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Development of a Temperature Controlled Water Heated Bath for Science Laboratories in Nigeria with Locally Available Materials

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Abstract: *Underdeveloped countries like Nigeria struggle to meet up to the world standard of laboratory equipment by importing low quality laboratory equipment at very high cost. This increases the cost of setting up research laboratories, reduces the technological advancement, and the frequency of conducting researches in Nigeria. Consequently, this work aims to develop a temperature controlled water heated bath from locally available materials in Nigeria to maintain laboratory specimen at a constant temperature for a period of time. This was achieved by designing and fabricating a temperature controlled water heated bath, with a performance evaluation conducted on the fabricated device. Theoretical analysis showed that the temperature of water inside the water bath could be raised from 10°C to 100°C within 2 - 3 minutes. Experimental validation revealed that the water in the bath reached the boiling temperature of 100°C at approximately 3 minutes. These results show a correlation between the increased temperature and the measured water content in the bath. This further proves that the developed water bath can be adopted to maintain laboratory specimen at a constant temperature for a period of time due to its low production cost when compared with the cost of the imported water heated baths.*

Key words: *Water Heated Bath, Laboratory Equipment, Science Laboratory, Local Fabrication, Improvised Laboratory Equipment.*

INTRODUCTION

Reliable cooling and heating are used everywhere, from organic synthesis distillation towers to mass spectrometer vacuum diffusion pumps (Michael and Felton, 2004). It is an established fact that heating and cooling have always been necessary in the laboratory (Council, 2011). People are familiar with Bunsen burners, hot plates, and trips from the laboratory to the ice machine to prepare ice baths for experiments. In addition, baths and circulators are essential for those who frequently need to heat in order to maintain a certain temperature or cool experiments to effect a reaction (Shukla and Kulkarni, 2017). This is a major device in most laboratories in schools, companies and hospital/medical test centers.

A laboratory bath is a device that is used to maintain a set temperature by means of indirect heating or cooling. The laboratory bath has an enclosed container in which the temperature in it is constant. This container is where the specimen or whatever needs to be kept at a constant temperature. Laboratory bath is a preferred heat source for heating flammable chemicals instead of an open flame to prevent ignition (Hasim et al., 2011). Laboratory baths vary according to their uses, heating medium, sizes and specifications. They are classified according to the actions they perform or meant to perform. Examples are heating baths that heat up the laboratory bath to a certain temperature above room temperature and remains constant at that temperature, and the cooling baths that cools a liquid mixture which is used to maintain low temperatures typically between -12°C and −78°C (Jensen and Lee, 2000). Even though there are different heating baths, this work is concerned with the water heated bath.

A. Water Heated Bath

A water bath is laboratory equipment made from a container filled with heated water. It is used to incubate samples in water at a constant temperature in the microbiological laboratory over a long period of time (WHO, 2008). All water baths have a digital or an analogue interface to allow users to set a desired temperature (Hasim et al., 2011) as shown in Fig. 1 for a one chamber water bath. When the water bath reaches the set temperature, it will cycle on and off to maintain constant temperature. Most water baths have a second control called the safety. This control is set at the maximum temperature the water bath should attain. It is usually set just above the temperature control. Often an indicator light is associated with the safety control. If the water bath reaches the temperature that the safety control is set at, the light will go on. It will be impossible for the water bath to heat higher than the safety setting even when the temperature setting is higher. If in any circumstance, the water bath temperature is lower than the temperature control setting, it is advisable to increase the safety control setting in order to increase the water bath temperature. It is worthy of note that at the same temperature, heat transfer in liquids are more efficient when compared to air chambers. This is because the thermal capacity of water is greater than that of air. It is however to use water as the heated fluid because water is an excellent liquid, cheap, safe and readily available (Ibrahim et al., 2014).

Fig. 1 One Chamber Water Bath (Memmert, 2020)

Water heated bath are utilized for warming of reagents, melting of substrates, incubation of cell cultures and to enable certain chemical reactions to occur at high temperature. It is reported that the growth of many microorganism requires a temperature controlled environment and most enzymatic reactions occurs at 37ᵒC as their optimal temperature. Although many chemical reactions can be accelerated with changes in temperature ranges, some biochemical procedures require strict temperature control (Berry and Foegeding, 1997). Water heated bath has different types. They include; circulating water baths, also called stirrers are ideal for applications when temperature uniformity and consistency are critical, non-circulating water baths that relies primarily on convection instead of water being uniformly heated and the shaking water baths that has extra control for shaking, which moves liquids around (WHO, 2008).

Nigerians are already looking at specializing in the fabrication of these water heated baths but most of the work and fabrication is done abroad, so basically it is not fabricated in Nigeria and are always very expensive. Table 1 shows a few foreign fabricated constant temperature water heated baths and their costs.

Table-1 Cost of foreign fabricated water heated baths (Alibaba.com)

S/No.	Foreign fabricated water heated bath	Cost/piece	
		$	N
1.	Medical constant temperature water bath produced by Jiangsu Yuli Medical Instrument Co., Ltd, China	100	45,000.00
2.	Water heated bath developed by Shanghai Lianhua Industrial Co., Ltd. China	120	54,000.00
3.	Constant temperature water bath produced by Biobase Meihua Trading Co., Ltd., China	300	135,000.00
4.	Laboratory High Temperature Circulating Water Bath developed by Guangzhou Fan Bo Lun Import And Export Trade Co., Ltd., China	600	**270,000.00**

Thus, fabrication of the water heated bath locally and at low cost can reduce its importation when compared with the high costs of foreign fabricated water heated baths presented in Table 1. This would also ensure end users' input into the development, and hence customized laboratory equipment can be developed locally. The aim of this project is to develop a temperature controlled water heated bath, thereby showing that laboratory equipment can be fabricated locally to user's specifications and at a lower cost. This would be achieved by designing and fabricating a temperature controlled water heated bath, and also by carrying out performance evaluation on the fabricated device.

MATERIAL AND METHODS

For this work, the design and development strategy of water bath is divided into four sections namely: design of the electrical circuit and control; metal design and fabrication of the frame; fabrication of the bath cover; and fabrication of the tank.

2.1 Design of the Electrical Circuit

The schematic electrical diagram of the water bath was designed and simulated using PROTEUS 8 CAD. PROTEUS 8 CAD is an electrical software suite that contains schematic, simulation and PCB designing which is adopted for circuit simulation purposes. The electrical circuitry comprises of Microcontroller, Control buttons, Display units, Relay and heater, Power supply and the Temperature sensory circuit. This is as shown in Fig. 2. The specification of the circuit include; Voltage of 240/220 V, Power required to carry the circuit 2400 W, board with size 100 x 130 mm x 1 mm and temperature sensor ranges from 27 ºC to 99.9 ºC with error allowance of ±0.5 ºC. The PROTEUS 8 also has the capabilities of transforming the electrical design circuitry to a 3D PCB model. The 3D PCB model of the water bath design using PROTEUS CAD software is as shown in Fig. 3. This 3D was simulated for correctness and accuracy. The embedded control program was written using micro C in the C language. This involved the programming of the LCD display unit and the button function and also the LM35 temperature sensors actions of switching the relay.

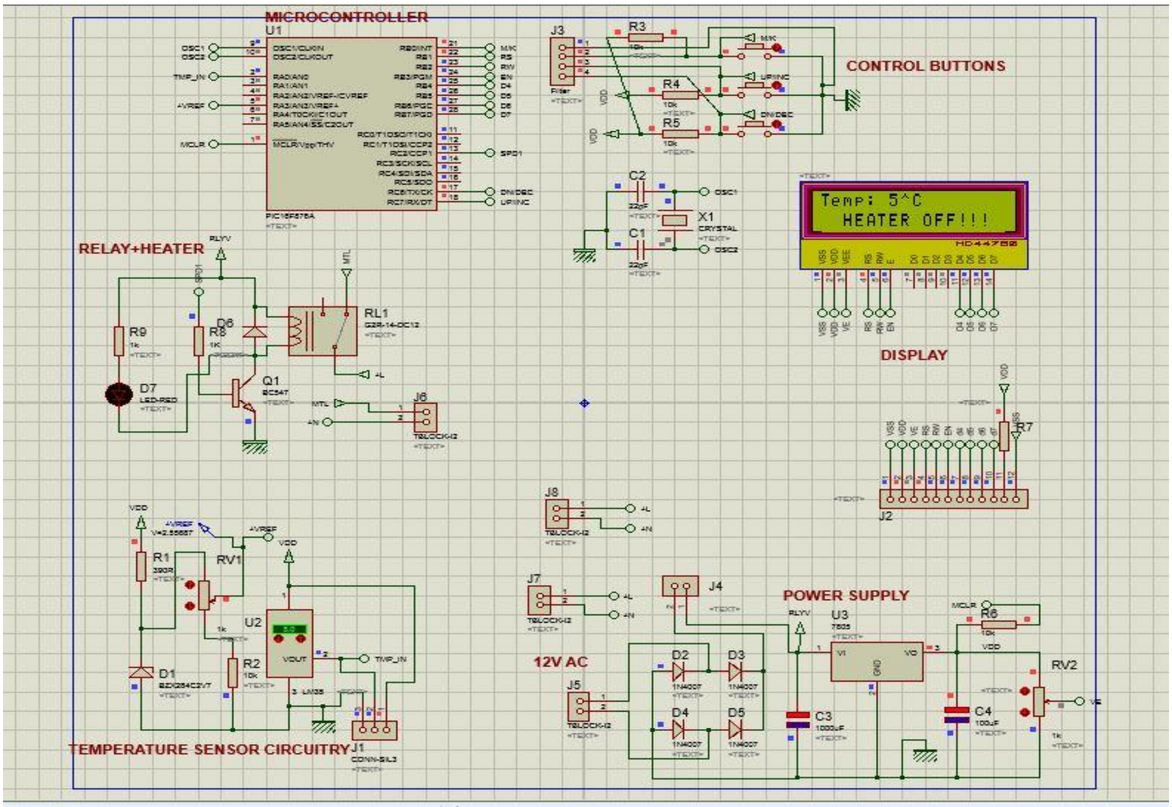

Fig. 2 Schematic Electrical Diagram of the Water Bath

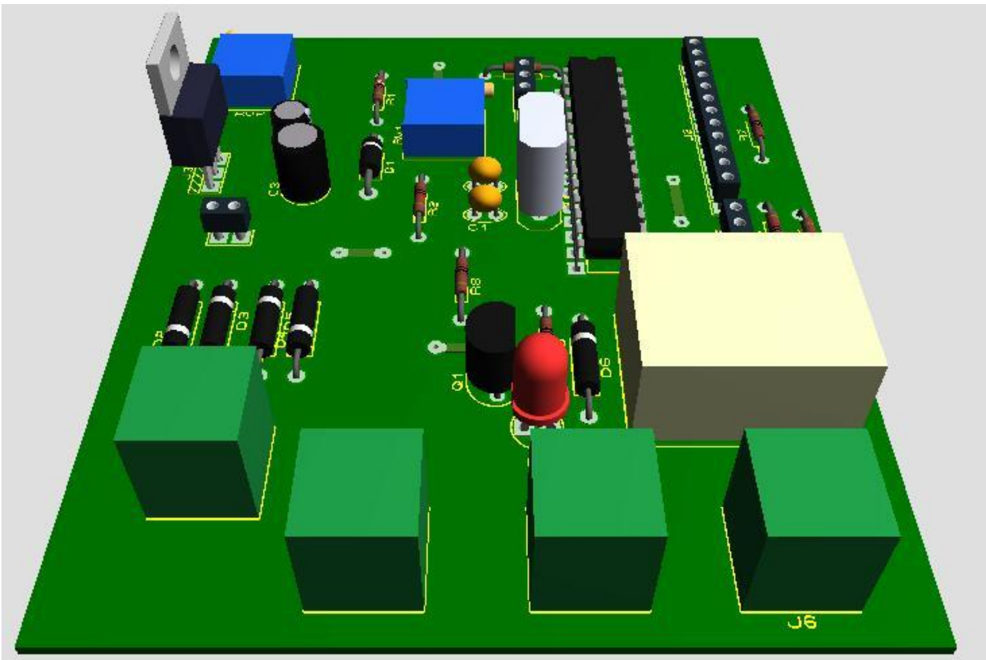

Fig. 3 3D Simulation and Design of the Circuit

2.2 Electrical Calculation

A. Heating Speed of the Heating Element

The heating speed of the water depends on the wattage of the heating element which is 2400 W

Embedded energy of water = specific heat x change in water set point x weight of water

Adopted parameter: Specific heat of water = 4.2 J/g/°C, 1 litre of pure water (roughly 1000g) at room temperature of 10° C (50°F) and the set point of water bath is 100°C

Therefore, change in temperature $= (100 - 10) = 90°\text{C}$
Embedded energy of water = $4.2J/g/°\text{C} \times 90°\text{C} \times 1000g = 378kJ \; or \; 378000J$
The heating element capacity 2400 W or 2400 J/s,
Therefore, Time required for heating the water in the bath to 100°C = $\frac{378000J}{2400J/s} = 160 \; s = 2.67mins$
It is therefore estimated that it will take between 2-3mins to raise water from 10°C to 100°C using the 2400 W water heater.

B. Energy Balance

The well-mixed assumption implies that all water in the tank is at the same temperature. To calculate the water temperature, the model analytically solves the differential equation governing the energy balance of the water tank:

$$\rho V C_p \frac{dT}{dt} = Q_{net} \tag{1}$$

Where, Q_{net} is the net heat transfer rate to the tank water, ρ is the density in kg/m³, V is the volume of the tank in m³, C_p is the specific heat of water in J/g/°C, T is the temperature of the tank water in °C and t is the time in s.
Since density is ratio of mass to the volume, the density and volume can be replaced with the total mass m of water in the tank thus:

$$mC_p \frac{dT}{dt} = Q_{net} \tag{2}$$

Incorporating all available parameters,
Q_{net} = 1000 x 4.2 x 90/2.67 =141573.033J/s or 141.57 kJ/s

Again, the net heat transfer rate Q_{net} is the sum of gains and losses due to multiple heat transfer pathways within the proposed design hence;

$$Q_{net} = q_{heater} + q_{oncycpara} + q_{offcycpara} + q_{oncycloss} + q_{offcycloss} \tag{3}$$

where, q_{heater} is the heat added by the heating element or burner, $q_{oncycpara}$ is the heat added due to on-cycle parasitic loads (zero when off), $q_{offcycpara}$ is the heat added due to off-cycle parasitic loads (zero when on), $q_{oncycloss}$ is the heat transfer to/from the ambient environment (zero when off), $q_{offcycloss}$ is the heat transfer to/from the ambient environment (zero when on), $q_{oncycloss}$ and $q_{offcycloss}$ are defined as:

$$q_{oncycpara} = UA_{oncyc} \, T_{amb} - T \tag{4}$$

$$q_{offcycloss} = UA_{offcyc} \, T_{amb} - T \tag{5}$$

where, UA_{oncyc} is the on-cycle loss coefficient to ambient environment (zero when off), UA_{offcyc} is the off-cycle loss coefficient to ambient environment (zero when on), T_{amb} is the temperature of ambient environment.
Incorporating all of these equations into the original differential equation,

$$mCp \frac{dT}{dt} = q_{heater} + q_{oncyc} + q_{offcyc} + UA_{oncyc} \, T_{amb} - T + UA_{offcyc} \, T_{amb} - T \tag{6}$$

Associating terms not dependent on temperature T and terms dependent on temperature T yields the differential equation in equation 7 and has the form;

$$\frac{dT}{dt} = a + bT \tag{7}$$

Where,

$$a = \frac{1}{mCp}\left(q_{heater} + q_{oncyc} + q_{offcyc} + UA_{oncyc} \, T_{amb} + UA_{offcyc} \, T_{amb}\right)$$

$$b = \frac{-1}{mCp} UA_{oncyc} + UA_{offcyc}$$

The solution to the differential equation 4 can be written in terms of a and b as shown in equation 8.

$$T(t) = \left(\frac{a}{b} + Ti\right) ebt - \frac{a}{b} \tag{8}$$

where, *T(t)* is the temperature of the tank water at time *t*, and T_i is the initial temperature of the tank water at time *t* is 0.
However, if b is 0, the solution instead is shown in equation 9.

$$T(t) = at + Ti \tag{9}$$

Since the control algorithm must sometimes calculate the time needed to reach a specified temperature, the equations above can also be rearranged to solve for t as shown in equation 10.

$$t = \frac{1}{b}\ln\left(\frac{{}^{a}/_{b}+Tf}{{}^{a}/_{b}+Ti}\right) \tag{10}$$

Or, if b = 0,

$$t = \frac{Tf - Ti}{a}$$

Where, T_f is the final temperature of the tank water at time t in °C.

2.3 Design of the Tank, Frame and Cover of the Water Bath

A. Surface Area of the tank

The area of the rectangular tank can be evaluated as in equation 11 thus;

$$Area\ of\ a\ cuboid = 2(Lb + Lh + bh) \tag{11}$$

For this work, Length of the tank = 370mm, Breadth of the tank = 240 mm and Height of the tank = 200 mm. Then:

$Area\ of\ a\ cuboid = 2((370 \times 240) + (370 \times 200) + (200 \times 240)) = 421600mm^2$

$Area\ of\ tank = Area\ of\ cuboid - area\ of\ opened\ top$

$Area\ of\ tank = 421600 - (370 \times 240)$

Area of tank = 332800mm^2

B. Volume of the tank

The volume of the tank is thus;

$Volume\ of\ cuboid = volume\ of\ tank$

$$Volume\ of\ tank = L \times b \times h \tag{12}$$

$Volume\ of\ tank = 370 \times 240 \times 200$

= 17760000mm^3 ~17.8litres

Therefore the maximum amount of water in the tank is 17.8 liters.

The CAD design of this work was done using Autodesk Inventor 2016. Fig. 4 and Fig. 5 show the isometric and 3D view of the Water Bath based on the evaluated dimensions respectively. All dimensions are in *mm*.

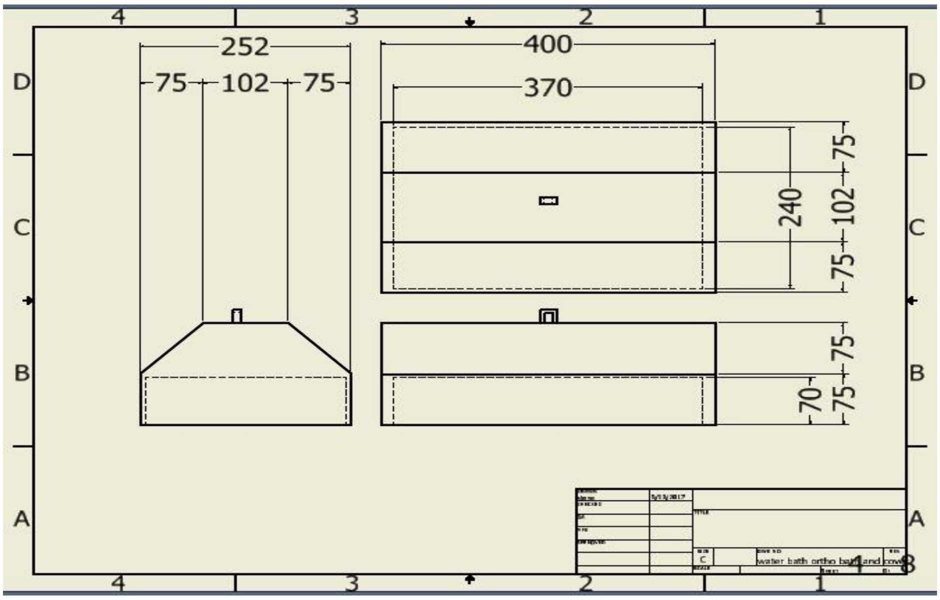

Fig. 4 **Isometric view of the designed water bath**

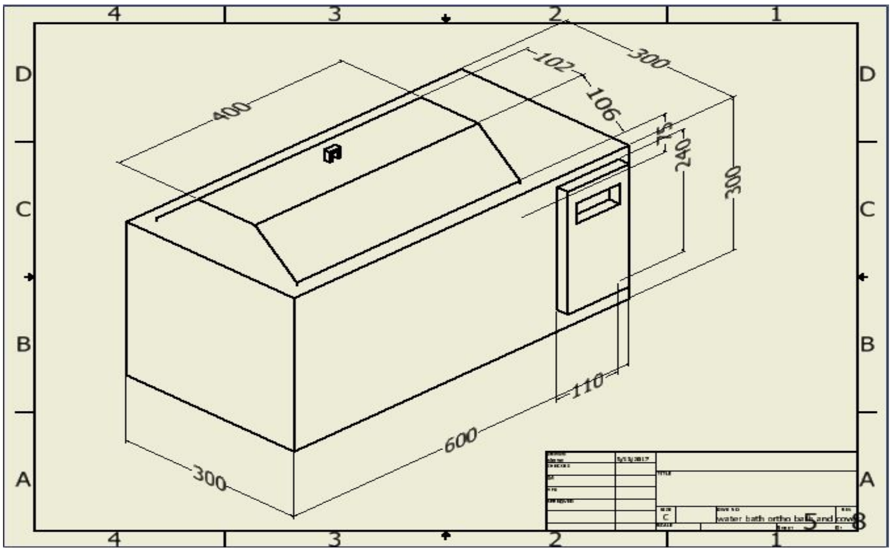

Fig. 5 **3D view of the developed water bath**

C. Metal Fabrication of the Water Bath

Materials used for the water baths include; 1mm metal sheet, hinges for metal joint, welding electrodes and fiber glass for lagging. The following procedures were carried out in the fabrication of the water bath frame, tank, and cover:

i. Marking the dimensions: the metal sheet was measured and marked using a meter rule and a scriber according to the design of the water bath, the dimensions were marked on the metal sheet.
ii. The marked regions were cut: the marked regions were cut into shapes using a cutting disk.
iii. The cut sheets were folded into shapes: Using a bender machine and according to the shape the sheets were bent and folded into their respective shapes.
iv. The shapes were welded using the electric arc welder.
v. Holes for electrical components, tap for the drainage heating element were drilled and cut.
vi. The tank was lagged using fiber grass.
vii. All the parts which are the tank frame and cover were assembled together as shown in Fig. 6.

(a) Lagging Process of the Tank

(b) Completed water bath after lagging

Fig. 6 Assembly of all Parts of the Water Bath

2.4 Bill of Engineering Material and Evaluation (BEME)

The list of components procured and the cost of procurement is presented in Table 2

Table-2 Bill of Engineering Material and Evaluation (BEME)

S/N	Description of materials	Qty	U/Price (N)/($)	Total Cost (N)/($)
1	Metal sheet	1	1500.00 ($3.3)	1500.00 ($3.3)
2	PCB board	1	2000.00 ($4.4)	2000.00 ($4.4)
3	Transformers	1	1500.00 ($3.3)	1500.00 ($3.3)
4	LCD	1	500.00 ($1.1)	500.00 ($1.1)
5	Microcontroller	2	250.00 ($0.6)	500.00 ($1.1)
6	Etching solution	1	500.00 ($1.1)	500.00 ($1.1)
7	Heating element	1	2500.00 ($5.6)	2500.00 ($5.6)
8	Relay	2	750.00 ($1.7)	1500.00 ($3.3)
9	Electrical component		2000.00 ($4.4)	2000.00 ($4.4)
10	LM35 sensor	4	500.00 ($1.1)	2000.00 ($4.4)
11	Tap/union	1	500.00 ($1.1)	500.00 ($1.1)
12	Fiber grass	1	10000.00 ($22.2)	20000.00 ($44.4)
13	Miscellaneous		2000.00 ($4.4)	6000.00 ($13.3)
	TOTAL			**41,000.00 ($91)**

The total cost for the fabrication of the temperature controlled water heated bath is seventy thousand naira only. This is equivalent to **$91 (approximately N41, 000.00)** in Nigeria.

RESULTS AND DISCUSSIONS

After the successful development of the water bath, the heating speed of the water bath was evaluated according to the theoretical formulae. Given that the Specific heat of water is 4.2 J/g/C and a litre (roughly 1kg) of water at 10°C (50°F) was poured inside the bath and the set point of the bath set to 100°C. The temperature change can be evaluated thus:
$\text{Change in temp} = (100 - 10) = 90°\text{C}$
Hence, the energy required to increase the temperature of the water bath from 10°C to 100°C can be evaluated thus:

$$Energy\ required = 4.2\ J/g/C \times 90\ C \times 1kg = 378kJ = 378000J$$

If the rating of the heating element is 2400 W, it therefore implies that the heating element is consuming 2400 J of energy per second. Hence, the heating element can quickly increase the temperature of the water bath if inserted into the water as stated thus:

$$Time = \frac{Energy\ required}{Power\ rating} = \frac{378000\ J}{2400\ W} = 160\ sec$$

It therefore implies that it will take between 2 - 3 minutes to raise the temperature of water inside the water bath from 10°C to 100°C.
In order to validate the heating time and heat loses in and outside the water bath, a graph of time against temperature to show the heating speed of different temperature difference was plotted as shown in Fig. 7. The water bath was tested for over 3 hours and the water temperature was kept constant throughout. The heating speed was also tested by increasing the set temperature, in order for the water bath to be able to last longer while in operation. Although a pressure release valve was not incorporated into the design, it is anticipated that this will be required in the future to reduce the pressure build up inside the bath at certain intervals. The time of heating through each temperature difference was taken and plotted as shown in Fig. 7.

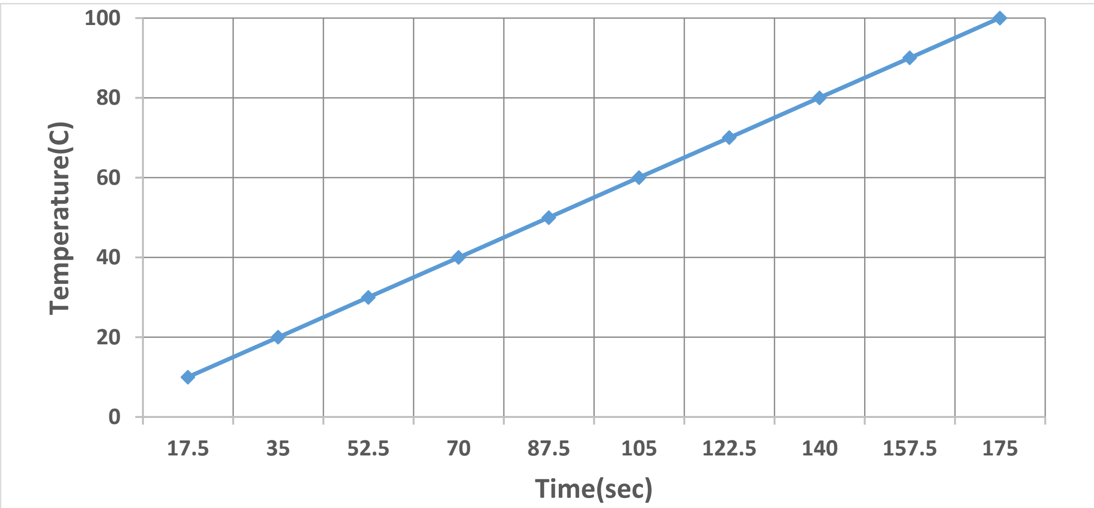

Fig. 7 Temperature variations with time inside the water bath.

From Fig. 7, it is revealed that the water in the bath reaches the boiling temperature of 100°C at approximately 3 minutes. This validates the theoretical estimation of between 2 to 3 minutes calculated for the water bath to attain a set temperature of 100°C. It is also an indication that heat losses are minimized in and around the water bath due to the lag materials used. A low heat loss was noticed though at a higher temperature hence, the system was allowed to cool down by changing the water in the bath to avoid unnecessary outside wall temperature rise. Therefore it is important to always set the temperature set point to a temperature below the boiling point so that the lagging put in place could be effective. At a temperature below the boiling point, the body of the water bath was a little bit warm, showing that the lagging of the tank was effective. The cost of the local fabrication is equivalent to $91 (N41000.00**)** while the cost of the imported ones ranges from $100 (N45, 000.00) to $600 (N270, 000.00). This is a further proof to show that local content should be encouraged and developed in Nigeria particularly in our tertiary institutions for scalability of inventions such as the temperature controlled water bath.

CONCLUSIONS

The work has demonstrated the development of a water bath controlled. It considers the design concepts, theoretical analysis and evaluations, bill of engineering materials and cost. It is interesting to know that the project shows that a water bath can be designed and fabricated locally at low cost. This is a further challenge for local fabricators in the development of other laboratory devices and equipment. The work also shows among other things:

- The temperature of the water bath can be reached between 2 to 3 minutes. This confirms the theoretical values deduced from the energy formulae.
- The use of locally available materials could spur Nigeria to a new level of technology development if harnessed.
- The total cost of the local water bath is approximately $91 (N41, 000.00). This is cheaper compared to the imported water bath with price ranges from $100 (N450, 000.00) to $600 (N270,000.00).
- Local content should be encouraged and developed in Nigeria particularly in our tertiary institutions for scalability of local inventions.

RECOMMENDATIONS

Further work can be undertaken to improve the functionability and efficiency of the water bath. It is therefore recommended that:

- the tank should be made using stainless steel to reduce or eliminate corrosion.
- extra heating element should be added to speed up heating speed.
- pressure relief valve should be installed to allow quick discharge of pressure and a cooling system could also be added to enable rapid cooling of the bath.

CONFLICT OF INTEREST

I hereby state that no conflict of interest will arise in any form from the publishing of this study.

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