Study on the micro direct ethanol fuel cell (Micro-DEFC) performance

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Abstract. The direct ethanol fuel cell (DEFC) is selected for this research. DEFC uses ethanol in the fuel cell instead of the more toxic methanol. Ethanol is more attractive than methanol by many reasons. Ethanol is a hydrogen-rich liquid and it has a higher specific energy (8.0 kWh/kg) compared to that of methanol (6.1 kWh/kg). Ethanol can be obtained in great quantity from biomass through a fermentation process from renewable resources such as sugar cane, wheat, corn, and even straw. The use of ethanol would also overcome both the storage and infrastructure challenge of hydrogen for fuel cell applications. The experimental apparatus on the micro direct ethanol fuel cell for measuring the cell performance has been set for this research. The objective is to study the micro direct ethanol fuel cell performance for applying with the portable electronic devices. The cell performance is specified in the terms of cell voltage, cell current and power of the cell at room operating temperature and 1 atm for the pressure and also includes the ethanol fuel consumption. The effect of operating temperature change on the electrical production performance is also studied. The steady-state time for collecting each data value is about 5-10 minutes. The results show that with the increase of concentrations of ethanol by volume, the reactant concentration at the reaction sites increases so the electrochemical rate also increases but when it reaches the saturated point the performance gradually drops.

1. Introduction
Nowadays an increasing number of the population is going fast and the demand of energy is very much increased. Energy from fossil fuel is one of the main energy sources to use today, but it causes environmental pollution and tends to cost more. It has a chance to expire in the near future. We cannot deny that we will use energy because energy is essential for the lives of human beings at the present and in the future. Presently, humankind realizes about the importance of using renewable energy as a clean alternative to preserve the environment. In the future, it cannot be denied that alternative energy will be utilized. Many alternatives have been found and studied, including solar energy, hydropower from dams and, not long ago, fuel cells.

A fuel cell is a device that converts the chemical energy from a fuel into electricity through a chemical reaction of positively charged hydrogen ions with oxygen or another oxidizing agent. Fuel cells are different from batteries in that they require a continuous source of fuel and oxygen or air to sustain the chemical reaction, whereas in a battery the chemicals in the battery react with each other to generate an electromotive force (emf) [1]. Fuel cells can produce electricity continuously for as long as these inputs are supplied. The first fuel cells were invented in 1838. Since then, fuel cells have been used in many other applications. Fuel cells are used for primary and backup power in commercial, industrial and
residential buildings, in remote or inaccessible areas. They are also used to power small electrical appliances as well as vehicles. There are many types of fuel cells, but they all consist of an anode, a cathode, and an electrolyte that allows positively charged hydrogen ions (or protons) to move between the two sides of the fuel cell. The anode and cathode contain catalysts that cause the fuel to undergo oxidation reactions that generate positively charged hydrogen ions and electrons. The hydrogen ions are drawn through the electrolyte after the reaction. At the same time, electrons are drawn from the anode to the cathode through an external circuit, producing direct current electricity. At the cathode, hydrogen ions, electrons, and oxygen react to form water [1]. As the main difference among various fuel cell types is the electrolyte, fuel cells are classified by the type of electrolyte they use and by the difference in startup time ranging from 1 second for proton exchange membrane fuel cells (PEM fuel cells, or PEMFC) to 10 minutes for solid oxide fuel cells (SOFC). In the present, the fuel cells are divided into 9 types [2]: 1. Alkaline Fuel Cell (AFC) 2. Phosphoric Acid Fuel Cell (PAFC) 3. Molten Carbonate Fuel Cell (MCFC) 4. Solid Oxide Fuel Cell (SOFC) 5. Proton Exchange Membrane Fuel Cell (PEMFC) 6. Regenerative Fuel Cell (RFC) 7. Direct Alcohol Fuel Cells (DAFCs) that are divided into 2 types, 8. Direct Methanol Fuel Cell (DMFC) and 9. Ethanol Fuel Cell (DEFC).

For a fuel cell that uses hydrogen gas, and equipment to store hydrogen is quite expensive. Fuel cell such as a Proton Exchange Membrane Fuel Cell (PEMFC) has high performance but needs to use the purity of hydrogen and the platinum electrodes, making it rather expensive. Fuel cells that use alcohol as fuels are divided into 2 types: 1. Direct Methanol Fuel Cell (DMFC) and 2. Direct Ethanol Fuel Cell (DEFC). Previously, a lot of research focused on the study and development of Direct Methanol Fuel Cell (DMFC). There is a downside and many other problems in reaction kinetics for the slow oxidation of methanol fuel and across the water from one electrode to the one electrode (Crossover) [3, 4]. Matsuoka et al. [5] reported that Direct Methanol Fuel Cell (DMFC) electrodes have slow reaction kinetics because of obstruction of carbon monoxide (CO) catalyst platinum (Pt) at low temperatures and high surface quality of the catalysts for membrane.

Methanol is non-renewable energy described as volatile and highly flammable. Ethanol fuel, which is good choice for fuel cell is less toxic and has higher energy density than methanol. Also ethanol can be produced from biological processes in agriculture [6]. Ethanol can be obtained in great quantity from biomass through a fermentation process from renewable resources such sugar cane, wheat, corn, and even straw. Bio-generated ethanol (or bio-ethanol) is thus attractive since growing crops for biofuels absorbs much of the carbon dioxide emitted into the atmosphere from fuel used to produce the biofuels, and from burning the biofuels themselves. This is in sharp contrast to the use of fossil fuels. The use of ethanol would also overcome both the storage and infrastructure challenge of hydrogen for fuel cell applications. In a fuel cell, the oxidation of any fuel requires the use of a catalyst in order to achieve the current density required for commercially viable fuel cells, and platinum-based catalysts are some of the most efficient materials for the oxidation of small organic molecules [7].

Due to fast development in science and technology, fuel cells are developed to smaller and more compact size for usage with the portable electronic devices. Direct Ethanol Fuel Cells (DEFCs) have dimensions of about 125 mm x 115 mm x 102 mm and can produce the electric power about 102 W for longer than 3,600 hours [8]. Ethanol also remains the easier fuel to work with for widespread use by consumers. In addition, ethanol is a hydrogen-rich liquid and it has a higher specific energy (8.0 kWh/kg) compared to that of methanol (6.1 kWh/kg).

The objective of this research is to study the micro direct ethanol fuel cell performance especially on the ethanol fuel consumption rate for applying with the portable electronic devices. The cell performance is specified in the terms of cell voltage and power density at any specific current density for several operating conditions. In this work, the power is limited to 10 W, which is suitable for portable electronic devices. The experimental results will be compared with the theoretical calculations.
2. Experimental apparatus

![Figure 2](image)

(a) (b) (c) (d)

Figure 2. (a) direct ethanol fuel cell; (b) drawing front view; (c) drawing side view; (d) drawing top view (all dimensions are in millimeters)

The experimental apparatuses are composed of 1. Micro-DEFC, 2. Ethanol fuel 95% by volume, 3. Pure water, 4. 100-ml cylinder, 5. 10-ml syringe and 6. Paper measure acid-alkaline. The details on the figure 2 are: 1. Lid set (Micro-DEFC), 2. Vane set, 3. Membrane (MEA), 4. Set structure (Micro-DEFC) and 5. Cylinder solution. Bio-energy feed ethanol set demonstrate changing the ethanol fuel to electrical energy without combustion in the process. It can work continuously for many hours. The main experimental study is about the consumption of ethanol fuel for electricity production.

3. Theoretical calculations

3.1. The density of electrical current

Ideal gas law is an equation of state with the number of moles (N) and volume (V) [9]:

$$PV = NRT$$

where $P =$ Pressure (Pa), $V =$ Fuel feed rates (mm$^3$/min), $N =$ Number of moles (mole/s), $R =$ Universal gas constant = 0.082 m$^3$atm/kg mol k, and $T =$0°C. Lateral move (N) to get number of moles to represent the following equation to determine density of electrical current ($i$). The density of electrical current ($i$) from 1 molecule of hydrogen gas can transfer 2 electrons so flow rate of hydrogen gas can be calculated as [3]:

$$i = \frac{n \times 2}{t}$$
\[ N_{i_2} = \frac{i}{2F} \]  

(2)

where \( i \) = Density of electric current (A/m\(^2\)) and \( F \) = Faraday constant = 9.64853 x 10\(^4\) (C/mol).

One molecule of oxygen can transfer 4 electrons, so the flow rate of oxygen is

\[ N_{o_2} = \frac{i}{4F} \cdot \]  

(3)

When using air instead oxygen that the air flow rate can be calculated as

\[ N_{air} = \frac{i}{4F} \times \frac{1}{0.21} \cdot \]  

(4)

The density of electrical current \((i)\) can be calculated as

\[ i = N \cdot 2F \]  

(5)

3.2. The cell voltage

According to the theory, the voltage of a single-cell DEFC when fed ethanol at 25 (°C) and 1 (atm) by the chemical reaction is as follows [10]:

Anode : \( \text{C}_2\text{H}_5\text{OH} + 3\text{H}_2\text{O} \rightarrow 12e^+ + 12\text{H}^+ + 2\text{CO}_2 \quad (E_{\text{anode}}^0 = 0.084 \text{ V}) \)  

(6)

Cathode : \( 12e^+ + 12\text{H}^+ + 3\text{O}_2 \rightarrow 6\text{H}_2\text{O} \quad (E_{\text{cathode}}^0 = 1.229 \text{ V}) \)  

(7)

Overall : \( \text{C}_2\text{H}_5\text{OH} + 3\text{O}_2 \rightarrow 3\text{H}_2\text{O} + 2\text{CO}_2 \quad (E_{\text{cell}}^0 = 1.145 \text{ V}) \)  

(8)

**Figure 3.** The system of direct ethanol fuel cell (DEFC).

In figure 3, the texts with their corresponding meanings are PEM : Membrane, CDL: Cathode gas diffusion layer, ADL : Anode gas diffusion layer, CCL : Cathode catalyst layer, ACL : Anode catalyst layer, CFC : Splice plate cathode, and AFC : Splice plate anode. The voltage (V) in a single-cell DEFC for portable electronic devices can be calculated using the following equation [10]:

\[ E_{cell} = E_{cell}^0 - \eta_{\text{conc}} - \eta_{\text{ohmic}} - \eta_{\text{act}} \]  

(9)

where \( E_{cell} \) = Voltage of fuel cell (V), \( E_{cell}^0 \) = Voltage of fuel cell according to the theory (V), \( \eta_{\text{conc}} \) = Concentration of voltage loss related to kinetics of reaction (V), \( \eta_{\text{ohmic}} \) = Voltage loss related to resistance (V) and \( \eta_{\text{act}} \) = Voltage loss related to reaction involved to kinetics (V).

The movement of substrate on anode catalyst layer and cathode catalyst layer results in the loss concentration inside the cell. The concentration of voltage loss can be calculated from equation (10) [11]:

\[ \]
$$\eta_{conc} = \frac{RT}{zF} \ln\left(\frac{I_{lim}}{I_{lim} - i}\right).$$  \hspace{1cm} (10)

While limitation of electric current flow follows equation (11):

$$I_{lim} = Z_a F D_{eff}^{anode} \frac{C_b}{L_b}.$$  \hspace{1cm} (11)

where $R = $ Universal gas constant $= 8.314 \text{ (J/g mol k)}$, $z =$ Number of electrons in system, $D_{eff}^{anode} =$ Spread efficiency coefficient of ethanol at the anode , $C_b =$ Concentration of ethanol at the anode (molar) and $L_b =$ The width of flow channel at the anode (mm).

The cell voltage resistance loss can be calculated from equations (12)-(15):

$$\eta_{ohmic} = iR_{total},$$  \hspace{1cm} (12)

$$R_{total} = \eta_{membr} + \eta_{contact},$$  \hspace{1cm} (13)

$$\eta_{membr} = \frac{l_m}{K_m} i,$$  \hspace{1cm} (14)

$$\eta_{contact} = \frac{l_m + 2l_c}{K_s} i,$$  \hspace{1cm} (15)

while the voltage loss related to reaction involved to kinetics can be calculated from the equations (16)-(17) [12]:

$$\eta_{act, anode} = \frac{RT}{\alpha_z a z_a F} \ln\left(\frac{i}{i_o}\right)$$  \hspace{1cm} (16)

$$\eta_{act, cathone} = \frac{RT}{\alpha_z c z_c F} \ln\left(\frac{i}{i_o}\right)$$  \hspace{1cm} (17)

From equation (9), we can calculate the voltage in DEFC single cell as follows:

$$E_{cell} = E_{cell}^0 - \eta_{conc} - \eta_{ohmic} - \eta_{act}$$
$$E_{cell} = E_{cell}^0 - \left( \frac{RT}{z_a F} \ln\left(\frac{i_{lim}}{i_{lim} - i}\right) \right) - \left( i \frac{l_m}{K_m} + \frac{l_m + 2l_c}{K_s} \right)$$
$$\frac{RT}{\alpha_z a z_a F} \ln\left(\frac{i}{i_o}\right) + \frac{RT}{\alpha_z c z_c F} \ln\left(\frac{i}{i_o}\right)$$  \hspace{1cm} (18)

3.3. The flow rate of ethanol for electrochemical reaction

The ethanol fuel mole flow rate can calculate by equation (19) and the ethanol volume flow rate be calculated by equation (20) as shown below

$$n_i = \frac{i}{nF} \hspace{1cm} (19)$$
$$v_i = \frac{n_i M_i}{\rho_i} \hspace{1cm} (20)$$

where $n_i =$ Ethanol fuel mole flow rate (mol/s), $n =$ Number of electrons in system , $v_i =$ Ethanol volume flow rate (cm$^3$/h) , $M_i =$ Molecular (g/mol) and $\rho_i =$ Density of ethanol (g/cm$^3$).

3.4. The total power and efficiency of fuel cell

Electrical power (P) can be calculated from the following equation:

$$P = V_x I$$  \hspace{1cm} (21)

Once voltage (V) is known then we can calculate the efficiency of fuel cell ($\eta_{actual,E}$) from the ratio between actual electrical potential ($E_{cell}$) and electrical potential from the reaction between the ethanol and oxygen ($E_{cell}^0$) as
\[ \eta_{\text{actual}} = \frac{E_{\text{cell}}}{E_{\text{cell}}^0} \times 100\% . \]  

(22)

The parameters used in the calculations are shown below in table 1.

| Parameters                     | Constants | Units     | References |
|--------------------------------|-----------|-----------|------------|
| **Design parameters**          |           |           |            |
| Active area                    | 4         | cm²       | Fixed      |
| Current density                | 0.175     | A/cm²     | Fixed      |
| Catalyst layer thickness, \(l_c\) | 0.01     | cm        |            |
| Diffusion layer thickness, \(l_d\) | 0.14     | cm        |            |
| Membrane thickness, \(l_m\)    | 0.01778   | cm        |            |
| **Operating parameters**       |           |           |            |
| Pressure                       | 1         | atm       | Fixed      |
| Faraday constant, \(F\)        | 96,500    | Cmol⁻¹    |            |
| Gas constant, \(R\)            | 8.314     | J/molK    |            |
| Effective diffusion coefficient of ethanol in diffusion layer \(D_{\text{EtOH}}^d\) | \(3.916 \times 10^{-2}\) | cm²s⁻¹ | [13] |
| Void volume fraction of anode diffusion layer, \(\varepsilon\) | 0.4 | | [14] |
| Electronic conductivity of solid phase \((\text{PtRu/C}),K_s\) | \(8.13 \times 10^6\) | Scm⁻¹ | [13] |
| Protonic Conductivity of ionomer, \(K_m\) | 0.1416 | Scm⁻¹ | [13] |
| Anode transfer coefficient, \(\alpha_a\) | 0.089 | cm² | [13] |
| Cathode transfer coefficient, \(\alpha_c\) | 1.0 | A/cm² | [13] |
| **Component parameters**       |           |           |            |
| Oxygen density                 | 1.141     | gcm⁻³     | Fixed      |
| CO₂ density                    | 0.77      | gcm⁻³     | Fixed      |
| Ethanol density                | 0.785     | gcm⁻³     | Fixed      |
| Water density                  | 1         | gcm⁻³     | Fixed      |

### 4. Results and discussion

The goal of the DEFC study in this research was to study on the performance of the micro direct ethanol fuel cell (Micro-DEFC). It is also to study the consumption of ethanol fuel and its effects on the electrical production. The experimental performance testing studied both of the ethanol blended with pure distilled water and the ethanol blended with conventional drinking water. The effect of operating temperature change on the electrical production performance is also studied. The cell performance is specified in the terms of cell voltage and power of the cell for several operating conditions. The experimental results are shown below.

Table 2 shows the experimental results that all experiments were carried out by changing the ethanol concentration and changing the operating temperature of the fuel cell. The ethanol concentration changed from 5, 7, 9, 11, 13 and 15 ml dissolved in 60 ml of purified distilled water at operating temperature of 30, 35, 40, 45, 50 and 55 °C. The electrical production variables of the fuel cell, i.e. the electrical current, the electrical cell voltage and the electrical power were measured. Comparison of the results obtained from the theoretical calculations and the actual measurement of fuel cell performance that will be described in the next section.
The experiments observed that when increasing the concentration of ethanol 5 ml to 15 ml dissolved in 60 ml of pure distilled water and increasing the temperature to 30 to 55 °C, the electricity production variables, such as the value of the fuel cell current, the fuel cell voltages and the power of the fuel cell were increased in accordance with the ethanol concentration and increased with temperature. Electrical charges gradually increase from low ethanol concentration and low temperatures to the highest point at a concentration of 13 ml of ethanol dissolved in 60 ml of pure distilled water at 40-45 °C. The production

| Table 2. Experimental performance with ethanol blended with pure distilled water. |
|---------------------------------------------------------------|
| Ethanol concentration (95 %) (ml. blended with 60 ml of pure distilled water) | Experimental results no.1 | Experimental results no.2 |
| I (mA) | V (V) | P (mW) | T (°C) | I (mA) | V (V) | P (mW) | T (°C) |
|------|------|------|------|------|------|------|------|------|
| 5    | 11.2 | 0.95 | 10.6 | 30.8 | 11.2 | 0.96 | 10.5 | 34.6 |
| 7    | 12.8 | 0.92 | 12.8 | 30.8 | 15.4 | 0.92 | 14.2 | 34.4 |
| 9    | 13.1 | 0.90 | 11.9 | 31.2 | 14  | 0.95 | 13.3 | 34.6 |
| 11   | 10.3 | 0.92 | 9.58 | 31.2 | 15  | 0.94 | 14.2 | 34.8 |
| 13   | 12.1 | 0.89 | 10.8 | 31.2 | 15.3 | 0.91 | 13.9 | 34.8 |
| 15   | 11.2 | 0.91 | 10.2 | 30.8 | 15  | 0.92 | 13.8 | 34.4 |

| Ethanol concentration (95 %) (ml. blended with 60 ml of pure distilled water) | Experimental results no.3 | Experimental results no.4 |
|---------------------------------------------------------------|
| I (mA) | V (V) | P (mW) | T (°C) | I (mA) | V (V) | P (mW) | T (°C) |
|------|------|------|------|------|------|------|------|------|
| 5    | 12.3 | 0.88 | 10.9 | 41   | 12.9 | 0.95 | 12.2 | 44.4 |
| 7    | 11.7 | 0.94 | 11.1 | 40.8 | 15.9 | 0.94 | 15.0 | 44.6 |
| 9    | 12.4 | 0.94 | 11.7 | 40.8 | 14.6 | 0.94 | 13.8 | 44.4 |
| 11   | 13.6 | 0.94 | 12.9 | 41.2 | 14  | 0.94 | 13.2 | 44.6 |
| 13   | 13.9 | 0.94 | 13.1 | 41   | 15.3 | 0.92 | 14.1 | 44.4 |
| 15   | 14.0 | 0.95 | 13.3 | 40.8 | 15.4 | 0.92 | 14.3 | 44.4 |

| Ethanol concentration (95 %) (ml. blended with 60 ml of pure distilled water) | Experimental results no.5 | Experimental results no.6 |
|---------------------------------------------------------------|
| I (mA) | V (V) | P (mW) | T (°C) | I (mA) | V (V) | P (mW) | T (°C) |
|------|------|------|------|------|------|------|------|------|
| 5    | 13.3 | 0.95 | 12.7 | 51   | 13.9 | 0.96 | 13.4 | 54.6 |
| 7    | 14.6 | 0.96 | 14.1 | 50.8 | 16.7 | 0.95 | 16.0 | 54.6 |
| 9    | 15.3 | 0.97 | 14.8 | 51.2 | 14.8 | 0.95 | 14.1 | 54.4 |
| 11   | 18   | 0.96 | 17.3 | 51.2 | 15.7 | 0.95 | 14.9 | 54.6 |
| 13   | 18.8 | 0.96 | 18.2 | 50.8 | 16.6 | 0.93 | 15.4 | 54.4 |
| 15   | 19.3 | 0.98 | 19.0 | 51.2 | 14.6 | 0.94 | 13.7 | 54.6 |

| Ethanol concentration (95 %) (ml. blended with 60 ml of pure distilled water) | Experimental results no.7 | Experimental results no.8 |
|---------------------------------------------------------------|
| I (mA) | V (V) | P (mW) | T (°C) | I (mA) | V (V) | P (mW) | T (°C) |
|------|------|------|------|------|------|------|------|------|
| 5    | 14.3 | 0.97 | 13.9 | 60.4 | 15.9 | 0.99 | 15.8 | 64.6 |
| 7    | 16.6 | 0.96 | 16.0 | 60.6 | 16.9 | 0.98 | 16.6 | 64.6 |
| 9    | 15.7 | 0.96 | 15.2 | 60.4 | 17.4 | 0.98 | 17.2 | 64.6 |
| 11   | 16.9 | 0.97 | 16.5 | 60.4 | 17  | 0.98 | 16.7 | 64.4 |
| 13   | 15.8 | 0.95 | 15.1 | 60.4 | 17.7 | 0.98 | 17.3 | 64.6 |
| 15   | 16.3 | 0.95 | 15.5 | 60.4 | 15.9 | 0.96 | 15.3 | 64.6 |
of electric charge of the fuel cell gradually decreases over time until the fuel has been exhausted when the ethanol concentration was increased to more than 13 ml dissolved in 60 ml purified distilled water, the electrical conductivity of the fuel cell was reduced. At 30-35 °C, for ethanol fuel blended with pure distilled water at different concentrations, the fuel cell must wait for about 5-10 minutes before it will start producing electrical charges. The experimental temperature was increased to 40-55 °C, it was found that the fuel cell started reacting faster with electricity that it took only 2-3 minutes before it can produce electricity efficiently.

| Ethanol concentration (95 %) (ml. blended with 60 ml. of pure distilled water) | Average trial values | Temperature | Times |
|---|---|---|---|
| | I (mA) | V (V) | P (mW) | T (°C) | (S) |
| 5 | 11.2 | 0.95 | 10.6 | 31-32 | 20 |
| 7 | 15.4 | 0.92 | 14.2 | 34-35 | 20 |
| 9 | 12.4 | 0.94 | 11.7 | 39-40 | 20 |
| 11 | 14.0 | 0.94 | 13.2 | 44-45 | 20 |
| 13 | 18.8 | 0.96 | 18.2 | 49-50 | 20 |
| 15 | 14.6 | 0.94 | 13.7 | 54-55 | 20 |

Table 3. The average results of ethanol blended with pure distilled water.

Table 3 shows the average results obtained from data in table 2. The ethanol concentration and temperature were increased. It was found that the electrical production variables of the fuel cell, such as electrical current, voltage and power of fuel cell varied by increasing ethanol concentration and temperature. The maximum electrical value is at 13 ml of ethanol, dissolved in 60 ml of pure distilled water at 40-45 °C. The electrical current is equal to 18.8 mA, the voltage is equal to 0.96 V and the power is equal to 18.2 mW. Increasing the ethanol concentration and temperature affects these electric values of the fuel cell. By increasing the ethanol concentration and temperature, the fuel cell will gradually react to produce electrical charge and will gradually ramp up to the highest value and then gradually decrease until fuel is completely fed. It does not affect the output voltage of the fuel cell. In the experiment, when the ethanol concentration and temperature were increased, the cell voltage values were not significantly different. Increasing the concentration of ethanol and temperature affects the electrical current and power but does not affect the electrical potential at all or minimally. Table 4 is the theoretical calculation of the value of electrical currents, fuel cell voltages and power of the fuel cell for comparison these results with the experimental results as shown above and the last column of the table 4 is the fuel cell efficiency calculation results. Based on the calculation, the value of electrical current and power are even higher. On the other hand, the fuel cell electrical potential and the fuel cell efficiency decrease visibly. At the ethanol concentration of 5 ml dissolved in 60 ml of pure distilled water at a working temperature of 31-32 °C has the highest efficiency of 92.524% and the maximum voltage of 1.0594 V. At the concentration of 15 ml of ethanol dissolved in 60 ml of pure distilled water and at the working temperature of 54-55 °C, the maximum current is 695.214 mA and the maximum output power is 618.495 mW.
Table 4. The fuel cell efficiency calculation results when blended ethanol with pure distilled water.

| Ethanol concentration (95 %) (ml. blended with 60 ml of pure distilled water) | Average trial values | Temperature | Fuel cell efficiency (%) |
|---|---|---|---|
| 5 | 231.738 | 1.0594 | 245.503 | 31-32 | 92.524 |
| 7 | 324.433 | 1.0258 | 332.804 | 34-35 | 89.591 |
| 9 | 417.128 | 0.9917 | 413.699 | 39-40 | 86.618 |
| 11 | 509.822 | 0.9577 | 488.275 | 44-45 | 83.645 |
| 13 | 602.518 | 0.9236 | 556.541 | 49-50 | 80.671 |
| 15 | 695.214 | 0.8896 | 618.495 | 54-55 | 77.698 |

Next, the experiment was repeated but conventional drinking water, instead of pure distilled water, was used to blend with the ethanol. The experiment steps remain the same. When the ethanol concentration is increased from 5 ml to 15 ml dissolved in 60 ml of conventional drinking water and the operating temperature of the cell is in the range of 30-65 °C, the production of electricity such as electrical current, the fuel cell voltage and the power of the fuel cell increases with the ethanol concentration and increases with the temperature. The fuel cell electrical values are gradually increased from low ethanol concentration and lower temperatures to the highest point at a concentration of 13 ml of ethanol dissolved in 60 ml of conventional drinking water at 49-50 °C, the electric charge of the fuel cell will gradually increase. It continues to decrease over time until all the fuel is gone, when the ethanol concentration is increased to more than 13 ml, the electrical output of fuel cell is reduced. The experimental results are shown in table 5.

Table 6 shows the average results obtained from data in table 5. The experiment was conducted to change the blendture of ethanol from pure distilled water to conventional drinking water. It was found that the production of electrical values of the fuel cell, such as electrical currents, the fuel cell voltages and the power of the fuel cell varied by increasing ethanol concentration and temperature. The maximum electrical values were at 13 ml of ethanol dissolved in 60 ml of conventional drinking water at 49-50 °C. The electrical current was equal to 19.6 mA, the fuel cell voltage was equal to 0.91 V and the fuel cell power was equal to 18.0 mW. Increasing the ethanol concentration and temperature affects the electrical values of the fuel cell. By increasing the ethanol concentration and temperature, the fuel cell gradually reacted to produce the electrical value and gradually increased to the maximum value and then gradually decreased until the fuel is completely fed. However, it did not affect the production of the electric potential of the fuel cell. In the experiment, when the ethanol concentration and temperature were increased, the fuel cell voltages were not significantly different. Increasing the ethanol concentration and temperature affects the value of fuel cell electrical currents and power, but does not affect the voltage significantly.
Table 5. Experimental performance of ethanol blended with conventional drinking water.

| Ethanol concentration (95 %) (ml. blended with 60 ml. of conventional drinking water) | Experimental results no.1 | Experimental results no.2 |
|---|---|---|
| | I (mA) | V (V) | P (mW) | T (°C) | I (mA) | V (V) | P (mW) | T (°C) |
| 5 | 6.5 | 0.86 | 5.6 | 30.4 | 15.2 | 0.83 | 12.6 | 34.6 |
| 7 | 7.3 | 0.86 | 6.3 | 30.8 | 15.6 | 0.9 | 14.1 | 34.6 |
| 9 | 7.8 | 0.87 | 6.8 | 30.2 | 16.0 | 0.93 | 15.0 | 34.6 |
| 11 | 8.5 | 0.87 | 7.4 | 30.4 | 17.5 | 0.91 | 16.0 | 34.2 |
| 13 | 10.2 | 0.86 | 8.7 | 30.4 | 18.2 | 0.91 | 16.6 | 34.6 |
| 15 | 14.5 | 0.87 | 12.6 | 30.6 | 17.4 | 0.93 | 16.3 | 34.6 |

| Ethanol concentration (95 %) (ml. blended with 60 ml. of conventional drinking water) | Experimental results no.3 | Experimental results no.4 |
|---|---|---|
| | I (mA) | V (V) | P (mW) | T (°C) | I (mA) | V (V) | P (mW) | T (°C) |
| 5 | 17.8 | 0.89 | 15.6 | 40.6 | 15.9 | 0.9 | 14.3 | 44.4 |
| 7 | 17.4 | 0.91 | 15.8 | 40.4 | 17.5 | 0.9 | 15.7 | 44.4 |
| 9 | 18.2 | 0.90 | 16.4 | 40.8 | 18.5 | 0.9 | 16.7 | 44.4 |
| 11 | 18.1 | 0.92 | 16.7 | 40.4 | 18.4 | 0.90 | 16.7 | 44.4 |
| 13 | 18.5 | 0.90 | 16.7 | 40.4 | 18.4 | 0.90 | 16.6 | 44.4 |
| 15 | 19.9 | 0.90 | 18.0 | 40.4 | 17.3 | 0.91 | 15.8 | 44.4 |

| Ethanol concentration (95 %) (ml. blended with 60 ml. of conventional drinking water) | Experimental results no.5 | Experimental results no.6 |
|---|---|---|
| | I (mA) | V (V) | P (mW) | T (°C) | I (mA) | V (V) | P (mW) | T (°C) |
| 5 | 16.0 | 0.91 | 14.7 | 50.4 | 16 | 0.91 | 14.6 | 54.6 |
| 7 | 16.0 | 0.93 | 14.9 | 50.4 | 16.0 | 0.92 | 14.8 | 54.4 |
| 9 | 16.7 | 0.93 | 15.6 | 50.8 | 17.6 | 0.92 | 16.2 | 54.6 |
| 11 | 18.4 | 0.93 | 17.2 | 50.4 | 19.62 | 0.92 | 18.1 | 54.6 |
| 13 | 19.6 | 0.91 | 18.0 | 50.4 | 21.9 | 0.93 | 20.6 | 54.2 |
| 15 | 17.5 | 0.92 | 16.1 | 50.6 | 17.9 | 0.92 | 16.5 | 54.4 |

| Ethanol concentration (95 %) (ml. blended with 60 ml. of conventional drinking water) | Experimental results no.7 | Experimental results no.8 |
|---|---|---|
| | I (mA) | V (V) | P (mW) | T (°C) | I (mA) | V (V) | P (mW) | T (°C) |
| 5 | 16.7 | 0.91 | 15.2 | 60.4 | 16.7 | 0.91 | 15.2 | 64.4 |
| 7 | 17.3 | 0.92 | 15.9 | 60.4 | 17.8 | 0.92 | 16.4 | 64.6 |
| 9 | 17.2 | 0.92 | 15.9 | 60.4 | 18.8 | 0.92 | 17.4 | 64.6 |
| 11 | 20.2 | 0.92 | 18.5 | 60.4 | 20.4 | 0.92 | 18.7 | 64.6 |
| 13 | 23.0 | 0.92 | 21.2 | 60.4 | 25.0 | 0.92 | 23.2 | 64.4 |
| 15 | 19.0 | 0.92 | 17.3 | 60.8 | 21.1 | 0.92 | 19.5 | 64.2 |
Table 6. The average results of ethanol blended with conventional drinking water.

| Ethanol concentration (95 %) (ml. blended with 60 ml. of conventional drinking water) | Average trial values | Temperature | Times |
|---|---|---|---|
| I (mA) | V (V) | P (mW) | T (°C) | (S) |
| 5 | 6.5 | 0.86 | 5.6 | 30-31 | 20 |
| 7 | 15.6 | 0.90 | 14.1 | 34-35 | 20 |
| 9 | 18.2 | 0.90 | 16.4 | 39-40 | 20 |
| 11 | 18.4 | 0.90 | 16.6 | 44-45 | 20 |
| 13 | 19.6 | 0.91 | 17.8 | 49-50 | 20 |
| 15 | 17.9 | 0.92 | 16.5 | 54-55 | 20 |

From the experimental results, we can see that the electrical production of the fuel cell are not much different, in terms of the electrical currents, the electrical potential and the power of the fuel cell, and whether ethanol blended with pure distilled water or ethanol blended with conventional drinking water was used as fuel. Therefore, it can be concluded that ethanol can be used in combination with conventional drinking water instead of pure distilled water for electricity production in a direct ethanol fuel cell for reducing the operating costs. To increase the amount of electricity produced and the power of the cell, the fuel cells can be connected as a series of stacks according to the amount of electricity or power required.

5. Conclusion

Direct Ethanol Fuel Cells or DEFCs are a subcategory of proton-exchange fuel cells in which ethanol is used as the fuel. Their main advantage is the ease of transport of ethanol, which is an energy-dense yet reasonably stable liquid at all environmental conditions. DEFC is a new fuel cell that is similar to the PEMFC fuel cells, where both are used as polymer-type membrane electrolytes. However, in this fuel cell itself, it is an anode catalyst, extracting hydrogen from liquid ethanol. A more efficient version of a direct fuel cell would play a key role in the theoretical use of ethanol as a general energy transport medium, in the hypothesized ethanol economy. The goal of the DEFC study in this research was to study on the performance of the micro direct ethanol fuel cell (Micro-DEFC) for usage in portable electronic devices. It is also to study the consumption of ethanol fuel, which affects the electric current production. The effect of operating temperature change on the electric production performance is also studied too. The cell performance is specified in the terms of the cell voltage, the cell electrical current and power of the cell for several operating conditions. The results show that with the increase of concentrations of ethanol by volume, the reactant concentration at the reaction sites increases so the electro-chemical rate also increase but when it reaches the saturated point the performance gradually drops. From the averaged data, that the maximum current production, maximum cell voltage and maximum power of the fuel cell are 18.8 mA, 0.96 V and 18.2 mW, respectively. They are occurred at the ratio of ethanol equal to 13 ml in 60 ml of pure distilled water and at the cell operating temperature of 49-50 °C and atmospheric pressure. From the calculation results show that with increase of ethanol concentrations and the operating temperature of the fuel cell that the electrical current production and electrical power production also increase. On the other hand, the electrical potential of the fuel cell and the efficiency of the fuel cell are noticeably reduced. When changing the substance blended with ethanol from pure distilled water to conventional drinking water it was found that the production of electrical values of the fuel cell, such as electrical currents, the fuel cell voltages and the power of the fuel cell varied with increasing ethanol concentration and temperature. The maximum electrical values were at 13 ml of ethanol dissolved in 60 ml of conventional drinking water at 49-50 °C. The electrical current was equal to 19.6 mA, the fuel cell voltage was equal to 0.91 V and the fuel cell power was equal to 18.0 mW. By increasing the ethanol concentration and temperature, the fuel cell gradually reacted to produce the
electrical value and gradually increased to the maximum value and then gradually decreased until the fuel is completely fed. However, it did not affect the production of the electric potential of the fuel cell. In the experiment, when the ethanol concentration and temperature were increased, the fuel cell voltages were not significantly different. Increasing the ethanol concentration and temperature affects the values of fuel cell electrical currents and power, but does not affect the voltage.

The production of electricity, electrical potential and electrical power when using ethanol blended with pure distilled water or when using ethanol blended with conventional drinking water shows little difference. Therefore, it can be concluded that ethanol can be used in combination with conventional drinking water instead of pure distilled water for the production of electrical values in a fuel cell to save the operating costs. To increase the amount of electricity produced and the power of the cell, the fuel cell can be connected as a series of stacks according to the amount of electricity or power required.

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