A Review on Optimal Temperature Control of Milk Pasteurization Using Extremum Seeking Based Proportional Integral Derivative Controller

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Abstract- Milk is a rich nutrient white liquid food produced by the mammary gland of mammals vulnerable to bacteria that cause diseases to the human health. In a dairy plant, pasteurization process is the best heating procedure for a milk. It can be performed under High Temperature Short Time (HTST) or Low Temperature Long Time (LTLT). However, optimal temperature stability control has been a major challenge for milk pasteurization in a dairy plant due to non-linearity, time delay schemes, inaccuracy and unrealistic parameter variation of the modern and manual tuning techniques used without incorporate a numerous adaptive tuning control method. Therefore, this article proposed an optimization tuning technique of Extremum Seeking (ES) based Proportional Integral Derivative (PID) controller to optimize the heating process and eliminate the external perturbation of the system. In this article, a closed loop mathematical equation model using ES-PID controller was developed proposed to achieve the optimal performance characteristics. The due technique is expected to eliminate the offset of the system and minimize the percentage overshoot.

Keywords- Extremum Seeking, Milk Pasteurization, Proportional Integral Derivative, Temperature Control

1 Introduction

Milk is a highly nutritious growth medium for microbial when stored at ambient temperature pathogenic micro-organisms of lactic acid bacteria, viruses, protozoa and moulds proliferate. The contamination and growth of microbial organisms occurred through the milk handling process, the equipment used to automate the milk processing and the milk handle lines refrigeration bulk storage tanks (Kustanti, 2012). In a dairy plant, milk is an important biological fluid that must be heated so as to reduce the harmful pathogenic bacteria spoilage of Salmonella, Listeria, Bacillus, Cereus, Yersiniosis, Coxiella Burnetii, Staphylococcus Aureus and Escherichia Coli that caused diseases of tuberculosis, Mycobacterium Brucellosis, Diphtheria, Scarlet and Q-Fever to the human health (Hornsey, 2004).

Adequate pasteurization process is the best heating procedure for milk to achieve a suitable preservation with longer life span (Htin et al., 2019). The Low Temperature Long Time (LTLT) pasteurization, High Temperature Short Time (HTST) pasteurization and Ultra High Temperature (UHT) pasteurization are three method of milk pasteurization used in a dairy plant. The LTLT and HTST pasteurization process killed the bacterial cells but unable to destroy some thermophiles and micro-organisms while UHT pasteurization killed all the microbial pathogenic. UHT gives a drastic reduction in the number of microorganisms but damages the nutritional contents in milk (Holdsworth, 2009 & Hartayanie et al., 2010).

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Hence, this article would be limited to LTLT and HTST pasteurization. Temperature and time are important parameters to be controlled during pasteurization process. It is important to control the temperature adequately without time delay using adaptive tuning technique methodology to tuned the parameter of the PID controller gain to receive the optimal tuning procedure of time delay scheme (Liangyu et al., 2019). In a dairy plant, milk pasteurizer consumes a large amount of energy actuated by traction motor. Traction motor is an actuator device that energizes the pasteurizer plant and makes a rotation torque on the machine as a result of its high starting torque and high-speed operation (Walstra et al., 1999). The nonlinearity of the electromagnetic flux and field current winding of the motor operating in saturation condition makes the analytical modelling of the pasteurizer machine difficult to control the temperature without time delay scheme (Chan, 2009).

Anil et al. (2018) & Vijaya et al. (2019) proposed numerous optimization algorithms for designing PID controller to optimize the heat processing, external perturbation and control the inherent noise within the system. Nagel et al. (2000) & Hjalmarsson, (2005) proposed a modern tuning technique of Iterative Feedback Tuning (IFT), Multi Objectives Genetic Algorithm (MOGA), Internal Model Control (IMC) and Teaching Learning Based Optimization (TLBO) to optimize the temperature stability of milk pasteurizer to make it compete with fully controlled of DC and AC drives in the field of power electronics. However, the non-linearity, time delay and parameter variation of these techniques enable the system not to achieve a better control performance. Therefore, this gap motivates the interest of this article to develop an optimal tuning technique of Extremum Seeking (ES) combining the simplicity, adaptively and flexibility with the mathematical precision of PID controller for temperature control of milk pasteurizer to overcome the non-linearity problem, steady state error, overshoot

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percentages and speed control associated with pasteurizer plant.

Extremum Seeking (ES) is an adaptive control methodology used to optimize the steady state performance of a given plant (Ariyur et al., 2003). ES is a non-model method used to tuned the parameters of a PID so as to minimize the given cost function. The cost function minimization would be used to design the result of the steady state performance of constant plant parameters (Krstic et al., 2010 & Wang et al., 2015). While PID controller is a generic control loop feedback mechanism with optimum dynamics control and impressive properties due to its simplicity, reliability and applicability to linear system, reduce steady state error, no oscillations, higher stability and robust performance (Sangram & Mehetab, 2011).

The aim of this article is to review most of the tuning techniques used by some researchers for controlling the temperature of milk pasteurization at different operating condition. The continuation of this article is organized as follows: Section 2 presents the system description. Section 3 presents the system modelling, mathematical equations and the proposed simulation parameters. Section 4 chronologically showcase the tuning techniques via controllers proposed by researchers to optimize the milk pasteurizer temperature controller. The strengths and weaknesses of the controllers suggested for controlling the system, from the farthest to the earliest. The role of enumerated methods and their effectiveness in minimizing the overshoot and elimination of the steady state error of the milk pasteurization process was highlighted. Finally, section IV describes the further opportunities and challenges in the context of this article. Section 5 presents the conclusion and future recommendation.

2 System Description

The processing unit comprises of the two-feeding tank, heat exchanger, holding tube, hot-water tank, valves, pumps and sensors as shown in figure “1". The pasteurized milk passes through the tank A or tank B depend on the valve SOL2 which allow in choosing the available tank. The peristaltic pump N1 impulses the milk from these tanks to the regeneration phase of the heat exchanger. In this phase, the milk is preheated by the effluent of the holding tube before it passes to the heating phase of the same heat exchanger where the milk achieved the pasteurized temperature. The milk leaves the heating phase of the heat exchanger at high temperature T4 and passes through the holding tube to maintain the high temperature at a certain time. At the end of the holding tube, there is a valve SOL1 that opens in case the temperature at point T1 is higher than the desired temperature. If the valve is open the milk return to the heat exchanger and passes through the cooling phase, where milk uses water as cooling fluid.

When the temperature is not high enough on the milk, when the temperature T1 is lower than the desired temperature the valve SOL1 close and send the product back to the feeding tank for recycling (Sandoval et al., 1998 & Toledo, 2000). Where: SOL1: Product divert solenoid valve; SOL2: Feeding select solenoid valve of tank A or tank B; SOL3: Product cooling solenoid valve; SOL4: Tank A fill solenoid valve; SOL5: Tank B fill solenoid valve; PRV1: Pressure reducing valve; V1: Flow control valve; V3: Tank B pressure control valve; N1: Feeding peristaltic pump; N2: Hot water peristaltic pump; T1: Holding tube exit; T2: Hot water temperature; T3: Outflow temperature; T4: Heated product temperature; L1: Tank A level sensor; LL: Low level float switch of tank B; HL: High level float switch of tank B; F1: Turbine type flow sensor which measure the products flow rate. Section 2.1 motivates the various techniques that have been applied in controlling the temperature of the milk pasteurization without time delay.

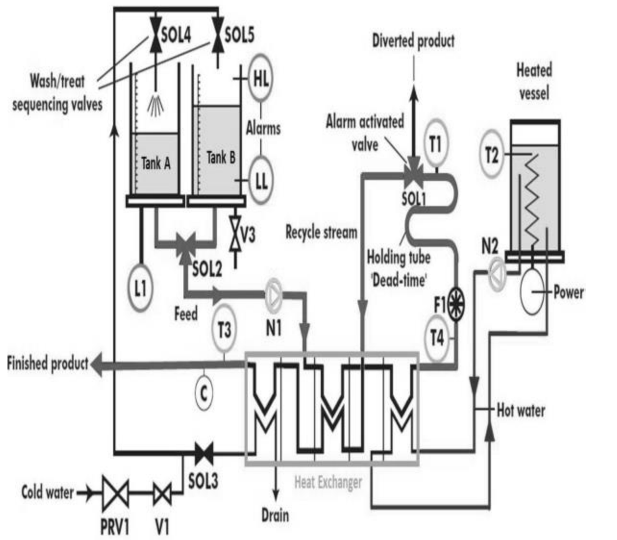

Fig. 1: Milk pasteurizer processing unit

2.1 Review Methods on Temperature Control of Milk Pasteurization

Boopathi et al. (2014) proposed Acorn Raggett Machine (ARM) based temperature monitoring and control for milk pasteurization. In dairy industries ARM processor computer aided control of physiological and sanitary parameters are used, which lead to increase in productivity and eliminated some tedious operations. This study worked on operations that carried out the temperature monitoring and control effectively through an ARM processor LPC2148 kit. The proposed system was implemented using Lab view development tools in monitoring and controls the applications. The server application reads the data from USB port and ARM processor. The client application uses the database actualized by the server in order to realize the system performance. The suggested automatic valve system was able to contribute to the development of the techniques of production and waste reduction by monitoring the quality of the product. However, there is an increase in parameters variations that lead to signal-noise ratio of the system.

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Niamsuwan et al. (2014) worked on control of milk pasteurization process using model predictive approach. Milk pasteurization process is a multivariable interacting system difficult to control by the conventional on-off controllers since the on-off controller can handled the temperature profiles for milk and water oscillating over the plant requirements. The proposed algorithm was tested for control of a milk pasteurization process in four cases of simulation such as set point tracking, model mismatch, time sample, difference control and prediction horizons. The results for the proposed algorithm show the well performance in keeping both the milk and water temperatures at the desired set points without any oscillation and overshoot but gives a less drastic control action compared to the cascade generic model control (GMC) strategy.

Jitendra et al. (2015) worked on temperature control loops of pasteurizer machine using Siemens S7-300 PLC self-tuning PID controller. In pasteurizer it becomes necessary to have a good temperature control. PID controller is one of the most popular controllers in industrial control loop due to its simplicity, easy to implement multi-loop control and smaller computing work load. However, most of the PID controller tuned in a convectional way as led to non-optimal temperature control most of the time. In this study, the self-tuner proves to be quite handy; it takes the parameter values based on model type with more precision and higher accuracy. The result shows that after using self-tuning PID controller, the system proved to be more stable quickly, the system suitability was very good, the steady state error was minimized and the errors was adjusted in time. However, due to its programmed with automatic set point change, the efforts to change the set point are unable to remove.

Diane et al. (2015) worked on configuration of PID feedback and feed forward controllers in temperature control of HTST heat exchanger. In orange juice and milk, the studied of pasteurization demonstrates that lower in temperatures are sufficient to inactivate microorganism activities. In order to prevent the loss of cloudiness (activity of enzyme pectin methyl esterase) higher temperatures are required. In this study, the three stages of heat exchanger (regeneration, heating and cooling) and holding tube were used to achieve a holding time of 40 seconds at 91℃ in processing of orange juice. The controller was tuned by the reaction curve methodology with dynamic compensation. The controlled were evaluated and compared through the relative performance indices of Integrated Absolute Error (IAE), Integrated Time Absolute Error (ITAE) and Integrated Square Error (ISE). The results showed the steady error of ± 0.5℃ range.

Tesfaye et al. (2017) worked on comparison of Proportional Integral Derivative (PID) with Model Predictive Controller (MPC) for milk pasteurization process. Temperature control plays an important role in pasteurization plants. In this study, the dynamics process of pasteurization was estimated using system identification from the experimental data. The quality of different model structures was checked using best fitted data validation, residual and stability analysis. The control performance was compared based on settling time, percentage overshoot and steady state. The output temperature was maintained at 72℃ which is the optimum temperature for HTST. The MPC controller has 0% overshoot and minimum settling time compared with PID controller. The rise time of PID controller was increased better than MPC. In consolidating the performance of all the responses, MPC is the best controller for pasteurization process due to its better set point tracking ability working in optimal condition.

Hariyadi, et al. (2017) worked on optimization of PID controller in temperature control of milk pasteurization. In this study, the LTLT method was tested in heating the milk to a temperature of 63℃ to 65℃ and maintained at that temperature for 30 minutes. In order to maintain the temperature stability and step responses in milk pasteurization process. The heating process is done using a tuning optimization technique of Ziegler Nichols PID controller implanted on Atmega 16 to control electrically heating element actuator that get input from platinum temperature 100 (PT100) temperature sensors. The test results for heating of milk shows decrease in rise time of 2400 sec, peak time of 2700 sec and down time of 3700 sec. The maximum overshoot at temperature of 2℃ increased to 1.5%, this gives the system a steady state error.

Jonathan et al. (2018) worked on process control of milk pasteurization on geothermal brine based PID controller. Temperature sensor was used to measure the hot water inlet temperature, the measured temperature data was transmitted using electrical signal to proportional controller. The proportional controller uses the error value equals to hot water inlet temperature. The error value is the difference between the measure value and the set point value for hot water inlet temperature of 90℃ at time t = 15 seconds with no time delay. In this study, the results show that the milk outlet stays constant at 72℃ even with 10℃ drop of hot water inlet temperature. The simulation run with 10 seconds time delay and the control valve react in 10 seconds after the disturbance is detected at time t = 15 seconds. Other results show that the temperature dropped to around 71℃ until it finally returned to permutable temperature range at time t = 65 seconds. The PID is capable to compensate the reduction of hot water inlet temperature that give a very slow response.

Atul, et al. (2021) worked on milk pasteurization temperature processes optimization using PID controller. Temperature control is very significant for milk pasteurization. The temperature must be precisely controlled to provide milk at the desired temperature and consistency in downstream operations. Therefore, this work involves modelling of pasteurization process for high temperature in optimum time for a dairy plant. Plate heat exchangers are widely used in this procedure to raise warmth of produce to desired pasteurization

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temperature. PID controller work in robust way in milk dairy plant to optimize the pasteurization temperature and complete process. The PID controller used also helpful for trouble-free operation and control. The energy saving is substantial in comparison to PID controller cost. The quality of milk also improves response efficiency and chances of rejection reduced. The energy consumption saving is around 10% of present consumption and environment saving is also achieved. Therefore, Numerous Optimization Algorithms (NOA) and Artificial Intelligence (AI) methods needs to be used so as to enhance the PID controller gain for receiving the optimal tuning procedure of time delay scheme.

2.2 Discussions on the Reviewed Works

Most of the review of related works in this research only lay emphasize on the temperature control of milk pasteurization under the control of conventional PID controller. Hence, no account was reported on the use of optimization tuning technique based adaptive controller approach to control the temperature of milk pasteurization. Therefore, it is pertinent to this research to incorporate so as to improve the system performances at different operating condition in terms of steady state response, overshoot and settling time.

2.3 Extremum Seeking Tuned PID Controller

Extremum Seeking (ES) is adaptive control scheme used to regulate the linear and nonlinear systems with a known set points or reference trajectories. ES is suitable to optimize the steady state performance of a dynamic plant by auto tuned the plant parameters based on measurement. The significance of extremum seeking compared to many other optimization techniques is that it does not rely on a model of the system and not subject to the unreliability (Tan et al., 2010). The aim of ES is to find the global extremum minimum of the objective function that represents the steady state relation between the plant parameters and the plant performance. ES seeks to tune the PID controller by finding a minimization cost function. In this article, the equivalent discrete time ES is developed to optimize the steady state plant performance in a sampled parameter setting. ES method would be implemented on the existing approaches to compare the fast-transient response of the convectional harmonic mitigation methods for optimizing the step response of a closed loop system consisting of a PID controller.

3 System Modelling

3.1 Pasteurizer Temperature Control

The pasteurizer temperature control actuated by traction motor model is shown in figure "2". The temperature set point would be set within the range of 65°C in 30 minutes of LTLT and 75°C in 20 seconds of HTST. The rotational speed of the motor in revolution per minutes would be determined by the adjustment of the applied voltage so as to keep the temperature in a steady state condition without time delay. The actual value measured would be sent into the comparator. The comparator would compare the output value with the input value to determine the system error. If the measured output value exceeded the set value, then the valve closes automatically. The ES would auto-tune the PID controller to regulate the system error and have the preset value as its output.

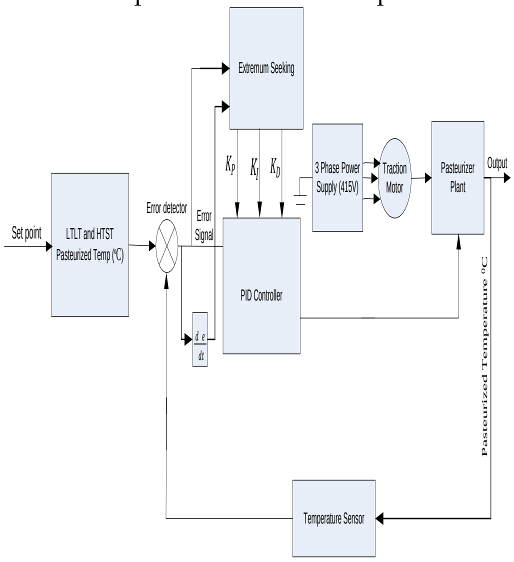

Fig. 2: Pasteurizer temperature control model

3.2 Mathematical Modelling Equation

Three different of heat transfer processes would be considered in this system.

1. The heat transfer Q_0 depends on the electrical power P.
2. The heat loss that occurs due to the recirculation flow in the heat exchanger Q_1
3. The heat lost to the environment Q_2 is described as the convectional equation

$$Q_1 = F_2 C_a (T_2 - T_{2r}) \quad (1)$$
$$Q_2 = UA(T_2 - T_a) \quad (2)$$

Applying an energy balance to the hot water tank system, the 'equation' would be expressed as;

$$C_i \frac{dT_i(t)}{dt} = \sum_{ij} E_{ij}(t) \quad (3)$$
$$C_A \frac{dT_2(t)}{dt} = P - F_2 C_a (T_2 - T_{2r}) - UA(T_2 - T_a) \quad (4)$$
$$K_1 = F_2 C_a \; ; \; K_2 = UA$$

To determine the value of specific heat capacity, therefore recirculation flow process would be closed. At this condition Q_1 is null.

$$C_A \frac{dT_2(t)}{dt} = P - UA(T_2 - T_a) \quad (5)$$
$$C_A \frac{dT_2(t)}{dt} = P - K_2(T_2 - T_a) \quad (6)$$

In order to achieve the SHC theorem, taking integral of the both sides;

$$\int_{T_0}^{T_2} C_A \frac{dT_2(t)}{dt} = \int_{T_0}^{T_2} [P - K_2(T_2 - T_a)]\, dT_2 \quad (7)$$
$$C_A = \frac{1}{K_2} In \left[\frac{P - K_2(T_2 - T_a)}{P - K_2(T_0 - T_a)}\right] \quad (8)$$

where ; C_a = Specific heat of water (KJ/Kg.K), F_2 = Mass flow of hot water that flows to the heat exchanger and returns (Kg), T_2 = Temperature inside the reactor (K), T_{2r} = Returned water temperature from the heat exchanger (K), U = Constant of heat transfer convection (Wm²/K), A = Area of the tank (m²) and T_a = Room temperature (K).

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The calorific capacity C_A of (J/K) is the product of the specific heat capacity C_p of the hot water of (JKg^{-1}K^{-1}), internal volume of the tank υ (m^3) and the density of the liquid ρ (kgm^{-3}).

$$C_A = C_P\rho\upsilon \quad (9)$$

$$C_p = \frac{\rho\upsilon}{K_2} In\left[\frac{P-K_2(T_2-T_a)}{P-K_2(T_0-T_a)}\right] \quad (10)$$

At 0^{o}C the initial temperature T_0 is negligible, the Laplace transform of 'equation 9' yields;

$$C_p = \frac{K_2 s}{\rho\upsilon}\left[\frac{P-K_2 s(T_2-T_a)}{P+K_2 s(T_a)}\right] \quad (11)$$

The closed loop temperature control based mathematical model for pasteurizer is achieved using ES-PID controller is presented in figure "3". The transfer function of the ES-PID controller is as shown in 'equation 12' while the temperature is shown in 'equation 15'.

$$G_c(s) = \frac{K_p T_d S^2 + K_p S + \frac{K_p}{T_i}}{S} \quad (12)$$

$$G_{(s)} = G_c(s) + C_p(s) \quad (13)$$

$$G_{(s)} = \frac{K_p T_d S^2 + K_p S + \frac{K_p}{T_i}}{S} + \left[\frac{K_2 s}{\rho\upsilon}\left[\frac{P-K_2 s(T_2-T_a)}{P+K_2 s(T_a)}\right]\right] \quad (14)$$

$$T_{sen}(s) = \frac{(h_{conv} A_{sen})T(S)}{(m_{sen}C_{sen})S + (m_{sen}C_{sen})} \quad (15)$$

m_{sen} = mass of sensor in Kg, C_{sen} = heat capacity of sensor in JKg^{-1}K^{-1}, h_{conv} = convection coefficient in Wm^2/K, T_{sen}= temperature sensor in K, A_{sen}= area of sensor in m^2, $G_{(s)}$= Overall forward path transfer function and $G_c(s)$= Forward path transfer function of the pasteurizer.

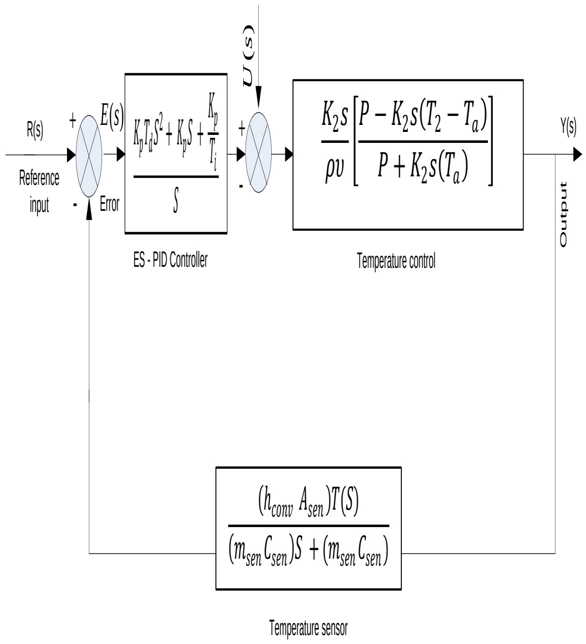

Fig. 3: Close loop temperature control model

3.3 Modelling Simulation

The simulation parameters for the developed closed loop mathematical model for the pasteurizer shown in Figure 3 were presented in Table 1. The model would be simulated using Simulink Package. This paper has provided a survey of the current research on methods for optimal temperature control of milk pasteurization using adaptive tuning controller in a dairy plant.

Table 1. Simulation Parameters for Pasteurizer Model

Variables	Descriptions	Values	Units
T_2	Temperature inside the reactor	347.6	K
T_a	Room temperature	273	K
k	Thermal conductivity of the wall	0.14	W/m K
ρ	Internal volume of the tank	100	m^3
υ	Density of the liquid	918.92	kgm^{-3}
m_{sen}	Mass of sensor	0.38	Kg
C_{sen}	Heat capacity of sensor	3.92	JKg^{-1}K^{-1}
h_{conv}	Convection coefficient	0.53	Wm^2/K
A_{sen}	Area of sensor	0.03	m^2

4 Conclusion and Future Recommendation

The paper discussed an overview control techniques and challenges arising in this context. A clear and general vision of methods used in controlling the temperature of milk pasteurization is presented. Also, this paper reveals limitations of the respective controllers used in controlling the temperature in terms of settling time, steady state response and overshoot.

For future references, an efficient Artificial Neural Network tuned PID controller which involves the optimization of a Fuzzy membership function parameters set should bring more benefit to the dairy plant in terms of temperature control of milk pasteurization without any time delay scheme. Also, it is envisaged that actuator motor speed used to energize the pasteurizer plant need to be control so as to enable the system to deliver more effectively.

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