AN OPTIMIZATION APPROACH FOR ENERGY MINIMIZATION AND TEMPERATURE CONTROL OF MILK PASTEURIZATION PLANT

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Energy minimization in temperature control of a milk pasteurization plant using an extremum seeking optimization approach

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A milk pasteurization plant is a dynamic, nonlinear system that is highly energy-intensive in unstable temperature conditions. It is important to ensure that an optimum temperature is maintained at the minimum energy cost during the pasteurization process—even in the face of disturbances which adversely affect the operation of the plant. Therefore, this paper presents an extremum seeking (ES) optimization approach for tuning a controller with proportional , integral ,and derivative (PID) terms so as to optimize the temperature stability of a milk pasteurization plant. The general mass and energy balance principle was used to model the plant, and an objective function was developed to reduce the rate at which liquefied petroleum gas (LPG) was used at the boiler s feeding rate within the 72–76 ˚C range. The mathematical model of each operational unit as well as the PID controller tuning for the optimal temperature control was simulated in MATLAB/ Simulink. Standard performance indicators were used to assess the stability performance of the pasteurized milk temperature control. In comparison to previous convectional controllers that produced lower output performances, the findings demonstrated that the ES-tuned PID controller gave the rise time of 0.103 s, settling time of 14.97 s, peak time of 14.97 s, and percentage overshoot of-0.034 %. Similarly, the LPG consumption rate of 1.80×10^{-3} kg/s at the boiler in terms of energy consumption, annual energy T saving and carbon emission reduction were reduced to $1.16 \times 10^{-3}$and 1.25×10^{-3} kg/s, 4.13×10^{5} and 4.23×10^{5} Baht/year, $89 \times 10^{-4}$and 92×10^{-4}metric ton,respectively, indicating the effectiveness of the ES-PID controller compared to the conventional controller as investigated. Therefore, as this research offers a better means of ensuring ideal temperature control throughout the pasteurization process of milk, it finds good application in the diary industry.

Keywords: Milk Pasteurization; Energy Minimization; Temperature Control; Extremum Seeking; PID Controller.

1. Introduction

The process of heating each and every milk particle to a certain temperature and holding it there for a set amount of time is known as milk pasteurization. Each phase in the entire process of pasteurization, but particularly the heat treatment stage, where appropriate temperature management is anticipated to eradicate the harmful bacteria that pose a risk to human health, becomes crucial for milk safety. Pasteurization is carried out at Ultra High Temperature (UHT), Low Temperature Long Time (LTLT), and High Temperature Short Time (HTST). The majority of bacterial cells are destroyed by LTLT and HTST

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pasteurization, but some thermophiles and spore-forming organisms are not destroyed; on the other hand, UHT pasteurization, because of its exceptionally high processing temperature of over 100 degrees, eliminates all harmful microbes. UHT significantly lowers the number of germs present in products, but it also ruins their nutritional value. The HTST method, which is the industry standard for pasteurizing milk, is largely accepted. The temperature at which the pasteurization process takes place has a significant impact on the final product's quality[1-4]. When the temperature is not appropriately regulated in a milk pasteurization facility, a significant quantity of energy—fuel and electricity—is often used. Liquefied petroleum gas (LPG) is used to heat the boiler for the purpose of producing steam, and electric power is often provided for the pumps, homogenizer, and refrigeration unit during the plate pasteurizer's cooling step. Steam is a useful heat treatment method for the heating step of milk pasteurization, where energy consumption is quite high, due to its efficiency, flexibility, and controllability. Energy and fuel expenses have been ranked second in the dairy industry behind capital production. The dairy industry needs to find ways to cut back on energy usage, as electricity and fuel consumption is rising at the moment[5,6]. Optimization is the process of applying a mathematical algorithm to find the best solution of an objective function under constraining conditions in order to determine the optimal processing condition. Therefore, optimization-based mathematical models and integrated models are important tools, mainly for lowering losses and minimizing the consumption rate of energy in a diary industry [7].

The time and temperature combinations used for heat treatment during milk pasteurization vary because of modifications to system parameters, system nonlinearities, and process-related changes in operating conditions. Additionally, it is crucial for the dairy sector to keep the milk pasteurization plant's temperature at the ideal level while using the least amount of fuel and electricity possible. Consequently, it is necessary to create a multi-variable control method to regulate and stop the temperature from increasing beyond an acceptable threshold. For an effective control strategy to be designed, a precise dynamic model linking the multivariable interactions between the controlled and manipulated variables must be built[8,9]. In this paper, both theoretical and empirical models are created. The empirical model is based on actual parameters and experimental data, whereas the theoretical model employs the principle of mass and energy balance.

Nonlinear dynamical behavior, multivariable interaction between the manipulated components, controlled factors, and limits on manipulated and state variables are all challenges faced by the pasteurization process of milk. Plant disturbances affect the pasteurization temperature's objective function, which raises the amount of LPG energy used at the boiler and the amount of electric power supplied at the ripple plate. It is difficult to operate the milk pasteurization plant with a conventional ON/OFF controller because of these problems[10-12]. Therefore, the main goal of this paper is to combine a standard cascade Proportional-Integral-Derivative (PID) controller with an Extremum Seeking (ES) optimization technique in order to ensure good system dynamic performance, increase process efficiency, and eliminate milk temperature fluctuations due to inlet milk temperature, milk flow rate, hot water temperature, and ice water temperature.

An ES optimization technique is an adaptive control strategy that modifies the plant parameters in response to measurement, improving the dynamical plant's steady-state performance [13]. ES is a non-model method for adjusting a PID controller's parameters in order to minimize the given cost function[14-16], and is utilized to handle control issues in which the system reference point is unknown, but a performance function describing the system ideal behavior must be maximized or minimized in real time [17]. In order to tune a PID controller based on the minimized cost function, ES seeks to identify the global extremum of the objective function that represents the steady state relation between the plant parameters and the plant performance [18]. In this study, the PID control action is specifically utilized due to its optimal control dynamics, simplicity, decreased steady state error, quick response time, ease of implementation, low oscillation, and high dependability. Furthermore, more than 95% of industrial process control applications use it [19, 20].However, functional changes in system parameters lead to a decline in the PID control scheme's performance. Thus, in order to have a more precise reaction from the plant, an adaptive control strategy must be put in place [21,22].

This remainder of the paper is arranged as follows. The supplies and techniques needed to pasteurize milk at the ideal temperature are considered in Section 2, the simulation results and discussion are presented in Section 3, and the conclusion is provided in Section 4.

2. Materials and methods

The goal of this section is to propose a milk pasteurization plant model. The process of pasteurizing milk utilized in the diary industries is illustrated in Fig. 1.Based on the general mass and energy conservation concept, each model is expressed mathematically as an Ordinary Differential Equation (ODE). The following assumptions form the basis of the model equations that are developed for every unit operation:

1. The liquid in every unit operation needs to be perfectly blended.
2. The liquid density and heat capacity must have constant physical and chemical characteristics.
3. The velocity and temperature of each fluid at the inlet flow over the cross-section area is constant.
4. The ripple plate, cooling tower, boiler, plate heat exchanger, and heating coil of a water tank must all have very little volume variation on both sides.
5. The temperature drops at the piping surface over the entire length of the piping are eliminated because the hot water piping of the boiler and the iced water piping of the ripple plate have good insulation [23-25].

(a) Water Tank

$$\frac{dT_{w,o}}{dt} = \frac{U_{HC}A_{HC}\Delta T_{HC}}{\rho_w C_{p,w} V_{WT}} - \frac{U_{WT}A_{WT}}{\rho_w C_{p,w} V_{WT}}\left(T_{w,o} - T_a\right) \quad (1)$$

$$\frac{dT_{hw,o}}{dt} = \frac{F_{hw}}{V_{HC}}\left(T_{hw,i} - T_{hw,o}\right) - \frac{U_{HC}A_{HC}\Delta T_{HC}}{\rho_{hw} C_{p,hw} V_{HC}} \quad (2)$$

$T_{w,o}$, $T_{hw,o}$ are the water tank's hot water outlet and make-up water temperature (°C); V_{HC}, V_{WT} are the water tank's and heating coil's volume (m^3); F_{hw} is the hot water's volumetric flow $(m^3 s^{-1})$; $T_{hw,i}$, $T_{hw,o}$ are the temperature of the hot water at the entry and output of the water tank (°C); T_a is the ambient temperature (°C); U_{HC}, U_{WT} are the over all heat transfer coefficients of the water tank and the heating coil $(Wm^{-2}K^{-1})$; A_{HC}, A_{WT} are the area of the water tank and heating coil (m^2); ρ_w, ρ_{hw} are the density of make-up and hot water (kgm^{-3}); $C_{p,w}$, $C_{p,hw}$ are the hot water heat capacity and makeup at steady pressure $(Jkg^{-1}°C^{-1})$; ΔT_{HC} is the logarithmic mean temperature difference of the heating coil (°C)

(b) Plate Heat Exchanger

$$\frac{dT_{h,o}}{dt} = \frac{F_h}{V_{PHE}}\left(T_{h,i} - T_{h,o}\right) - \frac{U_{PHE}A_{PHE}}{\rho_h C_{p,h} V_{PHE}}\Delta T_{PHE} \quad (3)$$

$$\frac{dT_{c,o}}{dt} = \frac{F_c}{V_{PHE}}\left(T_{c,i} - T_{c,o}\right) + \frac{U_{PHE}A_{PHE}}{\rho_c C_{p,c} V_{PHE}}\Delta T_{PHE} \quad (4)$$

$T_{h,o}, T_{h,i}$ are the hot water temperatures at the heat exchanger's input and output (°C); V_{PHE} is the heat exchangerwater volume (m^3) ; F_c , F_h are the hot and cold water flowvolumetrically$(m^3 s^{-1})$; $T_{c,o}, T_{c,i}$are the cold water temperatures at the heat exchanger's intake and output (°C) ; U_{PHE} isThe total heattransfer coefficient of the heat exchanger $(Wm^{-2}K^{-1})$; A_{PHE} is the area of heatexchanger (m^2) ; ρ_c, ρ_h are The cold and hot water'sdensities (kgm^{-3}); $C_{p,h}$, $C_{p,c}$ are the heatcapacitywhen hot and cold water pressure iscontinuouslyapplied $(Jkg^{-1}°C^{-1})$; ΔT_{PHE} isthe logarithmicmeantemperaturedifference of the heatexchanger(°C)

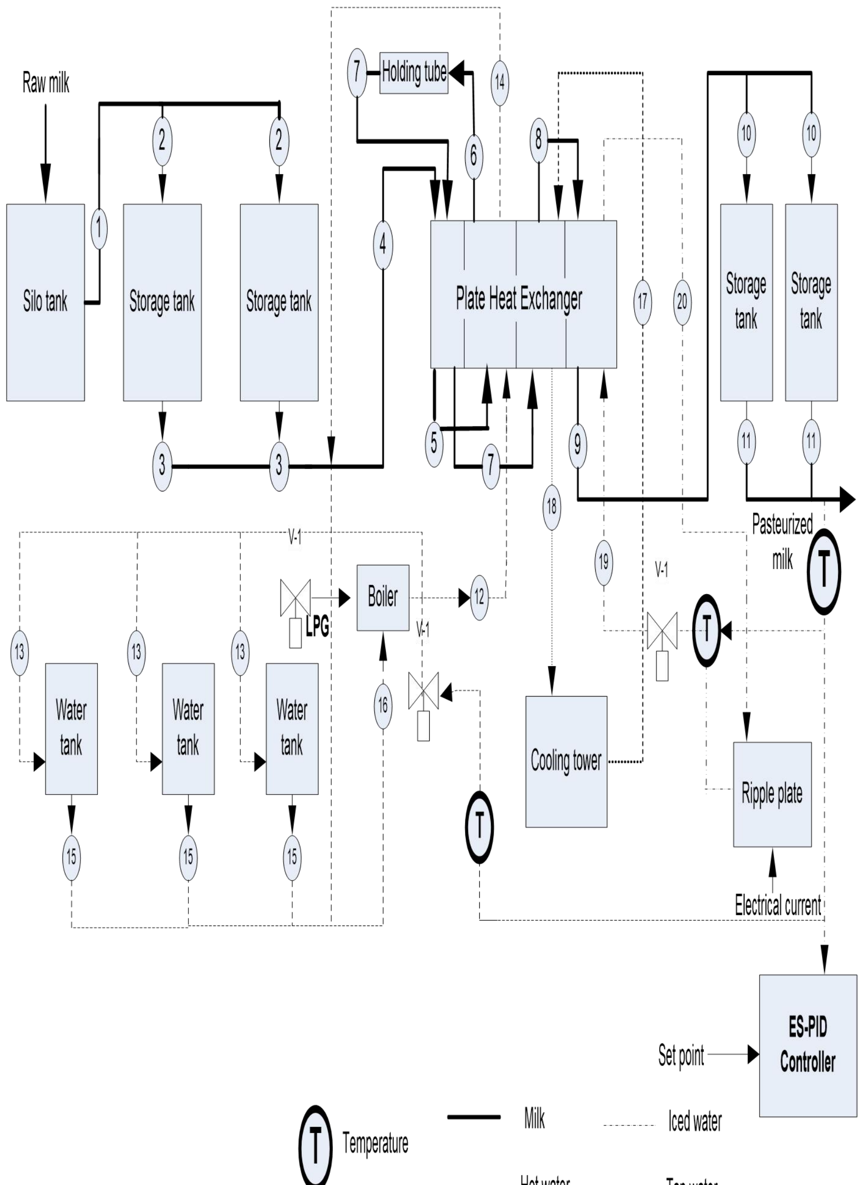

Fig. 1. Milk pasteurization plant model using ES-PID controller

(c) Holding Tube

$$T_{m,o}= T_{m,i} - \frac{U_p A_p}{\rho_m C_{p,m} F_m d_p}\left(T_{m,o} - T_a\right) \quad (5)$$

$$T_{m,o}= \frac{T_{m,i}\, \rho_m C_{p,m} F_m d_p - U_p 2\pi d_p L_p \left(T_{m,o} - T_a\right)}{\rho_m C_{p,m} F_m U_p d_p} \quad (6)$$

$$A_p = 2\pi d_p L_p \quad (7)$$

$T_{m,o}$, $T_{m,i}$ are the milk's temperature at the entry and output of the holding tube (°C); F_m is the volumetric flow of milk $(m^3 s^{-1})$; T_a is the ambient temperature (°C); U_p is the overall heat transfer coefficient of the holding tube $(Wm^{-2}K^{-1})$; A_p is the area of holding tube (m^2); ρ_m isdensity of milk (kgm^{-3}); d_p is the diameter of holding tube (m); L_p islength of the holding tube (m); $C_{p,m}$ is ability to continuously heat milk under pressure $(Jkg^{-1}°C^{-1})$.

(d) Boiler

$$\frac{dT_{hw,o}}{dt} = \frac{F_{hw}}{V_B}\left(T_{hw,i} - T_{hw,o}\right) + \frac{m_f \times LHV}{\rho_{hw} C_{p,hw} V_B} - \frac{U_B A_B \left(T_{hw,o} - T_a\right)}{\rho_{hw} C_{p,hw} V_B} \quad (8)$$

$$\frac{dT_{hw,i}}{dt} = \frac{F_{hw}}{V_B}\left(T_{hw,o} - T_{hw,i}\right) - \frac{U_B A_B \Delta T_B}{\rho_{hw} C_{p,hw} V_B} \quad (9)$$

$T_{hw,i}$, $T_{hw,o}$ are the tap water temperatures at the input and output of the cooling tower (°C); m_f is the boiler fueling rate (kgs^{-1}); F_{hw} is the tap water volumetric flow rate $(m^3 s^{-1})$; LHV is the lowheating value of fuel combustion $(KJkg^{-1})$; T_a is the ambient temperature (°C); U_B is the boiler's overall heat transfer coefficient $(Wm^{-2}K^{-1})$; A_B is the boiler's area (m^2); ρ_{hw} is the heated water's density (kgm^{-3}); $C_{p,hw}$ isbeing able to heat water under pressure constantly $(Jkg^{-1}°C^{-1})$; ΔT_B is the boiler's logarithmic mean temperature differential (°C); V_B isthe boiler's volume (m^3).

(e) Cooling Tower

$$\frac{dT_{tw,o}}{dt} = \frac{F_{tw}\left(T_{tw,i} - T_{tw,o}\right) - L_D F_{cw} T_{tw,i}}{V_{CT}} + \frac{\rho_m C_{p,mw} F_{mw} T_{mw}}{\rho_{tw} C_{p,tw} V_{CT}} - \frac{\left(E\rho_m \lambda_v + h_A\left(T_{tw,i} - T_a\right)\right)}{\rho_{tw} C_{p,tw} V_{CT}} \quad (10)$$

$$\frac{dT_{tw,i}}{dt} = \frac{F_{tw}\left(T_{tw,o} - T_{tw,i}\right)}{V_{CT}} - \frac{U_{CT} A_{CT} \Delta T_{CT}}{\rho_{tw} C_{p,tw} V_{CT}} \quad (11)$$

$T_{tw,o}$, $T_{tw,i}$ are the input and output temperatures of the cooling tower's tap water (°C); V_{CT} is the volume of cooling tank (m^3); F_{tw} isthe volumetric flow rate of tap water $(m^3 s^{-1})$; F_{cw}, F_{mw} are the volumetric flow rates of milk and cold water $(m^3 s^{-1})$; L_D is cooling mechanical drift loss towers (%); T_a is theambient temperature (°C); U_{CT} is the overall heat transfer coefficient of the cooling system t $(Wm^{-2}K^{-1})$; A_{CT} is the cooling tank's area (m^2); ρ_{tw} is the density of tap water (kgm^{-3}); $C_{p,tw}$ is the ability to continuously heat water under pressure $(Jkg^{-1}°C^{-1})$; ΔT_{CT} is the cooling tower temperature differential logarithm (°C); h_A isthe water's surface coefficient of heat transfer (WK^{-1}); E is the cooling tower evaporation rate $(m^3 s^{-1})$; λ_v is the heatvaporization of water $(KJkg^{-1})$; ρ_m is the density of milk (kgm^{-3}) ; $C_{p,mw}$ is the ability to continuously heat milk under pressure $(Jkg^{-1}°C^{-1})$.

(f) Ripple Plate

$$\frac{dT_{iw,o}}{dt} = \frac{F_{iw}}{V_{RP}}\left(T_{iw,i} - T_{iw,o}\right) + \frac{CL}{\rho_{iw}C_{p,iw}V_{RP}} - \frac{U_{RP}A_{RP}\left(T_{iw,o}-T_a\right)}{\rho_{iw}C_{p,iw}V_{RP}} \quad (12)$$

$$\mathrm{CL} = \frac{\pi n_s d_f h_{fg} A_f}{60} \quad (13)$$

$$\frac{dT_{iw,i}}{dt} = \frac{F_{iw}}{V_{RP}}\left(T_{iw,o} - T_{iw,i}\right) - \frac{U_{RP}A_{RP}\Delta T_{RP}}{\rho_{iw}C_{p,iw}V_{RP}} \quad (14)$$

CL is The ripple plate's refrigeration load(J); $T_{iw,o}$, $T_{iw,i}$ are the ice water's temperatures at the ripple plate's entrance and exit (°C); F_{iw} is the volumetric flow of ice water (m^3s^{-1}); ρ_{iw} is the density of ice water (kgm^{-3}); $C_{p,iw}$ is the ice water's thermal capacity at constant pressure $(Jkg^{-1}°C^{-1})$; V_{RP} is the volume of ripple plate (m^3); A_{RP} is the area of ripple plate (m^2); U_{RP} is The overall heat transfer coefficient of the ripple plate $(Wm^{-2}K^{-1})$; n_s isThe rotating speed of the impeller in the ripple plate compressor(rpm); d_f is the ripple plate compressor's impeller diameter (m); h_{fg} is the refrigerante vaporation latent heat in ripple plates $(KJkg^{-1})$; A_f is the flow area of the ripple plate compressor(m^2);ΔT_{RP} is the logarithmic mean temperature differential of ripple plates(°C).

2.1.Objective function for energy minimization

The fact that energy expenses represented the significant production cost in a diary industry. The optimization approached ployed, focused on the maximum energy utilization with a single objective cost function presented in Equation 15. The objective function sought to reduce the annual energy costs associated with the rate of fuel consumption and the cost of electricity used in the manufacture of pasteurized milk. The cost of fuel supplied to the boiler is shown in the first objective function, and the cost of all the electricity used in the ripple plate is shown in the second objective function. The process model operating units of the ripple plate in Equation 12 and the boiler in Equation 8 were represented by Equation 15.

$$f_{min} = n_w \sum_{t=1}^{36,000}\left(C_{LPG}m_f + C_{elect}\frac{(CL+W_e)}{3.6\times10^3}\right) \quad (15)$$

f_{min} = Minimum energy cost per year (baht/year), n_w = Production rate of pasteurized milk(kg/day), t = Production period of pasteurized milk(s), C_{LPG} = The price of LPG (kg/s), m_f = Rate of boiler fueling(kg/s), C_{elect} = Cost of electricity(kWh), W_e = The equipment's total electrical power (J/s) and CL = The ripple plate's refrigeration load (J).

The single objective cost function is subjected to the following constraints: Hot water temperature- $72°C \leq T_{m,7} \leq 76°C$;Ice water temperature- $4°C \leq T_{m,9} \leq 6°C$; Boiler fueling rate-$0 \leq m_f \leq 0.00180$.$T_{m,7}$ = Milk temperature at the outlet holding tube (stream 7), $T_{m,9}$= Milk temperature at the outletripple plate (stream 9).

2.2. Optimization approach based cost minimization

Extremum seeking is used to optimize the parameters of the PID controller to minimize the given cost function, which is de fined as

$$J(\theta) = \frac{1}{T-t_0}\int_{t_0}^{T} e^2(t,\theta)dt \quad (16)$$

where $e$and θ are given as

$$e(\theta,t) = r - y(\theta,t) \quad (17)$$

$$\theta = [\mathrm{K}, T_i, T_d]^{\mathrm{T}} \quad (18)$$

Equation (16) defines the cost function J(θ), which takes the mistake into account throughout the time interval $[t_0, \mathrm{T}]$ .The t_0 and T is the time intervalduring the stepresponseexperiment at whichitbegins and ends considering the error during the calculation of the cost function.

2.3.Extremum seeking algorithm based PID tuning scheme

The approach of ES tuned PID controller is to drive the system to its optimum operating point. The technique combines a time-varying estimation algorithm with proportional gain K_p, Integral gain τ_i, Derivative constant τ_d. The development stability and convergence analysis in discrete time isachieved in nonlinearsystems of the form as shown in Fig. 2.

$$x_{k+1} = x_k + f_{(x_k)} + g_{(x_k)}u_k \quad (19)$$

$$y_k = h(x_k) \quad (20)$$

The cost$h(x)$ is relative order one and satisfies the optimal conditions of :

$$\frac{\partial h(x^*)}{\partial x} = 0 \quad (21)$$

$$\frac{\partial^2 h(x)}{\partial x \partial x^T} > \beta I \quad (22)$$

whereβ is a positive constant, x_k is the vector of state variables at time k, u_k is the input variable at time k and y_k is the objective function at step k, $f_{(x_k)}$ and $g_{(x_k)}$ are smooth vector valued functions.

The rate of change of the cost function$y_k = h(x_k + 1)$ is given as :

$$h(x_k+1) - h(x_k) = h(x_k + f_{(x_k)} + g_{(x_k)}u_k) - h(\propto(x_k)) + h(\propto(x_k\, \hat{u}_k) - h(x_k) \quad (23)$$

Using the second order Taylor expansion on the first two terms

$$h(x_k + f_{(x_k)} + g_{(x_k)}u_k) - h(\propto(x_k, \hat{u}_k))$$

$$= \nabla h(\alpha(x_k,\hat{u}_k))g(x_k)(u_k - \hat{u}_k) + \frac{1}{2}(u_k - \hat{u}_k)^T g(x_k)^T \nabla^2 h(\hat{y}_k) g(x_k)(u_k - \hat{u}_k) \quad (24)$$

Rewrite the cost dynamics

$$y_{k+1} - y_k = \Psi_{0,k}(x_k,\hat{u}_k) + \Psi_{1,k}(x_k,u_k,\hat{u}_k)(u_k - \hat{u}_k) \quad (25)$$

$$y_{k+1} = \Psi_{0,k}(x_k,\hat{u}_k) + \Psi_{1,k}(x_k,u_k,\hat{u}_k)(u_k - \hat{u}_k) + y_k \quad (26)$$

$$\Psi_{0,k}(x_k,\hat{u}_k) = h(\propto(x_k\, \hat{u}_k) - h(x_k) \quad (27)$$

$$\Psi_{1,k}(x_k,u_k,\hat{u}_k)(u_k - \hat{u}_k) =$$

$$\left(\nabla h(\alpha(x_k,\hat{u}_k)\right) g(x_k) + \frac{1}{2}(u_k - \hat{u}_k)^T g(x_k)^T \nabla^2 h(\hat{y}_k) g(x_k) \quad (28)$$

$$\hat{y}_k = (\alpha(x_k,\hat{u}_k) + \theta g(x_k)(u_k - \hat{u}_k) \quad (29)$$

where$\theta \epsilon$ (0,1); ϵ is the estimator time scale separation parameter.

$$\hat{y}_{k+1} = \hat{y}_k + \hat{\theta}_{0,k} + \hat{\theta}_{1,k}(u_k - \hat{u}_k) + K_k e_k - \omega_{k+1}(\hat{\theta}_k - \hat{\theta}_{k+1}) \quad (30)$$

where $\hat{\theta}_k = [\hat{\theta}_{0,k}, \hat{\theta}^T{}_{1,k}]^T$ is the vector of parameter estimates at time step k, K_k is a correction factor at time step k, $e_k = y_k - \hat{y}_k$ is the estimator error.

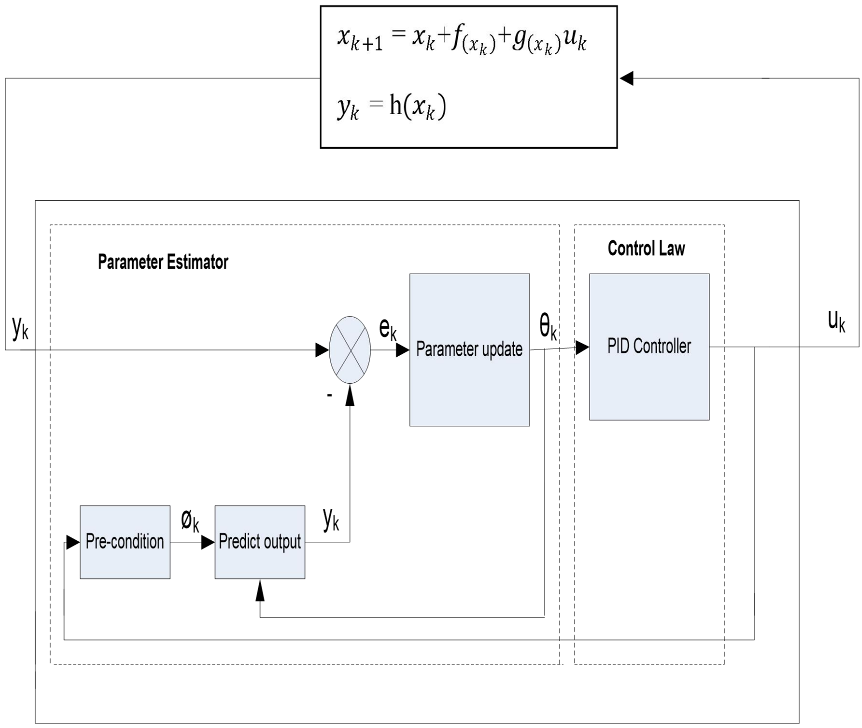

Fig. 2. Closed-loop model of the ES-tuned PID controller

2.4. Simulation parameters

The Table 1 displays the data from the processing plant used in the simulation modeling [26-29]. A temperature gauge and a digital thermometer are used to track the process data throughout processing. Performance indicators like the rise time (RT), settling time (ST), peak time (PT), and percentage overshoot(PO) are used to analyses and assess the mathematical model's output graphically. The LPG feeding rate of 1.80×10^{-3} kg/s at the boiler (m_f) isoptimized at the desiredtemperature of 72ºC – 76ºC for the holding tube, while 92ºCisset as the actual boiler temperature. Based on the ES-PID controller in Fig. 1, the Simulink model displayed in Fig.3depicts the general operating units of the milk pasteurization plant. The process data shown in Table 1 isused to simulate the system.

Table 1: Processing plant data

Symbols	Parameters	Values
d_f	Ripple plate impeller diameter(m)	0.4
A_f	Area of ripple plate flow (m^2)	0.002
A_{RP}	The ripple plate's area (m^2)	2.5
A_B	Boiler area (m^2)	2.3
A_T	The storage tank's area (m^2)	2.2
$A_{HC}A_{WT}$	Move the water tank and the heating coil region(m^2)	0.507
$V_{HC}V_{WT}$	The volume of the water tank and heating coil (m^3)	4.9
V_B	Boiler volume (m^3)	1.20
V_{RP}	The ripple plate's volume (m^3)	0.50
V_{CT}	The cooling tower's volume (m^3)	0.05
d_p	Retaining the tube's diameter(m)	3.83×10^{-2}
L_p	The holding tube's length(m)	12
n_w	Production rate of pasteurized milk(kg/day)	1×10^4
$T_{m.i}$	Milk's temperature at the inlet(℃)	72
F_m	Milk flow rate volume (m^3/s)	4×10^{-4}
$F_{m,i}$	Inlet milk flow rate volume (m^3/s)	5×10^{-4}
$F_{m,o}$	Outlet milk flow rate volume (m^3/s)	4×10^{-4}
F_{hw}	Hot water flow rate volume (m^3/s)	1.60×10^{-3}
F_{tw}	Tap water flow rate volume (m^3/s)	4.80×10^{-3}
F_{iw}	Ice water flow rate volume (m^3/s)	1.92×10^{-3}
F_{hw}	Hot water flow volumetrically returned to the boiler (m^3/s)	3.20×10^{-3}
T_w	Water temperature for makeup(℃)	27
T_a	Ambient air temperature(℃)	30
E	Rate of evaporation in a cooling tower(m^3/s)	$1.7 \text{ x } 10^{-5}$
h_A	Surface heat coefficient of water (W/K)	2000
λ_v	Heat vaporization of water $(KJkg^{-1})$	2410
L_D	Mechanical drift loss in cooling towers(%)	2
n_s	Rotating speed (rpm)	5000
m_f	Boiler fueling rate (kg/s)	1.80×10^{-3}
LHV	Low heating value fuel combustion $(KJkg^{-1})$	49,888
CL	Rate of refrigeration at ripple plate (J/s)	5.20×10^{-4}
ρ_m	Milk density(kgm^{-3})	1015.96
ρ_{tw}	Tap water density(kgm^{-3})	997
ρ_{iw}	Ice water density(kgm^{-3})	917
ρ_{hw}	Hot water density(kgm^{-3})	977.3
$C_{p,m}$	The milk's ability to retain heat$(Jkg^{-1}°C^{-1})$	3.855
$C_{p,tw}$	The tap water's heat capacity$(Jkg^{-1}°C^{-1})$	2.356
$C_{p,hw}$	The hot water's heat capacity$(Jkg^{-1}°C^{-1})$	108.376
$C_{p,iw}$	The frozen water's potential to hold heat$(Jkg^{-1}°C^{-1})$	2.108
ΔT_{PHE}	Temperature differential in a heat exchanger(℃)	15.6
$T_{m,i}T_{m,o}$	Milk's temperature at the holding tube (℃)	76
$U_{HC}U_{WT}$	Heat transfer coefficients in water tanks and heating coils (W/m^2. K)	490
h_{fg}	Latent heat of vaporization in ripple plate $(KJkg^{-1})$	217

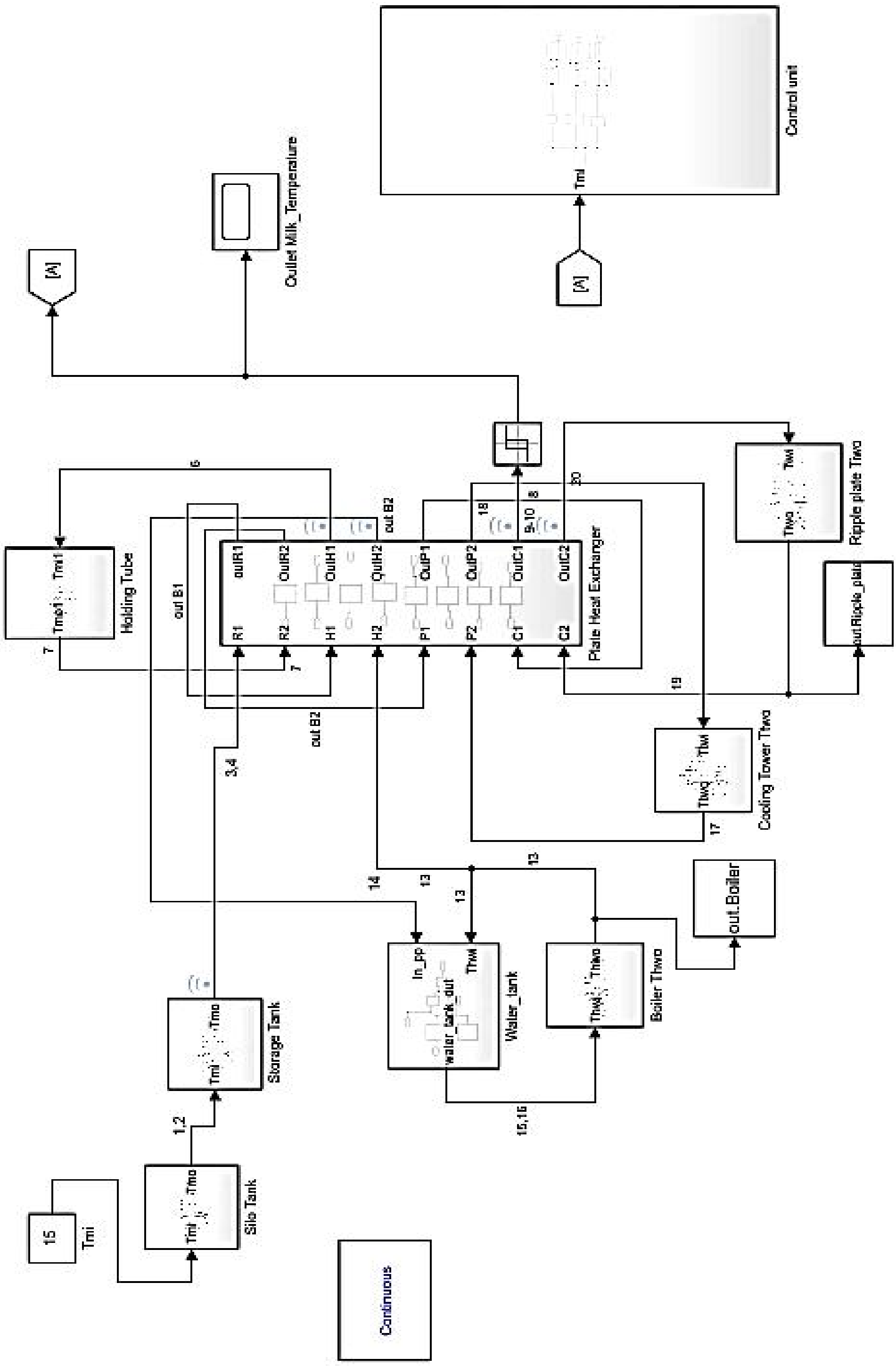

Fig. 3. Simulink model of the milk pasteurization plant using the ES-PID controller

3. Results

This part presents the graphical results of the simulation procedure and provides additional explanation through discussion. The effectiveness and performance of the control strategy for the modeled pasteurization temperature that is subject to energy reduction in the MATLAB/Simulink environment are verified through simulations. The pasteurization temperature simulation results are presentedFigs.5-10.

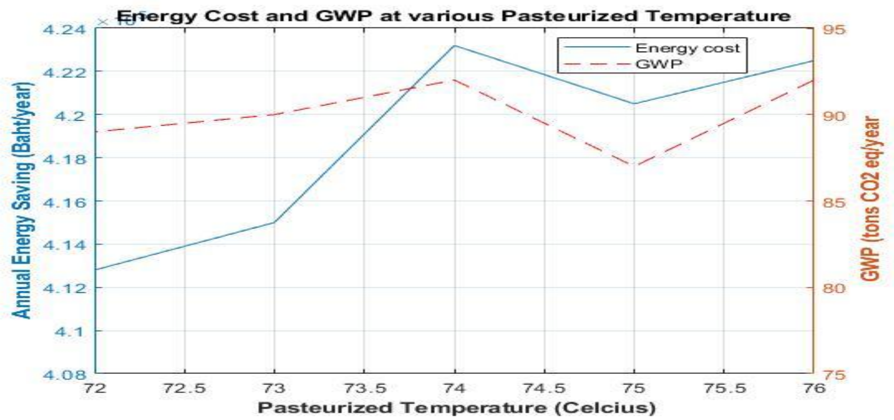

Fig.4. Energy cost at various pasteurized temperatures

The Global Warning Potential (GWP) and Annual Energy Expense (AEE) at different pasteurization temperatures were calculated using the optimization result displayed in Fig.4.The maximum pasteurized temperature of76℃was shown to be associated with1.25×10^{-3} kg/s, annual energy saving of 4.23×10^{5} Baht/year, and carbonemissiondecrease of 92×10^{-4} metric tons per year. Subsequent optimization findings showed that the lower bound pasteurization temperature of72 ℃ correlated with 1.16×10^{-3} kg/sof energy consumption, 4.13×10^{5} Baht/year of annual energy savings, and carbon emission reduction of 89×10^{-4} metric tons per year

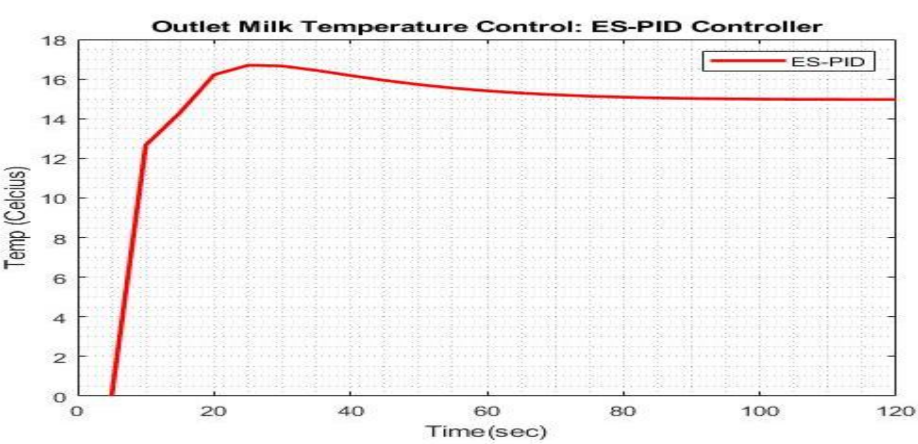

Fig.5. Temperature control of the milk output using the ES-PID

controller

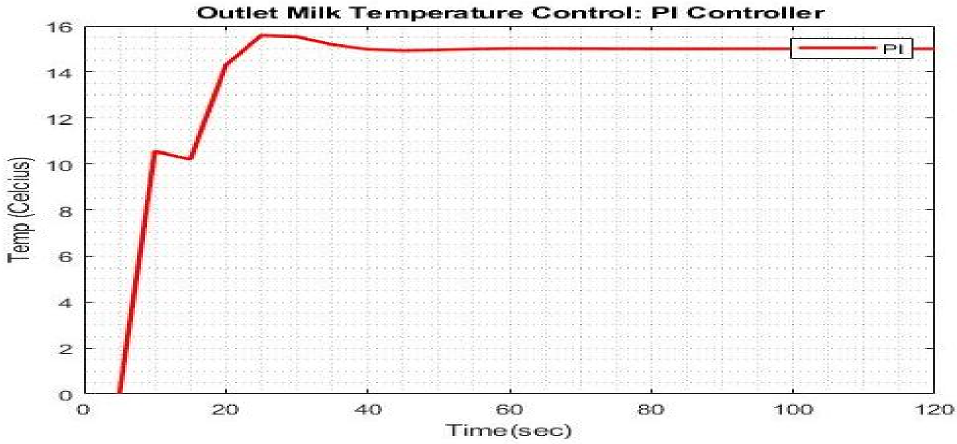

Fig. 6. Temperature control of the milk output usingthe PI controller

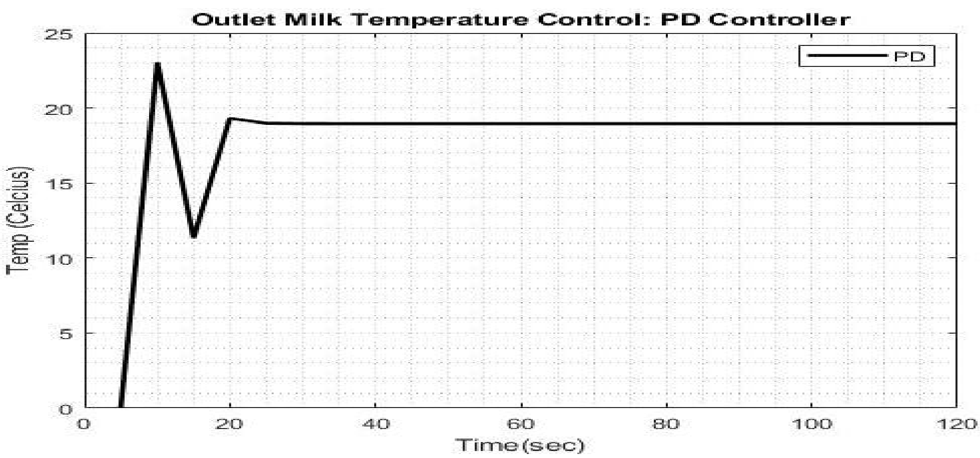

Fig. 7. Temperature control of the milk output using the PD controller

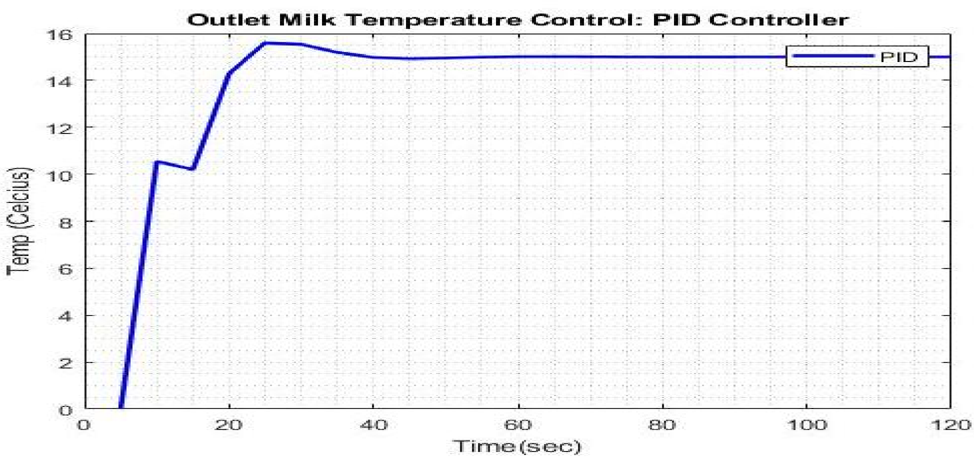

Fig. 8. Temperature control of the milk output using the PID controller

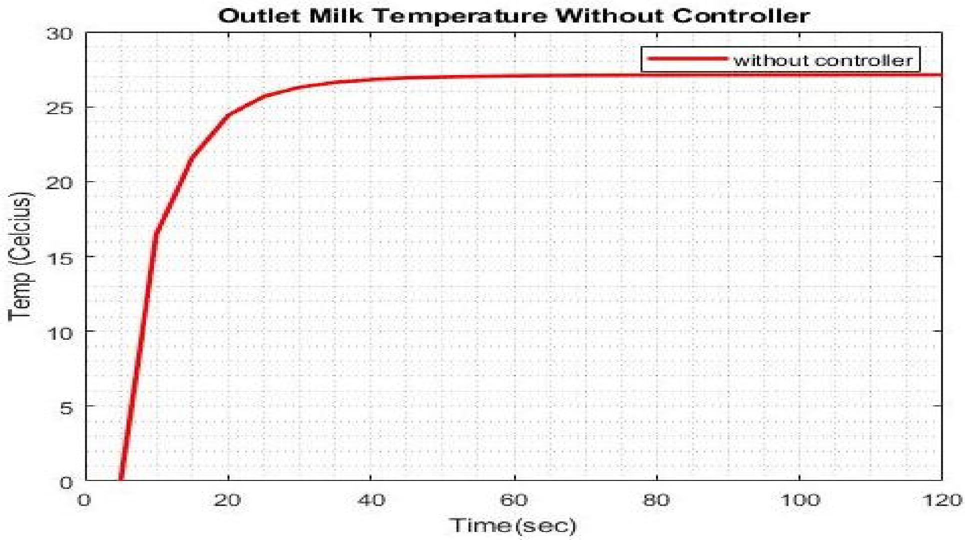

Fig. 9. Temperature control of the milk outputusingthe ON/OFFcontroller

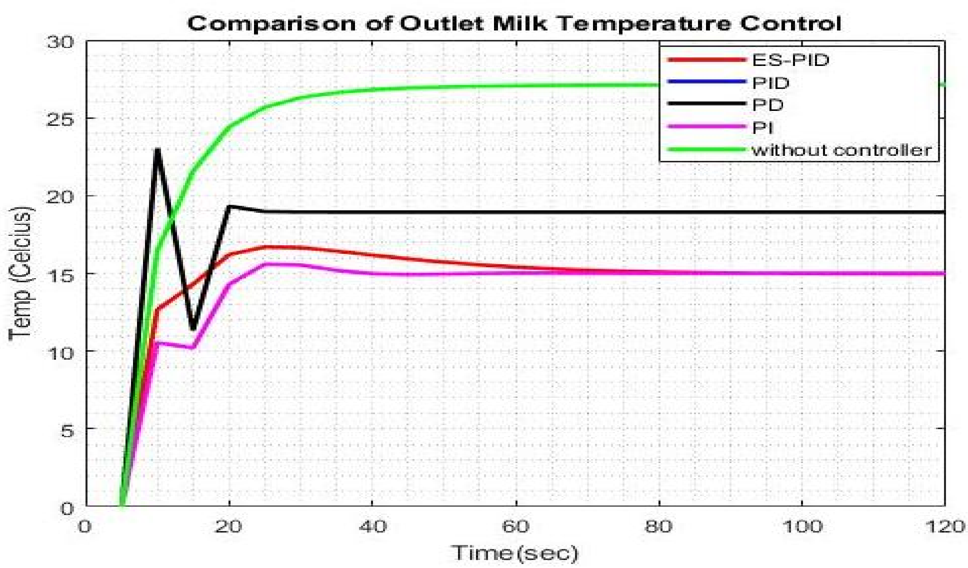

Fig. 10. Comparisonof temperature control of the milk output using the PI, PD, PID and ES-PID controller

4. Discussion

Fig. 5 illustrates the use of an ES-PID controller to manage the milk temperature (T_{mo}), at a set point of 15°C. In order to avoid over shoot and allow the process to reach a predefined set point in the least amount of time, the PID parameters were tuned using the ES optimization technique. Nevertheless, after processing for 25 seconds, the temperature rose to 16.7 °C and then dropped to 15 °C, which was the intended settling temperature. In that order, the RT, ST, PT, and PO were 0.103 seconds, 14.97 seconds, 14.97 seconds, and -0.034 percent, respectively. When compared to present controllers, the outcome shows less oscillations, less overshoot, and a reduction in rise and settling times. Fig. 6 displays the output milk temperature control (T_{mo}), which uses a proportional integral (PI) controller at a set point of 15°C.Utilizing a PI controller reduced energy costs by regulating the pasteurization temperature below the necessary level. Nevertheless, after a processing period of 25 seconds, the temperature rose to 15.6°C and then dropped to the ultimate temperature of 15°C. In that order, the RT, ST, PT, andPOwere3.574 seconds, 14.99 seconds, 15.00 seconds and 0.000percent, respectively. Because of the distortion present along the settling path, the result shows the existence of steady-state inaccuracy. Fig. 7 displays the output milk temperature control (T_{mo}), which uses a proportional derivative (PD) controller at a set point of 15°C. The pasteurization temperature was controlled by the PD controller so that its output would be the predetermined value. Nevertheless, after a processing period of 10 seconds, the temperature rose to 23°C and then dropped to the ultimate temperature of 19°C. In that order, the RT, ST, PT and POwere5.219 seconds, 18.95 seconds, 18.95 seconds and0.395 percent, respectively. The outcome shows that there is steady-state inaccuracy because there is more overshoot and distortion along the settling path. Fig. 8 displays the outlet milk temperature control (T_{mo}), utilizing a proportional integral derivative (PID) controller at a fixed point of 15°C. In order to get the pre-set value as its output, the pasteurization temperature was controlled using a PID controller. Nevertheless, after a processing period of 25 seconds, the temperature rose to 15.6°C and then dropped to the ultimate temperature of 15°C. The RT,PT, ST, and PO were, in order, 3.573 seconds, 15.00 seconds, 14.99 seconds, and 0.000 percent. Because of the distortion present along the settling path, the result shows the existence of steady state inaccuracy. Fig. 9 displays the outlet milk temperature control (T_{mo}), with an ON/OFF controller at a set point of 15°C. After a 40-second processing time, the temperature rose from 26.8°C to 27°C, which was the ultimate temperature. The highest overshoot of 0.808 percent took 27.12 seconds to happen. The system responses took 4.696 seconds to increase, and it took 27.12 seconds to settle. The result demonstrates that there is steady-state inaccuracy, overshoot, and prolonged settling periods.

At a desired pasteurized temperature of 15°C, Fig. 10 compares the performance characteristics of the outlet milk temperature control (T_{mo}) for the PD, PI, PID, ES-PID, and ON/OFF controllers. The (PO, RS, ST, and PT) sets for the PD, PI, PID, ES-PID controllers were(0.395%, 5.219 sec, 18.95 sec, 18.95 sec), (0.000%, 3.574 sec, 15.00 sec, 14.99 sec),(0.000%, 3.574 sec, 15.00 sec, 14.99 sec),and (-0.034%, 0.103 sec, 14.97 sec, 14.97 sec), respectively. For the ON/OFF controller, the PO was 0.808 %, while the RT, ST and PTwere4.696 sec, 27.12 sec, and 27.12 sec, respectively. The simulation results show that, in comparison to other convectional controllers currently in use, the ES-PID controller takes less time to attain the steady state value and has a lower proportion of overshoot.

5. Conclusion

In order to effectively tune a PID controller to regulate the milk temperature and lower the energy costs associated with milk processing in a milk pasteurization plant, this work has investigated an extremum seeking optimization approach. This method is particularly useful at the LPG boiler feeding rate where energy consumption is high. The effectiveness of the controller is-a-vis the performance of the conventional PID controller has been demonstrated, with the results that an ES-tuned PID controller has the ability to provide good dynamic performance for the pasteurization plant without oscillations, resulting in less PO, RT, PT and ST compared with other existing convectional controllers. This optimization method will be improved in subsequent research to lower energy usage during the milk pasteurization plant's cooling phase.

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Credit author ship contribution statement
Awelewa A. Ayokunle: Control Design and Analysis ; APC Facilitation. **Isaac A. Samuel:** Conceptualization and Methodology; APC Facilitation. **Ojo K. Ebenezer:** Researchand Original Draft Preparation. **Oluwole A. Adegbola:** Revision and Editing. **TobilobaE. Somefun:** Software and Simulation; APC Facilitation. **David O. Aborisade:** Project Administration.

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