The Effect of Resistors in Splitting of Water in Galvanostatic Electrochemical Cell with Higher Efficiency

Science Fair Project Report

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Submitted by

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ABSTRACT

In this research I used energy in the form of electricity from battery to split water into its individual components. The water molecule is composed of two elements: hydrogen and oxygen or, more precisely, two hydrogen atoms (H2) and one oxygen atom (O). Splitting water into its two components is much easier to do and is called water electrolysis.

Because pure water is not good at conducting electricity, however, electrolysis requires the addition of an electrolyte, such as salt or acid. So I prepared ***0.1 M phosphate buffer solution as electrolyte*** and I used cobalt nitrate as the catalyst to increase the speed of the reaction.

The electrolyte dissolves in water and separates into ions (electrically charged particles) that move through the solutions and are able to conduct electricity this way. To add electricity to the solution, I used two nickel plates as electrical conductors that make contact with the water.

I build a galvanostatic electrochemical cell using the electrolyte, nickel electrodes and with a circuit on the breadboard consisting of the batteries, resistor, and voltmeter/multimeter. After passing current I saw bubbles appearing around each of the nickel electrodes in the water and floating upward. Those bubbles are the components of water—hydrogen and oxygen gas. The nickel electrode (cathode) attached to the negative terminal of the battery collects hydrogen gas while the nickel electrode (anode) connected to the positive terminal collects oxygen.

I added three different resistors (10KΩ, 330KΩ, 470 KΩ) one by one and calculated the voltage required to run the electrochemical cell at each current delivered by the galvanostatic circuit. The efficiency of the reaction is determined by the voltage drop across the electrochemical cell and the speed at which we produce hydrogen and oxygen. Higher voltages lead to lower efficiency. The resistors helped in dropping the voltage. The results showed higher the resistor value, higher the efficiency.

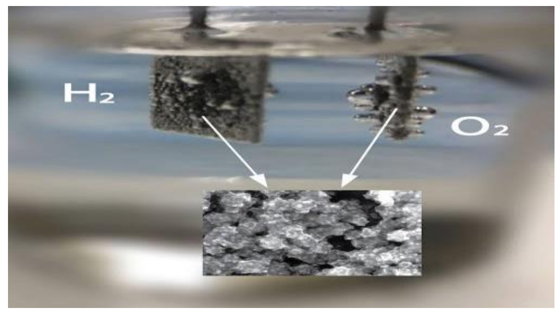
INTRODUCTION

Water splitting, provides attractive alternatives to hydrocarbon fuels. The hydrogen and oxygen gas can be stored separately, and later brought together as fuel in what is called a fuel cell. The combustion of hydrogen fuel (which is really the "burning" of hydrogen fuel, H_2, by letting it react with oxygen, O_2) releases water instead of carbon-based molecules, such as carbon dioxide and carbon monoxide. The water that is formed upon combustion of the hydrogen can be collected and "split" again to remake the fuel. In this way, the cycle is sustainable.

Equation 1:

2H2O+light⟷2H2+O2

- H_2O is water.
- H_2 is molecular hydrogen gas.
- O_2 is molecular oxygen gas



However, achieving efficient "splitting" of water requires a catalyst that assists oxygen-oxygen bond formation between two oxygen atoms derived from water to create oxygen gas. A catalyst is a material or molecule that increases the rate of a reaction between other starting materials, but is not used up in the reaction. Because the catalyst both increases the reaction rate and reduces the energy required to produce the product, the desired product can be made more quickly and with less total energy — is more energy efficient.

To split water, electrons and protons are removed from water to produce the O_2. The energy needed to drive this reaction is provided by changing the potential energy (or simply potential) of the electrons that are removed. If too high of a potential is used, the extra energy, known as overpotential, which does not get stored in O_2 is wasted as heat and makes the process inefficient. Thus, the goal of research is to reduce the overpotential required while increasing the rate of the reaction.

A catalyst formed from cobalt ions (Co) in a phosphate (Pi) buffered solution (Co-Pi) has recently been discovered, in Dr. Nocera's lab at MIT, that is capable of water oxidation to O_2 at low overpotentials and high rates. The catalyst is comprised of inexpensive, earth-abundant elements, and its formation is robust under a host of conditions.

A buffer solution is one which resists changes in pH when small quantities of an acid or an alkali are added to it. An acidic buffer solution is simply one which has a pH less than 7. Acidic buffer solutions are commonly made from a weak acid and one of its salts - often a sodium salt. Its pH changes very little when a small amount of strong acid or base is added to it. Buffer solutions are used as a means of keeping pH at a nearly constant value in a wide variety of chemical applications. In nature, there are many systems that use buffering for pH regulation.

A **galvanic cell** is a type of electrochemical cell. It is used to supply electric current by making the transfer of electrons through a redox reaction. It acts as a device in which simultaneous oxidation and reduction reactions take place. These reactions are used to convert the chemical energy into electrical energy, which can be utilized for any commercial purposes. The working of a galvanic cell is quite simple. It involves a chemical reaction that makes the electric energy available as the end result. During a redox reaction, a galvanic cell utilizes the energy transfer between electrons to convert chemical energy into electric energy.

Redox is a chemical reaction in which the oxidation states of atoms are changed. "Redox" is a word coined from two chemical terms, **red**uction and **ox**idation. Oxidation is the loss of electrons or an increase in oxidation state by a molecule, atom, or ion. Reduction is the gain of electrons or a decrease in oxidation state by a molecule, atom, or ion.

A galvanostat, (also known as amperostat) is a control and measuring device capable of keeping the current through an electrolytic cell in coulometric titrations constant, disregarding changes in the load itself. Galvanostatic refers to an experimental technique whereby an electrode is maintained at a constant current in an electrolyte. In galvanostatic tests, the change is plotted in potential verses time at constant current. A constant DC current is applied to the metal of interest while it is immersed in the electrolyte.

STATEMENT OF THE PROBLEM

Many forms of renewable energy, such as solar energy and wind energy, are not available at all times of the day and night. Without the sun, the solar cells on the roof cannot generate electricity to run our appliances. These renewable energies are intermittent sources of energy. We, as a society, however, need energy to be available at all times. For this reason, renewable energy sources like solar energy pose particular challenges to engineers if they are to be used by power plants that generate electrical energy for your house, or for your car in the place of gasoline.

Currently, power plants that supply energy to your house run on coal, natural gas, or gasoline as a fuel source and can do so 24 hours a day, 7 days a week. However, these fuels are carbon-based, meaning that they can generate pollutants. Additionally, fossil fuels are unsustainable, meaning that they will eventually run out. Using clean, renewable energy would be a solution to these problems.

Electrolysis is an important part of renewable energy research, and we can do it ourselves with household materials! During electrolysis of water, water is split into its two ingredients: hydrogen and oxygen. The pure hydrogen that is produced in this reaction can then be used in fuel cells to generate electricity. A drawback to many types of renewable energy is that the product isn't consistent. Solar power can't produce electricity at night, for example, and often the wind blows more at night than during the day.

The efficiency of the reaction is determined by the voltage drop across the electrochemical cell and the speed at which we produce hydrogen and oxygen. Higher voltages lead to lower efficiency. The resistors help in dropping the voltage. So I decided to research the effect of resistors in splitting of water in galvanostatic electrochemical cell with higher efficiency.

HYPOTHESIS

Resistors play important role in splitting the water in galvanostatic electrochemical cell with higher efficiency along with the catalyst.

DESIGN OF STUDY

INDEPENDENT VARIABLE:

- Resistors (10K, 330K, 470 K)

DEPENDENT VARIALBE:

- Efficiency of the Water splitting process
- Voltage drop across the resistor
- Current
- Time taken to stabilize the voltage

CONTROLLED VARIABLES:

- Battery Voltage
- Amount of buffer solution and catalyst
- Electrodes

MATERIALS:

- 9V batteries (4)/ Battery Eleminator
- 22-gauge electrical wire
- Alligator clips (12)
- Wire cutters and strippers
- Breadboard
- 10K Ohm resistor,   K Ohm resistor,   K Ohm resistor
- Digital multimeter
- Jar, plastic, 500 mL (large enough to completely fit the nickel metal strips)
- 250 mL glass beaker
- Small thermocol piece
- Nickel metal strips (2) (strips are approximately 5 inches tall and ¾ inch wide)
- Metal scoop for chemicals
- Cobalt nitrate hexahydrate
- 0.1 M phosphate buffer solution, pH 7.0 (500 mL) (To make this buffer);
    - Monopotassium phosphate (KH_2PO_4)
    - Sodium phosphate dibasic (Na_2HPO_4)

- Deionized water
- Measuring cup, 500 mL
- Digital scale

- Head screwdriver, small
- Cola
- Ruler
- Clock or stopwatch
- Permanent marker
- Lab notebook
- Glass stirrer

PROCEDURE:

- To prepare the ***0.1 M phosphate buffer solution*** add both, 2.63 g monopotassium phosphate (KH_2PO_4) (FW 136.09 g/mol) and 4.35 g sodium phosphate (Na_2HPO_4) (FW 141.96 g/mol) into the measuring cup (to lower the pH to 7.0). Then bring it to 500 mL using deionized (DI) water for a total phosphate concentration of 0.1 M. The pH should be around 7.

A. Creating the Galvanostatic Electrochemical Cell:

1. Build a circuit on the breadboard consisting of the batteries, resistor, and voltmeter/multimeter.
   a. Connect the four 9V batteries in series using some wire and 6 alligator clips so that the negative end of one battery is connected to the positive end of the next battery in the series.
   b. Using a piece of wire, connect the positive end of the series of batteries to the breadboard power bus.
   c. One end of the resistor is connected to the same column as the positive end of the batteries, and the other end of the resistor is connected to position 1a.
   d. Connect the positive (red) lead from the voltmeter/multimeter to the breadboard to a position in the same row as the end of the resistor.
   e. Connect the negative (black) lead from the voltmeter/multimeter to the breadboard to a position on the right half of the breadboard (7h).

    f. Connect a small piece of wire between a position in the same row as the voltmeter/multimeter's negative lead (7) and the ground bus.
    g. Using a piece of wire, attach the negative (-) end of the series of batteries to the ground bus (far right column) of the breadboard.
2. Use the nickel metal strips as electrodes. The nickel electrodes will serve as the scaffold for formation or electroplating of the cobalt catalyst.

   To clean the electrodes (nickel metal strips), pour some cola into a cup or jar. Put both electrodes in the cola. Make sure the nickel is entirely immersed. Cola contains phosphoric acid. This acid will do a great job of cleaning the surface of the electrodes. After a few minutes, remove the nickel electrodes, wash them off with plain water, and dry them.
3. Construct a method to secure electrodes within a small beaker or jar that leaves the top of the electrodes readily available to make an electrical connection to the rest of the circuit you started preparing above.
    a. It is important to ensure that the separation between the electrodes remains the same throughout the experiment. When securing the electrodes make sure to:
        - Position the electrodes 1-2 centimeters (cm) apart.
        - Make sure the electrodes are securely in place and not dangling freely or touching the sides of the beaker.
    b. Position the electrodes so that they will, later, once the buffer has been added to the beaker, only be immersed half way in the buffer. Note: It is critical that the top of the electrodes do not touch the buffer.
    c. Note: Use the Styrofoam disc and the 250 mL beaker for this step.
4. Add 0.1 M phosphate buffer solution, pH 7.0, to the beaker with electrodes so that the nickel electrodes are submerged half way in the buffer solution.

   Note: If have 500 mL of phosphate buffer only, the most you should fill the beaker with is 250 mL because in a later step you will need to use this same amount of phosphate buffer again.
5. Connect the nickel electrodes to the rest of the circuit using copper wire and alligator clips (one wire is connected to a position in the same row as the voltmeter/multimeter's positive lead, and the other wire is connected to a position in

the same row as the voltmeter/multimeter's negative lead (on the other half of the breadboard).

B. *Adding the Cobalt Catalyst and Measuring Its Effects*

1. Monitor the voltage readout on the voltmeter/multimeter. It should range between 1.9-2.4v and will take at least five minutes to stabilize. After the voltage reading has stabilized, record this voltage in lab notebook. This is the baseline voltage value for the electrochemical cell.
2. Using Equation below, and calculate the baseline efficiency of the water splitting reaction in electrochemical cell.

$$\%efficiency = (ideal\ voltage / measured\ voltage) \times 100\%$$

$$Ideal\ voltage = 1.23\ v$$

3. Now it is time to add the reactant necessary to form the cobalt-based catalyst. Put on a pair of disposable gloves and, using the metal scoop, add a pinch of the cobalt nitrate to the jar with the phosphate buffer and either start the stopwatch, or write down the time in your lab notebook. With the cobalt source and the energy provided by the batteries, the catalyst will start to form.
4. Adding small amounts of cobalt nitrate each time is critical. The cobalt nitrate concentration must remain very low so the solution does not become cloudy.
5. The cobalt-based catalyst will begin to electroplate onto the anodic (connected to + side of the battery) nickel electrode. As the catalyst film grows, a brown film growing on the anode, and the voltage readout on the voltmeter/multimeter will slowly drop. Eventually, after several minutes, the voltage will settle to a stable reading. Record this voltage readout. Also record how long it took, using either the stopwatch or clock, to reach a stable voltage reading.
6. As the reaction takes place, you will see tiny bubbles forming on the nickel electrodes.
7. Once the voltage readout stabilizes, add more cobalt nitrate to the solution to initiate formation of more cobalt-based catalyst. Again, add only a small amount of cobalt nitrate at a time. Record in lab notebook how long it takes the voltage to stabilize again and what that final voltage reading is.

8. Repeat step 7 until the voltage does not appear to change with the addition of more cobalt nitrate. This may take a total of four or five additions of small amounts of cobalt nitrate, and with each addition it may take around 5 to 20 (or more) minutes for the voltage to stabilize.
9. As you add more cobalt nitrate, how does the brown film on the anode change? Record observations in lab notebook.
10. At this point finished forming the cobalt-based catalyst on the nickel electrodes have finished. Measure and record the stabilized voltage one last time. The voltage readout in pure phosphate buffer reflects the operating potential of the electrochemical cell.

C. Add different resistors to the galvanostatic cell. Calculate the current that would pass through your cell. Determine the voltage required to run the electrochemical cell at each current delivered by the galvanostatic circuit.

D. Technical Notes:

i. The four 9-volt batteries generate a maximum of 36 (9v per battery x 4 batteries in series =36v). Typically will get less than 36 volts depending on how fresh the batteries are. The circuit is completed by two other resistors attached in series. One resistor is the electrochemical cell itself (the nickel electrodes in the phosphate buffer), and the other resistor is a 10,000 Ohm resistor we specifically place in series. This 10,000 Ohm resistor is critical to stabilize the electrochemical cell and ensure that a constant current is passed at all times. The reason for this is that most of the voltage (~30v) drops across the 10,000 Ohm resistor, and approximately 1.5-3v are dropped across the electrochemical cell. It is important to drop most of the voltage through the resistor because this will set the current that passes through the rest of circuit. Small variations in the electrochemical cell will have little effect because the 10,000 Ohm resistor is the dominant factor. Using Equation I=V/R and assuming that approximately 30 volts are dropped over the 10,000 Ohm resistor, the current can be calculated to be 3mA (30v / 10,000 Ohms = 0.003 A = 3mA). This calculation indicates there are 3mA of current flowing through the electrochemical cell.

ii. The voltage readout we measure is the voltage required by the electrochemical cell to maintain a constant current of 3mA. This voltage is the sum of the energy required to drive the water-splitting reaction 1.23v + over potential and any resistive losses in the cell. If there were no resistive losses, and the water splitting reaction was completely efficient, the necessary voltage to maintain the 3mA current would be 1.23v. The water-splitting reaction is not completely efficient and instead has a significant over potential. In the steps below, you are watching the over potential drop as the cobalt catalyst is electroplated onto the nickel electrode (specifically, the anode). This drop in over potential is reflected in a drop in the voltage you measure across the circuit. As the over potential required by the cell decreases (through addition of the catalyst), the voltage necessary to maintain the 3mA current also decreases. This indicates that we are running the water splitting reaction closer to the absolute, ideal limit. The efficiency of the reaction can be calculated using equation below.

$$\%\text{efficiency} = (\text{ideal voltage} / \text{measured voltage}) \times 100\%$$

$$\text{Ideal voltage} = 1.23 \text{ v}$$

iii. The efficiency of the reaction is determined by the voltage drop across the electrochemical cell. Higher voltages lead to lower efficiency. The cell is running at 3mA, and this current is directly proportional to the rate of hydrogen and oxygen production. Knowing the relationship between the current (rate) and the voltage (energy input) is essential to designing water splitting systems that are practical. Change the resistor so that the current is varied between 3mA and 30µA.

E. Analyze data.

- Calculate the final efficiency of the electrochemical cell with the cobalt-catalyst.
- Compare the original efficiency of the cell calculated to the final efficiency in case of the three resistors.
- How much does the cobalt-based catalyst increase the efficiency of the electrochemical cell in case of the three resistors?
- Plot the rate of increase in efficiency for the number of times you repeated step 7. Was the rate of efficiency increase constant?

COLLECTION OF DATA

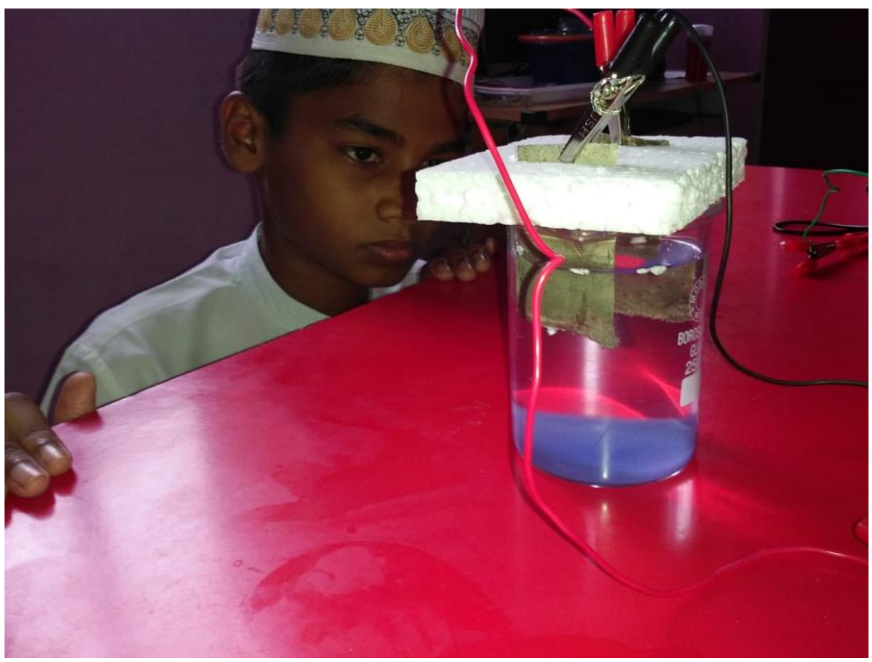
PHOTOGRAPHS

Inserting nickel plate

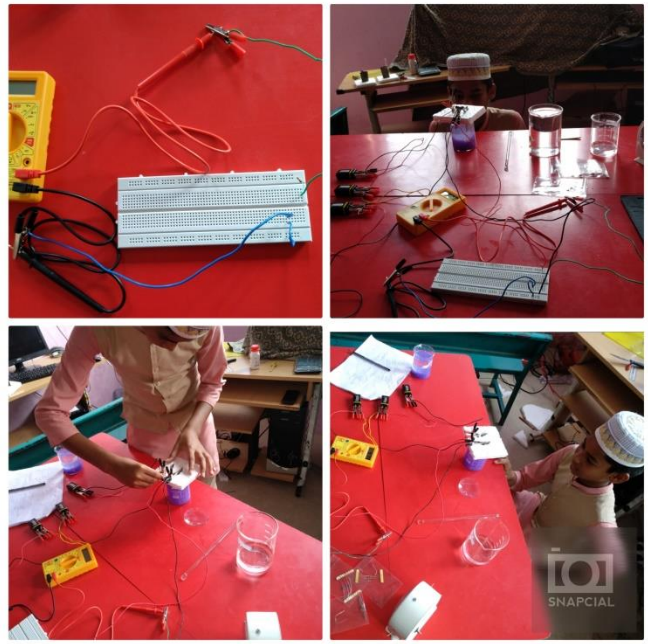
Bread board connection

Measuring coba nitrate salt

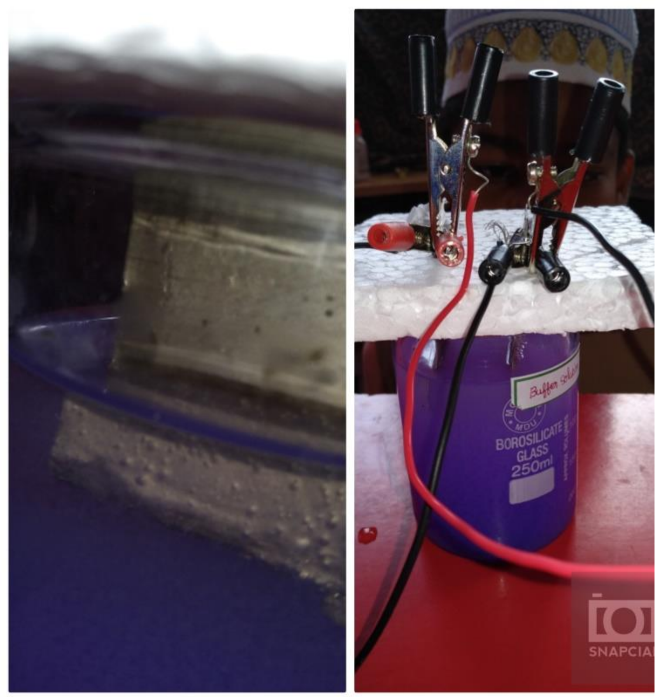


SNAPCIAL



SNAPCIAL

BOROSILICATE
GLASS
250ml
SNAPCIAL



BOROSILICATE
GLASS
250ml
SNAPCIAL

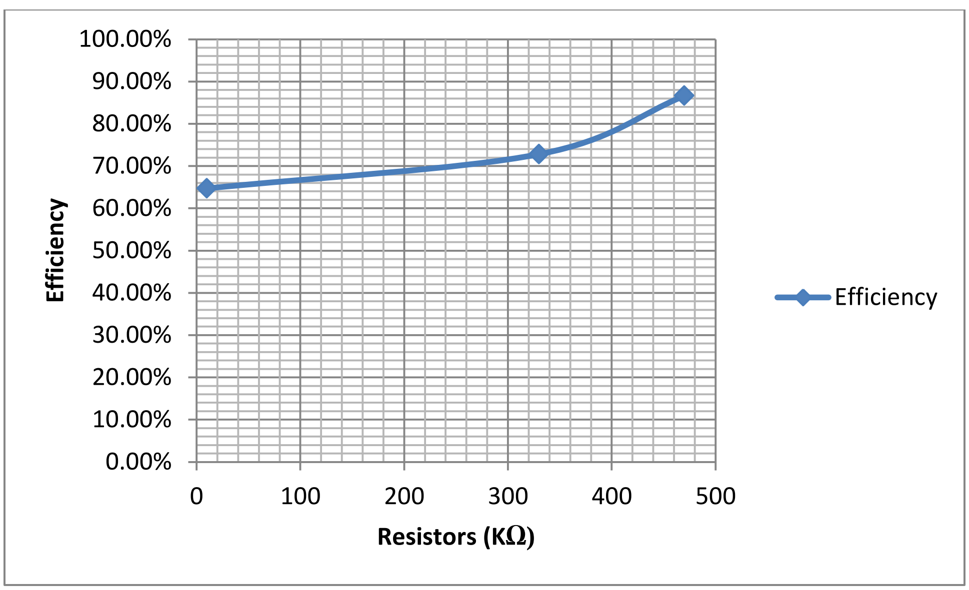
Qualitative Data:

Amount of Cobalt nitrate added= 0.73 g

Table: To calculate the efficiency of the galvanostatic electrochemical cell

S. No	***Resistors (ohm)***	***Stabilized voltage (V)***	***Time taken for the voltage to get stabilize (s)***	***Efficiency of the galvanostatic electrochemical cell***
1.	10 K	1.9	56	64.7%
2.	330 K	1.69	*51*	*72.8%*
3.	470 K	1.42	*47*	*86.6 %*

GRAPHICAL REPRESENTATION



The graph shows higher the resistor value, higher the efficiency

RESULTS AND DISCUSSION

- As soon as I connect the wires to the battery, I saw bubbles appearing around each of the nickel electrodes in the water and floating upward.
- Those bubbles are the components of water—hydrogen and oxygen gas—that have been split apart by the electricity as it travels through the water from one electrode to another electrode.
- The nickel electrode (cathode) attached to the negative terminal of the battery collects hydrogen gas while the nickel electrode (anode) connected to the positive terminal collects oxygen.
- I observed more bubbles in the cathode electrode than the anode electrode. I learned that because water molecule has two hydrogen atoms to every one oxygen atom.
- For the three different resistors (10KΩ, 330KΩ, 470 KΩ) added, I calculated the voltage required to run the electrochemical cell at each current delivered by the galvanostatic circuit.
- The resistors helped in dropping the voltage. The results showed that higher the resistor value, higher the efficiency.
- The cobalt-based catalyst increases the efficiency of the electrochemical cell in case of the three resistors.
- The speed at which hydrogen and oxygen are produced also got changed when I had changed the resistors.

CONCLUSION

- ***My hypothesis, "Resistors play important role in splitting the water in*** Galvanostatic electrochemical cell with higher efficiency along with the catalyst" has been proved.
- ***By increasing the value of resistors we can get more efficiency.*** Higher voltages lead to lower efficiency. The resistors helped in dropping the voltage. The results showed higher the resistor value, higher the efficiency.

APPLICATION

- Water splitting is the chemical reaction in which water is broken down into oxygen and hydrogen:

$$2\ H_2O \rightarrow 2\ H_2 + O_2$$

- Efficient and economical photochemical water splitting would be a technological breakthrough that could underpin a hydrogen economy. A version of water splitting occurs in photosynthesis, but hydrogen is not produced. No practical version of water splitting has been demonstrated, but the two component reactions (H_2 production and O_2 production) are well known. The reverse of water splitting is the basis of the hydrogen fuel cell.
- Electrolysis of water is the decomposition of water (H_2O) into oxygen (O_2) and hydrogen (H_2) due to an electric current being passed through the water.
- Society is already familiar with this concept of energy storage in chemical bonds in the form of fossil fuels (like gasoline and natural gas). By burning these fuels, energy contained within those high-energy bonds is released (and used by humans) along with carbon dioxide (CO_2) (which is not used by humans). The bonds between the carbon and oxygen in the carbon dioxide molecules have lower energy than the high energy bonds between the carbon and hydrogen in the fossil fuels. In this instance, the process is irreversible—once the carbon dioxide is created, it is released and cannot be easily converted back to fuel.
- One attractive approach for renewable energy storage is to use solar energy to drive the rearrangement of water (low-energy bonds) into molecular hydrogen gas and oxygen gas (high-energy bonds). This transformation, often called water splitting, provides attractive alternatives to hydrocarbon fuels. The hydrogen and oxygen gas can be stored separately, and later brought together as fuel in what is called a fuel cell. The combustion of hydrogen fuel (which is really the "burning" of hydrogen fuel, H_2, by letting it react with oxygen, O_2) releases water instead of carbon-based molecules, such as carbon dioxide and carbon monoxide. The water that is formed upon combustion of the hydrogen can be collected and "split" again to remake the fuel. In this way, the cycle is sustainable.

FUTURE ENHANCEMENT

- A primary goal for renewable energy research is to develop fuel storage methods that are scalable, sustainable and do not used carbon-based fuels. The ideal energy cycle would be a fully renewable one where the fuels can be utilized (burned to extract the energy from the high-energy bonds) and the waste products (low energy bonds) can be captured and reused to form the same fuel again.
- I want to do my further research on generating electricity from the renewable resources in more effective way without polluting the environment and to develop fuel storage methods that are scalable, sustainable and do not used carbon-based fuels.

ACKNOWLEDGEMENT

The success and final outcome of this project required a lot of guidance and assistance from many people and I am extremely privileged to have got this all along the completion of my project. All that I have done is only due to such supervision and assistance and I would not forget to thank them.

First I want to thank **Almighty Allah** for the successful completion of this entire project.

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