dot{n}_{O_2} (column 1 in Tables 2a and 2b). The second column

Table 2a
Operating parameters of the SOFC–gas turbine cycle for the system with steam generation (Fig. 1a)*

\dot{n}_{O_2} (mol s ⁻¹)	γ (%)	T_1^{out} (K)	T_2^{out} (K)	P_{max} (atm)	\dot{W}_{el} (kW)	$\sum_j \dot{W}_j$ (kW)	$\sum_j \dot{E}x_{D_j}$ (kJ s ⁻¹)	\dot{n}_{CH_4} (mol s ⁻¹)	\dot{n}_{H_2O} (mol s ⁻¹)	V_s (Volt)	η	η_{ex}
1.2	50	1147	1585	8.7	240.3	575.7	210.2	1	3.5	0.52	0.72	0.71
	65	1069	1523	7.0	312.4	600.4	190.5	1	3.0	0.675	0.75	0.74
	80	990	1457	5.5	384.8	625.5	170.0	1	2.5	0.83	0.78	0.77
1.4	50	1217	1551	7.7	280.5	589.5	199.3	1	3.2	0.52	0.73	0.72
	65	1127	1476	5.9	364.7	618.8	175.9	1	2.6	0.675	0.77	0.76
	80	1032	1395	4.4	448.8	648.6	151.2	1	2.0	0.83	0.81	0.80
1.6	50	1289	1516	6.8	320.7	603.3	188.4	1	2.9	0.52	0.75	0.74
	65	1188	1426	4.9	416.6	636.8	160.8	1	2.2	0.675	0.79	0.78
	80**	1078	1328	3.43	512.9	671.6	131.9	1	1.5	0.83	0.84	0.83

* \dot{n}_{O_2} is the molar flow rate of oxygen conducted through the electrolyte of the SOFC stack per mol of methane (scheme in Fig. 1a, Table 2a) or per the mixture of the combustible components with the energy content equal to that of 1 mol of methane (scheme in Fig. 1b, Table 2b), γ is the fraction of oxygen which oxidizes the fuel yielding energy which is directly converted to electricity in the SOFC stack, T_1^{out} , T_2^{out} are temperatures at the SOFC stack and combustion chamber outlets, respectively; P_{max} is the maximum pressure in the cycle; \dot{W}_{el} is the electric power generated in the SOFC stack; $\dot{E}x_q$ is the exergy flow rate of the heat transferred into the bottoming Rankine cycle; $\sum_j \dot{W}_j$ is the total power generated in the combined system; $\sum_j \dot{E}x_{D_j}$ is the total rate of exergy losses in the combined systems; \dot{n}_{CH_4} is the basic molar flow rate of methane consumed in the combined system upon which calculations are made; \dot{n}_{H_2O} is the molar flow rate of the pressurized steam; V_s is the operational circuit voltage of the SOFC stack; η , η_{ex} are the energy and exergy efficiencies of the scheme, respectively.

** These values are marked because the ratio of methane:steam equal to 1:2 or higher at the SOFC stack inlet is not maintained.

Table 2b
Operating parameters of the SOFC–gas turbine cycle for the system with recycling of combustion products (Fig. 1b)*

\dot{n}_{O_2} (mol s ⁻¹)	γ (%)	T_1^{out} (K)	T_2^{out} (K)	P_{max} (atm)	\dot{W}_{el} (kW)	$\dot{E}x_q$ (kJ s ⁻¹)	$\sum_j \dot{W}_j$ (kW)	$\sum_j \dot{E}x_{D_j}$ (kJ s ⁻¹)	\dot{n}_{CH_4} (mol s ⁻¹)	V_s (Volt)	η	η_{ex}
1.2	50	1202	1479	5.6	240.3	55.3	466.4	162.9	0.80	0.52	0.73	0.72
	65	1117	1396	4.2	312.4	38.5	494.9	134.4	0.80	0.675	0.77	0.76
	80	1030	1311	3.1	384.8	23.9	523.8	105.5	0.80	0.83	0.82	0.81
1.4	50	1262	1481	5.7	280.5	58.6	509.6	165.4	0.86	0.52	0.74	0.73
	65	1163	1384	4.1	364.7	38.9	542.6	132.3	0.86	0.675	0.79	0.78
	80	1063	1285	2.9	448.8	21.8	576.1	98.8	0.86	0.83	0.83	0.82
1.6	50	1323	1475	5.6	320.7	60.7	548.9	167.5	0.91	0.52	0.75	0.74
	65	1210	1364	3.8	416.6	38.1	586.6	129.8	0.91	0.675	0.80	0.79
	80	1097	1252	2.5	512.9	19.3	624.7	91.7	0.91	0.83	0.86	0.85

* Parameters are described in Table 2a.

relates to the efficiency of the fuel exergy or energy conversion to electricity in the fuel cells. The parameter γ identifies the fraction of oxygen which oxidizes the fuel yielding energy which is directly converted to electricity. The remainder is the oxygen which oxidizes the fuel, but where the released energy heats the input flows of methane and air and drives the endothermic methane reforming into hydrogen and carbon monoxide. When the SOFCs are the only source of electrical work, this heat corresponds to the activation, ohmic and concentration losses [1].

It can be seen in Tables 2a and 2b for equal values of \dot{n}_{O_2} and γ that the electrical power \dot{W}_{el} generated in the SOFC stack is the same for both schemes. This phenomenon occurs because the heat contents of the input fuel flows are equal under those conditions. However, the same capacities of electricity generation by the SOFC stacks are achieved at different input flow rates of methane, $\dot{n}_{CH_4}^a$ or $\dot{n}_{CH_4}^b$, for the entire schemes. This leads to different powers generated by the entire combined scheme, since $\dot{W} = \sum_j \dot{W}_j$. As can be seen in Fig. 3 the scheme with steam generation (Fig. 1a) yields more power \dot{W} .

The energy and exergy efficiencies η , η_{ex} of the combined systems are expressed as follows:

$$\eta^i = \frac{\sum_j \dot{W}_j^i}{\dot{n}_{CH_4}^i q_{CH_4}^{LHV}} = \frac{\dot{W}^i}{\dot{n}_{CH_4}^i q_{CH_4}^{LHV}} = \frac{w^i}{q_{CH_4}^{LHV}} \quad (16)$$

$$\eta_{ex}^i = \frac{\sum_j \dot{W}_j^i}{\dot{n}_{CH_4}^i ex_{CH_4}^0} = \frac{\dot{W}^i}{\dot{n}_{CH_4}^i ex_{CH_4}^0} = \frac{w^i}{ex_{CH_4}^0} \quad (17)$$

where index i denotes a for the scheme in Fig. 1a or b for the scheme in Fig. 1b, $\sum_j \dot{W}_j^i$ is the sum of electrical and mechanical power generated by the system, $\dot{n}_{CH_4}^i$ is the molar flow rate of methane consumed in the system (see Tables 2a and 2b), $q_{CH_4}^{LHV}$ is the lower heating value of methane ($802.6 \text{ kJ mol}^{-1}$), $ex_{CH_4}^0$ is the standard exergy of methane ($818.1 \text{ kJ mol}^{-1}$) and w^i is the work (electricity) produced per mole of methane consumed in the combined system. In the case when only electrical energy is generated in a system, it follows from Eqs. (16) and (17) that the energy and exergy efficiencies are very close to each other.

As can be seen in Fig. 4 the scheme with exhaust-gas recycle (Fig. 1b) yields more work w per mole of methane consumed and has the higher energy and exergy efficiencies (see Tables 2a and 2b) but lower power \dot{W} .

We now consider which scheme (Fig. 1a or b) permits a higher reduction in natural gas consumption (per unit time), $\Delta \dot{G}_{CH_4}^i$, in the case of its implementation instead of a contemporary combined gas turbine–steam cycle with its highest thermal efficiency of $\eta^{gt} \approx 0.55$:

$$\Delta \dot{G}_{CH_4}^i = \frac{\dot{W}^i}{Q_{CH_4}^{LHV}} \left(\frac{1}{\eta^{gt}} - \frac{1}{\eta^i} \right) \quad (18)$$

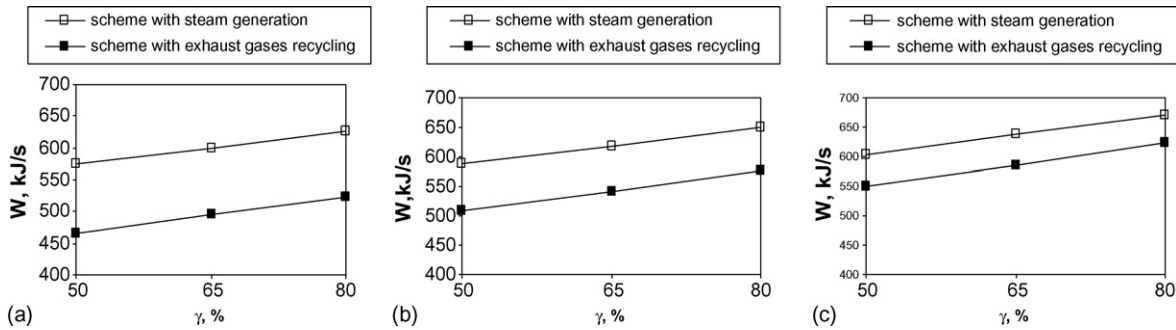


Fig. 3. The power generated in the two compared systems as a function of the fraction of oxygen γ which oxidizes the fuel yielding energy which is directly converted to electricity in the SOFC stack. The moles of oxygen \dot{n}_{O_2} conducted through the SOFC electrolyte per heating value of 1 mol of methane (scheme in Fig. 1a) or the mix of fuels with the heating value equal to 1 mol of methane (scheme in Fig. 1b) at the SOFC inlet: (a) 1.2 mol of oxygen; (b) 1.4 mol of oxygen; (c) 1.6 mol of oxygen.

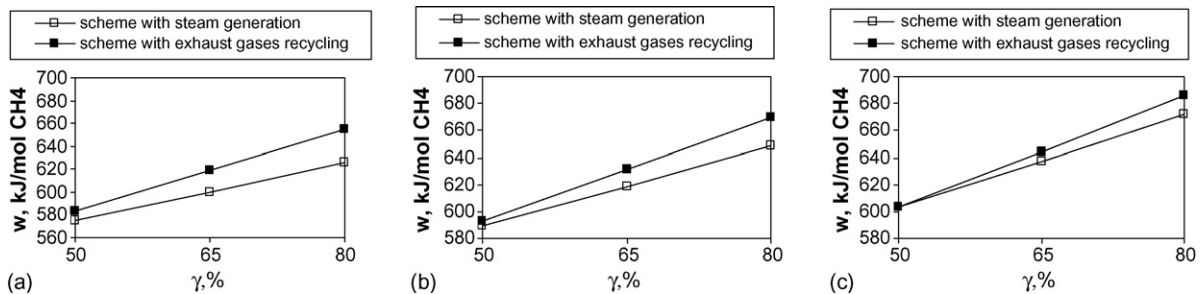


Fig. 4. The work w produced per mole of methane consumed in the two compared systems as a function of the fraction of oxygen γ which oxidizes the fuel yielding energy which is directly converted to electricity in the SOFC stack. The moles of oxygen \dot{n}_{O_2} conducted through the SOFC electrolyte per the heating value of 1 mol of methane (scheme in Fig. 1a) or the mix of fuels with the heating value equal to 1 mol of methane (scheme in Fig. 1b) at the SOFC inlet: (a) 1.2 mol of oxygen; (b) 1.4 mol of oxygen; (c) 1.6 mol of oxygen.

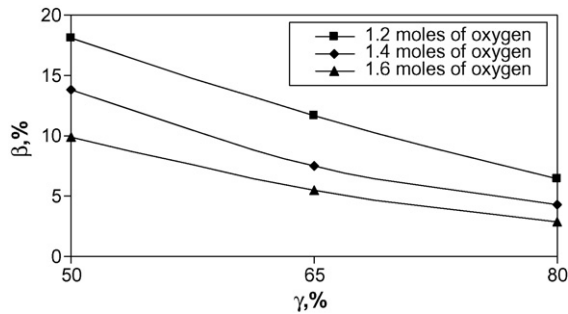


Fig. 5. The relative reduction in natural gas consumption β as a result of substitution of the scheme in Fig. 1b with the scheme in Fig. 1a as a function of the fraction γ of oxygen which oxidizes the fuel yielding energy which is directly converted to electricity in the SOFC stack at different oxygen conductivity values \dot{n}_{O_2} .

Here, i denotes a (scheme in Fig. 1a) or b (scheme in Fig. 1b), \dot{W}^i is the power and η^i is the energy efficiency. The relative reduction in fuel consumption in the scheme in Fig. 1a relative to the scheme in Fig. 1b β can be expressed as:

$$\beta = \frac{\Delta \dot{G}_{CH_4}^a - \Delta \dot{G}_{CH_4}^b}{\Delta \dot{G}_{CH_4}^b} \quad (19)$$

Expressing the power generated in the systems through their energy efficiencies in line with Eq. (16) we obtain the following relationship:

$$\frac{\dot{W}^a}{\dot{W}^b} = \frac{\dot{n}_{CH_4}^a \eta^a Q_{CH_4}^{LHV}}{\dot{n}_{CH_4}^b \eta^b Q_{CH_4}^{LHV}} = \frac{\dot{n}_{CH_4}^a \eta^a}{\dot{n}_{CH_4}^b \eta^b} \quad (20)$$

After substitution of Eq. (18) into Eq. (19) and taking into account Eq. (20) the following expression for β is derived:

$$\beta = \frac{\dot{n}_{CH_4}^a \eta^a / \eta^{gt} - 1 / \eta^a}{\dot{n}_{CH_4}^b \eta^b / \eta^{gt} - 1 / \eta^b} - 1 \quad (21)$$

Fig. 5 shows the relative reduction in fuel consumption β as a function of the fraction of oxygen γ associated with electricity generation. It can be seen from this figure that at lower values of γ and oxygen conductivity \dot{n}_{O_2} , the relative reduction in fuel consumption for the scheme in Fig. 1a compared to the scheme Fig. 1b can reach about 20%. At higher values of γ and oxygen conductivity \dot{n}_{O_2} , the difference in β becomes less significant, remaining in the range of 3–8%.

From a practical point of view, the use of the scheme in Fig. 1a instead of that in Fig. 1b allows generation of more power with the same SOFC stack but with some decrease in efficiency of the fuel energy conversion to electrical work.

3. Conclusions

When using natural gas in SOFCs, it is necessary first to convert it to hydrogen and carbon monoxide. For effective methane conversion and to avoid catalyst carbonization the molar ratio between methane and steam (or steam with carbon dioxide) should be 1:2 or higher at the SOFC inlet. In this article two possible technological approaches for providing this desirable ratio in combined SOFC–gas turbine systems are compared. The

first approach involves generation of the required steam in the coupled gas turbine cycle. The second approach (which is more traditional) involves recycling part of exhaust gases back to the SOFC stack.

It is determined that with a fixed SOFC stack the scheme with recycling has higher energy and exergy efficiencies (requiring less natural gas for a fixed electricity output) and the scheme with steam generation is associated with a higher capability of power generation. The question of which scheme permits a higher reduction in natural gas consumption (per unit of time), in the case of its implementation instead of a contemporary combined gas turbine–steam power cycle is considered. The greater capability of power generation while retaining high efficiency of fuel consumption in the scheme with steam generation makes its implementation more favorable. At lower values of oxygen conductivity \dot{n}_{O_2} and fraction of oxygen γ which oxidizes the fuel yielding energy which is directly converted to electricity in the SOFC, a relative reduction in natural gas consumption (relative to the scheme with exhaust gas recycling) calculated per unit of time reaches values of about 20%. At higher values of \dot{n}_{O_2} and γ in the SOFC stack (which corresponds to a much larger and more expensive SOFC stack) this reduction becomes less significant, remaining in the range of 3–8%. We conclude that when advanced SOFC–gas turbine systems replace a not substantial part of the gas turbine power generation capacity, the introduction of the scheme with steam generation (Fig. 1a) is more favorable.

Acknowledgements

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