

Method of Hydrogenous Fuel Usage to Increase the Efficiency in Tandem Diverse Temperature Oxidation System

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Abstract. This paper presents the results of estimation energy efficiency, the collation data of thermodynamic calculations and data on material balance for an assessment of electric and thermal components in considered ways to use convention products, performance enhancement in the tandem system containing the high-temperature fuel cell and the low-temperature fuel cell with full heat regeneration for hydrogenous fuel (CH₄). The overall effective efficiency ($\eta_{\Sigma ef}$, making full use of the recovered heat) considered tandem system depends on the efficiency of its constituent fuel cells. The overall effective efficiency of the tandem installation including the fuel converter, separating system, high-temperature oxidation system, and hydrogen disposal system in case of fuel use in the low-temperature fuel cell, is higher than for each of the fuel cell elements separately.

1 Introduction

An integrated approach to the task of creation the economic systems of power supply involves obtaining electricity and heat in systems with heat recovery, which will reduce losses and improve the reliability of the process of ensuring energy consumer [1].

Natural gas is currently the main energy resource in a global sense, and the cheapest source for hydrogen production [1,2], but the task of the active involvement of renewable energy, it becomes actual at the present moment [2-5]. Energy resource biomethane is of interest for autonomous energy supply and basic [3-8] in problems of urban civil engineering and municipal facilities [9-12]. Use for these purposes fuel cells, offering direct energy conversion supplied fuel into electrical energy, is a promising direction for the solution of such tasks [1,3-6,13].

Special equipment and arrangements of the fuel reforming and heat recovery process proposed in [14] solves the problem of the heat exchange, but it does not fully ensure the heat recovery due to its partial dissipation. However, even with the structural chain simplification, i.e. in the flow and reforming conditions and electrochemical reactions in a one system (in the fuel cell) ensuring the heat exchange conditions for the heat recovery [15] has some essential faults:

- non-equal anode thermal conditions due to the endoergic reaction input stream zone cool down;
- incomplete use of the fuel cell performance thermal component (emergence of the excess heat in the fuel cell exothermic reaction compared with the endothermic reforming requirements);

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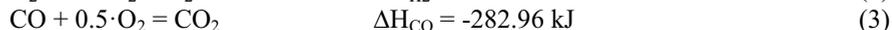
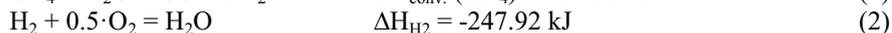
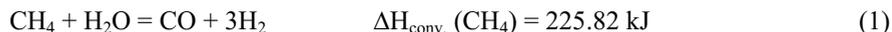
- CO oxidation on the anode is carried out under conditions of competing dynamic hindrance relating to the H₂ degrading on the same electrode.

The hydrogen produced by the reforming can be used directly in the low-temperature fuel cell (LTFC) to produce the electrical power or transferred to storage [16]. This requires CO and H₂ separation, which in the high-temperature conditions is achieved by pressure swing absorption [17,18] or by a hydrogen elicitation using the palladium membranes [19].

Construction solution concept of the heat exchange arrangement with several interaction types of reformer and fuel cell assemblage, considered by the US 7.008.711 [20], offers the possibility to use the thermal resource of the high-temperature fuel cell exothermic process in the better way.

2 Experimental studies

It is known that it is possible to produce the electric power by carrying-out the electrochemical change in the fuel cell using the hydrogenous fuel only if there is a fuel internal conversion that can take place in the high-temperature fuel cell, operating on the temperature range of 800 – 1200K (in this paper the process is considering at T = 1000K). Hydrogenous fuel (CH₄) reforming into a syngas (CO and H₂ mixture) within the said temperature range is an endothermic process (Eq. 1), and the further anode reaction of the hydrogen and carbon monoxide oxidation (Eq. 2,3) give an exothermic effect [21].



In the high-temperature conditions thermal component augments, therefore system performance depends on the heat efficiency.

Heating of the conversion agents to the required temperature and levelling of the endothermic conversion reaction input is a step-ahead solution for the high-temperature fuel cell performance thermal component use. In some cases, the thermal component implementation problem is solved by of hybrid systems installation paired by the heat engines [17,22,23], which certainly balances to a varying degree the use of heat, but only concerning the exergy, and thus results in the losses characteristic of every heat engine.

The object of the present invention is hydrogenous fuel estimation energy efficiency, the collation data of thermodynamic calculations and data on material balance for an assessment of electric and thermal components in considered ways to use convention products, performance enhancement in the tandem system containing the high-temperature fuel cell (HTFC) and the low-temperature fuel cell (LTFC) with full heat regeneration.

The fuel processing method according to the scheme [24] shown on the Figure 1 is carried out in the following way: hydrogenous fuel and the conversion agent flow to the converter (C) where at the T=800-1000K as the result of endothermic reactions (1) the syngas (gaseous mixture (CO + H₂)) is formed. The syngas is transferred from the converter to the separating system. In the separating system a part of H₂ (released H₂) is extracted from the incoming syngas by separating the incoming syngas stream into at least two outgoing streams: depleted gas mixture (CO and H₂), with the H₂ content depleted to the set level, and the H₂ stream, released from the initial syngas stream and transferred to the hydrogen disposal system.

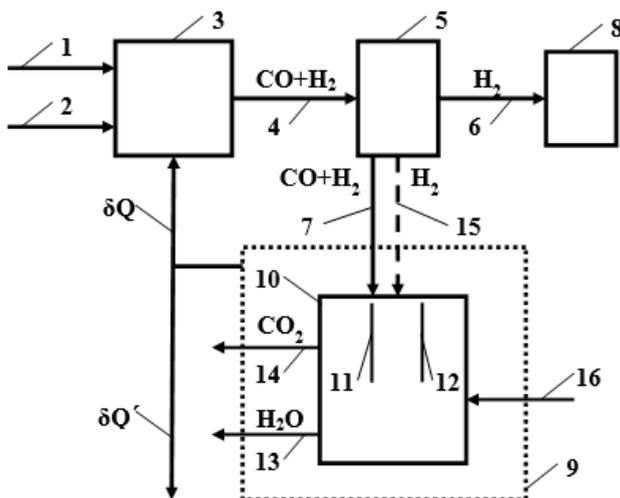


Figure 1. The fuel processing method: 1 – fuel; 2 – conversion agent; 3 – converter; 4 – syngas (CO and H₂); 5 – separating system; 6 – released H₂; 7 – depleted gas mixture (CO and H₂); 8 – hydrogen disposal system; 9 – high-temperature oxidation system (HTOS); 10 – high-temperature fuel cell (HTFC); 11 – fuel cell anode; 12 – fuel cell cathode; 13 – output streams H₂O 14 – output streams CO₂; 15 – separate stream of H₂; 16 – oxidizing gas mixture (e.g. oxygen or air oxygen).

The depleted gas mixture is transferred to the high-temperature oxidation system (HTOS), comprising high-temperature fuel cell (HTFC). In the high-temperature oxidation system, including the high-temperature fuel cell, the CO and H₂ are oxidized at the $T > T_{conv.}$. The hydrogen depleted gas stream is directed to the high-temperature fuel cell anode. To the high-temperature fuel cell cathode an oxidizing gas mixture (e.g. oxygen or air oxygen) is conducted. On the high-temperature fuel cell anode CO electrochemical oxidation takes place according to reaction:



H₂ electrochemical oxidation according to reaction:



with electric energy production (δQ) and emission of heat ($\delta Q'$).

The edges of the calculation are determined the values of the electric component η_{HTFC} and η_{LTFC} from 50 to 60%. Unattainable ideal limits the effectiveness for LTFC and HTFC equal to $\eta = 83\%$ (ideal) and $\eta = 73.2\%$ (ideal) respectively [21].

Table 1 presents data on the electrochemical oxidation heats (ΔH^{el}) required amount of H₂ in stages HTFC processes in accordance with the efficiency (η) of the fuel cell system under consideration tandem.

Heat transfer from the high-temperature fuel cell to the converter is carried out by way of heat and mass transfer, heat exchange, emission or their combinations. Part of the heat carried over by the output streams (H₂O, CO₂) is regenerated in the counter flow heat exchanger to heat the input streams [24] (Fig. 2).

At the high-temperature fuel cell output H₂O and CO₂ are formed as a result of the electrode reaction, which can be used as a conversion agent of the vapor and carbon dioxide conversion. It is suggested to use the solid oxide fuel cell or a molten-carbonate fuel cell or its combination as the high-temperature fuel cell with the anion conductance. The heat emitted in the process (δQ) is transferred to the converter. The amount of heat emitted in the high-temperature oxidation system during the CO and the specified H₂ amount oxidation reaction must be at least enough to maintain the prescribed temperature in the converter.

Table 1. Electrochemical oxidation heats of H₂ on stages of the process in HTFC and LTFC.

LTFC	$\eta=50\%$ ΔH^{el} [kJ]	$\eta=55\%$ ΔH^{el} [kJ]	$\eta=60\%$ ΔH^{el} [kJ]	$\eta=83\%$ (ideal) ΔH^{el} [kJ]
HTFC, $\eta=50\%$, $\alpha=0.29$				
CO (HTFC)	-141.5			
H ₂ (HTFC) 0.68 moles	-84.3			
H ₂ (LTFC) 2.32 moles	-331.5	-364.7	-397.8	-550.3
B=C-H	11.22			
HTFC, $\eta=55\%$, $\alpha=0.42$				
CO (HTFC)	-155.6			
H ₂ (HTFC) 0.88 moles	-120.0			
H ₂ (LTFC) 2.12 moles	-302.6	-332.8	-363.1	-502.3
B=C-H	12.73			
HTFC, $\eta=60\%$, $\alpha=0.61$				
CO (HTFC)	-169.8			
H ₂ (HTFC) 1.14 moles	-169.0			
H ₂ (LTFC) 1.86 moles	-266.4	-293.1	-319.7	-442.3
B=C-H	14.6			
HTFC, $\eta=73.2\%$ (ideal), $\alpha=3.04$				
CO (HTFC)	-207.1			
H ₂ (HTFC) 2.26 moles	-409.7			
H ₂ (LTFC) 0.74 moles	-106.1	-116.7	-127.4	-176.2
B=C-H	23.0			

B=C-H – heat balance cooling minus heating streams.

$\alpha = H_2(\text{HTFC})/H_2(\text{LTFC})$, depends only on the efficiency HTFC.

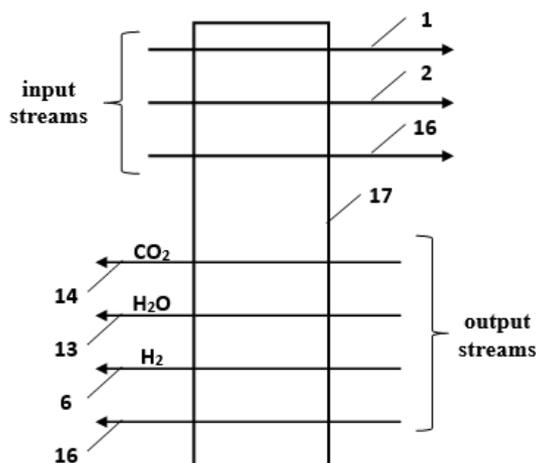


Figure 2. Counter flow heat exchanger scheme: 1 – fuel; 2 – conversion agent; released H₂; 13 – output streams H₂O; 14 – output streams CO₂; 16 – oxidizing gas mixture (e.g. oxygen or air oxygen); 17 – counter flow heat exchanger.

The heat from the hot gases released from the high-temperature oxidation system is transferred to the high-temperature oxidation system input oxidizer stream as well as to the carbon-containing fuel and the conversion agent at the converter input.

Adjusting of the amount of H_2 transferred to the high-temperature oxidation system can be done by way of H_2 extraction rate adjustment from syngas in the separating system. It is preferable to maintain the steady H_2 extraction rate from syngas in the separating system. Adjusting of the amount of H_2 transferred to the high-temperature oxidation system is performed by means of additional H_2 amount from the extracted part, which is transferred the high-temperature fuel cell either in a separate stream of or joining the depleted gas mixture stream (CO and H_2).

The amount of hydrogen directed to the high-temperature fuel cell must be at least enough to maintain the prescribed temperature in the converter by means of the heat emitted in the high-temperature oxidation system during the CO and the specified H_2 amount oxidation reaction. To raise the converter temperature, the amount of heat (δQ) transferred from the high-temperature oxidation system to the converter is increased by way of increasing the amount of the hydrogen fed to the high-temperature fuel cell. To lower the converter temperature accordingly the amount of heat (δQ) transferred from the high-temperature oxidation system to the converter is decreased by way of increasing the amount of the hydrogen fed to the high-temperature fuel cell. Thus in case of the small heat losses the heat (δQ) emitted in the high-temperature oxidation system is nearly fully absorbed by the endothermic reaction (1) in the converter.

Table 2 presents data per 1 mole of hydrogenous fuel (CH_4) on thermodynamic balance on thermal streams of heating initial substances and cooling reaction products

The H_2 share transferred to the high-temperature fuel cell after the separating system, which is the H_2 proportion in the syngas, is further characterized by the γ parameter – quantity of hydrogen moles (from the 1 mole of the hydrogenous fuel formed in the syngas according to reaction (1)) transferred to the high-temperature fuel cell. The γ value is defined by the high-temperature fuel cell coefficient of efficiency value. The higher is the high-temperature fuel cell coefficient of efficiency, the bigger is the prescribed γ for the converter temperature regulation. Increase of the heat leakage ($\delta Q'$) (through the heat insulation) as well as the heating of the input streams ($\delta Q'$) of the hydrogenous fuel, conversion agent and the oxidizer-rich gas results in the need for γ increase.

Table 2. Thermodynamic balance on thermal streams of heating initial substances and cooling reaction products.

Heating [kJ]		Cooling [kJ]		
HTFC	HTFC	HTFC	HTFC	C→LTFC
O_2/H_2	O_2/H_2	CO_2	H_2O	H_2
HTFC $\eta = 50\%$				
($\Delta = 0.3$)				
7.7	11.4	33.1	50.2	48.2
Σ heat. =131.2		Σ cool. =131.5		
HTFC $\eta = 55\%$				
($\Delta = 8.7$)				
10.0	11.4	33.1	65.2	44.0
Σ heat. =133.5		Σ cool. =142.2		
HTFC $\eta = 60\%$				
($\Delta = 19.3$)				
12.9	11.4	33.1	83.9	38.7
Σ heat. =136.4		Σ cool. =155.7		

When considering the data presented in Table 2, it should be borne in mind that:

heating 1 mole of fuel (CH_4) for the conversion (38.3 kJ) is it added to the calculation sum of expenses for heating (Σ heat.);

heating 1 mole of converting agent (H₂O) (73.8 kJ) is it added to the calculation sum of expenses for heating ($\Sigma\text{heat.}$);

$$\Delta = \Sigma\text{cool.} - \Sigma\text{heat.};$$

C→LTFC – heat flow from the converter to LTFC.

Table 3 based on the results of the calculations presented in Tables 1 and 2 shown the distribution of hydrogen produced by the conversion of (Eq. 1) is supplied to HTFC for expenses endothermic converter reaction and for input streams heating losses compensation, as well as the amount of hydrogen released (for LTFC), ignoring losses during the heat recovery for the compensation of losses of the amount of heat necessary for the input streams heating. For all considered values of efficiency HTFC there is a positive thermal balance and flow of H₂ in HTFC not required for input streams heating losses compensation [24].

Table 3. Distribution of H₂ on the electrochemical oxidation systems.

Efficiency HTFC, [%]	(γ) Amount of hydrogen, fed to HTFC, including:		Released hydrogen (LTFC)	
	For the converter reaction, [mol]	For input streams heating losses compensation, [mol]	[mol]	contained in the syngas, [%]
50	0.68	not required	2.32	77.3
55	0.88	not required	2.12	70.6
60	1.14	not required	1.86	62.1

The data analysis presented in Tables 1-3 shows that for all values considered HTFC efficiency observed positive heat balance, and feed H₂ HTFC not required to fill the heating expenses of input flows, as high temperature heat of the electrochemical oxidation of CO in HTFC enough to ensure expenses converter process. Oxidation of H₂ remained quantity in LTFC increases a contribution of useful work on this stage with growth of LTFC efficiency.

When the temperature of the conversion is reduced (lower than the minimal prescribed – 800K) the rate of H₂ extraction from the mixture is lowered, and when the temperature of the conversion raises (higher than the maximal prescribed – 1100K) it is increased. The amount of H₂ transferred to the high-temperature oxidation system is changed in the separating system using the selective membrane [19] (permeable for H₂ and impermeable for CO) or pressure swing absorption (PSA) [17] by way of adjusting the rate of H₂ extraction from the mixture. The rate of H₂ extraction is adjusted by changing the pressure swing on the membrane or by changing the frequency of cycles or the pressure swing in the PSA cycle. The amount of H₂ extracted from the mixture in the separating system is adjusted by adjusting its quantity and transferred to the high-temperature oxidation system.

To ensure the maximum methane fuel efficiency the hydrogen released from the separating system is transferred to the low-temperature fuel cell included in the hydrogen disposal system.

3 Results and discussion

Estimation of the effective efficiency tandem diverse temperature oxidation system was carried out in two ways: based on the Gibbs energy change (ΔG) stages helpful electrical work is done in a low-temperature fuel cells and high-temperature fuel cells [21] and heat balance burnt fuel (ΔQ) making full use of the recovered heat.

$$\eta(\Delta G) = \frac{\Delta G_{CO}(HTFC) + \gamma\Delta G_{H_2}(HTFC) + (3-\gamma)\Delta G_{H_2}(LTFC)}{\Delta H_{comb.CH_4}}, \quad (6)$$

where:

$\Delta G_{CO}(HTFC)$ – the Gibbs energy change oxidation reaction CO (Eq.3) in HTFC;

$\Delta G_{CO}(HTFC) = -196.6$ kJ;

$\Delta G_{H_2}(HTFC)$ – the Gibbs energy change oxidation reaction γ moles H_2 (Eq.2) in HTFC to repay the expenses of the endothermic reforming reaction;

$$\Delta G_{H_2}(HTFC) = -193.1 \text{ kJ};$$

$\Delta G_{H_2}(LTFC)$ – the Gibbs energy change oxidation reaction $(3 - \gamma)$ moles H_2 (Eq.2) in LTFC;

$$\Delta G_{H_2}(LTFC) = -237.3 \text{ kJ};$$

$\Delta H_{comb.CH_4}$ – heat combustion CH_4 in oxygen (Eq.7).

$$\Delta H_{comb.CH_4} = -800.9 \text{ kJ}.$$



In calculating the effective efficiency of the heat balance burnt fuel (ΔQ) (Eq. 8) it is believed that helpful work is all the heat except the water heat formation at $T = 300 \text{ K}$ in LTFC.

$$\eta(\Delta Q) = \frac{\Delta H_{comb.CH_4} - \Delta H_{form.H_2O(l)} \cdot (3 - \gamma) \cdot (1 - \eta^{el}(LTFC))}{\Delta H_{comb.CH_4}}, \quad (8)$$

where:

$\Delta H_{form.H_2O(l)}$ – liquid water heat formation (Eq. 2);

$$\Delta H_{form.H_2O(l)} = -241.81 \text{ kJ};$$

$\eta^{el}(LTFC)$ – electrical efficiency of LTFC;

$\frac{\Delta H_{form.H_2O(l)} \cdot (3 - \gamma) \cdot (1 - \eta^{el}(LTFC))}{\Delta H_{comb.CH_4}}$ – the amount of non-convertible heat.

Table 4 presents data on the effective values of the efficiency of the tandem and multi-temperature oxidation system. The edges of the calculation are determined the values of the electric component η_{HTFC} and η_{LTFC} from 50% to 60%.

Table 4. The overall effective efficiency ($\eta_{\Sigma ef}$) tandem diverse temperature oxidation system.

HTFC	LTFC			
	$\eta=50\%, \alpha=0.293$		$\eta=60\%, \alpha=0.604$	
	0.68 moles H_2 (HTFC) 2.32 moles H_2 (LTFC)		1.13 moles H_2 (HTFC) 1.87 moles H_2 (LTFC)	
	based on ΔG	based on ΔQ	based on ΔG	based on ΔQ
	$\eta_{\Sigma ef} [\%]$	$\eta_{\Sigma ef} [\%]$	$\eta_{\Sigma ef} [\%]$	$\eta_{\Sigma ef} [\%]$
$\eta = 50\%$	61.7	63.3	68.5	69.7
$\eta = 60\%$	69.1	70.6	74.6	75.8

Considering the data presented in Table 4, it should be noted that the overall effective efficiency ($\eta_{\Sigma ef}$, making full use of the recovered heat) considered tandem system depends on the efficiency of its constituent fuel cells.

When $\eta_{HTFC} = 50\%$ the overall effective efficiency ($\eta_{\Sigma ef}$) increases from 61% to 69% (making full use of the recovered heat). Step CO oxidation in HTFC contributes ~ 15% into helpful work, H_2 oxidation step in HTFC ~ 9%, H_2 oxidation step in LTFC ~ 37% to 45% (depending on the efficiency of LTFC). When $\eta_{HTFC} = 60\%$ the overall effective efficiency ($\eta_{\Sigma ef}$) increases from 69% to 75% (making full use of the recovered heat). Step CO oxidation in HTFC contributes ~ 19% into helpful work, H_2 oxidation step in HTFC ~ 19%, H_2 oxidation step in LTFC ~ 31% to 37% (depending on the efficiency of LTFC).

Integrated approach addressing this issue involves getting electricity and heat in the area of consumption, which will reduce losses and improve the reliability of power supply. Thus, the appropriateness of hydrogen production from organic waste, followed by its usage for production of electrical energy and heat may be implemented in the considered approach.

4 Conclusions

1. With the η_{HTFC} growth, the amount of hydrogen transferred to the high-temperature fuel cell to compensate the losses of the endothermic reaction in the converter increases and accordingly the amount of hydrogen transferred to the high-temperature fuel cell to compensate the losses connected with the input streams heating decreases. The additional hydrogen for the compensation of the losses connected with the input streams heating in the high-temperature fuel cell is not necessary for all the considered η_{HTFC} values.
2. With the η_{LTFC} growth when burning the H_2 moles left the useful yield (ΔG) contribution of this stage increases, and $\eta_{\Sigma\text{ef}}$ rises.
3. To compensate the losses connected with the input streams heating in the high-temperature fuel cell it is required to transfer additional hydrogen, and the heat emitted during its burning quenches the cold input streams heating creating positive heat balance.
4. The overall electric efficiency of the tandem installation including the fuel converter, separating system, high-temperature oxidation system, and hydrogen disposal system in case of fuel use in the low-temperature fuel cell, is higher than for each of the fuel cell elements separately.
5. The suggested solution based on the preliminary conversion out of the high-temperature fuel cell eliminates the high-temperature fuel cell input section cooling by the endothermic reaction, which is one of the most important reasons for the direct fuel-fired high-temperature fuel cell accelerated degradation.

References

1. D.O. Dunikov, V.I. Borzenko, S.P. Malysenko, D.V. Blinov, A.N. Kazakov, *Teploenergetika [Thermal Engineering]*, **60(3)**, 202-211 (2013)
2. S.P. Malysenko, O.V. Nazarova, Yu.A. Sarymov, *Atomic hydrogen energy and technology*, **7**, 105-126 (1986)
3. G. Gahleitner, *International Journal of Hydrogen Energy*, **38(5)**, 2039-2061 (2013)
4. A.N. Chusov, M.Yu. Zubkova, V.V. Korablev, V.I. Maslikov, D.V. Molodtsov, *St. Petersburg State Polytechnical University Journal*, **4-1(183)**, 78-85 (2013)
5. M.Yu. Zubkova, V.I. Maslikov, D.V. Molodtsov, A.N. Chusov, *Advanced Materials Research*, **941-944**, 2107-2111 (2014)
6. M.Yu. Zubkova, V.I. Maslikov, D.V. Molodtsov, A.N. Chusov, *Applied Mechanics and Materials*, **587-589**, 330-337 (2014)
7. V.V. Zhazhkov, M.Yu. Zubkova, V.I. Maslikov, D.V. Molodtsov, A.N. Chusov, D.V. Semenenko, *Applied Mechanics and Materials*, **725-726**, 1602-1607 (2015)
8. R. Chaubey, S. Sahu, O.O. James, S. Maity, *Renewable and Sustainable Energy Reviews*, **23**, 443-462 (2013)
9. V.V. Okrepilov, M.V. Leonidovich, *Asian Social Science*, **11 (7)**, 312-325 (2015)
10. N.I. Vatin, A.S. Gorshkov, D.V. Nemova, A.A. Staritsyna, D.S. Tarasova, *Advanced Materials Research*, **941-944**, 905-920 (2014)
11. V.V. Okrepilov, V.L. Makarov, A.R. Bakhtizin, S.N. Kuzmina, *Economy of Region*, **2**, 301-313 (2015)
12. R. Kamnik, B. Kovačić, B. Pribicević, A. Đapo, *Geodetski List*, **69 (3)**, 171-188 (2015)
13. S. Giddey, F.T. Ciacchi, S.P.S. Badwal, *Ionics*, **11**, 1-10 (2005)

14. U. Bossel, inventor; Asea Brown Boveri Ltd., assignee. Device for conversion of chemical energy from hydrocarbons into electric energy by an electrochemical high-temperature process. United States patent US 5,079,105 (January 7, 1992)
15. B.G. Keefer, M.L. Babicki, M.H. Kirby, inventors; QuestAir Technologies Inc., assignee. Enhanced solid oxide fuel cell systems. United States patent US 7,285,350 (October 23, 2007)
16. R.A. Geisbrecht, M.C. Williams, inventors; The United States of America as represented by the Department of Energy, assignee. Fuel cell-fuel cell hybrid system. United States patent US 6,623,880 (September 23, 2003)
17. B.G. Keefer, inventor; QuestAir Technologies Inc., assignee. High temperature fuel cell power plant. United States patent US 7,097,925 (August 29, 2006)
18. B.G. Keefer, D.J. Connor, C.F. Hunter, inventors; QuestAir Technologies Inc., assignee. Energy efficient gas separation for fuel cells. United States patent US 7,087,331 (August 8, 2006)
19. A.I. Livshits, *Proc. Reports. 4-th Russian Conference "Physical Problems of Hydrogen Energy"*, 1-3 (2007)
20. J.M. Pondo, D.J. Goodwin, C.P. Sishla, J. Randy, R.J. Remick, inventors; Gas Technology Institute, assignee. Thermally integrated fuel cell power system. United States patent US 7,008,711 (March 7, 2006)
21. A.A. Stroganov, M.U. Zubkova, *Ivanovo: XVI International conference "Chemical Thermodynamic in Russia (RCCT 2007)" and X International conference "Problems Solvatic Complex Formation in Solution"*, II, 382-384 (2007)
22. P.L. Micheli, M.C. Williams, F.A. Sudhoff, inventors; The United States of America as represented by the United States Department of Energy, assignee. Indirect-fired gas turbine dual fuel cell power cycle. United States patent US 5,541,014 (July 30, 1996)
23. M.J. Skowronski, inventor; Southern California Edison Company, assignee. Power generation system utilizing turbine and fuel cell. United States patent US 5,811,201 (September 22, 1998)
24. A.A. Stroganov, M.Yu. Zubkova, inventors and assignee. Carbon-bearing fuel use in the system containing the high-temperature fuel cell. Russian Federation patent 2475899 RU (February 20, 2013)