DESIGN OF A CONTROL SYSTEM TO ENHANCE PROCESS PERFOMANCE IN THE PRODUCTION OF SORGHUM BEER

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Abstract

The quality of products produced over the years has been the major concern for many industries. In brewing, the introduction of automated brewing systems has helped to reduce the variability of beer produced. The reasons for introducing the automated systems are to reduce energy usage and the batch processing time by increasing equipment utilization. The main aim of the paper is to design a control system that helps in monitoring and controlling the mashing process, temperature and monitor the water level that is put in the cookers during sorghum beer brewing. The research carried out showed that companies in Zimbabwe use dry bulb thermometers to measure the temperature of mash in the cooker. The companies also have no level measurement sensors that would measure the amount of water that would be poured into the cooker to primarily cool the mash. The design of the control circuit was done using sensors and controllers. For controlling the temperature a PID controller was used. The model for the temperature control system was build and processed in the identification tool box from the Matlab environment. The mash was raised to 50˚C for 50minutes and the hydrolysis of protein, β glucons and pentasons by proteolic enzymes. The temperature was then raised to 80˚C and maintained constant for 10minutes at this stage for the optimal activity of β-amylase. It was then raised to 95˚C for the optimal activity of α- amylase.

Finally, the temperature was raised to 100˚C and held constant for 60minutes for enzyme inactivation

Keywords: Control system, Mashing, Sorghum beer

Introduction

Control systems are useful in the brewing process. Breweries in Zimbabwe need to improve their sustainability, in particular their use of water and energy. Brewers have responded to the need to enhance process efficiencies by adopting technologies to re-engineer their processes to save costs and reduce waste.

Sorghum beer is brewed from maize and sorghum. Breweries are experiencing variation in the viscosity of the beer they produce. This variation is due to differences in the manufacturing process and amounts of inputs used in the brewing process. In Zimbabwe, the viscosity of beer should be between 80 – 100Ns/m^2 after the first conversion and 60-80Ns/m^2 after yeast addition. The viscosities of beer produced in Zimbabwe are generally in the range of 110Ns/ m^2 after the first conversion process and 90Ns/ m^2 yeast addition. These problems can be ascribed to lack of effective control systems that regulate production processes. For example, in most breweries there is no monitoring and control of boiling in the cookers. Yet this is a critical process that must be regulated within specific parameters [Belgium Brewing Company, (2008)].

There are nine major steps in the process of brewing sorghum beer. These are dry milling, mashing, boiling, cooling for first conversion, heating, straining, pasteurization, second conversion and packaging [Chikezie I, (2012)]. The dry milling process involves grinding sorghum and maize grains in a motorized mill to obtain coarse flour [Roger D, 2013]. These grains are mixed with water so as to hydrolyze them. After the mashing process, the wort is boiled so as to sterilize the wort, coagulates grain protein, stops enzyme activity, drives off volatile compounds, causes metal ions, tannin substances and lipids to be insoluble [Olajire A, (2012)]. The first conversion process involves adding barley and sorghum malt so as to solubilise the adjunct and malt physically and enzymatically [Taylor J, et al, (2012)]. The spent grain is removed by the process known as straining. Yeast is then added to allow fermentation to occur. Fermentation is a process in which the singled-celled yeast convert sugars in the wort into carbon dioxide and alcohol, follows [Tabernash, (2012)]. The beer is then cooled and allowed to ferment for twelve hours.

Critical processes that require control systems are boiling, fermentation, cooling, heating and pasteurization [Christna G, (2003); Emmerson, (2008) and Jacobs E, (2012)]. For boiling the critical parameters are 50˚C, 80˚C and 95˚C. The mashing process can be optimized using a mashing program with temperature-time stands of 50°C × 50 min, 80°C × 10 minutes and 95°C × 40minutes [Declan G, (2002)]. The process of all-grain brewing requires the brewer to hit targeted temperatures and hold those temperatures over an extended period of time [Crandal et al, (2008)].

The types of controllers used in beer brewing processes are Programmable Logic Controllers (PLC), microcontrollers and OMRON CPM2A. PLCs are used because of their simplicity, robustness, I/O interface and reliable performance [Normanyo E, (2011)]. Microcontrollers have reliable built in hardware programmer, simplified programming language and lively user base that offer plenty of sample codes. The objective of this study was to design appropriate control systems that helps in monitoring the parameters in beer brewing process such as temperature, mashing process and level of water in the cooker which in turn affect the viscosity of beer produced. The correct control of the brewing process ensures the production of a consistent beer which in turn satisfies the consumers.

Methods

The following section illustrates how the system was designed and the software that helped to create the control system.

Controller for the brewery

VersaMax Modular PLC CPUE05, OMRON CPM2A and Microcontroller PIC 16872 were the types of controllers selected for the brewery. VersaMax Modular PLC CPUE05 was chosen because it had 2048Input/Output points. The system designed had 30 Inputs and 19 Outputs and system can be able to expand hence 2048I/O points could be utilized. The system can also be interfaced with SCADA through Ethernet using RJ45 pin.

Modeling the control section for the mashing process

This is where milled maize and sorghum are mixed with lactic acid and water. A solution of lactic acid at a concentration of $\mathbf{C_f = 8.5}$moles/dm^3 is mixed with water to obtain an outflow stream with lactic acid concentration of $\mathbf{C_0}$. Fig 1 shows how the stirring takes place.

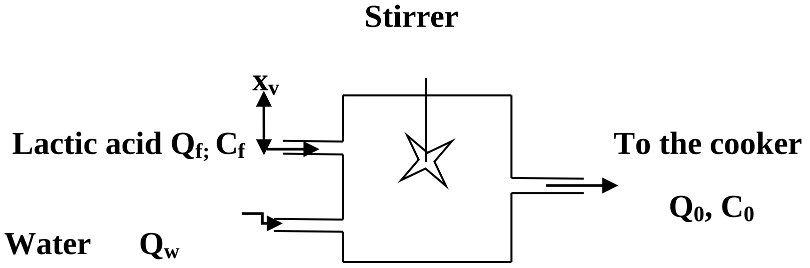

Fig 1 Mashing tank

Where: $\mathbf{Q_f}$ **=** Flow rate of lactic acid into the tank, $\mathbf{Q_w}$ = Flow rate of water in to the tank, $\mathbf{Q_0}$ = Flow of mash out of the tank, $\mathbf{C_f}$ = Concentration of lactic acid, $\mathbf{C_0}$ **=** Outflow stream with lactic acid concentration, **V** = Volume of tank, $\mathbf{m_i}$ = Rate of lactic acid flow into the tank, $\mathbf{m_a}$ = Rate of lactic acid accumulation in the tank, $\mathbf{m_0}$ **=** Rate of lactic acid outflow from the tank, $\mathbf{x_v}$ = Volume of water into the tank, $\mathbf{K_v}$ = Valve coefficient

$$Q_w = K_{v*}\, x_v \quad (1)$$

$$Q_0 = Q_w + Q_f \quad (2)$$

Rate of lactic acid inflow into the tank ($\mathbf{m_i}$)

$$m_i = Q_f\, C_f \;(m^3/s * \text{moles}/\, m^3 = \text{moles}/s) \quad (3)$$

$$m_0 = Q_0\, C_0 \quad (4)$$

Rate of lactic acid accumulation in the tank ($\mathbf{m_a}$)

$$m_a \frac{d}{dt}[V\, C_0(t)] = V \frac{dC_0}{dt} \quad (5)$$

Where $V\, C_0(t)$ is the lactic acid hold up for the tank at time t

Consider the law of conservation:

$$Q_f\, C_f = V \frac{d}{dt} C_0 \quad \text{or} \quad \tau \frac{d}{dt} C_0 + C_0 = K\, x_v \quad (6)$$

Where $K = C_f K_v / Q_0$ and $\tau = V/Q_0$

The transfer function of the system:

$$\frac{C_0(s)}{X_v(s)} = \frac{3.247}{30s+1} \quad (7)$$

The equation for the system was later tested for unit step response using Matlab.

Choosing the right temperature sensor for the brewery

Platinum resistance thermometers (Pt100) were chosen because of their improved high responsiveness, high sensitivity and long term stability in wet conditions. RTDs are also easy to install and also have the highest accuracy temperature averaging thus making them the best suitable though the RTDs are expensive.

Modeling for temperature

Fig 2 shows a cooker control system. The output signal from a temperature sensing device which is Pt100 is compared with the desired temperature. The error causes the controller to send a control signal to the solenoid gas valve which produces linear movement of the valve stem, thus adjusting the flow of steam to the cooker.

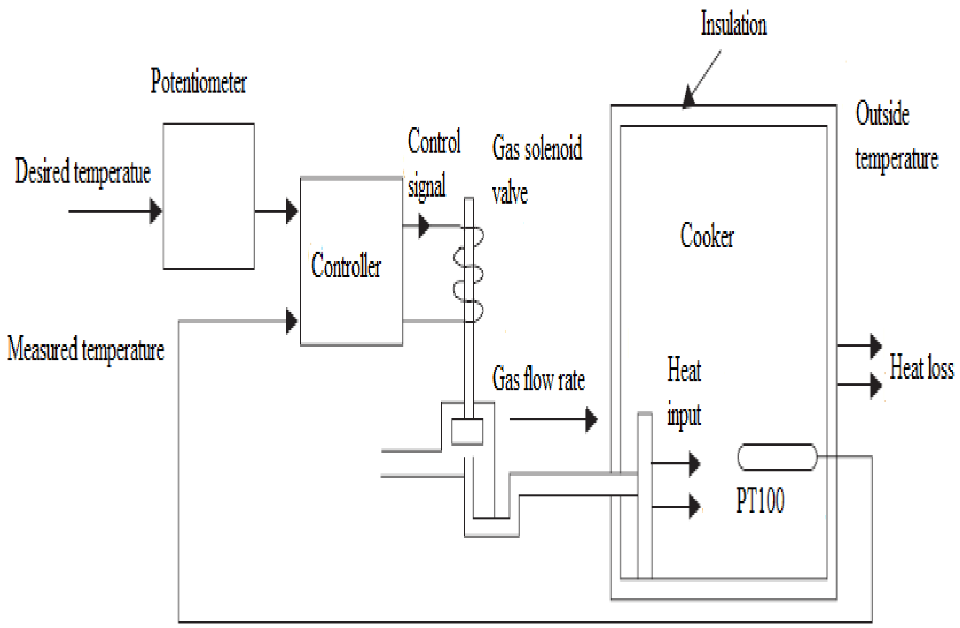

Fig 2 Cooker Control System

The PID system controller is connected to the current- pressure actuator. The actuator is connected to the gas solenoid valve which continuously actuates to open or close so that the correct amount of steam will flow into the cooker so as to raise or lower the temperature. The temperature in the cooker is measured by the Pt100 which gives feedback to the system controller for adjustment and control. The disturbance will account for the heat losses, steam leakages and other non-ideal fluctuations.

Fig 3 Shows a block diagram for the temperature control loop using the PID controller.

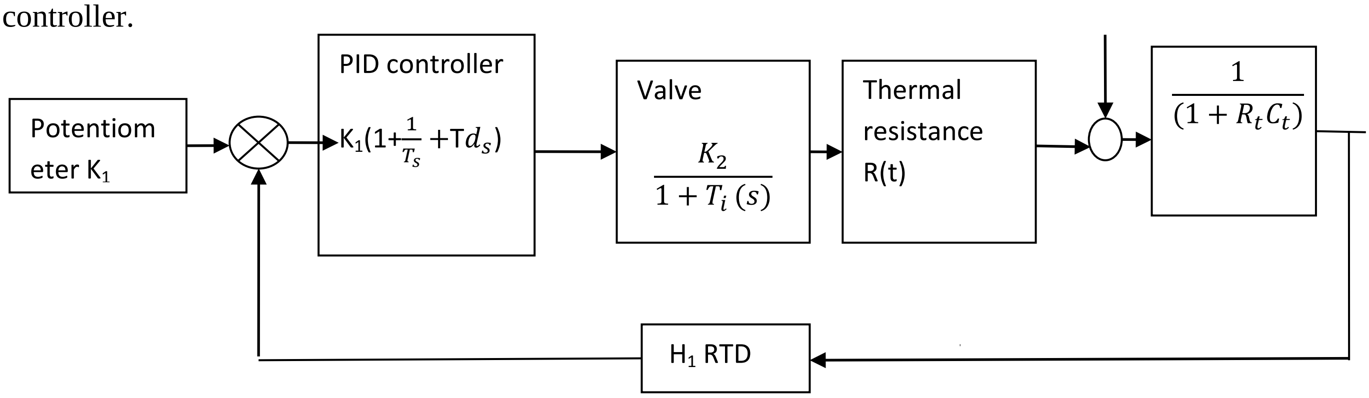

Fig 3 Temperature control using PID controller

Where: C_t = Thermal capacitance, R_t= Thermal resistance, K_1 = Constant for PID, K_2 = control steam valve constant, $\theta_d(t)$ = desired temperature, $\theta_m(t)$ = Measured temperature (V), $\theta_0(t)$ = Actual temperature(˚C), u(t) = Control signal, V(t) = steam flow rate(m^3/s), $Q_i(t)$ = heat flow rate into the cooker(J/s = W), $Q_o(t)$ = Heat flow through the walls of the cooker (W), C_T = Thermal capacitance, R_T = Thermal resistance of the walls.

System equations

Controller: The control action is PID of the form of $1+\frac{1}{T_{i(s)}}+T_d(s)$ (8)

$U(s) = K_1\,[1+\frac{1}{T_{i(s)}}+\ T_d\,(s)][\,\theta_d(s) - \theta_m(s)$ (9)

The gas solenoid valve has a first order dynamics of the form;

$\frac{V}{U}\,(s) = \frac{K_2}{1+T_i(s)}$ where K_2 is the valve constant m^3/s (10)

Room dynamics

$Q_i(t) – Q_0(t) = C_T\frac{d\theta}{dt}$ (11)

Heat through the walls of the cooker is as given in equation (12)

$Q_0(t) = \frac{[\theta_0(t)\ - \theta s(t)]}{R_T}$ (12)

Substituting equation (11) into (12)

$Q_i(t) – [\frac{\theta_0(t) - \theta s(t)}{R_T}]= C_T\frac{d\theta}{dt}$ (13)

Multiplying by R_T

$$R_T Qi(t) + \theta s(t) = \theta_0(t) + R_T CT\frac{d\theta}{dt} \quad (14)$$

Taking Laplace Transforms

$R_T Qi(s) + \theta s(s) = [1+R_T C_T]\,\theta_0(s)$ (15)

The thermometer equation

$\theta_m(s) \ = H_1\theta_0(s)$ (16)

The block diagram can be reduced to:

$$\frac{K_1K_2R_T(T_d\,sT_{i\,(s)})+1)[\theta_d(s)-1+\theta_0(s)}{T_i(s)(1+T_1(s)} + \theta_0(s) = 1 + R_T\ C_T\theta_0(s) \quad (17)$$

Hence the forward gain $K_f = K_1K_2R_T$

$R_T = 0.75$

$C_T = 11J/K$

$T_1 = 2.2634$

The transfer function of the system:

$\frac{Ha(s)}{V1(s)} = \frac{0.95}{1+411.255s}$ (19)

The equation for the system was later tested for unit step response using Matlab.

Modeling for water level control system

The level sensor ensures correct amount of water is poured into the cooker. Greyline LIT25 sensor was chosen because the signal relay is programmable for ON/OFF pump control, level, temperature or echo loss alarm. Figure 4 shows a level control system for the cooker.

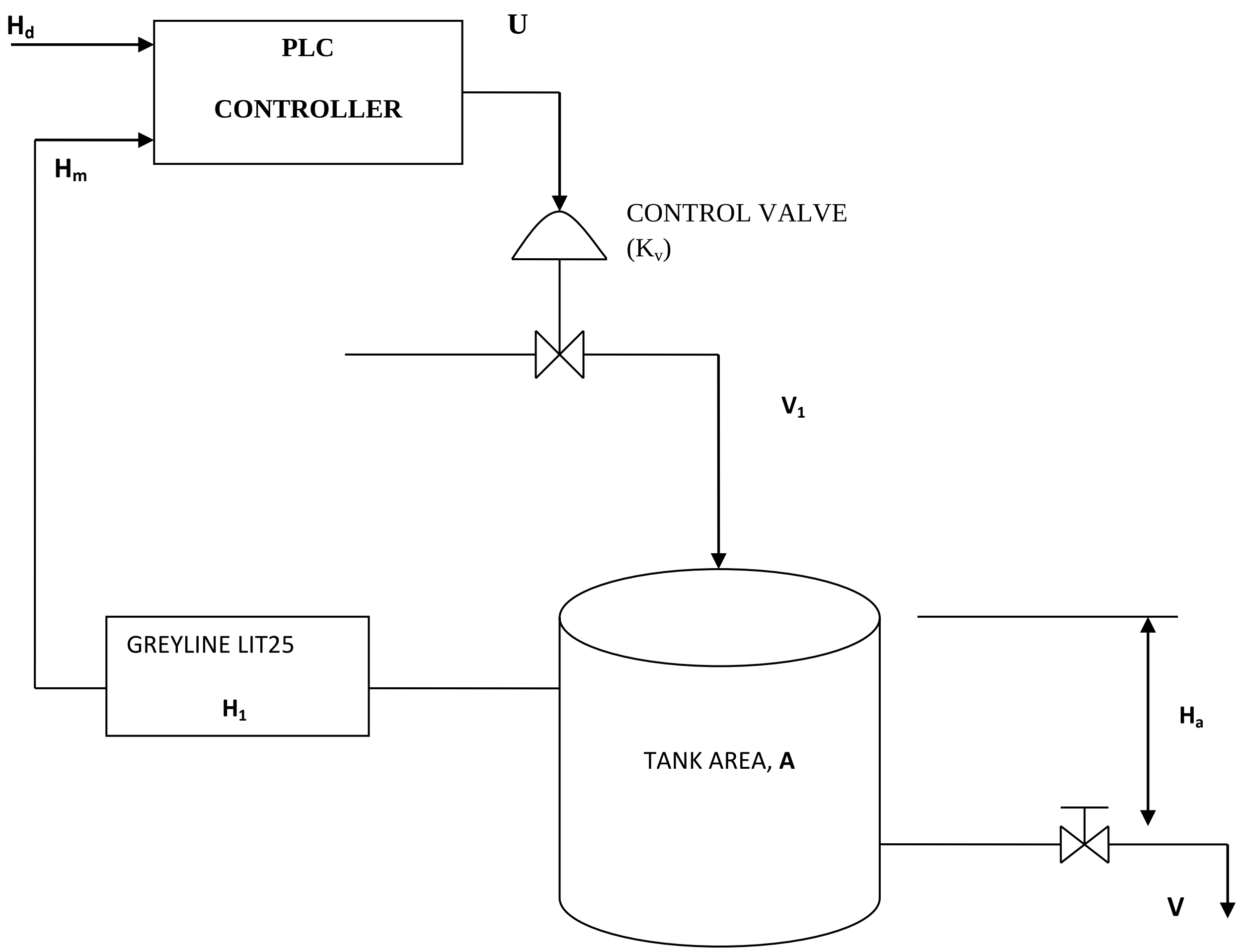

Fig 4 Modeling the control system for water level

Where K_v = flow coefficient for water, R_f = 15s/ m^2 , U_t = Signal from the controller, V_1 = Volume of tank when it has reached the required level, V_2 = Volume of tank at a particular time, A = Area of tank, H_a = Height of tank, R_f = Outlet resistance of water.

V_1 (t) = K_vU_t (20)

Tank dynamics $V_1 (t) – V_2(t) = \frac{Ad}{dt} h_a$ (21)

To linearise the flow $V_2 (t) = \frac{ha(t)}{Rf}$ (22)

The measured head $h_m = H_1 . h_a$ (23)

$V_1(s) - \frac{ha(t)}{Rf(s)} = A_sH_a$ (24)

$\frac{Rf(s)V1(s) - Ha(s)}{Rf(s)} = A_sH_a$ (25)

$\frac{Rf(s)V1(s)}{Rf(s)} = A_sH_a + \frac{Ha(s)}{Rf(s)}$ (26)

$\frac{Rf(s)V1(s)}{Rf(s)} = H_a(A_s + \frac{1}{Rf(s)})$ (27)

$\frac{Ha(s)}{V1} = \frac{Rf}{1+A(s)Rf(s)}$ (28)

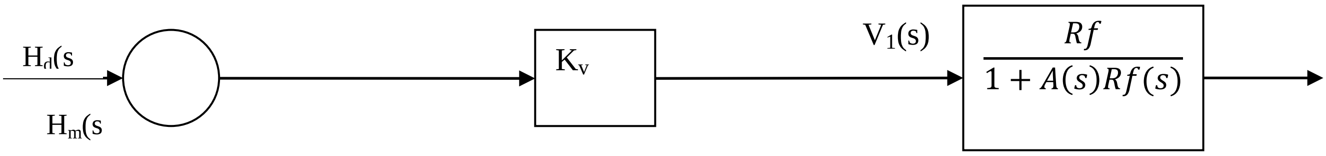

Fig 5 Open loop system

$$\frac{H_a(s)}{V_1(s)} = \frac{K_v R_f}{1+411.255s}$$

K_v = 0.1 **R_f** = 9.5m^3/s

The transfer function of the system:

$$\frac{H_a(s)}{V_1(s)} = \frac{0.95}{1+411.255s} \qquad (29)$$

The system was later tested for unit step response using Matlab.

Results and discussion

The research focused on the design of the control system for sorghum beer brewing process. The research illustrated on the designing of the system from first principles and the simulation of the temperature control system was done using Matlab.

Results for the mashing tank

The transfer function for the mashing process was obtained from first principles. The transfer function for the process obtained was:

$$\frac{\mathbf{C_0(s)}}{\boldsymbol{X_v(s)}} = \frac{\mathbf{3.247}}{\mathbf{30s+1}} \qquad (7)$$

The system was then tested for open loop unit step response and it produced an amplified input response signal by a factor of 3.25. The PID control algorithm was then implemented and the system was tested using a Proportional controller. The system managed to achieve a unit step function with no overshoots, however the rise time was 105seconds. The system was again tested with the aid of the proportional derivative controller so as to reduce the rise time and system response time. The system rise time was 0.5 seconds and the system achieved the desired set point with no overshoot. The Proportional Derivative controller was selected for the mashing section. This can be seen in figure 6 shown below.

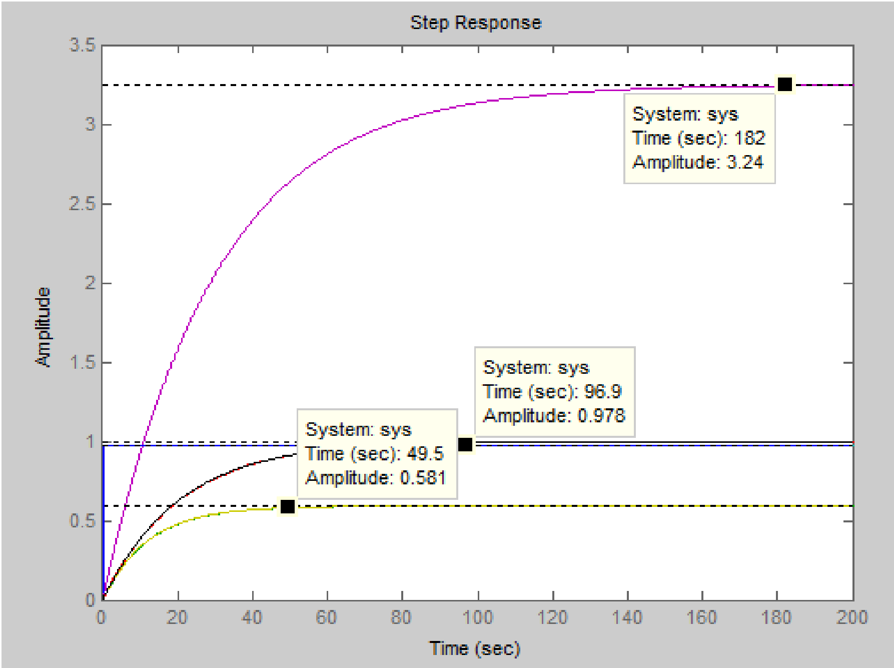

Fig 6 Combined graphs for the PID control system

Water level control the system

The transfer function that was obtained from first principles was $\frac{H_a(s)}{V_1(s)} = \frac{0.95}{1+411.255s}$ (19)

The system was tested for unit step open loop response. The gain of the transfer function was 0.95. The rise time was 1500seconds and the settling time was 500seconds. The proportional controller was introduced so as to lower the rise time. The gain of the system was 0.865 and the settling time was 250seconds. This showed that the proportional controller reduced the gain from 0.95 to 0.865. The proportional derivative was the introduced. It reduced the controller gain to 0.815 and the rise time was 250seconds. The proportional integral was also introduced so as to increase the gain of the system. The amplitude obtained showed that the system was now unstable. An overshoot of 0.8 was achieved and the settling time increased to 500seconds. The Proportional Integral Derivative control system was introduced and the system was tested for unit step response. The response time for the system was reduced from 500seconds to 10seconds. Figure 7 shows the combined graphs for the control system.

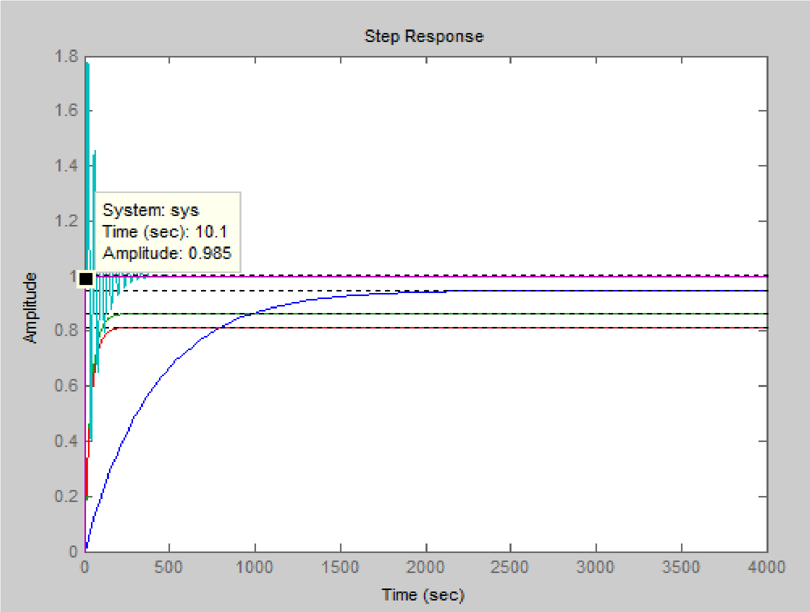

Fig 7 Combined graphs for the PID control system

Results for the temperature control system

The model that was designed using Simulink was run to check if the temperature would rise in the desired manner. The graph shown in Figure 8 was obtained after running the model. The system was able to perform as per desired response. The mash was raised to 50˚C for 50minutes and the hydrolysis of protein, β glucons and pentasons by proteolic enzymes. The temperature was then raised to 80˚C and was maintained constant for 10minutes for the optimal activity of β-amylase. It was then raised to 95˚C and maintained for 40minutes for the optimal activity of α- amylase. Finally, the temperature was raised to 100˚C and was held constant for 60minutes to inactivate the enzymes.

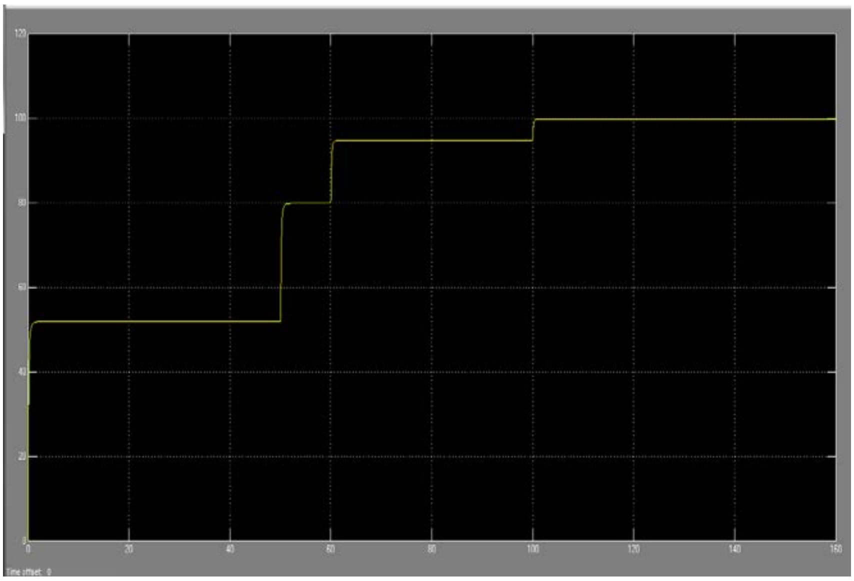

Fig 8 Temperature control graph

Conclusions and recommendations

The main aim of the research was to design a control system that that would monitor and control the mashing process, boiling of the mash in the cooker and the amount of water added in the cooker during the beer brewing process. The temperature control system was designed that gave the desired responds to raise temperature initially to 50˚C and maintain it for 50minutes, to raise the temperature to 80˚C and maintain it for 10minutes. The system managed to raise the temperature to 95˚C and maintain it for 40minutes and finally the temperature was also raised to 100˚C and maintained at that stage for 60minutes.

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