Hydrogen Electrolyser Demonstration Unit

Introduction

This project aims to give a simple demonstration of hydrogen energy technology using a lab-scale hydrogen electrolyser as an interactive teaching tool. By flicking the switch, the user can trigger reaction within an electrolyser to produce hydrogen gas, and observe how water can be split into hydrogen and oxygen.

Hydrogen (H) is the universe's simplest, lightest, and most abundant element. We find hydrogen compounded on Earth with other elements, like in H_2O, and various hydrocarbons. When hydrogen is on its own, it exists as a gas, H_2. This gas is odourless, colourless and tasteless, but it is useful. We can burn H_2 and O_2 to produce energy, and the only byproduct is water, or H_2O. Using hydrogen as fuel means we can produce energy without emitting any carbon.

The cleanest and most sustainable route to produce hydrogen is by electrolysis. Electrolysis uses electricity to split water molecules into hydrogen and oxygen gases. In an electrolyser, a direct current is passed through water containing an electrolyte. At the negatively charged cathode, hydrogen gas is produced, while at the positively charged anode, oxygen gas forms. A membrane separates the two sides, preventing the gases from mixing and ensuring pure hydrogen is collected. This document will give the user an overview of how to use the demonstration unit and how it works. Embedded links are included throughout to provide more detail on circuit diagrams, CADD drawings, data sheets and the Arduino script used for the unit.

The Reaction:

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

Cathode:

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$$

Anode:

$$2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$$

System Overview

The demonstration unit in front of you is a lab-scale hydrogen electrolyser. The system is built from three main parts:

- **Electrolyser:** Produces hydrogen and oxygen from water and electricity. The electrolyser in use in the demonstration unit is from HTEC Education.

Figure 1: Lab-sized Electrolyser

- **Control Circuit:** Uses an Arduino, relay, and sensors to manage power flow, ensure safety and allow for user control.

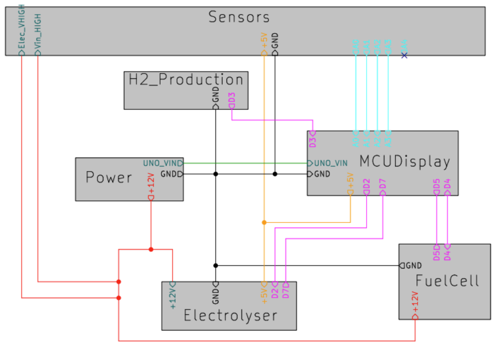

Figure 2: Circuit Diagram

- **Liquid and Gas Management Rig**: Consists of two tanks and a system of tubing to allow water to flow into the electrolyser, hydrogen and oxygen to flow out into separate tanks. The system is supported by a T-slot rig to keep the tanks at the appropriate heights.

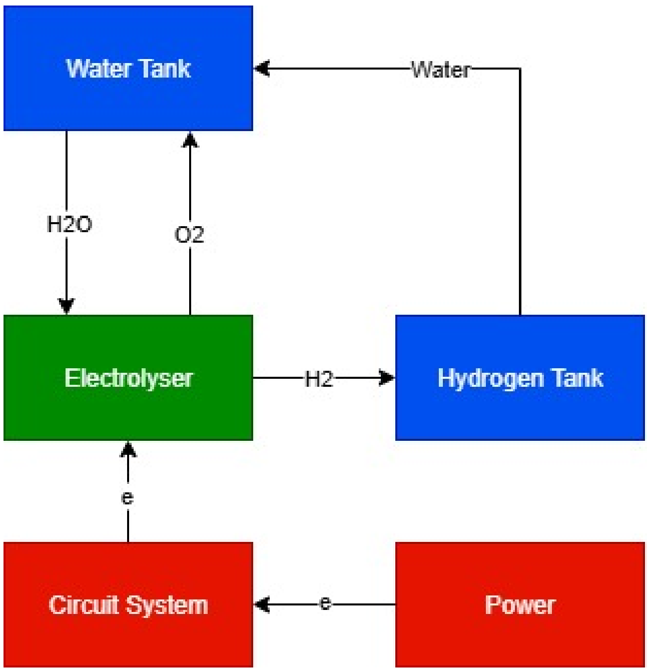

Figure 3: System block diagram of the electrolyser project.

Figure 3 above shows an overview of how electricity, water, oxygen and hydrogen flow through the system.

The fuel the electrolyser uses to create hydrogen is electricity and water. Electric current flows from the power source, through the control circuit and into the electrolyser, the electrolyser is also being fed with water from the water tank.

As electrolysis occurs, the electrolyser releases hydrogen through two tubes as labelled on the rig into the bottom of the hydrogen tank. The hydrogen tank is full of water, and as the hydrogen enters the tank it rises to the top and the additional pressure pushes the water out. This water flows back into the water tank to be re-cycled.

Oxygen is another by-product of the electrolysis, as it is released from the electrolyser it travels out through two tubes, and it carries some water with it. It is tubed back into the water tank for the water to be re-cycled into the system.

It is worth noting that in large scale hydrogen electrolysers, the water must be de-ionised for longevity and efficiency. This means that it can't be re-cycled as it is in this lab-scale setup.

Circuit Design

The purpose of the circuit is threefold:

1. **To control how much power enters the electrolyser cell**

   The cell needs enough power to meet the thermodynamic requirement of splitting the water, the Gibbs Free Energy Barrier. The minimum voltage required to break this barrier is $1.23V$ [1]. However, in practice, $1.23V$ will not electrolyse water at a useful rate. Overpotential is needed to account for any resistance in the electrolyte and to overcome activation barriers. The circuit is designed to supply exactly $1.6875V$ to each cell of the electrolyser, which ensures it will consistently electrolyse the water supplied. The voltage is controlled precisely by the use of a buck converter.

2. **To monitor system conditions for safety purposes**

   The circuit system uses an array of sensors to monitor voltage and current at the input of the circuit system, voltage and current as they enter the electrolyser, water level and pressure in the hydrogen tank. These values are given limiting ranges; if something were to go wrong with the system and the values got too high or too low, the system would automatically shut off for the user's safety. The water level limits the system to producing a safe amount of hydrogen.

3. **To allow the user control of the system**

   The circuit system employs a rocker switch and an LCD to allow the user to control the system. The user can flick the switch on or off to begin supplying power to the electrolyser. The LCD will light up to give the user information about the conditions of the system.

System Components

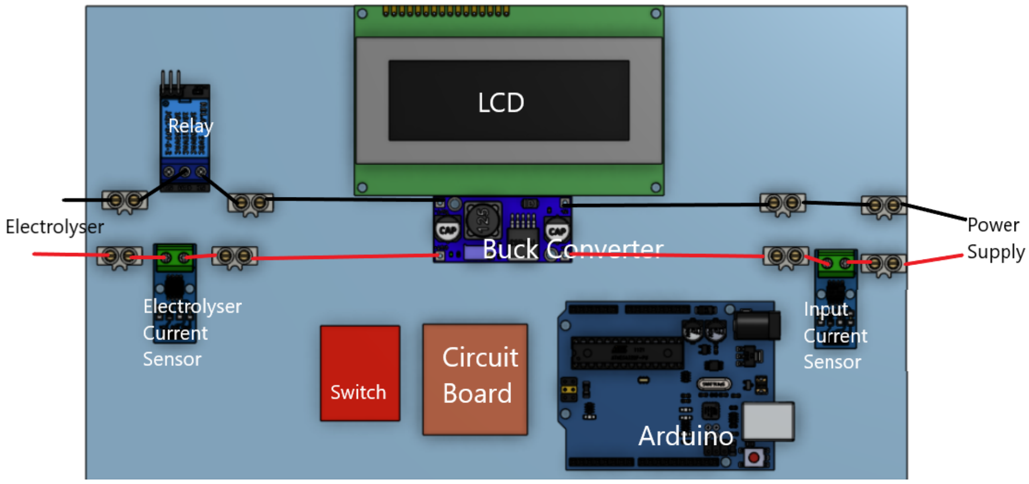

Figure 4: Overview of System Components

- **Arduino Uno**

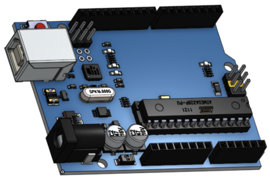

Figure 5: Arduino

The Arduino acts as the control and monitoring unit for the circuit. It reads information from various sensors and outputs the information to the LCD. The Arduino also continuously runs a program through its processor, which applies the logic of the code written for it and makes decisions based on the sensor inputs. For instance, if the water level is too low, it will send a message to the relay to switch off the whole system.

- **Relay**

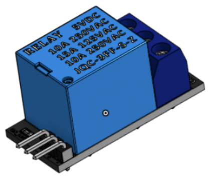

Figure 6: Relay

The relay is essentially a switch that is controlled by the Arduino. If the switch is on, power flows through the circuit, and if it is turned off by the Arduino, it stops power flow through the circuit. The relay is influenced by the level of hydrogen that is in the tank, the pressure in the tank, the power being supplied by the power source into the and the status of the switch. All conditions have to be met for the relay to switch on. The relay is connected to the power supply ground rail.

- **Current Sensor**

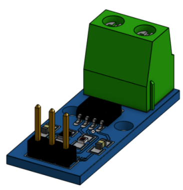

Figure 7: ACS712 Current Sensor

Two current sensors are connected to the circuit. The first sensor is connected before the buck converter. It measures the current at the power supply to verify a good connection from the power supply to the circuit, and sends an analogue signal to the Arduino. The second current sensor is connected after the buck converter, and it measures the current as it enters the electrolyser. This is important to ensure the current the electrolyser receives is in a safe range.

The sensors work by using the Hall effect. The Hall effect is the production of a voltage experienced by a conductor when current passes through it in the presence of a magnetic field. Under zero load, the sensor outputs a voltage of $2.5V$ to the Arduino. As the current passes through the sensor, it outputs a higher or lower voltage than $2.5V$ depending on the direction of current. The Arduino converts this voltage to a corresponding current based on the sensitivity rating of the sensor.

- **LCD Display**

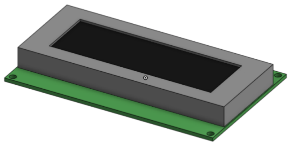

Figure 8: LCD

The LCD displays information about the status of the system, whether it is producing hydrogen or not. It also displays the sensor values. The LCD works by I^2C protocol, meaning it has an SDA and an SCL line. SDA (Serial Data Line) is a bidirectional line on which the actual data is transferred between the LCD and Arduino. The SCL (Serial Clock Line) carries the clock signal, which keeps everything in sync.

A software library is implemented into the Arduino code to allow the SDA and SCL lines to work on the digital pins of the Arduino, as opposed to taking up space on the analogue side of the board.

- **Rocker Switch**

Figure 9: Rocker Switch

The Rocker Switch allows the user to turn the system on and off. The principle of operation is simple. If the switch is closed, a VCC $5V$ signal from the Arduino travels through the switch, through a COM wire that sends a signal back to the Arduino to tell it the switch is closed, through a resistor and to ground. But if the switch is open, the VCC $5V$ has no path to travel through, and the Arduino does not receive the signal from the COM wire.

- **Buck Converter**

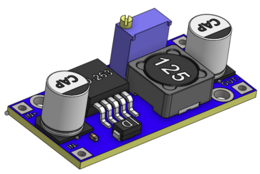

Figure 10: Buck Converter

The buck converter is used in the circuit to step down the input supply voltage to the exact required voltage for the electrolyser. The buck steps the voltage down to $6.75V$, or $1.6875V$ for each of the four cells in the electrolyser. It was important to use a buck converter here instead of other linear step-down methods because a buck converter operates at a much higher efficiency. Instead of burning off extra voltage as heat, it delivers the same amount of power to the electrolyser at a lower voltage but a higher current.

- **Circuit Board**

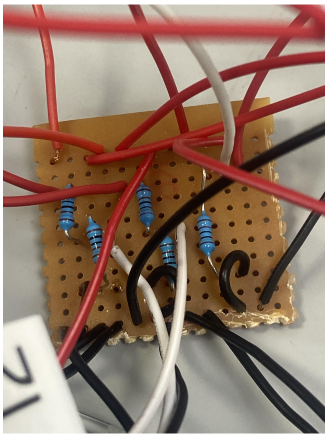

Figure 11: Circuit Board

The circuit board consists of wires and resistors soldered to a breadboard. Its purpose is to provide power and grounding to all components and measure the voltage at the input and electrolyser. All red wires on the top of the board are part of the $+5V$ rail, powered by the Arduino reference voltage and sent to each external component to power them. All black wires on the bottom of the board provide grounding to external components in the same way.

The two left-most resistors are the voltage divider circuit for the input voltage, and the two to the right of them are the voltage divider circuit for the electrolyser voltage. Voltage dividers are required to step down the voltage below $5V$ so that the Arduino ADC can read the voltage. This is a linear step-down that occurs by having two resistors of different resistances in series, and measuring the voltage at their junction. $R1$ and $R2$ were resistors of $10k\Omega$ and $5k\Omega$. The Voltage Divider Rule states:

$$V_{\text{out}} = V_{\text{in}} \cdot \frac{R_2}{R_1 + R_2}$$

Meaning that the $Vout$ measured at the junction is a third of the Vin. This is accounted for in the Arduino script to ensure an accurate reading of the voltage that the Arduino ADC can safely read.

Arduino Script Workflow

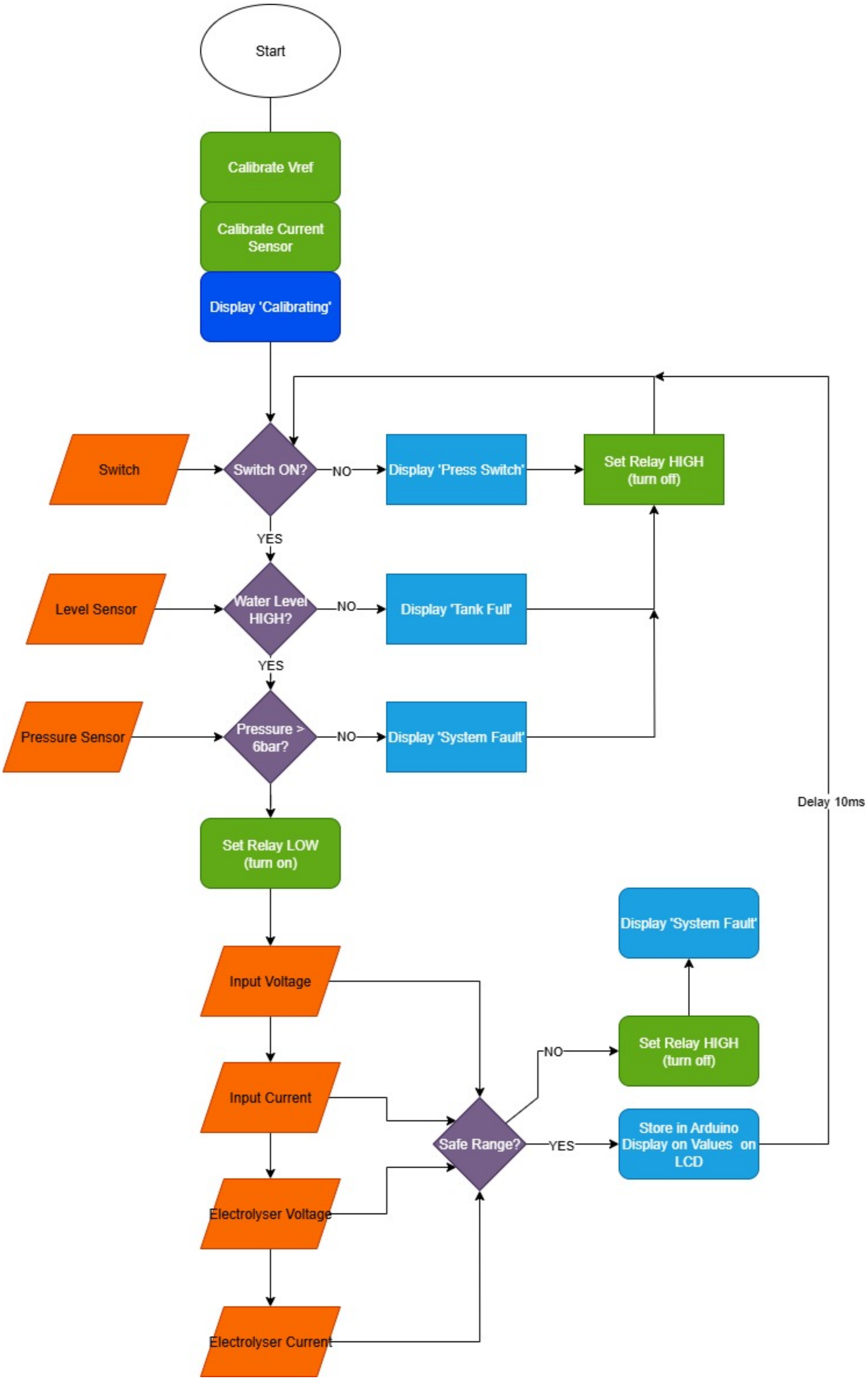

Figure 12: Simplified Flowchart of the System Workflow Logic of the Arduino Script.

- **Calibration Stage**

  Upon beginning, the code enters a calibration stage. The first thing it aims to calibrate is the Arduino's reference voltage (Vcc). This should be exactly 5V; however, wear on the components of the Arduino can cause slight inaccuracies, which lead to inconsistent sensor readings. The script takes 10 readings of the Vcc using the internal AVR $1.1V$ bandgap on the Arduino, and uses the average as Vcc.

The second stage of the calibration is for the current sensors. The current sensors' reference voltage of $2.5V$ can also drift due to wear and tear of the components. By reading the zero-load voltage of both sensors 2000 times, and taking the average as the reference voltage instead of trusting it to be $2.5V$, the inaccuracy is eliminated. The sensors do still experience noise due to the high-frequency switching activity of the buck converter. But the calibration reduces error.

- **Status Check Stage**

  The status check stage consists of a series of decision blocks, where only if conditions are safe will the script allow the system to turn on. The Arduino reads the signal from the switch, the water level sensor and the pressure sensor and performs a logic check to ensure values are correct before signalling the relay to turn on. If conditions are not met, a signal is sent to the LCD to display a corresponding message, and the relay is set to turn off as a safety measure.

- **Main Loop** Once the relay is on, current is flowing through the system, and the cells begin to electrolyse. At this point, the sensors continuously measure their analogue values and convert them to digital values, while ensuring they are in a safe range. If they are, their values are displayed on the LCD, a delay occurs, and it is looped back to also continuously measure the switch status, water and pressure levels. If there are unexpected issues, the Arduino shuts off the relay and displays an error message on the LCD.

References

[1] Martin Chaplin. Electrolysis of water, June 2022. Page established 2012; last updated 20 June 2022.