



Optimal Temperature Control Scheme for Milk Pasteurization Process Using Different Tuning Techniques for a Proportional Integral Derivative Controller

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Abstract: Milk is one of the important dairy foods, which forms an essential building block in the feed formulation for infant and growing children, and adults alike. However, the quality of the final product largely depends on the temperature of the pasteurization process. It is, therefore, a necessity to ensure that optimum temperature is maintained during pasteurization process, as over-temperature kills all the essential nutrients contained in the final product and similarly, low temperature is not desirable as the final product will not yield the desired nutritional value. As a result, the application of optimal temperature control scheme is a critical requirement for milk pasteurization. It is, on this background, that this paper presents the use of a Proportional (P), Integral (I), Derivative (D) abbreviated as PID controller for optimal control of temperature in the milk pasteurization process. The milk pasteurization temperature was modeled based on the first law of thermodynamics, while three different tuning techniques namely; Zigler-Nichols (ZN), Chien-Hrones-Reswick (CHR) and Cohen-Coon (CC) were employed to tune the PID controller for optimal control of the milk pasteurization temperature. The control schemes were simulated in MATLAB/Simulink, and the performance of each tuning technique was evaluated using the rise time, settling time, peak amplitude, and overshoot. Results showed that ZN tuned PID controller gave the lowest rise time, settling time, and peak amplitude of 0.177s, 0.34s, and 0.993, respectively, while the lowest overshoot of 0% was attained by both ZN and CHR. Based on these results, CC tuned PID controller exhibited moderate rise time of 1.02s, settling time of 6.49s, and overshoot of 5.67%, indicating that its performance is comparatively preferred with respect to other tuning techniques investigated. The results of this research find application in dairy industries as it provides insight into the appropriate tuning technique for the PID controller to ensure optimum temperature control during milk pasteurization.

Keywords: Controller, Milk, Pasteurization, PID, Temperature, Tuning.

1 Introduction

FOOD processing industries are an indispensable pillar of national development, as they serve as a

means of job creation, agricultural produce processing, and source of hygienic and nutritious food for subsistence of mankind. The goals of a good food processing system include extending the shelf life of foods, enhancing the nutritional value, sustaining food quality, and reducing wastages [1-3]. Modern-day industrial processes are generally complex due to several systems automation which requires adequate control strategies to coordinate various processing units in the automation system to achieve prime objectives which are the quality final product [4]. One of such food processing industries is the milk industry; milk is one of the nutritious farm products produced through a lactation process in female mammals like goats, cows, camels, donkeys, sheep, and others for human consumption and healthy living [5].

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The raw milk undergoes a pasteurization process during the processing stage in the industry. This is because unpasteurized milk is a good habitat that encourages avalanche multiplicity of harmful microorganisms, most especially when kept at a temperature either below or at room temperature [6, 7]. Therefore, heat treatment is usually required before further preservation to get rid of all the harmful pathogenic organisms in milk. This is why regulation of milk temperature is central to dairy industries to prevent fouling and damage to milk quality such as the color, flavor, fat, protein, and other useful nutrients.

Pasteurization consists of heating the milk to a pre-determined minimal temperature for a pre-set minimum time to remove prescribed pathogenic micro-organisms. Authors in [8] posited that increasing the temperature is a way of enhancing positive contribution to the entropy of unfolding. From this position, it can, therefore, be said that heat transfer occupies a core position in food engineering. Several heat exchangers that have been modeled and widely deployed for diverse industrial processes include plate heat exchangers, tubular exchangers, spiral flow exchangers, shell and tube exchangers, and scraped surface exchangers among others [9] and their basic role is to transport heat to a fluid or between two fluids based on thermal specification [10].

Fig. 1 shows the process of milk pasteurization and the various components of milk obtained during the process. The essential components are labeled thus; 1) balance tank, 2) product feed pump, 3) flow controller, 4) deaerator, 5) separator, 6) constant pressure valve, 7) density transmitter, 8) flow transmitter, 9) regulating valve, 10) shut-off valve, 11) check valve, 12) homogenizer, 13) booster pump, 14) holding tube, 15) flow diversion valve, 16) plate heat exchanger, and 17) process control accordingly.

Physical modeling of an industrial pasteurizer based on plate heat exchangers (PHE) of type Clip 10-RM and brazed heat exchangers (BHE) of type CB76 from Alfa Laval was investigated by [12] examined numerical modeling and experimental validation for earth air tunnel heat exchanger and it was found that the performance of earth air tunnel heat exchanger is independent of buried pipe material. Also, authors in [13, 14] presented a solar furnace temperature control employed for material testing where proportional-integral control architecture was designed for solar furnaces. Samples were tested both in high-temperature stress cycles and by imposing a solar radiation flux profile. The actuator was found to be faster compared to the thermic system and the likely effect of this is that the overall control system may be destabilized. Therefore, control architecture for solar furnaces was designed and the application of singular perturbation methods to derive conditions for the speed of actuator dynamics and stabilize the closed-loop system was

developed. Similarly, authors in [15], presented heat transfer capability enhancement of milk pasteurization plate heat exchangers by the addition of multi-walled carbon nanotubes (MWCNT) to water.

Authors in [16] were concerned with parametric modeling and simulation of photovoltaic panels with earth water heat exchanger (EWHE) cooling. The work concluded that PV/T system along with EWHE may be used for the purpose of PV power plants cooling in hot and semi-arid regions where solar irradiation is ample and ambient temperatures are very high. It has also been established that industrial processes exhibit an integrating response characteristic when heated up to the set-point and tend to assume a stable manner within a given temperature range as a result of air-convection losses [17]. The associated problem with these processes is chiefly temperature overshoots in the heating-up stage. Also, maintaining the set-point temperature with respect to load disturbances and process variations poses a serious challenge to industries. Consequently, there arises the need to deploy a controller whose function is to ensure that the product is of good quality and that the plant is characterized by minimum rejection and short response time [18]. The quest for a system with high-performance indices and uniqueness of each system, has, therefore, led to increasing demand for control means which varies from one system to another.

The milk pasteurization process requires a high precision temperature control means to ensure that the quality of the milk is preserved as shown in Fig. 1 and several scholarly works support the same conception [19-21]. There are four distinctive methods of pasteurization namely; low-temperature short time (LTST) pasteurization, high-temperature short time (HTST) pasteurization, flash pasteurization, and UHF pasteurization, which are meant to destroy disease-carrying germs and prevent souring of milk [22]. A typical automated pasteurizer is presented in Fig. 2, which shows the motor, control valve temperature transmitter (TT), and PLC components.

Several control strategies have been developed and deployed for temperature control in milk pasteurization, for instance, model predictive control technique has been employed severally for milk pasteurization by researchers [24-26]. However, the approach has inherent drawbacks such as noisy signal, model accuracy, and hardware limitations [27]. Consequently, the use of a PID controller for optimal control of the pasteurization process is necessitated in food processing. PID control remains a control tool of choice due to its wide availability, simplicity in deployment and operation, and off-the-shelf tuning [28-30].

A good number of industrial control processes have been previously handled with PID controller, and the results obtained have been a huge success [31, 32]. In a

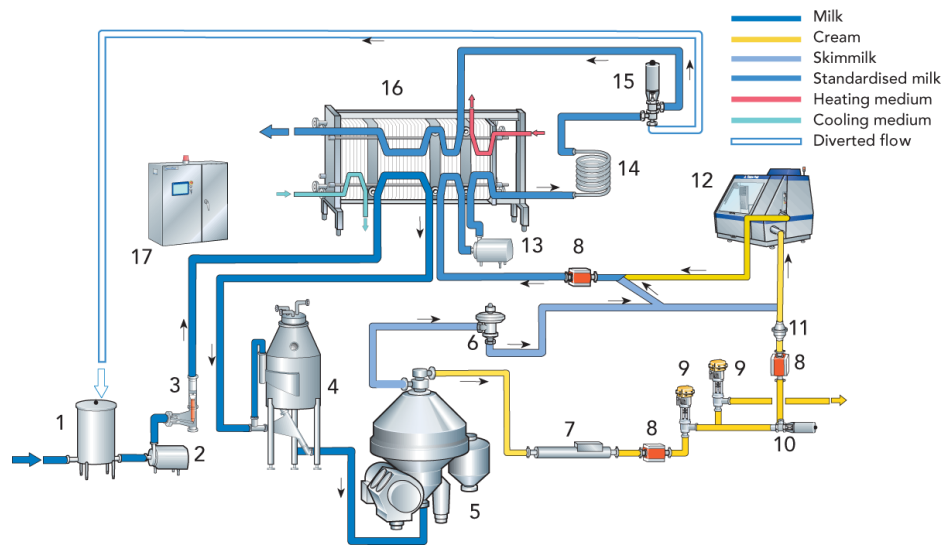


Fig. 1 Milk pasteurization flow processes [11].

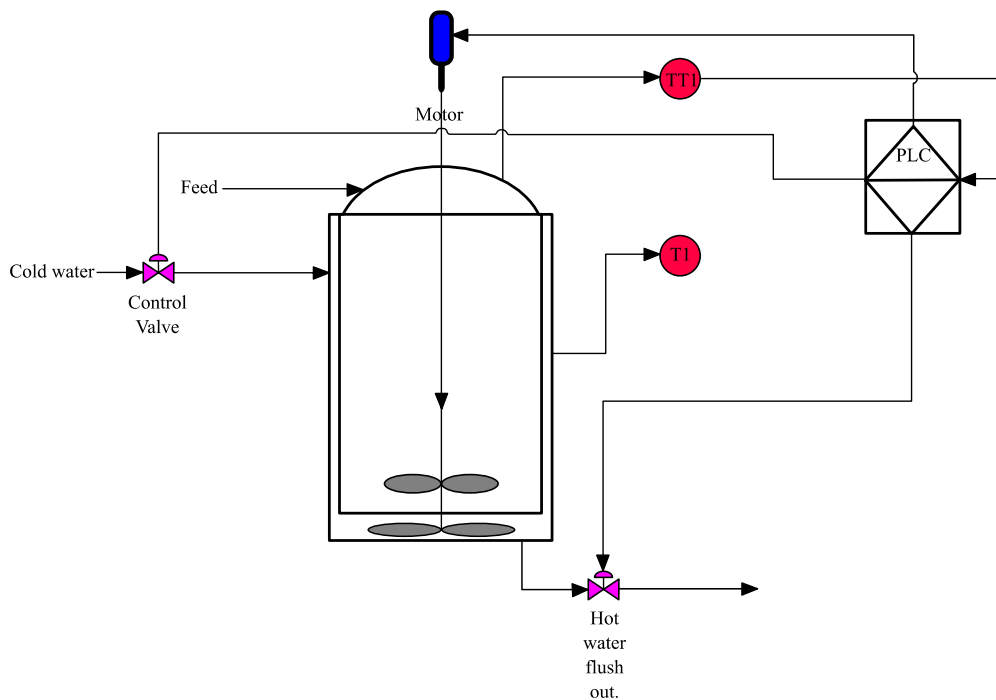


Fig. 2 A typical automated pasteurizer [23].

similar vein, previous studies have shown that approximately 90% of entire controllers employed in processing industries are more of PID structure [33-35]. The choice of PID controller in this present study was based on its ability to correct error emanating from the measured process variable and the desired set-point, such that the difference between the measured and set-point can be used to adjust the control process. Similarly, its essential parameters P, I, and D permit fine-tuning adjustments and guaranteed better control with any tuning techniques such as ZN, CHR, and CC and artificial intelligence techniques such as genetic algorithm (GA), particle swarm optimization (PSO), and artificial neural network (ANN) among others. Unlike

on-off controllers which suffer oscillation, the proportionate controller reduces this oscillation caused by an overreaction of the on-off controller, the integral controller has the capability of eliminating steady-state error while the derivative controller offered help in activating “forward-looking” correction which implies estimating the anticipated system behavioral error. Several authors have investigated temperature control in industrial processes via simulation and optimization [17], [35-38]. For instance, effective control of the plastic melting temperature for injection molding with a view to ensuring product quality and prevention of thermal degradation of the melt was presented by authors in [39]. In a related work,

researchers in [40] presented a Fuzzy-PID controller for the main steam temperature system based on the variable universe for thermal power plants. The simulation was done using different working conditions for the proposed methods; Fuzzy-PID, PID, Fuzzy-neural network, generalized predictive PID, and Smith predictive control. The simulation results show that Fuzzy-PID controller-based has faster response speed, smaller overshoot, and error, better tracking performance and reduces the lag effect when compared with other control strategies.

Also, temperature control of the pasteurization process has been examined by some researchers; for instance, the works of [41] proposed an automatic PID control of a microwave heating process for in-package pasteurization. It was found that the concentration of *Listeria monocytogenes* decreased linearly with the specified heating time. Generally, the PID controller requires tuning to perform optimally for various processes under different operating conditions. It is on this basis that several works have been dedicated to the performance improvement of the PID controller [42-45]. In a like manner, [46] reported that the development of tuning methods for PID controllers has been one of the most prolific research areas in automatic control. To substantiate these claims [47] performed a tuning of PID controllers using the direct synthesis method for unstable FOPTD and unstable SOPTD systems with and without a zero. Attempts to ensure that the PID controller performs its expected function in the control of different plants have resulted in the different modified forms of the PID controller and these modifications mostly result from the tuning of the controller.

As an example, the need for performance optimization in chemical industries has led to the application of different tuning techniques like fuzzy, particle swarm optimization (PSO), Genetic Algorithm (GA), Simulated Annealing (SA), and H-loop shaping synthesis [48-52]. Also, for performance optimization of power systems and industrial machines, the PID controller has been modified to suit the control objective of gas turbine, servo systems reactors and for stabilization purpose using fuzzy, PSO, and GA [53-55]. PID controller has been widely used for control of industrial pasteurization processes; the literature survey also revealed that model predictive control like dynamic matrix control (DMC) for HTST pasteurization process has been discussed [56, 57]. The cascade standard PID controllers have been proposed for the reduction of the instability of the milk temperature which is caused by disturbances such as inlet milk temperature, milk flow rate, hot water temperature, hot water flow rate, etc. [58, 59].

The contributions of these existing studies form the relevant background for this current paper, most of which directly examined the temperature control scheme. However, this present work extends the effort

of other researchers by investigating the performance of different classical tuning techniques for PID-based temperature control of the milk pasteurization process. It presents a detailed comparative analysis of the performances using the rise time, settling time, peak amplitude, and overshoot parameters. The results are expected to provide useful insights into the appropriate tuning strategy for the PID controller to ensure optimum temperature control for milk pasteurization.

The rest of this paper is organized as follows; Section 2 discussed the model formulation for the temperature of the milk pasteurization process, Section 3 presented the design of the PID controller for pasteurization temperature and performance evaluation metrics, Section 4 presented simulation results and discussions while the last section discussed the conclusion.

2 Model Formulation

The model in this research was developed based on experimental data obtained while applying the thermodynamic principle to the pasteurization process. The steam regulation method whereby milk flow rate (F_a) and hot water recirculation flow rate (F_b) due to PP01 and PP03, respectively, in Fig. 4 were fixed based on the experimental data obtained while regulating the steam valve to maintain the required temperature for the raw milk pasteurization. The set-point for the pasteurization temperature was set higher than the minimum value required for HTST of cream in Table 1 to ensure that the minimum holding temperature is achieved. Table 1 shows experimental data of flow rate F_a against PP01 speed N_a , Table 2 shows experimental data of flow rate F_b against PP03 Speed N_b , while Table 3 shows the experimental result of K and KN_b due to N_b and F_b . The model verified procedures were as outlined thus;

Step I: Identification of essential components in process control- Milk Circulation compartment, Hot Water Circulation compartment.

Step II: Development of governing equations for the identified process components.

Step III: Obtain experimental data from any milk industry to obtain essential constants in the modeled equations for the system.

Step IV: Obtain the transfer function of the controller to be used-PID controller.

Step V: Introduction of tuning technique to aid the response of the controller based on some set of established tuning rules.

Step VI: Development of a Simulink model for steps II, III, IV, and V.

Step VII: Set the pre-set temperature and the sampling time.

Step VIII: Evaluate the system performance using rise time, overshoot, peak amplitude, and settling time.

Step IX: Compare the results for each tuning technique with the results obtained for the metrics used in step VIII.
Step X: Determine the optimal tuning techniques based on the techniques that have the moderate rise time, settling time, and overshoot.

2.1 Milk Circulation Model

The pasteurization temperature T_p measured by temperature transmitter TT01 in Fig. 3 is the milk temperature after heat exchange has taken place in the heat exchanger. To control the temperature, the effect of change in pump PP01 speed (N_a) on the milk flow rate, F_a , is presented in Table 1. It was observed that the value of F_a was zero when N_a was increased from 0% to 20.4%, however, when the value of N_a was 100%, the flow attained a value of 325 L/m. Consequently, the relationship between N_a and F_a can be modeled as follows;

$$F_a = 4.112(N_a - 20) \tag{1}$$

2.2 Hot Water Circulation Model

A similar procedure was applied to develop a model for the hot water circulation pump PP03 in Fig. 4, the effect of variation of speed on the flow rate is measured to prevent cross-coupling. The observation in Table 2 may be expressed linearly as follows;

$$F_b = 9.819N_b - 141.9 \tag{2}$$

$$F_b = KN_b(N_b - 81.9) \tag{3}$$

Table 3 was obtained from the application of (3), in Table 2. Then, the average of KN_b in (3) was obtained from Table 3, which is expressed in (4).

$$F_b = 11.64(N_b - 20) \tag{4}$$

The industrial HTST pasteurization process demands that hot water re-circulate to exchange heat with the milk which leads to a fall in the temperature of hot water in circulation through the heat exchanger.

The heat loss and gain can be calculated using the thermodynamics theory. Recall that heat capacity (Q)

Table 1 Experimental data of flow rate (F_a) against PP01 speed N_a .

PP01 speed N_a [%]	Milk flow rate [L/h]	Milk flow rate [L/m]
10	0	0
20	0	0
30	3000	50
40	4800	80
50	7200	120
60	9600	165
70	12000	200
80	15000	250
90	17400	290
100	19500	325

Table 2 Experimental data of flow rate (F_b) against PP03 speed N_b .

PP01 speed N_a [%]	Hot water flow rate [L/h]	Hot water flow rate [L/m]
10	0	0
20	0	0
30	9000	150
40	15000	250
50	21000	350
60	27000	450
70	32700	545
80	38640	644
90	44510	742
100	50400	840

Table 3 Experimental result of K and KN_b due to N_b and F_b .

N_b	F_b	K	KN_b
30	150	0.500	15.00
40	250	0.313	12.50
50	350	0.233	11.66
60	450	0.188	11.25
70	545	0.156	10.90
80	644	0.134	10.70
90	742	0.118	10.60
100	840	0.105	10.50

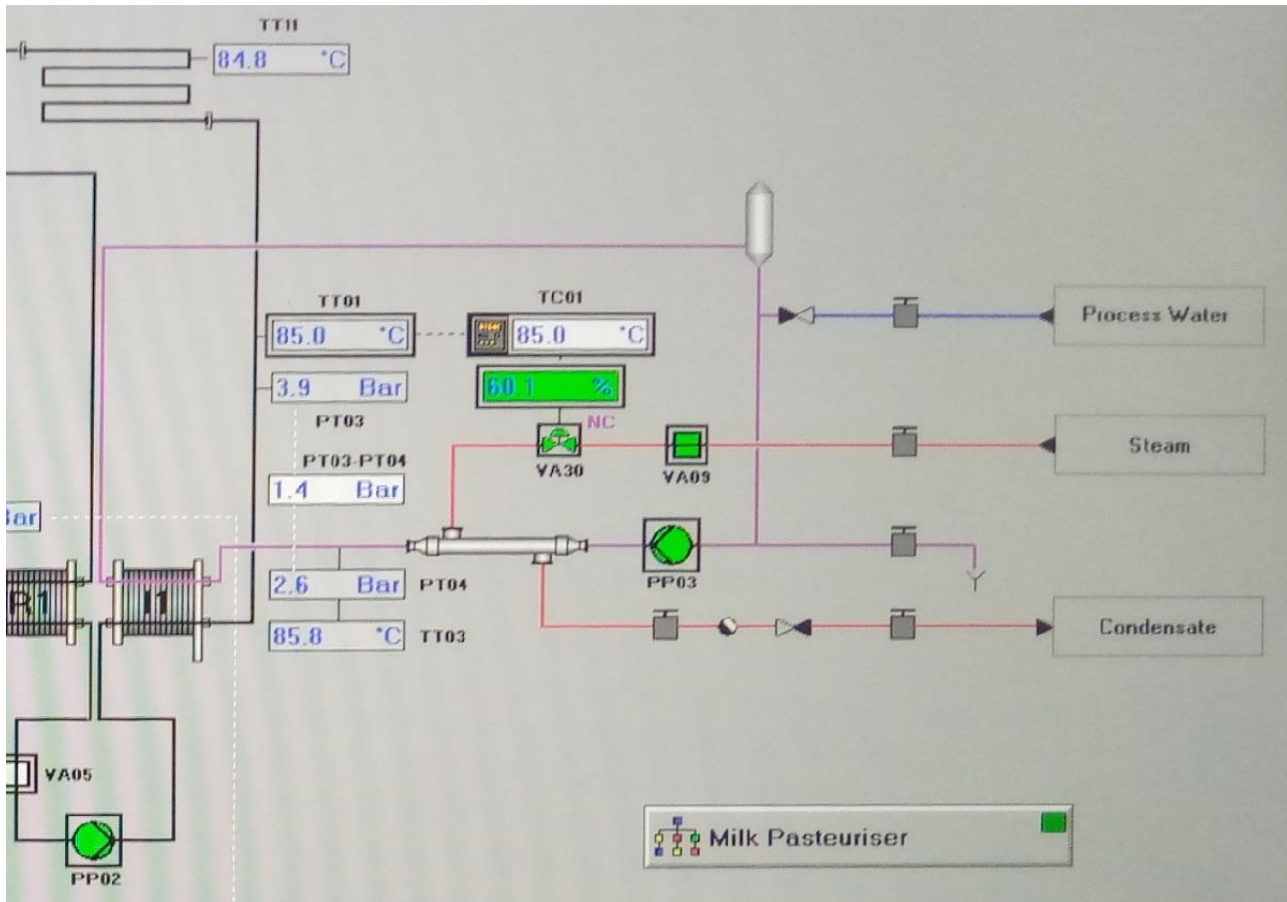


Fig. 3 Hot water circulation P & ID.

can be expressed as;

$$Q = mC\Delta T \quad (5)$$

$$Q = C\Delta T \quad (\text{Considering a unit mass}) \quad (6)$$

$$C = \frac{Q}{\Delta T} \quad (7)$$

where, Q is heat transferred, m is mass of substance, ΔT is change in temperature, and C is specific heat (which depends on material).

The measurement of heat capacity (Q) depends on the thermodynamics state variables like temperature, pressure, and volume and it represents the quantitative relation between transferred heat and change in temperature. Specific heat is the amount of heat required to raise the temperature of 1kg by 1°C and it is measured in j/(kg.K) or j/(kg.°C). Total heat (calorific) capacity

$$C_t = mC \Rightarrow C = \frac{C_t}{m} \quad (8)$$

$$C = \frac{C_t}{\rho V} \quad (9)$$

where, ρ is density of substance and V is volume of water circulating in the pipe.

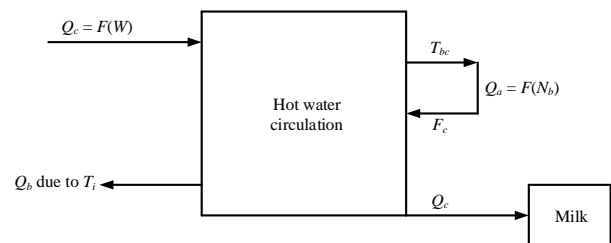


Fig. 4 Hot water circulation loop.

The temperature of the hot water in the heat exchanger through the hot water re-circulation loop needs to be maintained at a certain temperature enough to achieve the minimum holding tube T_h required. However, to account for all heat loss and gained during the opening of the steam valve for heat compensation, the loss heat by hot water to the milk and the environment can be a model based on Fig. 4 which represents the heat transfer by the hot water re-circulation loop. From Fig. 4 the following heat transfer took place between the steam, hot water circulation, heat exchanger environment, and the raw or product milk.

- (i) Heat loss Q_a as a result of heat exchange that took place in the heat exchanger.

$$Q_a = F_b C_w (T_b - T_{bc}) \quad (10)$$

where, C_w is specific heat capacity of water, F_b is mass flow of hot water, T_b is temperature of hot water in the loop, and T_{bc} is temperature of water returning from the heat exchanger.

(ii) The heat gained (Q_b) by the environment or heat loss by the system to the environment.

$$Q_b = HA(T_b - T_i) \tag{11}$$

where, T_i is room temperature, H is heat exchange constant, which is measured in Wm^2/k , and A is area of the hot water loop.

(iii) Heat transferred by the steam line to hot water circulation loop Q_o which depends on the thermal power P_t of the steam applied which ranges between 0 and 1600W.

(iv) The actual transferred heat (Q_c) equation was developed from (3)

$$Q_c = C_h \frac{dT_b(t)}{dt} \tag{12}$$

where, C_h is Hot water caloric capacity.

According to the first law of thermodynamics, the algebraic sum of all the heat transferred is equal to zero. Considering Fig. 4, from the arrow direction of heat transferred, which invariably implied that only Q_o was positive while others were indicated negative to the system. Therefore,

$$Q_c = Q_o - Q_a - Q_b \tag{13}$$

Assume $Q_o = P_t$, to be the thermal power as a result of steam supply to the plant, Q_a and Q_b may be recalled from (5) and (6), respectively.

$$C_h \frac{dT_b(t)}{dt} = P_t - F_b C_w (T_b - T_{bc}) - HA(T_b - T_i) \tag{14}$$

F_b which is the hot water flow rate depends on the speed of the hot water pump N_b . Therefore, Q_a can be expressed based on (3) as;

$$Q_a = KN_b (N_b - 20) C_w (T_b - T_{bc}) \tag{15}$$

$$C_h \frac{dT_b(t)}{dt} = P_t - KN_b (N_b - 20) C_w (T_b - T_{bc}) - HA(T_b - T_i) \tag{16}$$

where, $KN_b C_w = K_a$ and $HA = K_b$.

$$C_h \frac{dT_b(t)}{dt} = P_t - K_a (N_b - 20) (T_b - T_{bc}) - K_b (T_b - T_i) \tag{17}$$

It was observed that when the hot water circulation pump speed is at 0%, the heat transfer by the circulation loop to the environment (Q_a) and useful heat (Q_c) is equal to zero which reduced (12) to;

$$P_t = K_b (T_b - T_i) \tag{18}$$

K_b was calculated by the mean value of several data of T_b (66 °C) in the experimental data while setting (T) thermal power P_t and room temperature at 50.4W and 24.39 °C, respectively. And it was found that $K_b = 1.21 J/s^{\circ}C$, which is the hot water model constant value. The value of the constant K_a was evaluated by assuming a fixed value of 39.9% for both N_a and N_b while fixing Thermal Power at 205.2W. However, the constant value of the difference between T_b and T_{bc} was observed. Therefore, (15) expressed the result of the experiment;

$$0 = P_t - K_a (N_b - 20) (T_b - T_{bc}) - K_b (T_b - T_i) \tag{19}$$

Table 4 showed that T_b does not reach a steady state until it attained 68.5 °C at T_i (room temperature) of 29.05°C and T_{bc} at 46.46 °C. K_a was calculated based on (3) and was found to be 0.36 J/s°C.

Therefore, Eq. (9) can be written as;

$$C_h \frac{dT_b(t)}{dt} = P_t - 0.36 (N_b - 20) (T_b - T_{bc}) - 1.21 (T_b - T_i) \tag{20}$$

From the experiment carried out, the difference between T_b and T_{bc} or T_b and T_i can be assumed to be constant owing to the fact that $T_i = T_{bc}$, and their values were small and negligible, while C_h was calculated based on (7) where $C_h = C_t$, C is specific heat capacity of hot water and V is the volume water circulating in the pipe which depends on length L ($V = \pi L r^2$) where $L = 15m$, $r = 0.04m$, $P = 1000 kg/m^3$ and $= 4186 J/kg^{\circ}C = 4.189 J/g^{\circ}C$, therefore, $C_h = 210.4$.

Based on the above-given conditions, Eq. (20) was reduced to (21).

$$C_h \frac{dT_b(t)}{dt} = P_t - K_a (N_b - 20) (T_b) - K_b (T_b) \tag{21}$$

3 PID Based Pasteurization Temperature Controller

PID controller design for the plant requires the transfer function of the system model equation. A PID controller can be modeled mathematically using (20) [59];

Table 4 Result of experiment on T_b at time interval of 200s.

Time [s]	Temperature T_b [°C]
0	25
200	35
400	42
600	47
800	52
1000	56
1200	58
1400	62
1600	68.5
1800	68.5

$$u(t) = K_p \left(e(t) + \frac{1}{K_i} \int_0^t e(t) dt + K_d \frac{d}{dt} e(t) \right) \quad (22)$$

where, K_p is proportional gain, K_i is integral gain, and K_d is derivative gains.

However, to determine the transfer function, an expression for output per input needs to be obtained from the model equation. Therefore, based on the needed parameters for the pasteurization process, the required temperature is attained due to heat supply by the thermal energy over a given time. Therefore, pasteurization temperature was taken as output and thermal power as input. So, Eq. (16) can be expressed as;

$$\frac{dT_b(t)}{dt} = \frac{P_t}{C_h} - \frac{K_a(N_b - 20)(T_b)}{C_h} - \frac{K_b(T_b)}{C_h} \quad (23)$$

$$\frac{dT_b(t)}{dt} = \frac{P_t}{C_h} - \left(\frac{K_a(N_b - 20)}{C_h} + \frac{K_b}{C_h} \right) T_b \quad (24)$$

$$\frac{P_t}{C_h} = \left(\frac{d}{dt} + \frac{K_a(N_b - 20)}{C_h} + \frac{K_b}{C_h} \right) T_b \quad (25)$$

$$\frac{T_b}{P_t} = \frac{\frac{1}{C_h}}{\frac{d}{dt} + \frac{K_a(N_b - 20)}{C_h} + \frac{K_b}{C_h}} \quad (26)$$

By finding the Laplace transform of (26),

$$\frac{T_b(s)}{P(s)} = \frac{\frac{1}{C_h}}{s + \frac{K_a(N_b - 20)}{C_h} + \frac{K_b}{C_h}} \quad (27)$$

$$\frac{T_b(s)}{P(s)} = \frac{\frac{1}{C_h}}{s + \frac{K_a(N_b - 20) + K_b}{C_h}} \quad (28)$$

The plant also required that PP02 speed N_b need to be fixed at 90% while setting K_a and K_b as calculated. Recall that, $C_h = 210.4$, $K_a = 0.36$, $K_b = 1.21$, therefore,

$$G_{T_b} = \frac{T_b(s)}{C_h(s)} = \frac{0.004753}{s + 0.125523} \quad (29)$$

There were several temperatures measured during the experiment, however, this work focused on controlling milk pasteurization temperature T_p which must be set higher than 75 °C, the minimum required holding tube temperature [21]. As a result, T_p was set to 85 °C, and the model obtained for T_b was adopted, based on the observation from the plant operation that T_b approximately equals T_p ($T_p = T_b$) as this is evident from Fig. 3, where the values of TT01 and TT03 values are very close. Therefore, the scheme for the pasteurizer temperature control is as shown in Fig. 5. The step response of the transfer function was generated as shown in Fig. 7. However, the step response indicates the need for tuning consequently; classical tuning methods namely; Ziegler-Nichols (ZN), Cohen-Coon (CC), and Chien-Hrones-Reswick (CHR) were examined in this work.

3.1 Ziegler Nichols (ZN) Tuning Method

This is a widely applied tuning technique for industrial and process control systems which approximately models the plants as [60]:

$$G(s) = \frac{k}{1 + sT} e^{-sL} \quad (30)$$

where; k is system gain, L is delay time, T is time constant as shown in Fig. 6 and were measured from Fig. 7 as $L = 0.1$, and $T = 9.9$ to calculate the controller parameters stated in Table 5.

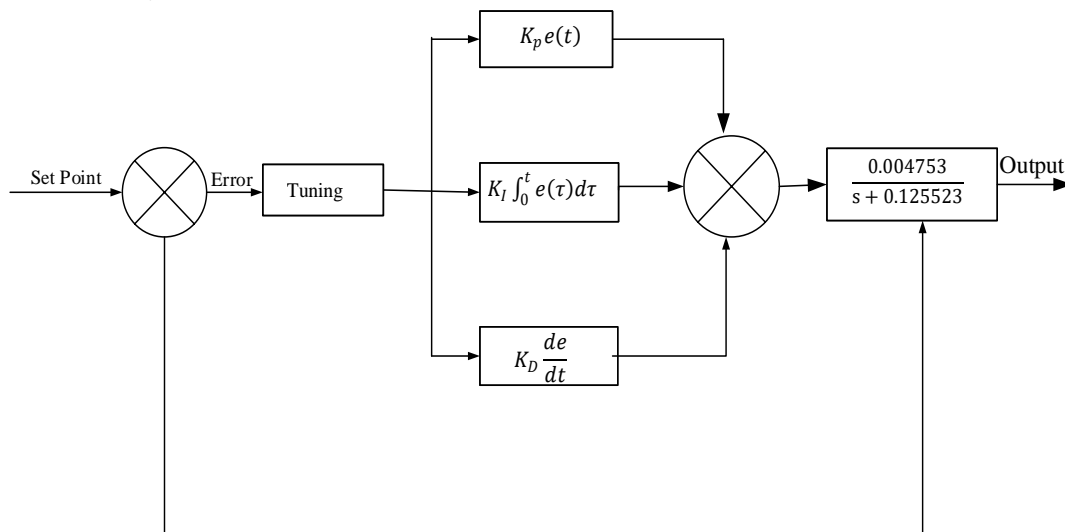


Fig. 5 Scheme for the control of temperature T_p .

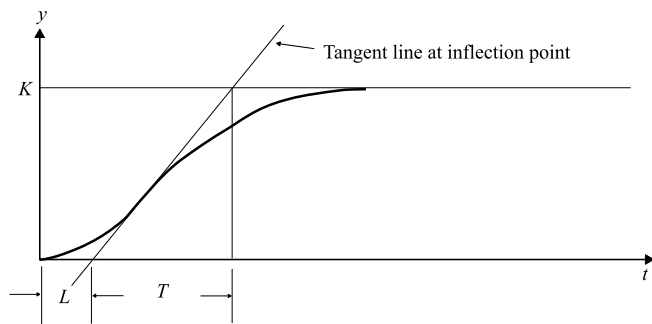


Fig. 6 Process Reaction Curve [63].

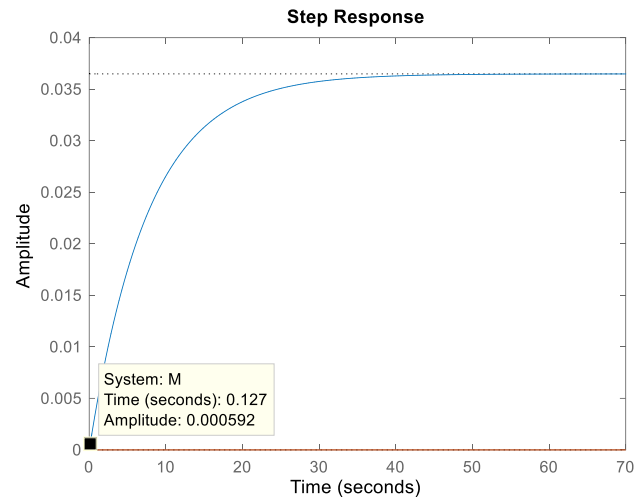


Fig. 7 Step response of temperature T_p scheme.

Table 5 Tuning rule table for Ziegler-Nichols, Cohen-Coon method, and Chien-Hrones-Reswick.

Methods Employed for Tuning	K_p	K_i	K_d	T_i	T_d	
Zigler-Nichols	$1.2T/L$	$0.6T/L^2$	$0.6T$	$2L$	$0.5L$	
Cohen-Coon method	$\frac{1.24}{a} \left(1 + \frac{0.13\tau}{1-\tau} \right)$		$K_p T_d$		$\frac{0.27-0.36\tau}{1-0.87\tau} L$	
Chien-Hrones-Reswick	0% LD	$0.95/a$	$0.396/aL$	$0.399L/a$	$2.4L$	$0.42L$
	20% LD	$1.2/a$	$0.6/aL$	$0.5L/a$	$2L$	$0.42L$
	0% SP	$0.6/a$	$0.6/aT$	$0.3L/a$	T	$0.5L$
	20% SP	$0.95/a$	$0.643/aT$	$0.423L/a$	$1.4T$	$0.47L$

Table 6 Values of tuning parameters for the tuning techniques.

Tuning methods		K_p	K_i	K_d	T_i
Zigler-Nichols		2673	89.1	0	N/A
	LD 0% OS	240	6	0	N/A
Chien-Hrones-Reswick	LD 20% OS	280	1216	0	N/A
	SP 0% OS	120	11.798	0	N/A
	SP 20% OS	240	24	0	N/A
Cohen-Coon		363.3	3.23	0	112.48

3.2 Chien-Hrones-Reswick (CHR) Tuning Method

This method stemmed from the Ziegler-Nichols method and with this method, the plant time constant (T) is explicitly utilized [61]. It can be classified as either load disturbance (LD) or set-point (SP) and can be examined under zero percent overshoot or twenty percent (20%) overshoot as shown in Table 5.

3.3 Cohen and Coon (CC) Tuning Method

This method simply measures the output with reference to the time constant and time delay with an offline tuning technique and the initial parameters can be estimated via the step response [62]. From Fig. 6, $a = kL/T$ and $t = L/(L + T)$ and were measured from Fig. 7 as $L = 0.1$, $T = 9.9$, and $a = 0.0025$, to calculate the controller parameters stated in Table 5.

Table 6 was formulated based on Table 5 using the measured value of a , L , and T from the step response in Fig. 7. The values of the controller parameters in

Table 6 were used to tune the PID controller and the system was simulated in MATLAB/Simulink 8.1.0.604 (R2013b) environment as shown in Fig. 8. The performance of the tuned PID pasteurization process was subsequently evaluated using rise time, settling time, overshoot, and peak amplitude as performance metrics.

4 Results and Discussion

Simulations were carried out to verify the efficiency and performance of the control schemes for the modeled pasteurization temperature in the MATLAB/Simulink environment. The results of the simulation of the pasteurization temperature are presented in Figs. 9 to 15. The simulation results for ZN-PID temperature control of the pasteurization process are as presented in Fig. 9, the input temperature $T_p = 80^\circ\text{C}$ with a sampling time of 5s was used. The line graph represented by Fig. 9 was observed to have a rise time of 4.242s and an overshoot of -1.322% . The graph showed that ZN-PID

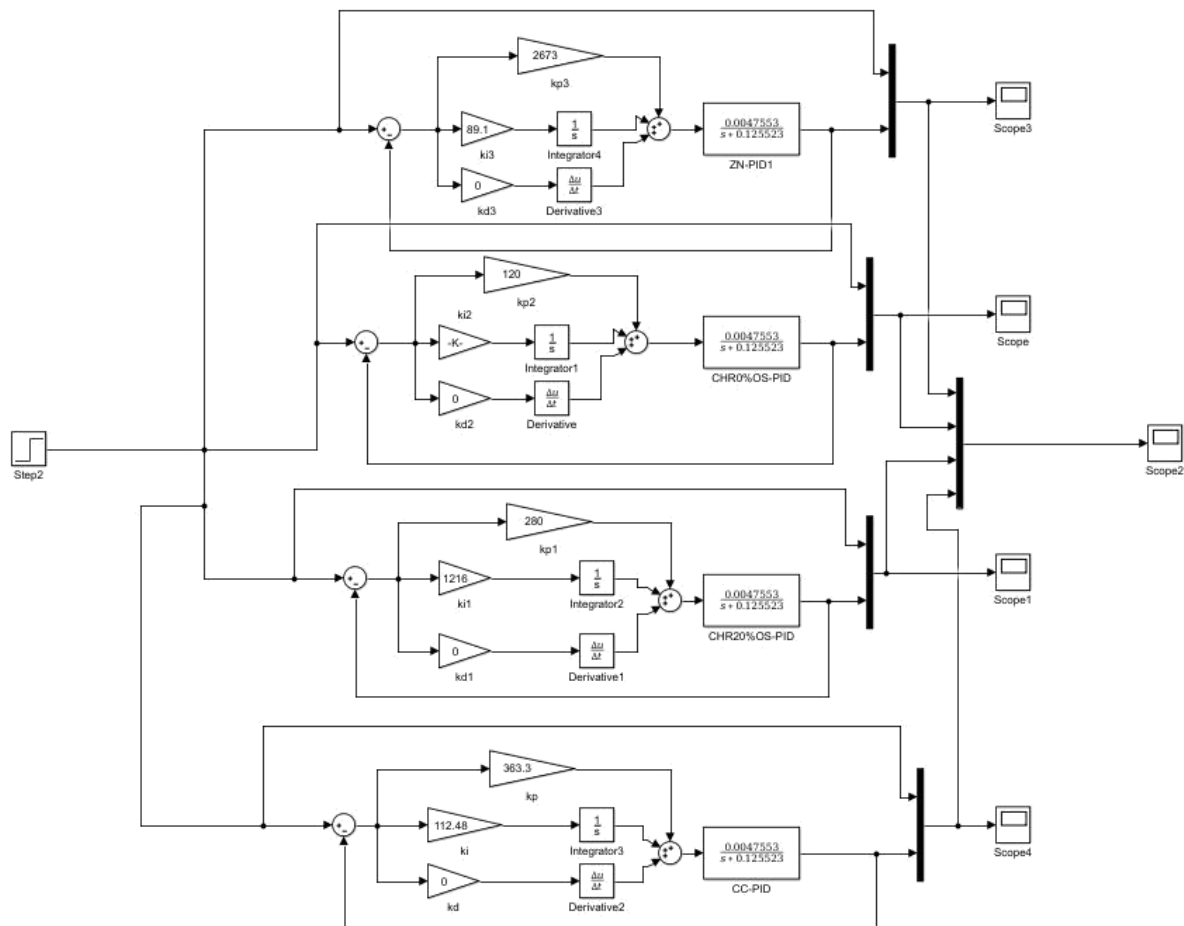


Fig. 8 Simulink block diagram of the tuned PID temperature control of pasteurization process.

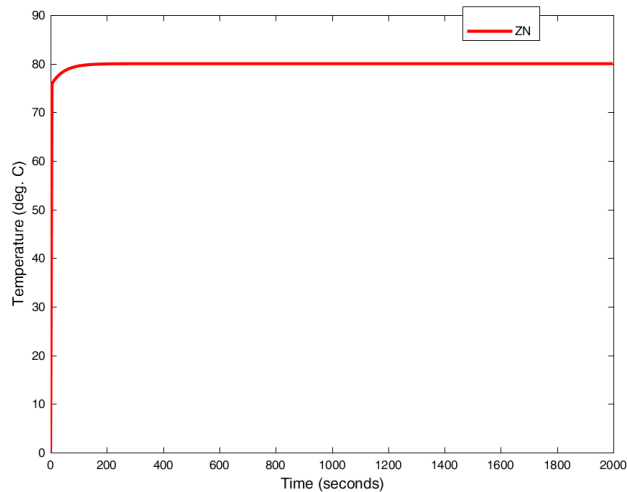


Fig. 9 PID based on ZN tuning method.

is effective in maintaining the set temperature. Also, for CHR-PID, the obtained simulation results of temperature control of the pasteurization process are as shown in Fig. 10. The input temperature $T_p = 80\text{ }^{\circ}\text{C}$ with a sampling time of 5s was used. The graph was observed to have a rise time of 128.5s and an overshoot of 0.484%. The graph showed that the CHR-PID (0% LD) is less effective in maintaining the set temperature

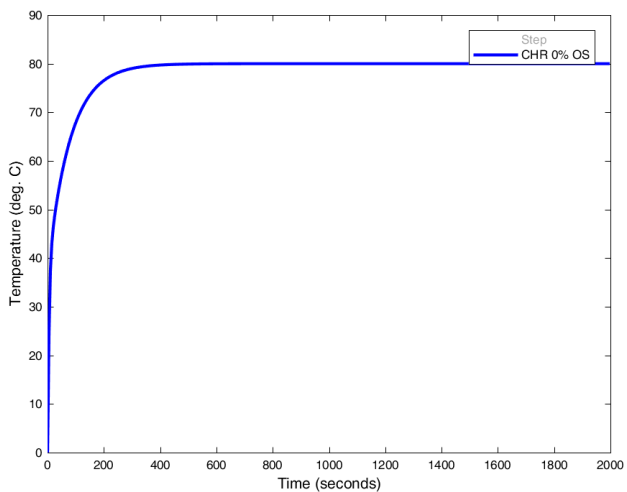


Fig. 10 PID based on CHR 0% OS LD tuning method.

when compared to ZN-PID. Furthermore, Fig. 11 shows the simulation results for CHR-PID (20% LD) temperature control of pasteurization process, the input temperature $T_p = 80\text{ }^{\circ}\text{C}$ with a sampling time of 5s was used. The graph was observed to have a rise time of 2.5s and an overshoot of 60.484%. The significance of the results presented in the graph is that the CHR-PID (20% LD) is ineffective

in maintaining the set temperature when compared to ZN-PID and CHR-PID (20% LD).

The simulation result for temperature control of the pasteurization process using CHR-PID (0% SP) is as shown in Fig. 12, the input temperature $T_p = 80\text{ }^{\circ}\text{C}$ with a sampling time of 5s was used. The line graph of Fig. 12 was characterized by a rise time of 51.5s and an overshoot of 0.499%. These results demonstrate that the CHR-PID (0% SP) performed poorly in controlling the set temperature when compared to ZN-PID and CHR-PID (0% LD). Furthermore, Fig. 13 shows the simulation results obtained for temperature control of the pasteurization process using CHR-PID (20% SP). The input temperature $T_p = 80\text{ }^{\circ}\text{C}$ with a sampling time of 5s was used, from the graph presented in Fig. 13, the rise time and overshoot were observed to be 25.95s and 0.489% respectively. The implication of this is that CHR-PID (20% SP) performed poorly in controlling the set temperature of the milk pasteurization process, when compared to ZN-PID and CHR-PID (20% LD). Fig. 14 shows the simulation results for CC-PID temperature control of the pasteurization process, the input

temperature $T_p = 80\text{ }^{\circ}\text{C}$ with a sampling time of 5s was used. The percentage overshoot and the rise time were found to be 10.556% and 7.494s respectively. This implies that CC-PID is effective like ZN-PID in controlling the set temperature of the pasteurization process when compared to CHR-PID (0% LD).

The performance comparison of the three tuning techniques (ZN-PID, CHR-PIDs, and CC-PID) employed in controlling the temperature of milk pasteurization was as shown in Fig. 15. The results demonstrate that the ZN-PID and CC-PID methods are better in terms of lower performance indices but for practical purposes, the CC-PID is preferred due to moderate overshoot which ensures that all the volume attains the pasteurization temperature.

Table 7 presents a summary of the performance metrics of all the tuning techniques examined in this work. From Table 7, the least overshoot of 0% was achieved by ZN-PID, CHR-PID (0% LD and SP), and CHR-PID (20% SP) while the highest of 43.4 % was obtained for CHR-PID (20% LD). Also, the lowest peak amplitude of 0.993 was obtained by ZN-PID while the

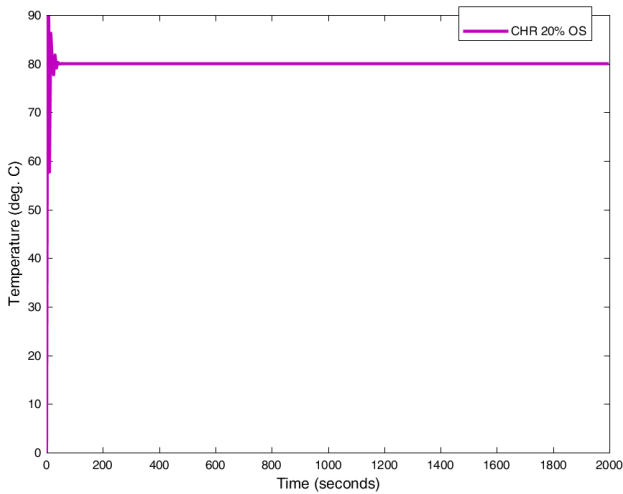


Fig. 11 PID based on CHR 20% OS LD tuning method.

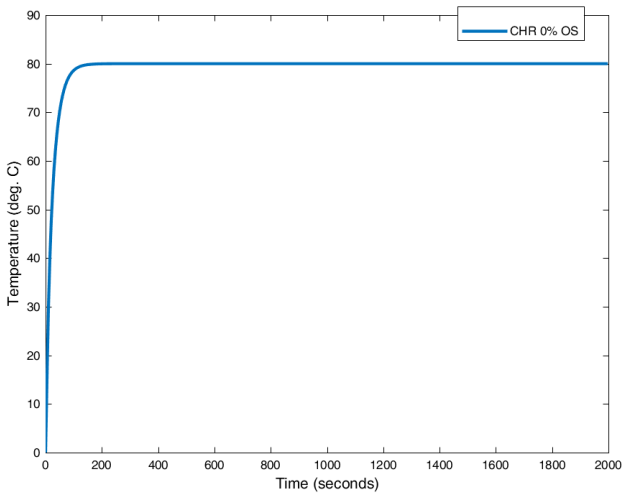


Fig. 12 PID based on CHR 0% OS SP tuning method.

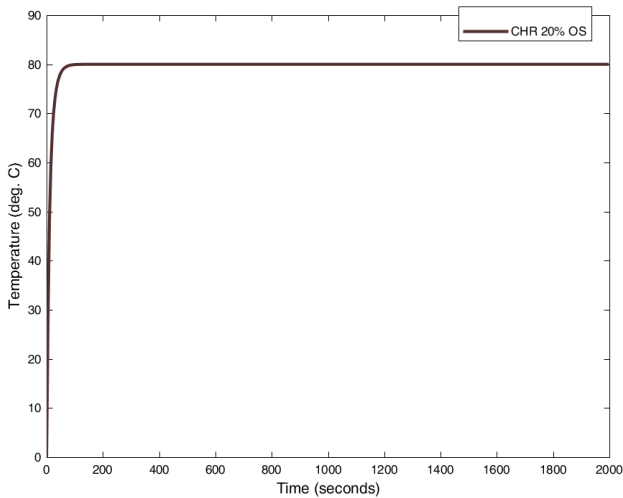


Fig. 13 PID based on CHR 20% OS SP tuning method.

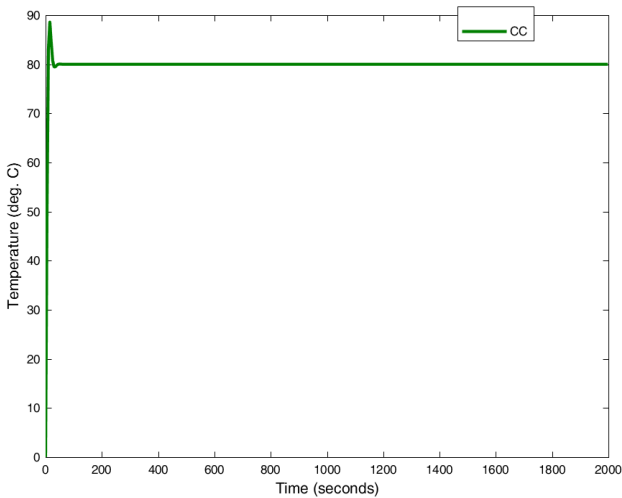


Fig. 14 PID based on CC tuning method.

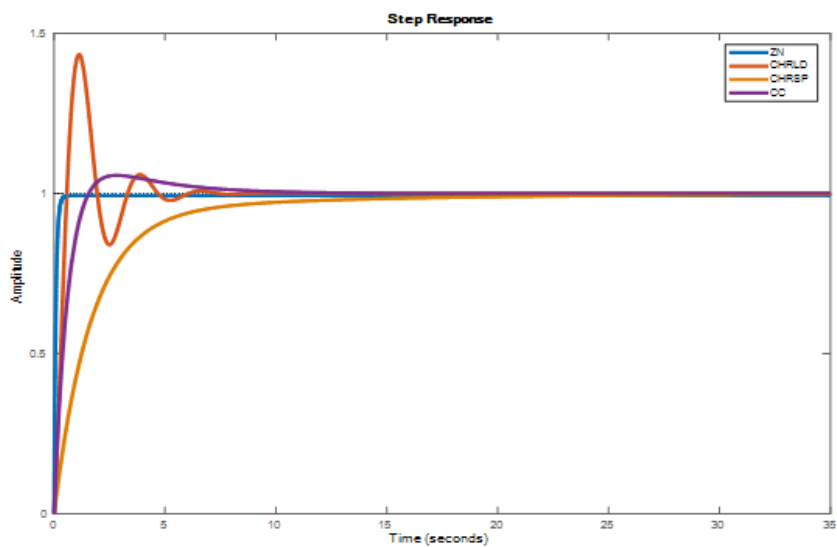


Fig. 15 Performance comparison of ZN, CHR, and CC PID.

Table 7 Summary results for all the tuning techniques investigated.

Tuning techniques	Overshoot [%]	Peak amplitude	Rise time [s]	Settling time [s]
ZN	0	0.993	0.177	0.34
CHR 0% LD	0	0.997	2.92	62.6
CHR 20% LD	43.4	1.43	0.443	5.41
CHR 0% SP	0	0.998	4.24	12.7
CHR 20% SP	0	0.998	2.06	4.78
CC	5.67	1.06	1.02	6.49

highest of 1.43 was obtained with CHR-PID (20% LD). A rise time of 0.177s was also obtained for ZN-PID which was the lowest, while the highest value of 4.42s was obtained with CHR-PID (0% SP). Finally, the lowest settling time of 0.34s was obtained with the ZN-PID technique while the highest value of 62.6s was obtained with the CHR-PID (0% LD) technique. Generally, it can be inferred that ZN-PID gives the best means of controlling the temperature of the milk pasteurization process but for practical purposes, the CC-PID is preferred due to moderate overshoot which ensures that all the volume attains the pasteurization temperature.

5 Conclusion

This paper has presented a detailed comparative evaluation of the performances of different techniques for tuning the PID controller, meant for controlling the temperature in milk pasteurization. The appropriate temperature control strategy is a critical requirement so as to ensure that the final product yield required nutritional value. The pasteurization temperature of the milk was modeled using thermodynamic law, while three different tuning techniques (Zigler-Nichols, Chien-Hrones-Reswick, and Cohen-Coon) were employed to tune the PID controller so as to regulate the pasteurization temperature of the milk. The control schemes were simulated in MATLAB/Simulink

environment. The lowest rise time, settling time, and peak amplitude of 0.177s, 0.34s, and 0.993 respectively, have been obtained by the ZN technique, while the lowest overshoot of 0% was attained by both the ZN and CHR techniques. Though the ZN technique appears to have the lowest performance metrics, CC tuned PID exhibited an excellent performance compared to other tuning techniques, as it demonstrated moderate rise time, settling time, and overshoot of 1.02s, 6.49s, and 5.67%, respectively, which is needed to ensure that all the quantity of milk passing through the process even at the incipient stage is effectively pasteurized. The results reported in this paper reveal the capability of the CC tuned PID controller in regulating the temperature of the milk pasteurization process. The contributions of this work may be useful for understanding further studies in temperature control in food processing.

Intellectual Property

The authors confirm that they have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property.

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A. O. Amole: Supervision, Methodology, Project Administration. **O. E. Olabode:** Original draft preparation, Analysis. **D. O. Akinyele:** Revise & editing, Research & investigation. **S. G. Akinjobi:** Idea & conceptualization, Software and simulation, Data curation.

Declaration of Competing Interest

The authors hereby confirm that the submitted manuscript is an original work and has not been published so far, is not under consideration for publication by any other journal and will not be submitted to any other journal until the decision will be made by this journal. All authors have approved the manuscript and agree with its submission to "Iranian Journal of Electrical and Electronic Engineering".

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