Acta Montanistica Slovaca
ISSN 1335-1788
actamont.tuke.sk

Fuel cells – converting ethanol chemical energy into electricity

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Funding information:
The author (M. Rabe) express their gratitude to the project titled "Cluster for innovative energy" in the frame of the program "HORIZON-MSCA-2022-SE-01" under the grant agreement number 101129820. The study was co-financed by the Minister of Science under the "Regional Excellence Initiative".

How to cite this article:
Gawlik, A., Sobociński, M., Tapczewski, J., Rabe, M., Katarzyna, W., Śniegowski, M. and Łopatka, A. (2024). Fuel cells – converting ethanol chemical energy into electricity. *Acta Monstanistica Slovaca*, Volume 29 (2), 286-293

DOI:
https://doi.org/10.46544/AMS.v29i2.05

Abstract
The growing demand for stable energy sources related to today's armed conflicts and increasingly frequent natural disasters related to the ongoing climate change has increased interest in alternative sources of electricity. This research aimed to compare different concentrations/types of ethanol in the process of converting chemical energy into electric current using fuel cells. It was found that fuel cells can be used as an emergency energy source. The highest efficiency was obtained with the use of low concentrations of alcohol, between 5 and 10 %. The highest cell power was obtained using denatured alcohol (168.9 mW).

Keywords
Fuel cells, ethanol, electrical energy

Introduction

The irreversible depletion of the world's hydrocarbon reserves, the rising price of energy carriers, and environmental pollution problems force most developed countries to develop energy strategies aimed at developing alternative energy (Štreimikienė, 2021; Štreimikienė, 2022; Makarenko et al. 2023; Mukarati et al. 2023; Mukhtarov et al. 2024; Obagbuwa and Munhzhelele, 2024). Conventional energy has already ceased to be a reliable source of electricity generation, which can fully satisfy the needs of both industrial and household consumers (Mukhtarov et al., 2023; Tarczynski et al. 2023; Taher, 2024; Štreimikienė, 2024).

In today's times of growing energy demand, it is crucial to find an adequate and stable supply of electricity (Roscher et al., 2022; Kuzior et al., 2023; Sitenko et al., 2023). Rising electricity prices related to the armed conflict in Eastern Europe have increased the demand for electricity in that region. Fuel cells are one of the most effective technologies for converting chemical energy into electricity, which can be used in situations of temporary lack of stable supply (Tronstad et al. 2017). They are adapted for quick use in emergency situations, powering a specific technical device, quickly charging an electricity storage, or simply being used as an emergency energy source. Their achievable high efficiency makes them ideal for use for military-defense purposes and for civilian use (Chang et al. 2023). Basic fuel cells use ethanol to produce electricity. Many studies indicate the possibility of using lower alcohols, which means that their use can be economically beneficial and possible in field conditions (Liu et al., 2022). It is these specific features of fuel cells that make them increasingly popular, especially in times of critical energy demand (Fu et al. 2022).

The way such a cell works is based on the movement of electrons in a fixed circuit from the anode to the cathode. Ion transport depends largely on the type of cell (Samsudin et al. 2019). The principle of operation is based on positive or negative ions transferred in the form of a passage through a membrane made of a specific material, thus closing the entire circuit (Hren et al. 2021). It is possible to use the so-called cation exchange membrane, otherwise known as AEM, which is used to exchange positive cations. In the case of negative anion charges, anion exchange membranes are used, referred to as AEMs. These solutions are used in the so-called AFC alkaline fuel cell technology (Deborah et al., 2023). These are cells with the possible use of alcohol as the primary fuel for power and electricity production. A particularly important fact of this type of cell is the possibility of using the so-called catalysts made of base metals, which is associated with lower construction costs. Materials such as manganese, iron, nickel or cobalt, can be distinguished here, which can be used as building materials for electrocatalysts (Priya et al. 2024).

Direct Alcohol Fuel Cells (DAFC) are gaining popularity. This is mainly due to the higher efficiency of such cells compared to other types (Zakil et al. 2016). The operation of such a cell is based on the direct conversion of the chemical energy contained in alcohol into electrical energy and its possible rapid use. Two separate groups of cells can be distinguished here: DMFC and DEFC (Kamarudin et al. 2013).

The first is Direct Methanol Fuel Cells. The fuel conversion process occurs at the fuel cell's anode (Hou et al. 2024). This is a particularly attractive technological solution for the transport sector due to a safer solution than hydrogen-air cells, especially in zones with increased vibrations that may cause pressure changes (Liang et al. 2024). The only limitation that this type of fuel cell faces is the need to use precious metals to build the anode. According to many studies, the use of platinum as a material catalyzing methanol for electricity is crucial in achieving the acceptable efficiency of such fuel cells (Vecchio et al. 2023). This is related to obtaining the appropriate reactivity of this element in the conversion of methanol to electricity and its long durability, which in turn allows for the effective use of such cells for a long time (Bhunia et al. 2023).

The second, more popular type of cells directly converting alcohol into electricity are the so-called DEFC cells, i.e. Direct Ethanol Fuel Cells. The principle of operation is similar to the previously presented type, with the difference of the fuel used to generate energy, which is ethanol (Wnuk et al. 2020). This fuel is a non-toxic substance that is relatively easy to obtain, for example, through microorganisms using sugar-rich biomass. This is currently the most promising technological solution due to the significantly lower price of obtaining such fuel than in the case of methanol or hydrogen. In addition, their low weight, simple design, and relatively high efficiency compared to other fuel cells significantly affect the attractiveness of this type of solution (Irazoque et al., 2024). It is also worth mentioning that ethanol transport or storage conditions are much easier to ensure, which can be crucial, depending on where it is used as an emergency power source (Reddy et al., 2023). Due to the need to put a lot of energy into breaking the chemical chain of ethanol in order to achieve its full decomposition, it is necessary to use high-quality reaction catalysts (Antolini, 2009).

However, the highest conversion efficiency of ethyl alcohol is shown by elements from the periodic groups of platinum group metals, i.e. platinum or its cheaper counterpart, palladium (Chen et al. 2015). Palladium, like platinum, is a good dissociative material for organic compound molecules in the process of alcohol conversion and is relatively cheaper to obtain than platinum. This element shows extremely high activity and supports electron transport during the reaction. This is particularly important because it directly affects the efficiency of the entire cell. In addition, palladium exhibits very durable properties that can ensure a very long operation of such cells (Souza et al., 2020). The complete conversion of an ethylene alcohol molecule requires the release of 12 electrons, which in turn breaks the chemical bond between the two carbon molecules. This means that it can be passed through the so-called polymer-electrolyte membranes, i.e. EMF. This impacts the amount of financial contribution necessary if production were to be used on a larger scale (Ikuma et al., 2023).

The key issue is also the possibility of using different concentrations of ethylene alcohol in the generation of electricity using such cells (Rousseau et al. 2006). The ability to adjust the appropriate concentrations of ethyl alcohol is important in terms of achieving optimal electricity production. This allows for the reduction of the cost of obtaining fuel and extends the operating time of the cell while maintaining the high efficiency of the device (Sorensen et al. 2018).

This study aimed to compare different concentrations of ethanol from different origins in the process of converting chemical energy into electric current using fuel cells.

Material and methods of the research

A measuring station was prepared to conduct the experiment (Fig. 1). Before performing the experiment, the ethanol cell was rinsed with demineralized water to remove possible contaminants.

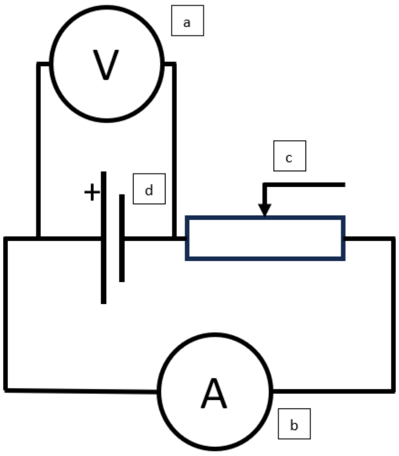

Fig. 1. Diagram of a test stand with a fuel cell a-voltmeter, b-ammeter, c-potentiometer, d-fuel cell. Source: Own study

A fuel cell powered directly by Horizon FCJJ-42 alcohol was used for the measurements. To determine the current, the Metex DG-Scope 20 MHz multimeter with a measurement accuracy of ± 0.001 mA was used, and for voltage measurements, the UNIT UT 531 multimeter with a measurement accuracy of ± 0.001 mV.

The experiment consisted of determining the current-voltage characteristics of a cell using three different types of ethanol: food vodka, laboratory ethanol and denatured alcohol. The fuels were mixed with distilled water to obtain mixtures of 5, 10, 15 and 20% ethanol by mass. Using a potentiometer, the resistance values were changed in the range from 0 to 100 Ω. After the values indicated by the meters stabilized, the measurements were recorded, and the resistance value was changed by 10 Ω, and another measurement was made after the results stabilized. After the last measurement, the resistance value of which was 100 Ω, an open circuit was created. When the measurements indicated by both meters stabilized, the measurements for the open circuit were recorded, and then the short-circuit current was measured after the reading stabilized. After all the readings in the sample, a mixture was created with an ethanol content 5% higher than the previous one. The cell was flushed with demineralized water to remove fuel from the previous test. The tank was filled with a new mixture, and measurements were made for the new mixture in the same way. After conducting experiments, the results were developed. A current-voltage characteristic was created, which was presented in the form of polynomial diagrams, and a statistical analysis of the results was performed using the Statistica program.

Results and discussion

The current-voltage characteristics for the mixture of fuel made from vodka and demineralized water (Fig. 1) in different proportions showed different results. The 5% mixture showed the fastest voltage drop with a slight increase in current. Subsequent mixtures were characterized by a slower voltage drop with resistance changes and a faster increase in intensity. A relatively long voltage drop was characterized by the 20% mixture, with these changes being the least different from the 15% mixture.

Tab. 1. Results for a mixture of vodka and demineralized water.

R [Ω]	5%			10%			15%			20%		
	U [mV]	I [mA]	P [mW]	U [mV]	I [mA]	P [mW]	U [mV]	I [mA]	P [mW]	U [mV]	I [mA]	P [mW]
0	0,8	3,14	2,512	1,1	4,68	5,148	1,3	5,23	6,799	1,3	5,51	7,163
10	3,3	3,05	10,065	5,1	4,68	23,868	5,9	5,22	30,798	6	5,3	31,8
20	7,6	2,93	22,268	11	4,22	46,42	14,8	4,67	69,116	13,3	4,97	66,101
30	11,9	2,83	33,677	16,9	3,96	66,924	19,6	4,5	88,2	20,5	4,65	95,325
40	16,6	2,77	45,982	22,7	3,79	86,033	25,9	4,26	110,334	27,5	4,34	119,35
50	20,9	2,73	57,057	27,4	3,59	98,366	32	3,77	120,64	33	4,06	133,98
60	24,8	2,72	67,456	30,4	3,28	99,712	36,1	3,54	127,794	36,3	3,75	136,125
70	29,2	2,72	79,424	33,6	3,08	103,488	36,7	3,25	119,275	39,5	3,49	137,855
80	32,4	2,72	88,128	37,3	2,96	110,408	38,7	3,08	119,196	41,1	3,18	130,698
90	36,7	2,68	98,356	39,4	2,85	112,29	40,3	2,82	113,646	43,3	2,98	129,034
100	35,7	2,55	91,035	39,6	2,76	109,296	40,2	2,76	110,952	42,8	2,91	124,548
Open circuit	149,9	0	0	150,2	0	0	146,5	0	0	143,3	0	0
Short-circuit current	1	4,55	4,55	1,2	5,18	6,216	1,2	5,44	6,528	1,2	5,33	6,396

Source: Own study

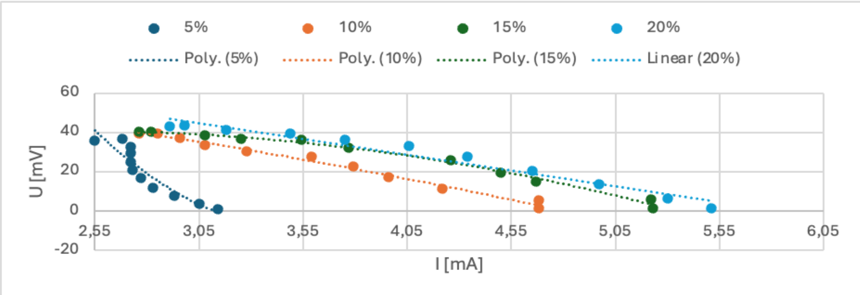

Fig. 2. Current-voltage characteristics for the vodka mixture (40%) + water in the proportions: 5, 10, 15 and 20%. Source: Own study

The fuel mixture, which consisted of laboratory ethanol and demineralized water (Figure 2), achieved the highest voltage and current readings at 10% of the mixture, but the mixture had a rapid voltage drop after reaching this point. The slowest voltage drop was characterized by a mixture of 20% with a simultaneous high-intensity value (6.35 mA). The 15% mixture was characterized by an almost linear voltage and current drop. The mixture in which the decrease of both values was the fastest was the 5% mixture. Saisirat and Joommanee (2018), in a study on an ethanol cell, used ethanol diluted to 5% and 15%, respectively, and obtained average intensity values of 231.738 mA for 5% and 695.214 mA for 15% and voltages: 1.0594 V for 5% and 0.8896 V for 15%. Such high values could have resulted from the much larger dimensions (125 mm x 115 mm x 102 mm) of the ethanol cell used for the research by the authors and the experimental conditions. If the cell was scaled to the dimensions used in this experiment, the energy yields would be similar to each other. According to CARVIÇAIS, the best current-voltage characteristics of the vodka-water mixture occur at a concentration of 3 M.

Tab. 2. Results based on a mixture of laboratory ethyl alcohol and demineralized water.

R [Ω]	5%			10%			15%			20%		
	U [mV]	I [mA]	P [mW]	U [mV]	I [mA]	P [mW]	U [mV]	I [mA]	P [mW]	U [mV]	I [mA]	P [mW]
0	0,6	3,03	1,818	1	4,54	4,54	1,2	5,69	6,828	1,3	6,35	8,255
10	2,8	2,91	8,148	4,2	4,39	18,438	5,9	5,42	31,978	1,2	5,51	6,612
20	6,9	2,76	19,044	10,7	4,33	46,331	11,4	4,65	53,01	4,7	5,05	23,735
30	10,3	2,66	27,398	20,9	4,2	87,78	18,2	4,31	78,442	11,7	4,54	53,118
40	14,2	2,57	36,494	23,9	4,12	98,468	23,7	4,09	96,933	15,4	3,84	59,136

50	*17,4*	*2,5*	*43,5*	*32,5*	*4,05*	*131,625*	*28,6*	*3,87*	*110,682*	*20,9*	*3,56*	*74,404*
60	*20,3*	*2,41*	*48,923*	*32,8*	*3,6*	*118,08*	*31,2*	*3,52*	*109,824*	*25,1*	*3,33*	*83,583*
70	*23,1*	*2,31*	*53,361*	*34,3*	*3,39*	*116,277*	*35,1*	*3,31*	*116,181*	*28,4*	*3,14*	*89,176*
80	*24,7*	*2,21*	*54,587*	*38,3*	*3,22*	*123,326*	*37*	*3,1*	*114,7*	*31,5*	*2,99*	*94,185*
90	*26,7*	*2,14*	*57,138*	*39,3*	*3,04*	*119,472*	*38,8*	*2,97*	*115,236*	*33,6*	*2,72*	*91,392*
100	*26,2*	*2,03*	*53,186*	*39,3*	*2,92*	*114,756*	*39,3*	*2,87*	*112,791*	*34,6*	*2,57*	*88,922*
Open circuit	*162,8*	*0*	*0*	*139,7*	*0*	*0*	*135,2*	*0*	*0*	*136,4*	*0*	*0*
Short-circuit current	*0,9*	*3,66*	*3,294*	*1,1*	*5,46*	*6,006*	*1,2*	*5,52*	*6,624*	*1,2*	*5,71*	*6,852*

Source: Own study

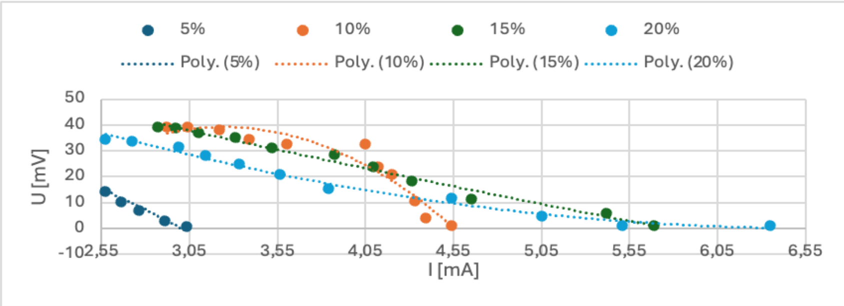

Fig. 3. Current-voltage characteristics for a mixture of laboratory ethanol (96%) + water in the proportions: 5, 10, 15 and 20%. Source: Own study

The mixture using denatured alcohol as a source of ethanol was distinguished by the fact that at 5%, a high voltage value (3.44 mV) was already achieved, and its low decrease was with increasing resistance. This mixture was characterized by a current (6.75 mA and a voltage of 7.6 mV) at the endpoint. Subsequent tests were characterized by worse current-voltage characteristics. The fastest voltage drop was determined in the 10% sample. Similar observations occurred in the study conducted by Wnuk et al (2019), where they also used laboratory ethanol where they used three different concentrations and obtained the highest value of 510 mV and 0 mA cm^{-2} with a change in resistance in the range from 0 to 100 Ω cm^2.

Tab. 3. Results for a mixture of denatured alcohol and demineralized water.

R [Ω]	***5%***			***10%***			***15%***			***20%***		
	U [mV]	***I [mA]***	***P [mW]***	***U [mV]***	***I [mA]***	***P [mW]***	***U [mV]***	***I [mA]***	***P [mW]***	***U [mV]***	***I [mA]***	***P [mW]***
0	*1,6*	*6,68*	*10,688*	*1,2*	*4,93*	*5,916*	*1,5*	*5,83*	*8,745*	*1,9*	*6,26*	*11,894*
10	*7,6*	*6,75*	*51,3*	*5,8*	*4,81*	*27,898*	*5,8*	*5,56*	*32,248*	*6,2*	*5,97*	*37,014*
20	*15,8*	*6,45*	*101,91*	*12,3*	*4,81*	*59,163*	*13,3*	*5,29*	*70,357*	*15,1*	*5,72*	*86,372*
30	*24,1*	*5,89*	*141,949*	*22,4*	*5,28*	*118,272*	*27,2*	*4,64*	*126,208*	*20,6*	*4,82*	*99,292*
40	*25,8*	*4,53*	*116,874*	*27,1*	*4,63*	*125,473*	*23,4*	*4,09*	*95,706*	*26,5*	*4,4*	*116,6*
50	*30,3*	*4,17*	*126,351*	*30,9*	*4,16*	*128,544*	*27,9*	*3,75*	*104,625*	*31,6*	*4,1*	*129,56*
60	*36,4*	*4*	*145,6*	*38*	*4,16*	*158,08*	*33,7*	*3,53*	*118,961*	*35,5*	*3,52*	*124,96*
70	*41,1*	*3,9*	*160,29*	*38,4*	*3,64*	*139,776*	*36,5*	*3,43*	*125,195*	*34,6*	*3,23*	*111,758*
80	*45,3*	*3,73*	*168,969*	*39,2*	*3,27*	*128,184*	*39,3*	*3,29*	*129,297*	*36,5*	*3,01*	*109,865*
90	*46,5*	*3,44*	*159,96*	*40,5*	*3,05*	*123,525*	*43,4*	*3,08*	*133,672*	*38,2*	*2,91*	*111,162*
100	*45,1*	*3,31*	*149,281*	*40,4*	*2,96*	*119,584*	*42,9*	*3,13*	*134,277*	*39,2*	*2,85*	*111,72*
Open circuit	*150,1*	*0*	*0*	*136,7*	*0*	*0*	*132,8*	*0*	*0*	*125*	*0*	*0*
Short-circuit current	*1,1*	*5,22*	*5,742*	*1,2*	*5,89*	*7,068*	*1,3*	*6,09*	*7,917*	*1,7*	*6,73*	*11,441*

Source: Own study

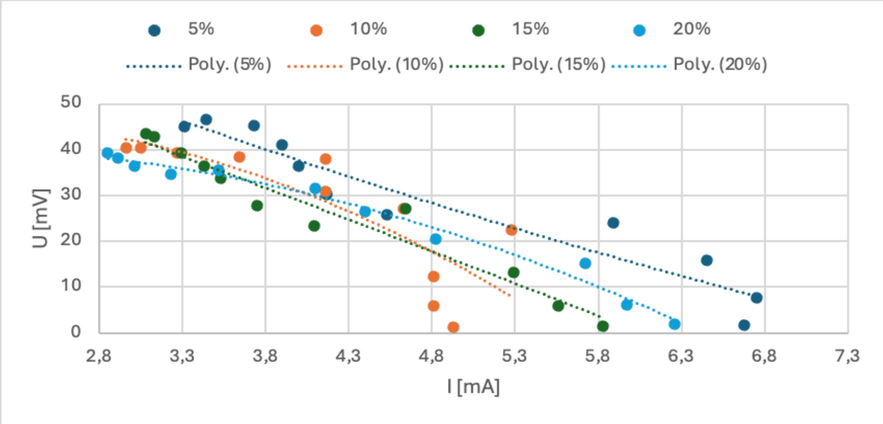

Fig. 4. Current-voltage characteristics for a mixture of denatured alcohol (96%) + water in the proportions: 5, 10, 15 and 20%. Source: Own study

The best results were recorded with denatured alcohol trials. This relationship could be due to the fact that denatured alcohol is not pure ethanol and contains impurities that can affect the operation of the ethanol cell. One such substance that is found in denatured alcohol is denatonium benzoate. According to Zheng et al. (2020), ethanol cells typically reach values of up to 1000 mV depending on the catalyst used in the cell. Low values in all cases could result from the size of the cell and the type of catalyst used. On the other hand, according to Kakaei and Rahnavardi (2021), the intensity can be up to 100 mA, depending on the materials used in the catalyst. Pereira et al. (2014) argue that the high ethanol content in the mixture reduces the efficiency of the ethanol cell. Such events occurred in the case of tests with laboratory ethanol and denatured alcohol, where a lower ethanol content had a positive effect on the cell's performance. However, in the case of the vodka-water mixture, the concentration of 20% performed best. In the research conducted by Tominak et al. (2009), the voltage dropped steadily from 425 mV with a simultaneous increase in current. After reaching 150 mV and 0.07 mA, there was a sharp drop in voltage to 25 mA. Such rapid voltage drops also occurred in the test when resistance increased, but the ethanol content in the mixture and the type of ethyl alcohol used also had an impact on this. An additional difference could have been the authors' use of methyl alcohol as fuel. Sahu and Basu (2014) measured the alcohol fuel cell with the best results for lower concentrations. Like previous authors, they used methanol as a fuel for research. The relationships between the current-voltage characteristics made by the authors and those made in this study were characterized by similar voltage drops with increasing resistance. The initial and final rapid voltage drop with a simultaneous slow increase in current was determined by Liao et al. (2015). The efficiency of the ethanol cell is also determined by experimental conditions. The cell works more efficiently at higher temperatures than at lower temperatures (Saisirirat and Joommanee, 2018).

Conclusions

Fuel cells that use ethanol directly are suitable for use as an emergency power supply for e.g. a satellite phone or means of transport, in the event of a shortage of dedicated fuel resulting from disasters or armed conflict.

The optimal concentration of ethanol in the mixture has a significant impact on obtaining high voltage and current. High efficiency of electricity production was achieved at lower alcohol concentrations, usually between 5 and 10 %. The exception was the vodka-water mixture, where the cell obtained the highest power (137.8 mW) at a concentration of 20% ethanol. Resistance plays a key role in the process of converting chemical energy into electrical energy. In the tests, the increase in resistance was directly proportional to the increase in electric voltage and cell power until their decrease occurred in the range of 80 to 90 Ω. The exception was the intensity of the electric current, which decreased in direct proportion to the increase in resistance.

Ethanol impurities contained in denatured alcohol can significantly impact the efficiency of conversion to electricity. The highest values were obtained for the mixture with the use of denatured alcohol, where already at a low concentration of this solution of 5%, a high value of cell power was obtained (168.9 mW), which indicates the high potential of mixtures with the use of denatonium benzoate.

In an emergency, alcohol-fueled fuel cells can run on low-quality fuel at the expense of uptime, giving you the necessary electricity.

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