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Research Paper

Design and Development of a Solar-Powered Smart Heater

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ABSTRACT

Renewable energy sources are those that replenish naturally without depletion. Examples of such sources are bioenergy, hydropower, geothermal, wind and solar energy sources. The alarming rate of global energy demand and consumption necessitates an immediate solution for energy conservation and maximum efficiency of new technological gadgets now being built. As a gadget, a solar water heater transforms dc electricity into heat energy, which is then transferred to the water in which it is immersed. The size of the heater is determined by its design, capacity, and intended purpose; it might be for household or industrial use. As an alternative to conventional electric water heaters, this effort focuses on the design and development of a solar-powered smart water heater. In tests using a variety of settings, the solar-powered smart heater that was constructed performed admirably. The components used include a PIC16F876A microcontroller, a 12 V/300 W monocrystalline PV, a 12 V/ 40 A charge controller, and 12 V / 150 W dc submersible heating element among others. The temperature control capacity of the fabrication makes it useful in water management system applications such as in aquaculture fingerling hatchery, hot water dispenser and shower among others. The system showed excellent performance in water temperature control using a 150 watts dc heater.

Keywords: Solar, heater, photo-voltaic, temperature-controlled, direct current, alternating current

1. INTRODUCTION

In today's modern world, with the introduction of new technologies, electrical energy use is greatly increasing. Fossil fuel which is the major electrical production contributor is not renewable and its continuous use can result in the depletion of petroleum reserve. Sources of renewable energy are those that replenish themselves naturally without depletion. Examples of such sources are bioenergy, hydropower, solar, geothermal and wind energies. Among these sources, solar energy is said to be the most efficient and abundant. The sun has been regarded as the ultimate life source on earth and its energy giving capacity has been harnessed through several means and for several purposes over the years. The most prominent term associated with sun energy harvesting is solar energy which is one of the major driving forces of technological advancements in recent years.

Solar is a clean renewable alternative to fossil fuel; it is also environmentally friendly, has diverse applications and low maintenance cost. Solar system converts irradiance from the sun into usable direct current (dc) electrical power. This makes solar energy a subset of renewable green energy sources and it is deemed the most stable free energy source. Several researches have been done on solar energy use as replacement for the epileptic power supply experienced in many parts of the world. The unanimous conclusion of such researches is that solar energy is clean, viable and sustainable. There have been several designs to harvest and harness solar power for both direct current (dc) and alternating current (ac) power systems both as standalone and grid-tied.

A solar dc power system consists majorly of the battery bank, solar panel array, battery charge controller and dc wiring. A solar ac power system consists of the inverter (dc to ac converter system), battery bank, solar panel array, battery charge controller, dc wiring and ac wiring. Solar technologies involve the generation of electricity from solar irradiance using photo-voltaic panel(s) and storage in batteries when the sun's irradiance is low [1] [2].

Solar water heater as a device, converts dc power to heat energy for onward transference to the water in which it is immersed. This consequently increases the temperature of the water until the desired hotness is attained. Commonly available heaters are manually operated, hence, a smart heater that can automatically control itself is needed. The scale of the heater depends on the design, capacity and usage, it could be either for domestic or industrial use [3] [4] [5] [6]. Studies for the transference of solar energy to water for storage or immediate use has been carried out and used since the 1970's when it was utilized for pool heating in the California. Continual research and innovations gave birth to product capable of heating water efficiently even in less sunny regions of the world [7] [8] [9] [10].

2. MATERIALS AND METHOD

Components used in this work include peripheral interface controller (PIC) PIC16F876A, Monocrystalline PVs, Charge controller, 20MHz crystal oscillator, LM35 Temperature sensor, PC817A Optocoupler, 12V DC submersible heating element, LM044L LCD and IRF3205PbF pulse width modulator (PWM) driver. This section gives details on the components used for the fabrication and design.

2.1 The Design

The design of the temperature-controlled solar-powered dc water heater is discussed in this section. The block diagram for the design is as shown in Fig. 1. The sectional interconnectivity and workflow of the design is indicated by the arrows and its directions. The PV array section harvests the solar energy and converts it to dc electricity, this is passed through the charge controller that controls the rate of charge of the connected battery. The battery serves as the power supply unit of the system, this is converted to a regulated 5V by the regulator circuit. The regulated 5V is used to power the microcontroller, the temperature sensor and the LCD while the heater driver is directly powered from the 12V battery.

2.2 DC Supply with Voltage Regulator

A 12 volts battery is used as the main supply for the system and to directly power the 12V heating element used. The temperature sensor, microcontroller and Liquid Crystal Display (LCD) are powered with 5V according to manufacturers' recommendations, which is the output of the voltage regulator LM7805.

The power supply circuitry is shown in Fig. 2. Capacitors of ratings 2,200uF and 100nF serve as charge accumulators to prevent the regulator's output voltage drop during power surges. The two 100nF capacitors are used to suppress high frequency voltage spikes in order to have a stable voltage at the output.

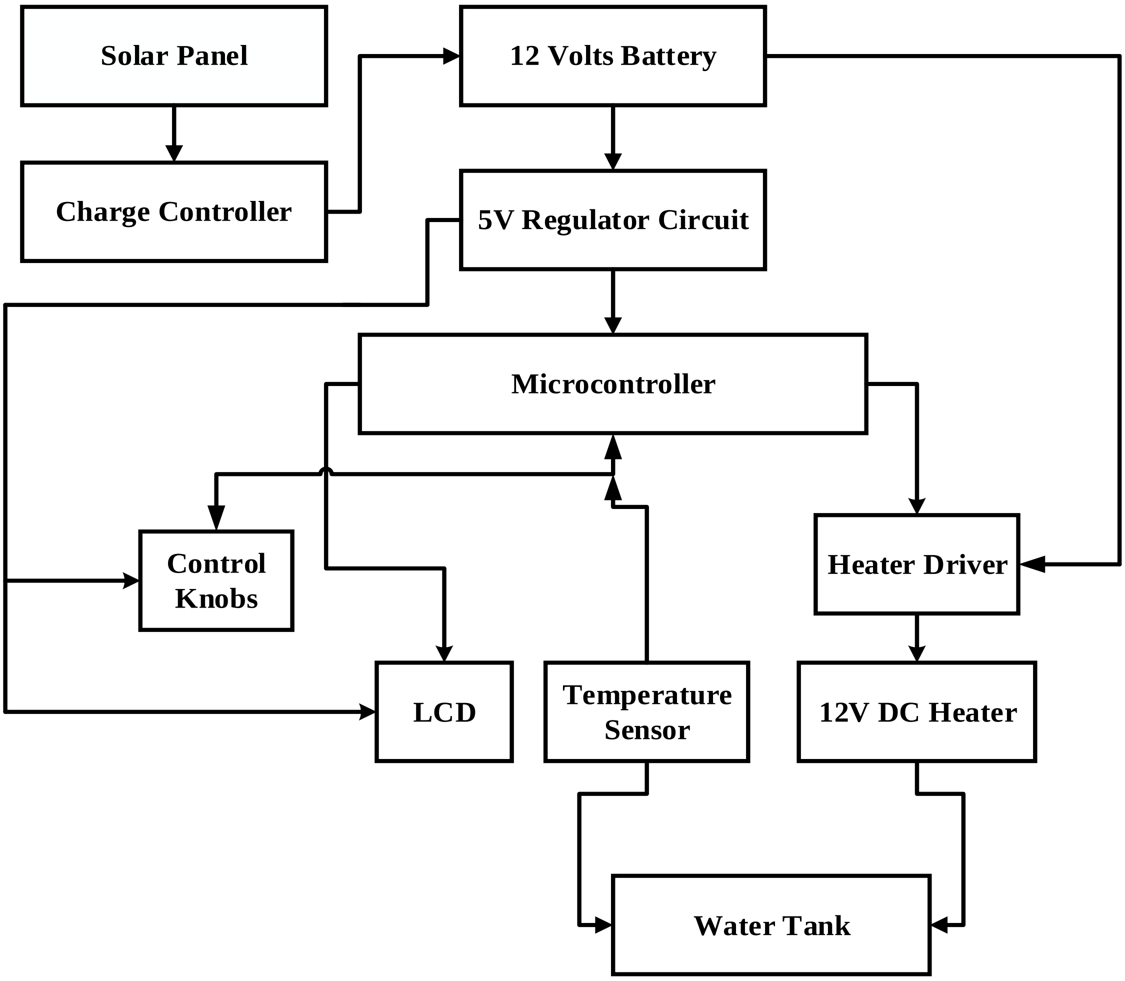

Fig.1: Block diagram of temperature-controlled dc powered water heater

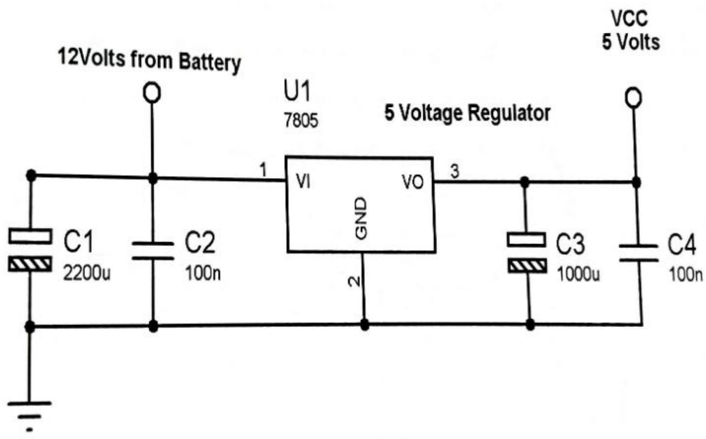

Fig.2: 12 Volts to 5 Volts regulator circuit.

2.3 Battery

One rechargeable deep cycle lead acid battery of 12V, 150AH was used in this work, the output of this battery is fed into the LM7805 which gives an output of +5V that is required to power the control unit section. The choice of 12V, 150AH deep cycle Lead acid battery is informed by the rating of the heating element, the need for regular deep discharging required by the design when there is low or no sun irradiance and cost. The Lead Acid battery used is a rechargeable type that consists of cells which can be discharged into load and recharged several times.

The mathematical basis for the choice is indicated in equations 1 and 2.

Heating element power rating $P_h = 150\text{W}$

Heating element voltage $V_h = 12\text{V}$

Heating element current $I_h = \frac{P_h}{V_h} = \frac{150W}{12V} = 12.5A$ (1)

To get a discharge time of 12 hours, the battery capacity = $I_h \times time = 12.5A \times 12H = 150AH$ (2)

Hence, the battery capacity that could power the heater element for 12 hours is 150AH.

2.4 Microcontroller (PIC16F876A)

PIC16F876A is a common 28-pin microcontroller that has been utilized for a wide range of applications. It is an integrated circuit (IC) with several components such as a processor core, input and output peripherals among others. It is a low power complementary metal oxide semiconductor with an operating speed of DC - 20MHz clock input and 200ns instruction cycle. It can operate under both industrial and commercial temperature ranges with operating voltage range of 2.0V to 5.5V. The pin number notations and physical structure of PIC16F876A is as shown in Fig. 3 and 4 respectively. The features of the microcontroller that made it the choice control unit of the design is listed in Table 1.

PIC16F876A, it is the brain of the design as it controls the operations of all the components in the design. To generate PWM with the help of a PIC16F877A microcontroller, built-in Capture /Compare/ PWM (CCP) modules are used. The program flowchart developed for the design is as shown in Fig.5. The flowchart was converted into a microcontroller program and transferred to the PIC16F876A via USBPICPROG (a USB programmer hardware).

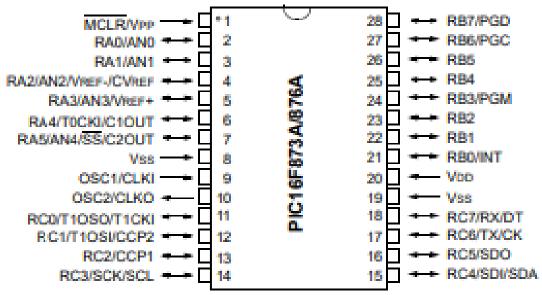

Fig.3: PIC16F876A Pin Out Diagram [11].

Fig.4: Physical Structure of PIC16F876A [12].

Table 1: PIC16F876A Features [12]

Key Features	PIC16F876A
Operating Frequency	DC – 20 MHz
Resets (and Delays)	POR, BOR (PWRT, OST)
Flash Program Memory (14-bit words)	8K
Data Memory (bytes)	368
EEPROM Data Memory (bytes)	256
Interrupts	14
I/O Ports	Ports A, B, C
Timers	3
Capture/Compare/PWM modules	2
Serial Communications	MSSP, USART
Parallel Communications	—
10-bit Analog-to-Digital Module	5 input channels
Analog Comparators	2
Instruction Set	35 Instructions
Packages	28-pin PDIP 28-pin SOIC 28-pin SSOP 28-pin QFN

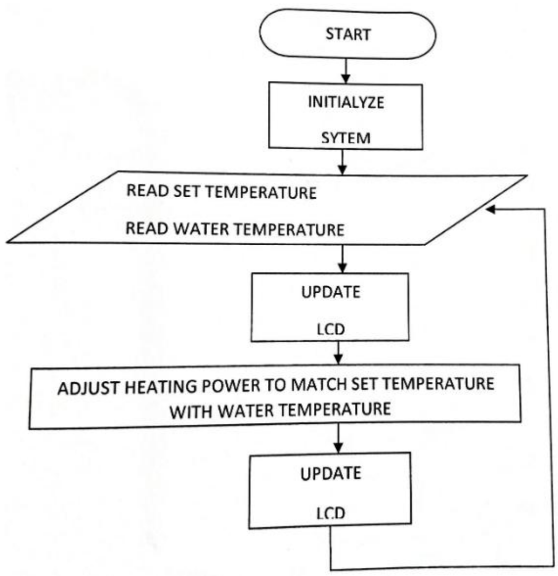

Fig. 5: Program flowchart

2.5 Temperature Sensor LM35

LM35 series are precision sensors that measures temperature in centigrade scale, its advantage over Kelvin scale sensor is that there is no need for calculating the centigrade equivalent. LM35 doesn't need external trimming to produce ±3/4^{0}C accuracies at the range of -55 to +125^{0}C and ±1/4^{0}C at room temperature. It is a low-cost sensor and has a linear output, low output impedance and an intrinsically precise calibration that makes interfacing with other components easy. It has temperature-limit alarm, less than 750ms query time, usable with dc power of 3.0 to 5.5V and uses 1-wire interface. LM35 can be installed like other ICs, its temperature is usually around 0.01^{0}C of its installed surface [13]. The pin out diagram of a waterproof LM35 is shown in Fig. 6, with red, yellow and black designated as V_{cc} (Voltage Input), Analog data Out and Ground respectively [14].

Fig. 6: LM 35 Physical Structure [14].

2.6 PC817A Optocoupler

Electronic components and signals can be exposed to voltage surges caused by electrostatic discharge, lightening, spikes and variations in power supply [15]. Up to 10KV surge can be induced into a circuit by a lightning strike, this is overly above the limits of most circuits' constituent electronic components. PC817A opto-coupler is an electronic component that can be used to prevent high voltage from a transmitting end of a circuit to get to its receiving end. It uses light beam (photon) to isolate the circuit's section so as to prevent damage. It is also known as an optical isolator or photocoupler [16]. Most opto-isolator are built to tolerate up to 10KV input-to-output voltages and up to 25KV/µs.

PC817A consist of a sensor-source combination such as phototransistor-LED, photodiode-LED and photoresistor-lamp, housed in an opaque package. It transforms inputted signals into light, transmit it via the dielectric channel, captures light at the output end and converts the light back into an electric signal. It is unidirectional, can transmit slow moving DC signals and has a current transfer ratio between 80 and 160%. The absolute maximum ratings for PC817A are as shown in Table 2.

Table 2: PC817A Absolute Maximum Ratings at an ambient temperature of 25^{0}C [17]

	Parameter	Symbol	Rating	Unit
Input	Forward current	IF	50	mA
	*1Peak forward current	IFM	1	A
	Reverse voltage	V_R	6	V
	Power dissipation	P	70	mW
Output	Collector-emitter voltage	V CEO	35	V
	Emitter-collector voltage	V ECO	6	V
	Collector current	IC	50	mA
	Collector power dissipation	PC	150	mW
	Total power dissipation	P tot	200	mW
	*2Isolation voltage	V iso	5 000	V rms
	Operating temperature	T opr	- 30 to + 100	˚C
	Storage temperature	T stg	- 55 to + 125	˚C
	*3Soldering temperature	T sol	260	˚C

**1 Pulse width<=100µs, Duty ratio: 0.001; *2 40 to 60%RH, AC for 1 minute; *3 For 10 seconds*

2.7 20MHz crystal oscillator

This is a circuit that converts mechanical resonance of a piezoelectric vibrating crystal to an electric signal of precise frequency. The frequency can be used to track time, provide stable clock for digital ICs and stabilize frequency for radio transmitter and receivers. A 20MHz crystal oscillator is included to provide the 20MHz clock signal needed for the smooth operation of the PIC16F876A microcontroller. Fig. 7 shows the physical structure of a 20MHz crystal oscillator while Fig. 8 shows its circuitry connection to a microcontroller.

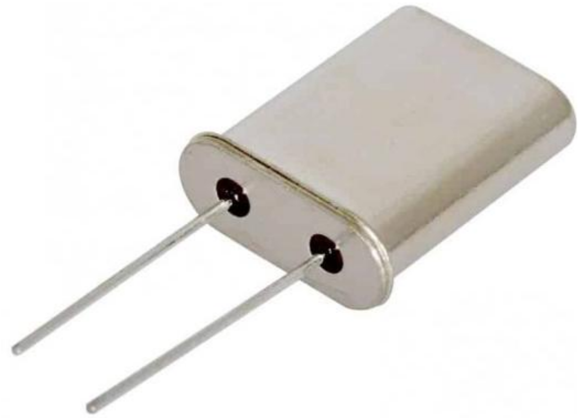

Fig. 7: HC-49U 20MHz Crystal Oscillator Physical Structure [18].

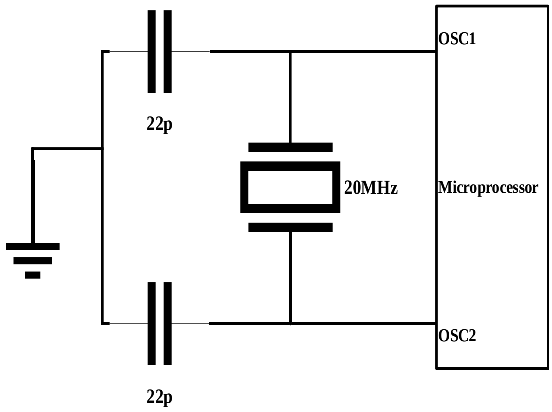

Fig. 8: Crystal Oscillator Circuitry connections.

2.7 LM044L

LM044L is a 20 character by 4 lines liquid crystal display with an inbuilt LSI HD44780 controller that can be powered with a +5V single power supply. It has an effective display area of 76.0 mm width by 25.2 mm height with a total weight of about 65g. It has an operating temperature range of 0^0C to 50^0C.

12V Hot Water Element

12 Volt DC submersible water heating element can be used directly with batteries, solar panels, wind turbine or hydroelectric dc generators. The element can be safely used as long as the supply voltage doesn't exceed the element's voltage. A submersible tubular water heater element of 12V, 150W is employed in the design of this work. The element is made of electropolished stainless steel to guide against rust with waterproof and flexible silicon sealing washer. It has a weight of 7.7 ounces, tube length of 7.5 Inch, diameter of 8mm and 1" National Pipe Straight Mechanical (NPSM) screw type. It can be used in applications such as hot water tanks, for home brewing and manufacture of diesel among others. The physical structure of the heater element is depicted in Fig.9.

Fig. 9: 12V Water Heating Element [19]

Heater Driver (IRF3205)

Tab.3: Absolute Maximum Ratings of IRF3205 [20]

	Parameter	Max.	Units
I_D @ T_C = 25°C	Continuous Drain Current, V_{GS} @ 10V	110	A
I_D @ T_C = 100°C	Continuous Drain Current, V_{GS} @ 10V	80	
IDM	Pulsed Drain Current	390	
P_D @T_C = 25°C	Power Dissipation	200	W
	Linear Derating Factor	1.3	W/°C
VGS	Gate-to-Source Voltage	± 20	V
IAR	Avalanche Current	62	A
EAR	Repetitive Avalanche Energy	20	Mj
dv/dt	Peak Diode Recovery dv/dt	5.0	V/ns
T_J	Operating Junction and	-55 to + 175	
TSTG	Storage Temperature Range		°C
	Soldering Temperature, for 10 seconds	300 (1.6mm from case)	
	Mounting torque, 6-32 or M3 srew	10 lbf•in (1.1N•m)	

Metallic oxide semiconductor field effect transistors (MOSFETs) are used majorly for signal amplification. They find use in application such as switching/driving a high-power load by a low rated power signal. MOSFETs are mostly used for the control of heavy current loads of up to 1000W with PWM signals and have three pins namely, gate, source and drain. In this work, a MOSFET with part number IRF3205 was used in conjunction with the PWM signal of the PIC16F876A to control a 150W heating element. IRF3205 is a lead-free, fast switching power MOSFET with an operating temperature of less than 175^0C and an ultra-low on-resistance. The maximum ratings of IRF3205 are as shown in Tab.3 while its physical structure is shown in Fig.10.

Fig.10: Physical Pin-Out Structure of IRF3205 [21]

2.10 Monocrystalline Silicon PV

Monocrystalline silicon PV are the most efficient solar panels available and require less space as compared to polycrystalline or thin-film panels. Although it is considerably expensive, it is long lasting than other types, hence, the reason for its choice in this work. A 300W, 12V monocrystalline panel is used in this work and the physical structure is as shown in Fig.11. A charge controller of 40A, 12V rating is considered for charging the battery. The mathematical basis for the choice is shown in equations 3 and 4.

This design considers a charging time of 6 hours for the battery, hence, the wattage of the required solar panel is calculated thus

Battery capacity = 150AH; Charging time = 6H;

Required charging current = $\frac{Battery\ Capacity}{Charging\ Time} = \frac{150AH}{6H} = 25A$ (3)

Required solar panel power rating = $Required\ charging\ current \times Battery\ Voltage = 25A \times 12V = 300W$ (4)

Fig.11: Physical Structure of a Monocrystalline Solar Panel [22].

2.11 Temperature-Controlled Smart Heater Working Principle

In the design, the temperature control is paramount for energy conservation to ensure optimal efficiency, meaning that the heater is not turned on indefinitely. Efficient temperature control will enable energy conservation by turning the heater on intermittently when absolutely necessary. The control knobs are calibrated so that the user can have control over the temperature range of the water in the tank for flexibility in the application of the design. The temperature of the water in the tank is monitored by LM35 and used to control when the heater gets turned on or off. The upper limit is pre-set as 100^0C (this can be reset by the user) and lower limit knob is pre-set as 70^0C (can also be reset by the user). Both values are used as thresholds by the microcontroller to efficiently monitor the upper and lower limit temperatures of the water in the tank and efficiently operate the heater. When the heater drops from the set lower limit temperature value, the microcontroller triggers the heater driver (IRF3205) to switch on the heater via the optocoupler and switch it off on reaching the upper temperature limit.

The complete circuit diagram of the water heater is as shown in Fig. 4. The circuitry shows the interconnectivities between the components of the design. The variable resistor 'RV1' in the circuit is configured as a voltage divider with its output voltage varying between 0V and 5V as shown in equations 5 and 6.

$$V_{out} = V_{cc}\frac{R_{tuned}}{R_{total}} \quad (5)$$

From the circuit diagram, R_{tuned} is 10KΩ and V_{cc} is 5 volts

Hence, $V_{out} = 5V * \frac{R_{tuned}}{10K\Omega} = 5 * 10^{-4} * R_{tuned}$ (6)

From equation 6, it can be deduced that R_{tuned} is directly proportional to V_{out}. This implies that when R_{tuned} is 10KΩ, V_{out} is 5 volt and when $R_{tuned}$is 0KΩ, V_{out} is 0 volt.

The microcontroller reads the V_{out} via the analog to digital converter port 'A0' and calibrates 0 to 5 volts as 0 to 100 degree Celsius. The water Temperature is measured by the LM35 Temperature sensor whose output is connected to analogue to digital converter port 'A1'. The LM35 supplies 10 mV per degree Celsius. It supplies 0 volts at 0 degree and supplies 1volt at 100 degree Celsius. PWM signal was generated through a CCP terminal of the microcontroller to automatically drive the mosfet transistor for switching the heating element. The power supply to the water heater is controlled by varying the duty cycle of the PWM driver signal from the microcontroller to trigger the driver IRF3205 that switches the heater on and off. Duty cycle of 100% operates the heater at its maximum power, 50% duty cycle operates the heater at half power and 0% duty cycle puts the heater off. The software program flowchart that ensures the smooth operation of the heater is presented in Fig. 5.

3. RESULT AND DISCUSSION

3.1 Tank Fabrication

The process of fabrication required welding of metals using two methods of welding which include electric welding and oxy-fuel welding. Electric welding was used with electrode to join the metal pieces to reduce the wide opening on the tank to the required size needed by the dc heating element to fit in. Oxy-fuel welding which uses fuel gases and oxygen was used to weld the fabricated metal piece to the water heater tank. Proper measures were taken to avoid leakage of heat and steam.

3.2 Control Circuit Fabrication

Having designed and analysed the circuit, it was converted to a printed circuit board (PCB) using Express PCB software. The back-copper layer of the designed PCB was printed on a glossy paper. Toner with hot iron transfer method was used to transfer the PCB artwork to the copper board. Ferric chloride solution was used to etch the board. The PCB was dried after washing in water to remove the etchant from the board. The black toner was removed using petrol and fine cotton.

3.3 Heater Testing Result

Water was filled into the water heater tank and $60^0c\ and\ 40^0c$ was set on the control as the upper and lower limit temperature respectively. The heater started with maximum power and the water temperature began to rise gradually, when the water temperature got to the preset 60^0c, the heater's power began to drop until it reaches 0%.

The water temperature remained at 60^0c for some minutes and started dropping until it reaches to 40^0c. The heater immediately powered up at 40^0c and stopped when the water temperature reaches 60^0c. The procedure was repeated for upper limits of 65^0c, 70^0c, $75^0c, 80^0c$ with lower limits of 40^0c, 50^0c, 45^0c *and* 60^0c respectively. The results were satisfactory for all pre-set values.

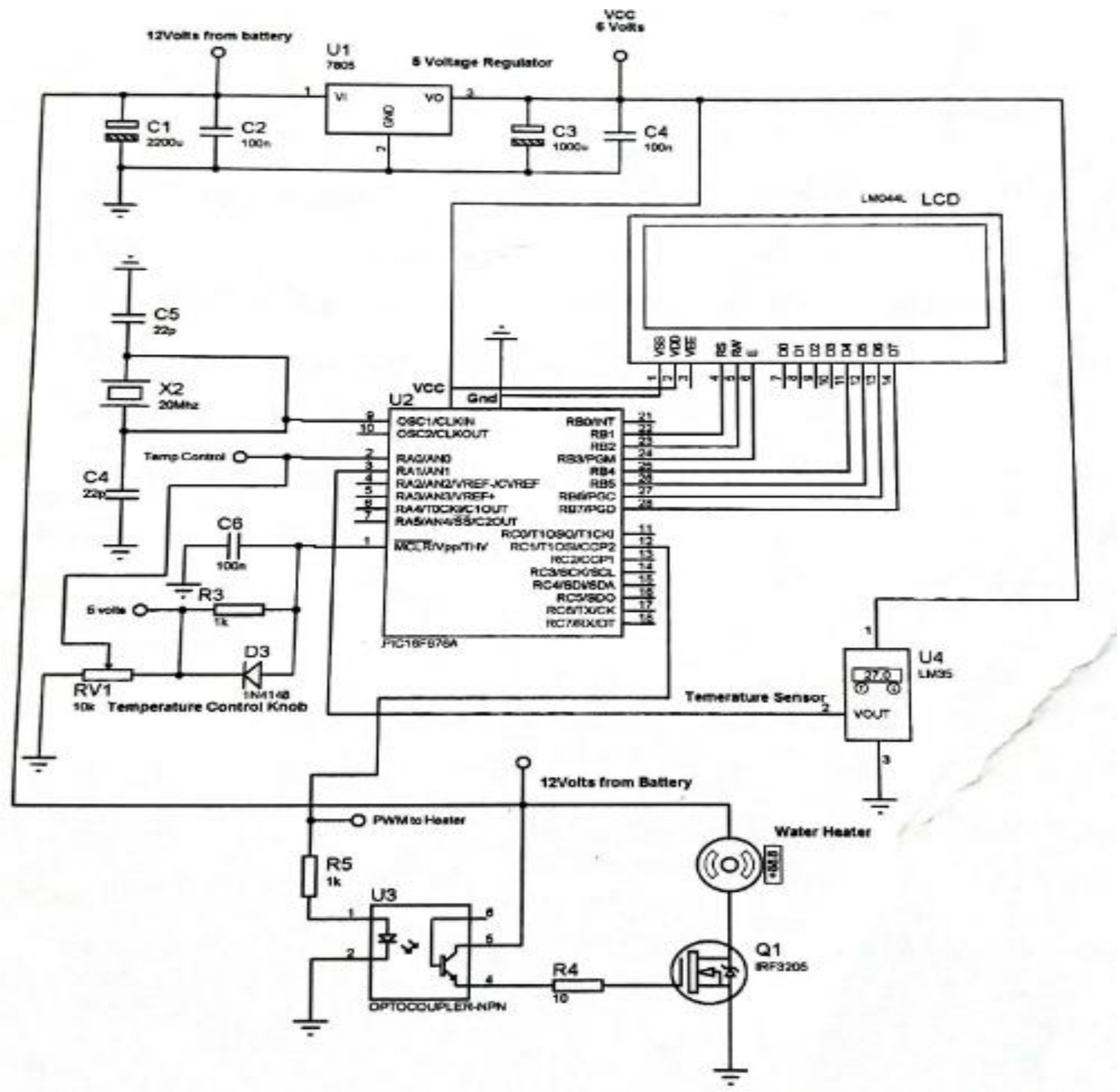

Fig. 12: The complete circuit diagram of the water heater with temperature control.

4.0 Software Implementation

Software is a set of algorithms, procedures, programs, and its documentation in relation to the operation of a data processing system. In this work, Arduino integrated development environment (IDE) software was used to achieve the aim of this work which is temperature control of a dc heater. Arduino hardware uses a Wiring-based programming language, it is akin to C++ with slight adjustment, and a processing-based IDE. Arduino is programmed with Arduino IDE that has been develop using Java and based on Processing, avr-gcc compiler, and some other open-source software. The aforementioned software was leveraged to instruct the Arduino board integrated in the design with adherence to the program flowchart of Fig. 5.

5.0 CONCLUSIONS

Conventional electric heating element consume large amount of energy which results in high cost of usage. Intermittent power supply also mitigates against the usage of ac heaters. This work presents an alternate, efficient, cost effective and automated dc water heater. The system showed excellent performance using a 150 watts DC heater. The temperature control capacity of the fabrication makes it useful in water management system applications such as in aquaculture fingerling hatchery, hot water dispenser and shower among others. Flexibility of manually setting the upper and lower temperature limits makes the fabricated smart heater adaptable for several applications.

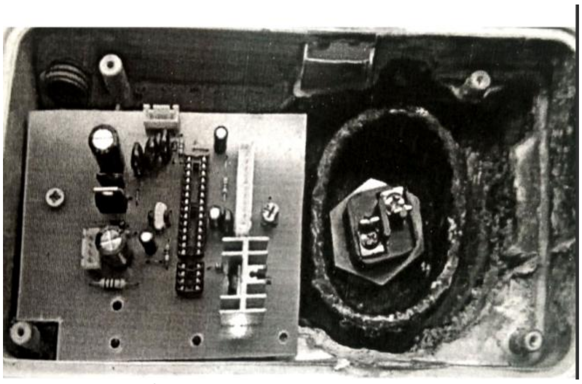

Fig. 13: Image of the Prototype Assembled Water Heater with Control Circuit

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