DESIGN AND TESTING OF THE MICRO FILTER PAPER FUEL CELL

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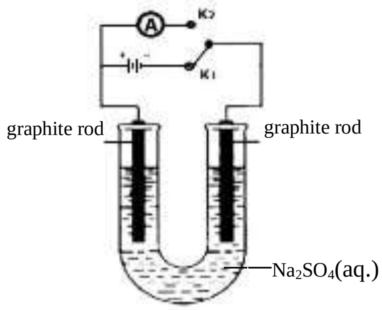
ABSTRACT

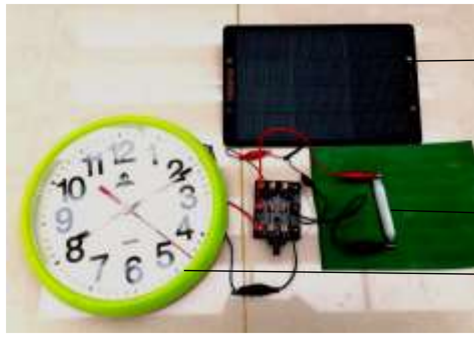
A micro filter paper fuel cell (MFPFC) has been developed. The hydrogen and oxygen used in the fuel cell are formed on the electrodes by electrolysis with solar energy. Illustrating a method of obtaining clean energy. Sensor-based and micro-scale designs serve as exemplars for Education for Sustainable Development (ESD) [1] in school-level chemistry experiments. They are expected to be capable of arousing students' participation in creative and innovative designs, appreciation of "Green Awareness", "Sustainable Development" and their necessity in a worldwide scenario. *[African Journal of Chemical Education—AJCE 12(2), July 2022]*

INTRODUCTION

In the traditional experimental device of H_2-O_2 fuel cell (Fig.1, switches K_1 ON), the electrolysis of a dilute solution of Na_2SO_4 with graphite electrodes liberates oxygen at the anode and hydrogen at the cathode [2][3]. This step is to provide fuel for the fuel cell (step①). After the electrolysis (switches K_1 out and K_2 on), the two electrodes with their absorbed gases form a voltaic cell, which is the simplest H_2-O_2 fuel cell (step②). In this cell, the electrode with oxygen is the positive pole and the electrode with hydrogen is the negative pole.

The two-step operation illustrates the basic principle of H_2-O_2 fuel cell, but the traditional experimental device has lots of drawbacks, including unacceptable amount of reagent used, unstable and rapid drop of discharge voltage and use of a battery (not a clean source of energy) for electrolysis. There are many papers on the microscale approach to fuel cell experiments [4-9]. In these, microwell plates are the basic reactors which use maybe 5 ml electrolyte. Our proposed design uses wet filter paper attached to a pencil lead as electrode and two such electrodes form a micro filter paper fuel cell (Fig.2). It uses less than 0.3 ml of electrolyte. The unfueled design needs a solar cell to form fuel and oxygen by electrolysis to establish the initial store of these on the electrodes. This micro filter paper fuel cell (MFPFC) can illuminate an LED for 5 mins, operate a quartz clock for 10 mins and drive a toy car for the distance of 5 meters.





(Fig. 1) Traditional experiment of oxygen-hydrogen fuel cell in textbook

(Fig. 2) MFPFC device

MATERIALS AND EQUIPMENT USED IN TESTING PERFORMANCE VARIABLES

Material/reagent/ description	Qty	Material/reagent/ description	Qty
Zhonghua Brand pencil lead (HB, 2B) 8cm (length) 2mm (dia)	2 pcs	1M H_2SO_4(aq)	1 ml
Graphite rod dismantled from used dry cell (12 mm dia×5 cm)	2 pcs	1M NaOH(aq)	1 ml
Sat. Na_2SO_4(aq)	2 ml	Qualitative filter paper (Shuangquan Brand, 101, 102)	Suitable number
1M Na_2SO_4(aq)	1 ml	Quantitative filter paper (Shuangquan Brand, 201, 203)	Suitable number
Sat. Na_2SO_3(aq)	1 ml	Napkin sheet	Suitable number
Sat. Na_2CO_3(aq)	1 ml	Deionized water	30 ml
Sat. K_2SO_4(aq)	1 ml		

Equipment description	Qty
Data logger (Vernier, LabQuest Mini)	1
Voltage sensor (Vernier, DVP-BTA)	1
Current sensor (Vernier, DCP-BTA)	1
Solar cell (MYGX 5W08)	1
Connecting wire and clip	6
Stopwatch	1
Thermometer, (-10 to 100) ºC	1
Beaker, 25 ml	2
Pipette (Dropper), 4 ml	12

DESIGN RATIONALE

Half-cell reactions of a concentration-dependent oxygen/hydrogen fuel cell are as follows (Ref: Wikipedia, Standard Electrode Potential, data page):

Reduction at cathode (positive pole): $O_2(g) + 4H^+(aq) + 4e \rightleftharpoons 2H_2O(l)$ E□ = +1.23 V

Oxidation at anode (negative pole): $2H_2(g) + 4OH^-(aq) - 4e \rightleftharpoons 4H_2O(l)$ E□ = - 0.828V

Overall cell reaction: $O_2(g) + 2H_2(g) + 4H^+(aq) + 4OH^-(aq) \rightleftharpoons 6H_2O(l)$

Cell diagram of a concentration-dependent oxygen/hydrogen fuel cell consists of the following two half-cells:

$$\overset{\ominus}{C_{(s)}} \mid H_2(g), OH^-(aq) \parallel O_2(g), H^+(aq) \mid \overset{\oplus}{C_{(s)}}$$

The carbon electrode with absorbed oxygen gas acts as the positive pole and that with absorbed hydrogen gas acts as the negative pole.

Nernst equation:

$$E = E^{\phi} - \frac{RT}{nF} \ln \frac{[Red]}{[Oxid]} = E^{\phi} - \frac{0.059}{n} \lg \frac{[Red]}{[Oxid]} \quad (T=298K)$$

Nernst equations for the two half-cells:

$$E_{(right)} = +1.23\ V - \frac{0.059}{4} \lg \frac{1}{[H^+]^4\, p_{O_2}} \quad \text{w.r.t. standard hydrogen electrode .....(1)}$$

$$E_{(left)} = -0.828\ V - \frac{0.059}{4} \lg \frac{(p_{H_2})^2[OH^-]^4}{1} \quad \text{w.r.t. standard hydrogen electrode .....(2)}$$

If $[H^+]$ and $[OH^-]$ = 1 mol l^{-1} and gas pressures of H_2 and O_2 are both 1 atm,

$$E_{(cell)} = E_{(right)} - E_{(left)}$$

$$E_{(cell)} = (1.23\ V) - (-\ 0.828\ V) = 2.058\ V,$$

The Nernst equation shows the e.m.f. of the cell is dependent on gas pressures of H_2 and O_2. The higher the pressure of oxygen, the larger the cell e.m.f. and the same for hydrogen. We could not measure these two variables but it was expected that the pressures of the absorbed oxygen and hydrogen should be higher than atmospheric pressure, as they were contained temporarily by the wet filter paper.

Suppose the solution concentrations around the electrodes after electrolysis are: $[H^+] = [OH^-] = 5$ mol l^{-1} and the gas pressures of H_2 and O_2 are both 1.5 atm. Substituting these values into eqt (1) and (2), we have:

$$E_{(right)} = [1.23 - \frac{0.059}{4} \times \lg\frac{1}{5^4 \times 1.5}]\ V = 1.274V$$

$$E_{(left)} = [-\ 0.828 - \frac{0.059}{4} \times \lg(1.5^2 \times 5^4)]\ V = -\ 0.874V$$

$$E_{(cell)} = (1.274\ V) - (-\ 0.874\ V) = 2.148V$$

The voltage of the fuel cell during discharge remained fairly stable at 2V (Fig. 3), which is consistent with the calculated value.

Innovative use of filter paper

The porous nature of graphite coupled with the absorbing property of filter paper is made use of in fabricating the MFPFC. Tight wrapping of electrodes by using wet filter paper enhances a high concentration of gaseous reactants, liberated after electrolysis, for cell reactions. This provides a way to increase the capacity of the fuel cell.

FABRICATION OF MFPFC

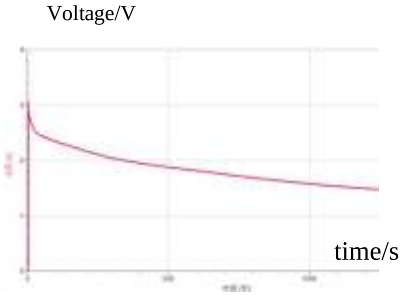
Take two pieces of HB pencil lead, each having a length of 8 cm and with a diameter of 2 mm. Separately wrap each twice with a section of 7 cm (width) filter paper, allowing 1 cm protrusion of pencil lead for electrical conduction. Place the two prepared electrodes in opposite direction so that the lead tips do not face each other. Wrap the two electrodes together with filter paper by a few rounds. Tie them up tightly by threads of string. Add drops of Na_2SO_4 solution (> 0.5 mol l^{-1}) to the bundled filter paper until it is completely soaked with the reagent. Connect the pencil leads to a solar cell (6V) and start electrolysis for 2 minutes, ensuring enough time for the generated oxygen and hydrogen gases to be absorbed by the pencil lead electrodes. A micro oxygen-hydrogen fuel cell is created when the solar cell is disconnected.

MFPFC VS TRADITIONAL FUEL CELL (Fig 1)

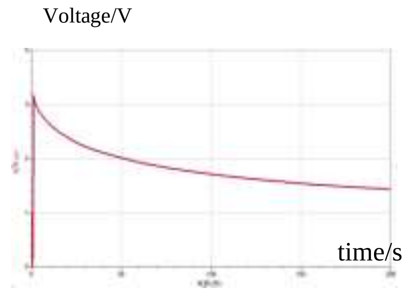
A voltage sensor is used to load the signal source (fuel cell) and the rate of drop of voltage of the fuel cell upon discharge over time was measured, as shown in Fig. 3.

Fig. 4 shows the voltage decay curve using MFPFC while Fig. 5 displays the corresponding curve for a traditional fuel cell.

(Fig. 3) Voltage decay curve test setup

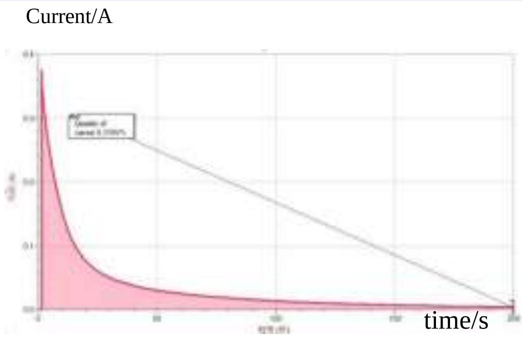


(Fig. 4) Voltage decay curve displayed by MFPFC

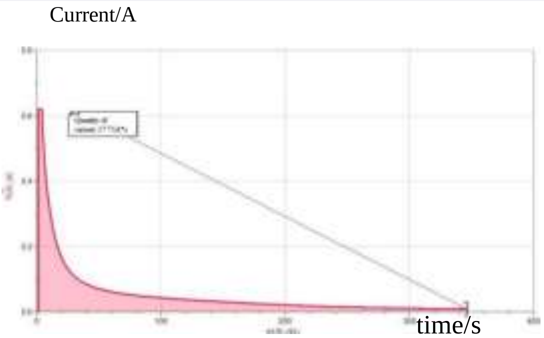


(Fig. 5) Voltage decay curve displayed by a traditional fuel cell

Replacing the voltage sensor by a current sensor for decay curve display overtime and by integrating current passed vs time, discharge current capacity for the two cases are illustrated in Fig. 6 and 7. Parameter values are listed in Table (1).



(Fig. 6) Current decay curve of MFPFC



(Fig. 7) Current decay curve of a traditional fuel cell

Table (1):

	Time required for voltage to drop to 1.5V / s	Peak current / A	Current half-life / s	Quantity of electricity / C
Traditional fuel cell	220	0.62	10.6	17.71
MFPFC	1184	0.37	8.0	6.34

(Table 1) Comparison of performance between MFPFC and traditional fuel cell

As shown in Table (1), output current of MFPFC is less than that of a traditional fuel cell, but the voltage discharge time is significantly longer. This feature is at an advantage for MFPFC to drive a quartz clock or a toy car which consumes weak current.

FACTORS AFFECTING PERFORMANCE OF MFPFC

a. Experimental method adopted

The suitable conditions for MFPFC to operate were tested sequentially according to the following list of variables. All measurements were made at an ambient temperature of 20^{o}C.

b. Choice of variables

1. Voltage of electrolysis

Various voltage supplies were used for the electrolysis startup for a duration of 2 minutes. A clean energy source using solar cell (MYGXS5W08) outputs 6V and 0.3A under decent sunlight irradiation. Table (2) shows the optimum supply voltage is 6V and a solar cell suits the design purpose, especially it meets the green requirement.

Table (2)

Electrolysis voltage / V	Time taken for MFPFC to attain 1.5 V / s
7.5	895
6.0	1184
4.4	351
2.7	103

(Table 2) Different electrolysis voltage for a duration of 2 mins

2. Time of electrolysis

As shown in Table (3), inspection of voltage decay time shows an electrolysis time of 2 or 3 minutes gave better results. Considering the amount of gas released factor and the small difference between voltage decay time for a 2 or 3 minute electrolysis time duration, the 2 minute time for electrolysis is considered to be the best duration time.

Table (3):

Electrolysis (6V) time / min	Time taken for MFPFC to attain 1.5 V / s	Amount of gas released from electrode
0.5	261	Small
1	745	Medium
2	1184	Large
3	1414	Very large

(Table 3) Voltage decay and electrolysis time

3. *Nature of electrode*

The device was tested with different kinds of graphite rod and ways of bundling them together. To remove the effect of organic residues and enhance the porosity of electrode, selected samples were heated strongly for a period of time. Table 4 shows single HB pencil lead performed better, and heating is not a suitable factor to be considered.

Table (4)

	Nature of electrode					
	Graphite rod dismantled from used dry cell	Three HB pencil leads bundled together	Single HB pencil lead (strongly heated)	Single HB pencil lead (unheated)	Single 2B pencil lead (strongly heated)	Single 2B pencil lead (unheated)
Time to attain 1.5 V / s	228	223	901	1184	1325	832

(Table 4) Discharge time and various kind of electrodes

4. Nature of electrolyte

Table 5 shows sat. Na_2SO_4 solution as electrolyte outperformed others tested.

Table (5)

	Nature of electrolyte					
	Sat. Na_2CO_3 (aq)	Sat. Na_2SO_3 (aq)	Sat. K_2SO_4 (aq)	Sat. Na_2SO_4 (aq)	1 mol l^{-1} NaOH(aq)	1 mol l^{-1} H_2SO_4(aq)
Time to attain 1.5 V / s	256	72	782	1184	50	131

(Table 5) Discharge time and various kind of electrolytes

5. Concentration of electrolyte

As shown in Table 6, a concentration of 0.5 mol l^{-1} performed better.

Table (6)

	Concentration of Na_2SO_4 solution					
	Saturated	1 mol l^{-1}	0.5 mol l^{-1}	0.25 mol l^{-1}	0.125 mol l^{-1}	0.0625 mol l^{-1}
Time to attain 1.5 V / s	1184	1124	1534	633	368	333

(Table 6) Discharge time and different concentrations of electrolytes

6. Nature of wrapping material

Various types of wrapping material were tested against voltage decay time of the constructed MFPFC. Table 7 shows the Shuangquan Brand 102 filter paper was the best choice.

Table (7)

	Type of wrapping material				
	Fast qualitative filter paper (101)	medium qualitative filter paper (102)	Fast quantitative filter paper (201)	Slow quantitative filter paper (203)	Napkin
Time to attain 1.5 V / s	1127	1184	992	969	1086

(Table 7) Effect of using different types of wrapping material

7. Dependence on temperature

The device was subjected to environmental temperatures of 6^{o}C and 20^{o}C. Table 8 shows a low temperature surrounding shortened the discharge duration time, a common phenomenon of dry cells. Investigation into methods of lengthening cell lifetime in low temperature weather conditions may be a topic for class discussion.

Table (8)

	Environmental temperature / ^{o}C	
	6	20
Time to attain 1.5 V / s	533	1184

(Table 8) Effect of temperature on discharge to 1.5 V

As shown by the above findings, the suitable conditions for operating a MFPFC are summarized by Table (9):

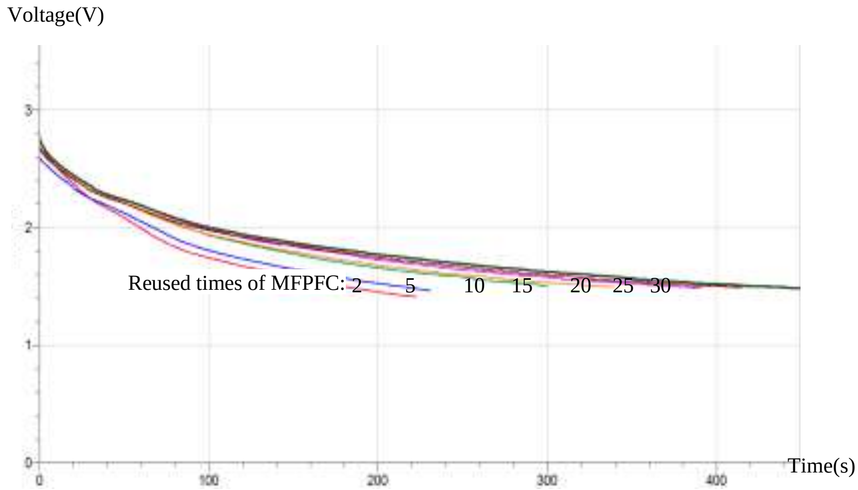
Table (9)

MFPFC specifications	
Electrode	Two pieces of HB pencil lead, 8 cm (length) by 2mm (dia), wrapped by filter paper to be wet with electrolyte
Electrolyte	0.5M Na_2SO_4 (aq.)
Environmental temperature / ºC	20
Initial electrolysis	
Duration of electrolysis / min	2
Voltage of electrolysis / V	6

(Table 9) Specifications of MFPFC and initial electrolysis

TESTING THE REUSE OF MFPFC

After the discharge of the MFPFC, a few drops of the electrolyte can be added to the micro fuel cell for keeping the filter paper wetted, then the electrolysis and discharging progress can be conducted again. We found that the MFPFC can be used repeatedly several times.



(Fig. 8) Voltage decay displayed by the used repeatedly MFPFC

Figure 8 shows the voltage decay curves displayed by the reused MFPFC discharged with a 220 Ω resistor, the digits indicating the number of times that the MFPFC has been reused.

CONCLUSION

The MFPFC was developed for use in school chemistry curricula which refer to Green Awareness and Sustainable Development. We have shown how convenient it can be for teachers and learners in school classrooms with limited resources. Our remaining concern is that teachers and learners understand the relation of what they observe in the classroom at microscale level to the global aim of sustainable development. The following points may help teachers establish this relationship and thereby achieve the broader educational aims of the curricula mentioned.

1. The fuel for the MFPFC (hydrogen) is produced by electrolysis of water. This process requires electrical energy and this must be generated by sustainable methods. This means avoiding electricity from coal-fired power stations and instead using solar energy resources. This is shown here by the use of a solar panel to cause the electrolysis at the start: simply plugging in to a traditional power supply or battery (as in Fig 1) is likely to confuse the sustainable development message.
2. On industrial scale the hydrogen produced is stored and/or transmitted to industrial users (eg for ammonia synthesis) and for users of hydrogen fuel cells. The fuel cell users do not electrolyse water! We do so here and both the hydrogen and oxygen are formed and 'stored' on the electrodes of the fuel cell itself. Bulk storage of the hydrogen does not take place in our experiments. We do not see the hydrogen (or oxygen). Separate microscale electrolysis of water can provide proof of the formation of these products.
3. The MFPFC is described as a fuel cell on the understanding that its fuel is 'stored' on one electrode. Strictly, cells are called fuel cells when the cell is a voltaic cell able to operate continuously as long as fuel is supplied. The MFPFC may claim to be a fuel cell as it can be used repeatedly provided its store of hydrogen and oxygen is replenished (see reuse of MFPFC).

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