Nigerian Journal of Engineering, Vol. 30, No. 2, August 2023, ISSN (print): 0794 – 4756, ISSN(online):2705-3954.

Nigerian Journal of Engineering,
Faculty of Engineering, Ahmadu Bello University, Zaria, Nigeria
journal homepage: www.njeabu.com.ng

A Microcontroller Based Proportional Integral Derivative Controller for Yam Tuber Storage Chamber Temperature and Humidity Control

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Research Article

Abstract

Adequate and suitable controlled atmosphere plays an important role in post-harvest yam tuber storage environment for sustaining the quality and quantity of yam tuber especially in a reputable country that produces largest quantities of yam in the world. The effect of post-harvest loss is caused due to lack of appropriate storage systems and these had been the most common problem faced by small-holder yam farmers. In order to avoid post-harvest losses and food wastages due to poor atmospheric condition in West Africa, this paper proposed a microcontroller based Proportional Integral Derivative (PID) controller for controlling the temperature and humidity of yam tuber post-harvest storage. The due technique would maintain a relatively constant temperature and humidity in a storage chamber so as to minimized high level of yam postharvest losses that has become a serious economic and food security threat in West Africa. Some mathematical equations were formulated based on temperature and humidity storage chamber models using heat and energy balance principles. The models were designed using Proteus tools and simulated in Simulink form. The parameters of PID controller were tuned with Ziegler Nichols to achieve a desirable steady state response. The system performances were evaluated in settling time, temperature and humidity set point tracking. The performance metrics were compared with existing technique of Fuzzy Logic Controller (FLC). The sensitivity of the results justified that proposed technique gave a better performance in terms of decreased in settling time, temperature and humidity.

doi: 10.5455/nje.2023.30.02.09

Keywords
Yam Storage, Proportional Integral Derivative (PID) Controller, Temperature, and Humidity Control

Article History
Received: – April, 2023
Reviewed: – June, 2023
Accepted: – July, 2023
Published: – August, 2023

1. Introduction

Yams (Dioscorea spp.) are perennial herbaceous vines cultivated for the consumption of their starchy tubers in West Africa. Yams have contributed significantly to food security in Nigeria and its availability in the market for a considerable part of the year helps prevent food shortages, particularly in the urban communities because it stores relatively longer than other root crops (Opara et al., 2015). The most common problems faced by farmers are post-harvest losses and issues of food insecurity in the country can be significantly traced back to post harvest losses (Umogbai, 2013). Postharvest loss, which has largely been associated with lack of appropriate storage systems, is the most common problem faced by smallholder yam farmers. The high level of yam postharvest losses has become a serious economic and food security threat. The convectional existing method used for the yam storage structures have all that is required of improved storage structures but the maintenance cost and adequate preservation facilities is a great disincentive to farmers, which has greatly affected their adoption over the years (Shadrack et al., 2015). Others are environmental factors such as transpiration, respiration and sprouting, attacks by mammals, birds and insects, which causes spoilage. Transpiration, respiration and sprouting are physiological processes which depend so much on temperature and relative humidity of storage environment, and have been identified as the major causes of post-harvest losses of stored agricultural products (Ray et al., 2013). These shortcomings motivate this work to presented a microcontroller based PID controller due to its simplicity, clear functionality, reliability, fast response, easy to implement, no oscillations, higher stability and robust performance (Ojo et al., 2019). The microcontroller was used to track the temperature and humidity levels within the storage system compartments. The PID controller was used to regulates the forced-air cooling and maintains a relatively constant temperature and humidity in a storage chamber. The tuning technique of Ziegler Nichols was employed to fine-tuned the parameters of the PID controller to overcome the overshoot problem of the reference input and eliminates the steady state error (Kanojiya et al., 2012). Few of the local and modern techniques adopted by past researcher were stated as review. Shadrack et al. (2015) designed and constructed an improved storage structure using locally-available materials and expertise to facilitate future adoption by small-holder yam farmers.

With dimensions of 3.66 m length, 1.83 m width and a height of 1.83 m, a storage capacity of 5000 tubers for *Pona* yam variety was considered for the structure design. AutoCAD software was used for the engineering design of the structure. The local materials used for the construction are Borassus *aethiopum* wood used for the structural frame, sawmill waste boards used for both outside and floor cladding, Ceiba boards used for the shelve and thatch material for roofing. After the design, the storage improved structure has the following features such as a good ventilation due to the presence of upper openings and side windows, presence of cooler environment within, adequate water proof using a well installed fresh thatch material, protection against rodents with the help of rat guards, protection against theft because the structure had a gate under lock, reduction of cost due to the use of locally available materials and local expertise.

Murtala et al. (2011) presented a paper on intelligent control for automation of yam storage system using Fuzzy Logic Controller (FLC). The expert control of yam storage system was formulated in the form of fuzzy rules. The inputs to the controller are the outside and inside temperature, wind speed and presences of rain. The output is the window opening angle. Simulations were performed for different typical levels of input parameters and also extreme fictious conditions. The results shown that, the controller is capable of responding to the changes in temperature conditions by adjusting the window opening angle to keep the internal temperature within the acceptable range. Also, the controller satisfies the security requirements due to sudden changes in wind velocity.

Abdulazeez et al. (2017) proposed a simulation of airflow and temperature distribution in yam tubers storage system. The study emphasized on the essence of maintaining uniform temperature across the entire storage structure for yam tubers. The essence of temperature distribution is to consider the temperature readings from different points in the storage system so as to ascertain the average temperature of the system. The air flow was modelled using Computational Fluid Dynamics (CFD) software simulation. Moreover, this is powerful tool used for prediction of air flow distribution around the building which proved to be a highly effective method based on the results obtained after simulation.

Adequate post-harvest storage condition that yam tubers are subjected to would determine the qualities and quantities of yam available for human consumption and sale of monopoly by rural and urban area farmers (Abdulazeez et al., 2017). The desire to attain universal food security would remain awkwardly if problems associated with food storage losses are not properly addressed (Akangbe et al., 2012). Therefore, it is imperative to provide an optimum post-harvest storage condition for yam tubers crop in order to increase the shelf-life after harvesting and reduce yam losses at the end of the farming season most especially in sub-Saharan Africa at large.

The remainder of this paper is organized as follows. In Section 2, the chamber structure and its operations are explained while Section 3 explained the Mathematical modeling of the chamber. The results and discussion are presented in Section 4. The work is concluded with further recommendation in Section 5.

2. Chamber Structure and its Operations

The 'figure 1' explained the storage compartment of yam tuber chamber been constructed using ceiba wood, size "12" × "1" with 25 pieces of wood, concrete nails of size "4" while 'figure 2' deduced the complete structure of yam storage chamber with rodent guard fixed. The chamber consists of 50 pieces of wood slabs, Thatch of 20 bundles with Aluminum roofing sheet of 4 ft × 8 ft and Mesh wire of ½ bundles. To ensure rodents don't have access into the storage structure, rodent guards, made from Aluminum roofing sheets are fixed on ground pillars of the storage structure (Akangbe et al., 2012 & Shadrack et al., 2015). The storage chamber consists of sensors, proportional valves and slab trays.

Figure-1: Yam Storage Chamber Constructed with Ceiba Wood

Figure-2: Complete Yam Storage Chamber with Rodent Guards Fixed

The storage chamber was designed successfully to accommodate 4000 tubers of yam. The storage chamber has 200 trays and each tray supported 20 tubers of yam. The calculations for the dimension of the storage chamber were presented in the following equations. Yam generally have an irregular shape, varying in sizes and weight. The dimensions used for the design were based on the average values assuming the yam tubers were cylindrical in shape. The dimensions of yam used for the design were calculated as:

Average length of the yam tuber = 50 cm (1)

Average diameter of the yam tuber = 10 cm (2)

The length of each tray can be calculated as number of yam tubers per tray × Diameter of yam tubers

Length of each tray = 20 × 10 cm = 200 cm (3)

The breadth of each tray would be equal to the length of one yam tuber

Breadth of each tray = 50 cm (4)

Adding a clearance of 2 cm for the breadth and 2 cm for the length, the tray dimension is given as

Tray dimensions = 202 × 52 cm (5)

When each tray was stacked one upon the other. Hence, it is separated by a height of 20 cm per each tray.

The total height of the chamber was calculated as: (Height difference per tray × Number of trays) + (Height of first tray from the ground level + Height of space for the electronic circuit).

The height of first tray is 30cm away from the ground level. Total height of the chamber per each row =

(20 × 6) + (30 + 10) cm = 160 cm (6)

The chamber width will be the width of each tray plus 5 cm for joining clearance.

Hence, the chamber width = 52 + 5 cm = 57 cm (7)

The length of the chamber was also calculated as the length of the tray + 2 cm clearance. Hence, the length of the chamber = 200 + 2 cm = 202 cm (8)

The chamber dimension would be 202 cm × 57 cm × 160 cm.

2.1 Design and Implementation of Humidity and Temperature control of the storage chamber

The compartment consists of an electronic valve that allowed inflow of the air from the air handling unit. The air handling device was connected in order to regulate the chamber's temperature and humidity. The controller maintained the state of the chamber's temperature and humidity by fine tuning the PID parameters using Ziegler Nichols. In electronics section, the sensors read the state of the chamber and send appropriate signals to the controller which then computes an appropriate pulse width modulation (PWM) signal and sends it to a relay connected to the control mechanism for proper adjustment. The Arduino Uno microcontroller shown in Figure 3 was used for this work due to its ease of programming. A variety of development boards (shields) and other circuits can be interfaced with the board's sets of digital and analog input/output (I/O) pins. The board features 6 analog I/0 pins, 14 digital I/0 pins, six of which can be used for PWM output, and it can be programmed using the Arduino IDE (Integrated Development Environment) with a type B USB connector. Its normal operating current is 5V DC while the pins can take current of up to 20mA (Tomasz, 2014 & Kamthe, 2020). The Arduino Uno programming code was written using C programming language and Figure 4 shown the flowchart of the processing.

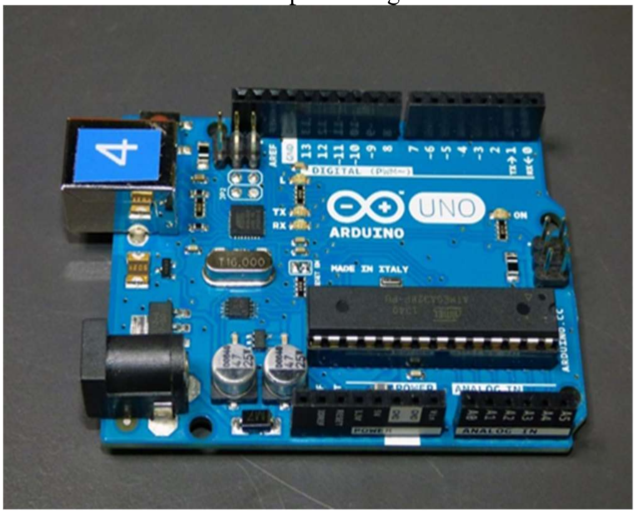


Figure-3: Arduino UNO Microcontroller

2.2 Circuit of Temperature and Humidity Control

The circuit diagram deduced in Figure 5 indicate the designed for controlling the chamber temperature and humidity of yam tubers storage. Keyes DHT11 sensor was used to measure the temperature and humidity values in heating, ventilation and air conditioning of the chamber. The sensor reads the humidity in the chamber and sends an analog signal to the microcontroller which displays the humidity value on the LCD display. The sensor depicted the humidity value in percentage, the set value was between 10 to 100 % RH and the temperature value in degree Celsius was between 0 to 50 °C. The Arduino microcontroller computes and sends an appropriate PWM signal to the relay through the transistor that acts as a switching device. The base resistor is calculated as:

$$R = \frac{(V-0.7)h_{fe}}{I} \tag{9}$$

Where; R is the base resistor in ohm, V is the base voltage in volts, h_{fe} is the forward current gain and I is the relay current in amps. Thus, from the datasheet the forward current gain value is 40 while the operating voltage is 5V. The relay current can be calculated using ohm's law.

$$I = \frac{V}{R} \tag{10}$$

Where; V is the supply voltage to the relay in volts and R is the relay resistance in ohms.

$$I = 12/240 = 0.05 \text{ Amps} \tag{11}$$

Hence, the base resistor is calculated as;

$$R = \frac{(5-0.7)\times 40}{0.05} = 3440 \text{ ohms} \tag{12}$$

Therefore, 3.9K resistor would be used as it is the closest standard resistor to it.

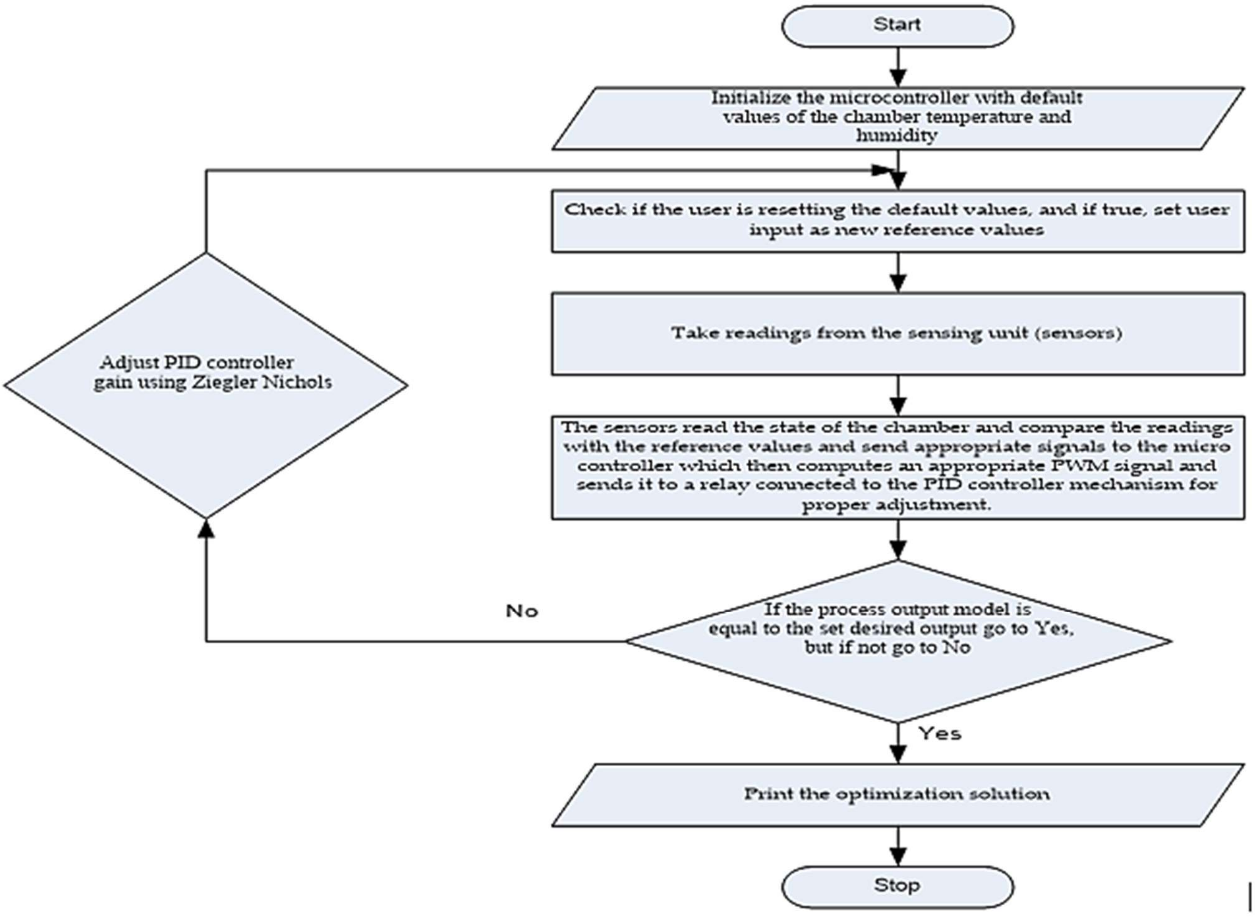
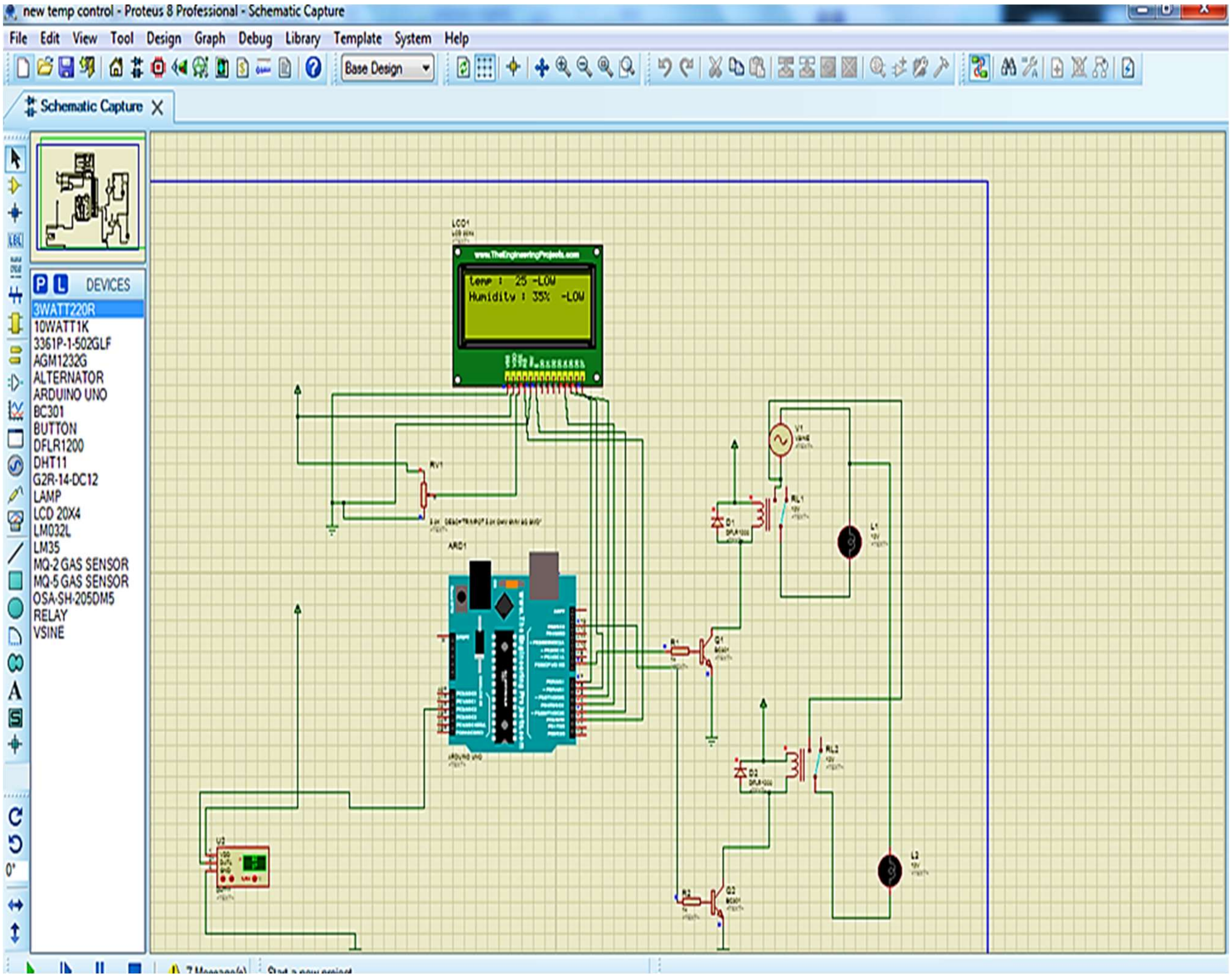


Figure-4:Flowchart for the Processing

3. Modeling Equations for Temperature and Humidity

The goal of the designed chamber is to maintain a relatively constant temperature and humidity by applying control theory (Tsung et al., 2014 & Takanori et al., 2011). The control process begins by first evaluating the difference between the output values and the set values of the temperature and humidity which is obtained by the sensors in the chamber. The flow of the air entering the storage compartment is then controlled by the exhaust air and the outdoor air is introduced to generate mixing air in the air handling unit. The mixing air undergoes cooling and dehumidifying via the cooling coil, heating coil and humidifying again via the heating coil and humidifier to ensure that the air in the chamber is maintained at the target value. The algorithm compares the difference between the chambers temperature and humidity levels and send to regulate through the PID controller if there is an error signal. The PID controller gives output to control the mass flow rate, heater input power and humidifier output power of the cooling coil and heating coil.



```
Temp :  25 -LOW
Humidity : 35%  -LOW
```

Figure-5: Designed Circuit of Temperature and Humidity Control

The modeling of HVAC has various levels of difficulty in obtaining a definite mathematical model due to the number of parameters involved (Kashara, 2000). Therefore, to simplify the model, the following assumptions were made:

1. The chamber boundaries are insulated and there is no leakage of air.
2. The air is regarded as the ideal gas with constant specific heat and density
3. The chamber is an open and unsteady flow system in constant volume.
4. The air temperature and humidity in the chamber compartment are distributed uniformly.
5. The chamber is considered as an enclosed single zone space (Takanori et al., 2011).

3.1 Chamber Temperature model

The change of energy in the chamber gives the difference between the energy supplied to the room and the energy removed from the room (Behrooz et al., 2018). This can be expressed as:

$$C\frac{d\theta}{dt} = Q_s(\theta_s - \theta) + \alpha(\theta_o - \theta) + Q_l \tag{13}$$

$$Q_s = \rho_a C_p f_s \tag{14}$$

$$V\frac{dx}{dt} = f_s(x_s - x) + \frac{n}{\rho_a}p \tag{20}$$

V is the chamber volume given as (1.54 ×0.57 × 2.2 [m^3]); x is the absolute humidity of the room in [kg/kg]; x_s is the absolute humidity of the supply air in [kg/kg]; p is the evaporation rate of a yam tuber and n is the number of yam tubers. The humidity model can also be represented as a FOPDT system and can be expressed as:

$$P(s) = \frac{K_p}{T_p s+1} e^{-L_p s} \tag{15}$$

$$\text{Gain constant } K_p = \frac{\theta_s}{Q_s+\alpha} \tag{16}$$

$$\text{Time constant } T_p = \frac{C}{Q_s+\alpha} \tag{17}$$

$$L_p = \frac{L_{po}}{Q_s+\alpha'} \tag{18}$$

In every control system, systems are designed to have a minimal dead time. Thus, the following values is given and it is substituted in 'equation 15' as the chamber temperature model parameters. L_p = 0.05; f_s = 50%; $Q_s = \rho_a C_p f_s$ = 10.63 KJ/min K; L_{po} = 1.01643 KJ/K; T_p= 18.522 K and K_p = 0.655. Hence,

$$P(s) = \frac{0.655}{18.522s+1} e^{-0.05} \tag{19}$$

3.2 Chamber Humidity model

The rate of change of moisture in the chamber determined the difference between the moisture added to the chamber and the moisture removed from the chamber (Behrooz et al., 2018). This can be expressed as:

$$V\frac{dx}{dt} = f_s(x_s - x) + \frac{n}{\rho_a}p \tag{20}$$

V is the chamber volume given as (1.54 ×0.57 × 2.2 [m^3]); x is the absolute humidity of the room in [kg/kg]; x_s is the absolute humidity of the supply air in [kg/kg]; p is the evaporation rate of a yam tuber and n is the number of yam tubers. The humidity model can also be represented as a FOPDT system.

$$P(s) = \frac{K_{ph}}{T_{ph}s+1} e^{-L_{ph}s} \tag{21}$$

$$\text{Gain constant } K_{ph} = \frac{f_s}{f_s} = 1 \tag{22}$$

$$\text{Time constant } T_{ph} = \frac{V}{f_s} = 6.98 \tag{23}$$

The deadtime is also assumed to be 0.05 (minimal) based on the same argument used for the temperature model.

$$L_{ph} = \frac{L_{pho}}{f_s} \tag{24}$$

$$P(s) = \frac{1}{6.95s+1} e^{-0.05s} \tag{25}$$

3.3 Mathematical Model of the Controller

Proportional Integral Derivative (PID) controller is a generic control loop feedback mechanism that have the optimum control dynamism. It is extensively selected as the most industrial process control applications. The three main parameters involved are Proportional (P): it is responsible for the desired set point and adjust the output controller. Integral (I): it is used to remove the steady state error of control system and improve the steady state response. Derivative (D): it is used to improve the transient response of the system as shown in ‘figure 6’ (Sangram et al., 2011 & Ojo et al., 2019). Zeiger Nichols tuning rule was applied to optimized the tuning parameters of the PID controller. The mathematical equation is expressed as;

$$U_{(t)} = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt}$$

Error $e(t)$ is the difference between the set point and chamber output.

The transfer function of the PID controller

$$G_P(s) = \frac{U(s)}{E(s)} = K_P + K_D s + \frac{K_I}{s}$$

Where; K_P is the proportional constant gain, K_D is the derivative constant gain, K_I is the integral constant gain and $G_P(s)$ is the forward path transfer function of PID controller.

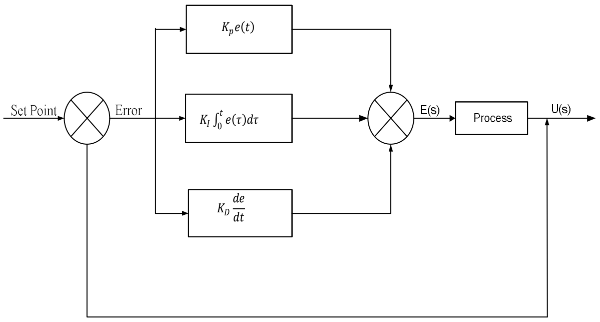


Figure-6: Schematic Model of a PID Controller

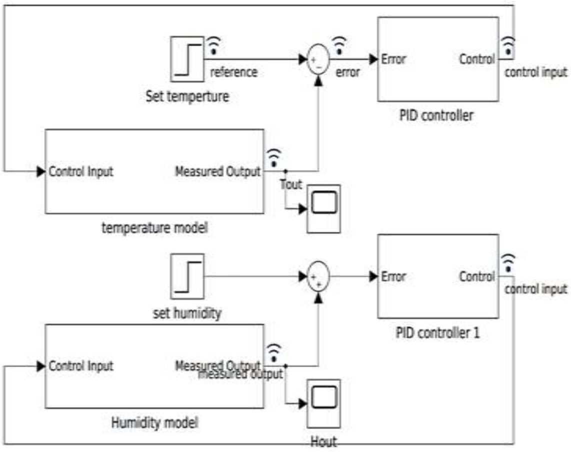


Figure-7: Simulink Model of Chamber Temperature and Humidity Control

4. Results and Discussion

The chamber was designed using a PID controller which was tuned to ascertain the best set of PID parameters required for the step response of the chamber temperature and humidity control to give a minimal overshoot, a desired rise time and settling time as well as a minimal steady state error while maintaining a desirable stability and robust disturbance rejection for the system. The simulation model was carried out in MATLAB/Simulink as shown in ‘figure 7’. The PID was tuned using Ziegler Nichols tuning rule by first set a proportional constant that make the system reach a stable oscillation. To ensure the stability and optimum temperature and humidity control of the chamber. Therefore, the proportional integral and derivative constant gain that has effect on each other were properly tuned by Ziegler-Nichols tuning rule to achieved the final optimized PID constant values as presented in Table 1.

Table 1. Optimized PID Constant Gain of Temperature and Humidity Control

Control Parameters	Temperature Control	Humidity Control
k_p	8.73	1.22
k_i	0.69	0.37
k_d	9.7	1.11

The result shown in 'figure 8' indicate the chamber temperature control. The temperature set point is 15℃ and the time required for the temperature to reach the steady state value (settling time) is 48 seconds. The temperature was observed to settle at 14.89 ℃ with an error of 0.105 ℃. Moreover, these results were compared with (Babawuro et al., 2015) using Fuzzy Logic Controller (FLC) with a set point of 16℃ and settling time of 5 seconds. The result shown in 'figure 9' indicate the chamber humidity control. The set point for the humidity is 85 % and the time required for the humidity settle within the steady state value (settling time) is 48 seconds. The humidity was observed to settle at 84.95 % with an error of 0.15 %. The result obtained were compared with (Babawuro et al., 2015) using Fuzzy Logic Controller (FLC) with a set point of 80 % and settling time of 5 seconds. It is deduced from the simulation results that, the proposed PID controller gave a better performance in terms of increase in settling time, decrease in temperature set point tracking and increase in humidity set point tracking which leads to lesser error signal in both temperature and humidity control. The performance metrics validation is shown in Table 2.

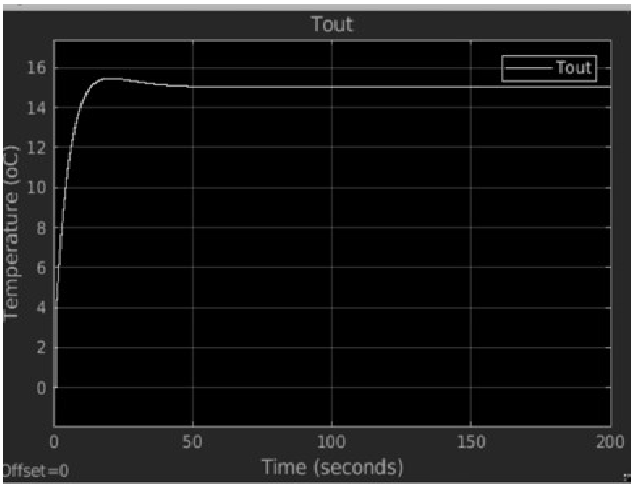


Figure 8: Chamber Temperature Control

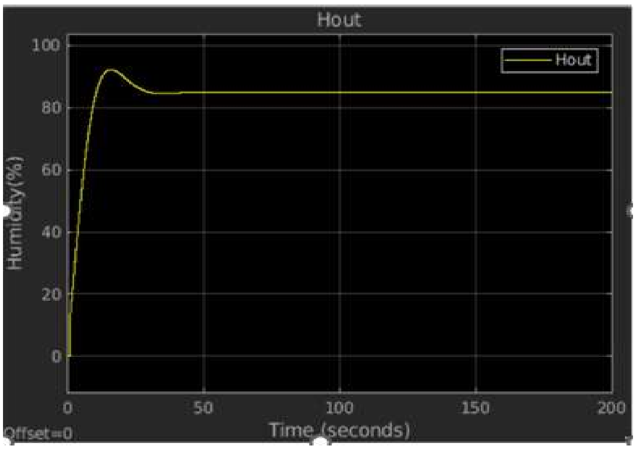


Figure 9: Chamber Humidity Control

Table 2: Performance Metrics of Temperature and Humidity Control

Parameter	Set point tracking	Result obtained	(Babawuro *et al.,* 2015)
Controller	PID	PID	Fuzzy logic
Settling time	50 sec	48 sec	5 sec
Temperature	15	14.895	16ºC
Humidity	85%	84.95%	80%

From the results, the effect of variation at the input delay of the temperature responses was also observed in 'figure 10'. The temperature responses begin initially zero, until it reaches the maximum value of 1.70. Though, there is presents of multiples overshoot and a damped oscillation which would require a minimal dead time to keep the system in steady state. Moreover, a further increase in maximum value would lead the chamber to an undesirable state with very high overshoot and settling time. The 'figure 11' deduced the comparison system response plot for the temperature and humidity when Ziegler Nichols fine tuning the PID gain so as to achieved the desired set point of the controller.

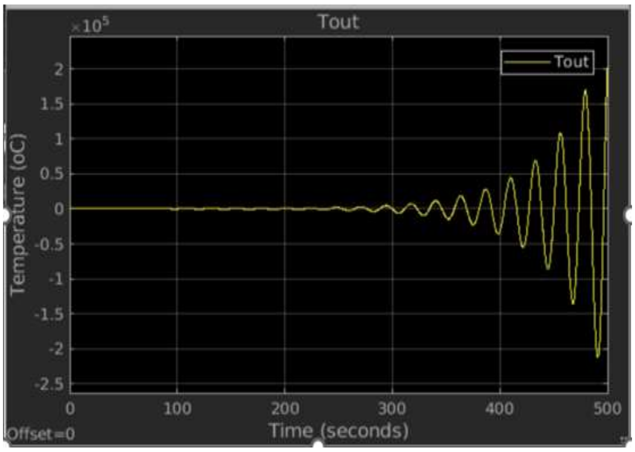


Figure 10: Temperature response with changes in input delay

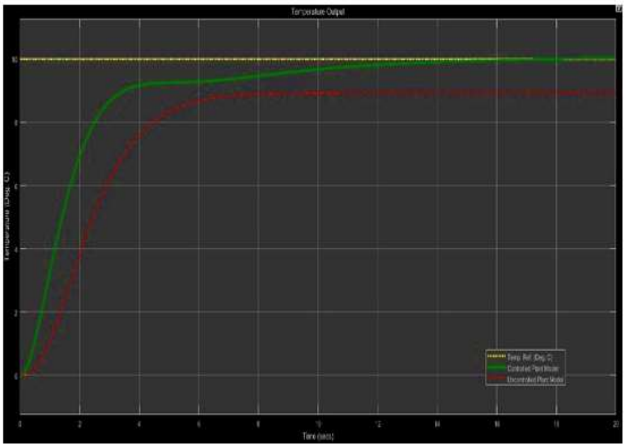


Figure 11: Comparison System Response Plot

5. Conclusion

This work presented a simple but robust intelligent approach based Proportional Integral Derivative (PID) controller for yam tuber storage temperature and humidity control. The intelligent controller was used to tracks the temperature and humidity levels within the storage system compartments while the PID controller was used to regulates the forced-air cooling and maintain a relatively constant temperature and humidity in a storage chamber at a certain set point. However, the validation of the results was compared with the existing technique of Fuzzy Logic Controller in terms of temperature set point tracking, humidity set point tracking and settling time. The proposed PID controller gave a better performance in terms of increase in settling time, decrease in temperature set point tracking and increase in humidity set point tracking.

For future references, an efficient hybridized controller of Fuzzy logic based PID controller which involves the optimization of a Fuzzy membership function parameters set should bring more benefit to the yam storage industries in terms of temperature and humidity control without any time delay scheme and maximum overshoot.

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