Fuzzy-proportional-integral-derivative hybrid controller design for ultra-high temperature milk processing

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Article Info

Article history:

Received Jan 19, 2023
Revised Mar 4, 2023
Accepted Apr 24, 2023

Keywords:

Ultra-high temperature
Feedforward controller
Fuzzy-proportional-integral-derivative hybrid

ABSTRACT

In the ultra-high temperature (UHT) process, fluid temperature is raised above 135 °C for a short period of time (typically 4 seconds) and then quickly cooled ensuring no microbes remain in the final product. To have better quality processed milk, a stringent temperature control system is necessary. To solve this problem a detailed control-oriented mathematical model of the heating system for UHT application is developed and a detailed block diagram is established by identifying various systems and signals. To draw the merits of a feedforward controller (transfer function or fuzzy logic based) and proportional-integral-derivative (PID) feedback compensator, a fuzzy PID hybrid controller is designed and simulated in a MATLAB environment. Findings of the simulation results indicate that the fuzzy-PID hybrid compensator concatenates the benefits of both controllers. PID controller processes the error signal and tracks the setpoint whereas the feedforward controller (transfer function or fuzzy) effectively rejects the disturbance signal's effect on the controlled variable. The fuzzy-PID hybrid controller performs better than the individual PID or fuzzy controller.

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1. INTRODUCTION

In the ultra-high temperature (UHT) process, milk is heated to a temperature above 135 °C for a short period of time (typically 4 seconds) and then quickly cooled ensuring no microbes remain in the final product. The final product may be kept at room temperature for several months for storage. During the UHT process, the holding time of milk and process temperature destroys pathogens and bacteria. The efficiency of killing the microorganism is measured by the Bacteriological Index B*9-log reduction of thermophilic spores and is considered as a bacteriological index of 1. The lower limit of the process is defined by bacteriological Index B* with a minimum value of 1. The upper limit of the process is defined as 3% destruction of thiamine (vitamin B1) and is measured as Chemical Index C*. Elevated process temperature during UHT results in an increase in B* with a decrease in C* [1]–[4]. To have a better quality of processed milk by keeping B* and C* in the allowable range, a stringent temperature control system is necessary.

The UHT process is usually conducted using direct or indirect heating of the milk. In the indirect UHT process, the heat transfer is carried out in a heat exchanger, where milk is on one side and heating media is on the other side. Heating media is either pressurize hot water or steam [5]. The heat transfer takes place between preheated milk and heating media. The milk is heated to the desired temperature in the final heater, kept in holding tubes for some time, and then cooled rapidly to ambient temperature. Generally, a feedback temperature controller is used to regulate temperature at the heating stage and a thermocouple at the end of the final heater is installed for temperature measurement. Since the controller is used in the forward path, that processes the error signal (difference between the set point and process value) and takes a control action on the steam flow rate in the heat exchanger. The control action is taken when the milk is at the output stage of the heating section and the milk batch under processing will remain unaffected. The issue may be resolved by the inclusion of a feedforward controller that considers the temperature disturbance of incoming milk stock and manipulates the control signal [6]. The constraint in the feedforward controller design and implementation for a UHT system is that it is a complex and multivariable process and the development of a mathematical model of the system is difficult and sometimes impossible [7].

Different control strategies have been used by researchers to control pasteurization at high temperatures for a short interval of time. Model predictive control (MPC) and generic model control (GMC) were studied on milk pasteurization and on heat exchanger application, the desired set points were achieved using an MPC controller without any overshoot [8]–[11]. Advanced control techniques like hybrid fuzzy proportional-integral-derivative (PID) controller, fuzzy self-adaptive PID controller, and adaptive network-based fuzzy inference system (ANFIS) controller associated with their instrumentation setups have been tested and deployed in various industrial process applications and promising results were reported in [12]–[19]. In a cascaded control on a high-temperature short time (HTST) pasteurization, better results were obtained than in traditional PID control [20]. The sensitivity analysis of the input and output variables was investigated in a plate heat exchanger, and it was found that flow is the most critical in sensitivity analysis. The fuzzy logic controller was used in an HTST heat exchanger and performance was compared with a PID controller. It was found that, although utilizing six fuzzy rules, the results of the fuzzy logic controller are not very effective and more research in the field was suggested [21].

For applications involving the regulation of various industrial parameters (e.g., temperature, pressure, and flow) researchers have used hybrid fuzzy PID controllers. A normalized fuzzy logic controller has been used to control the quadruple tank process and performance was comparable to a conventional PID controller [22]. The hybrid fuzzy logic controller in which fuzzy logic tunes the PID parameter has been used to control the temperature to optimize the energy consumption application and better control was achieved than the conventional PID controller [16], [23]. A fuzzy PID composite controller in which fuzzy and PID are used to control the power was studied and concluded that better control was achieved using a fuzzy PID composite controller [24]. Similarly, hybrid fuzzy and neuro-fuzzy controllers have been used in various power applications for energy optimization and conversion [17], [25]. The number of rules used to tune the fuzzy logic in the above studies is rather high, which makes the controller more complicated and less practical [26], [27].

The research works mentioned above are mainly related to industrial processes and power control applications; the current study is focused on the temperature control of milk and an effort to determine a suitable controller for UHT temperature control capable enough to reject the milk inlet temperature variation. The study aims to develop a hybrid fuzzy feedforward with a PID feedback controller. The fuzzy logic controller will compensate for the input milk temperature disturbance whereas the PID feedback controller will consider the milk output temperature. By eliminating the need for mathematical modeling, the hybrid fuzzy feedforward PID feedback controller has leverage over the PID with the feedforward controller.

In this study a simplified dynamic mathematical model of the UHT final heater is developed, the model is a first-order system with time delay (FOSTD). The developed model was imported to Simulink for open-loop and close-loop performance analysis. A comparison of open loop, PID feedback controller, PID with feedforward control, and hybrid fuzzy feedforward PID feedback control was done in this research. The PID parameters were tuned by using the Simulink PID tuner application. The performance of the developed control system is analyzed for steady-state error, rise time, overshoot, undershoot, disturbance impact, disturbance rejection settling time, and the need for a mathematical model [28]. The current study is an effort to develop a control system for the final heater of a simple UHT along with hybrid fuzzy feedforward and PID feedback temperature controller to effectively track the set point while rejecting disturbances.

2. METHOD

In a UHT control system, first, we have to identify the process/plant, actuator, controller implementation, and control variable measurement. The process/plant in this control system is a media accumulator tube that holds milk and heat and is applied to raise its temperature. A heat exchanger is an actuator that provides heat to drive the dynamics of milk under processing. The control action is applied to the steam flow rate in the heat exchanger to adjust the heat energy supplied. The controlled variable in this system is milk temperature and it is measured with a thermocouple at the end of the holding tube and this signal is taken as a feedback signal. This signal is compared with the reference signal (set point temperature for milk) and an error signal is generated. This error signal is processed by the PID controller and generates the manipulated signal. For the effective disturbance rejection, input milk temperature is measured and taken as a disturbance signal, provided to the feedforward controller for processing. The output of this controller is added to the response of the PID controller to generate the combined effect of both controllers and then it is used to drive the steam valve position. Through this valve, steam is injected into the heat exchanger, and it provides heat energy to raise the temperature of the milk in the media-holding tube. This complete control-oriented block diagram of UHT milk processing is depicted in Figure 1. A schematic diagram of the final heater of a UHT is depicted in Figure 2. To model the heat transfer in the heat exchanger the energy conservation approach is used keeping the assumption into consideration: i) no phase change of milk on the product side and only latent heat transfer, ii) negligible variation in steam and product pressure, and iii) negligible heat accumulation by the heat exchanger materials/walls.

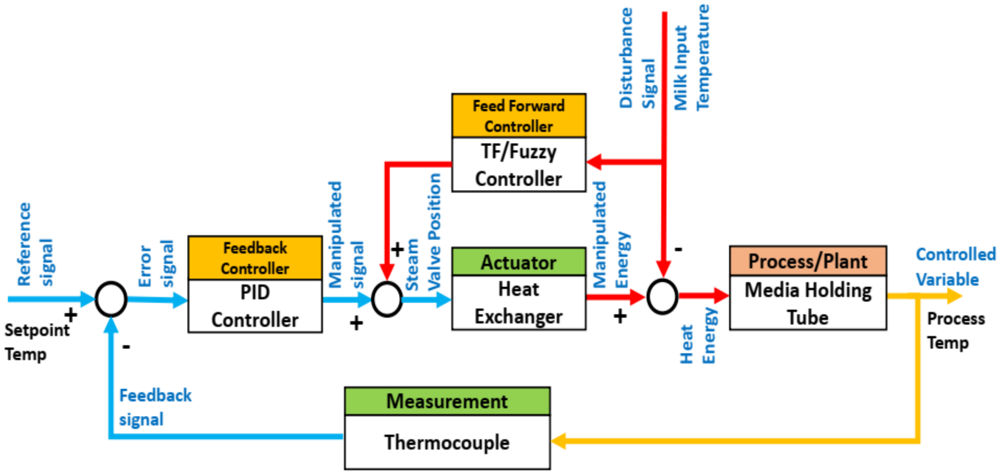

Figure 1. Control oriented block diagram of UHT system

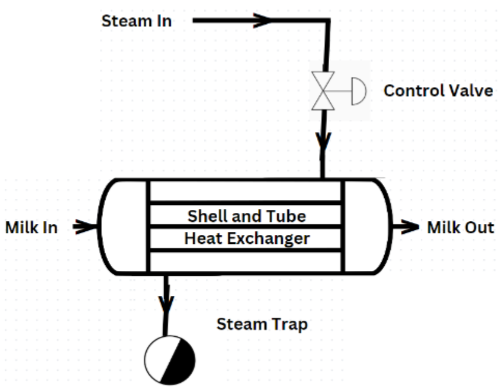

Figure 2. Schematic model of final heater of milk UHT

2.1. Mathematical model and block diagram

For the control system design, an adequate model of the process and actuator is of vital importance. For developing a mathematical model of the final heater shown in Figure 2, the following variables and constants are used.

$$Steam\ mass\ flow\ rate = \dot{m}_s(Control\ output)$$
$$Milk\ specific\ heat = C_m$$
$$Latent\ heat\ of\ steam = h$$
$$\text{Milk outlet temp} = T_{mx}\ \text{(Control variable)}$$
$$\text{Milk inlet temp} = T_{mn}\ (Disturbance\ variable)$$

In the final heater, heat from steam at the shell side is transferred to the milk (tube side) through the heat exchanger walls. Heat provided by steam transferred and retained by the milk is provided in (1) to (3).

$$Heat\ Out = \dot{m}_m C_p \Delta T \tag{1}$$

$$\text{Heat } In = \dot{m}_s h\ (Latent\ Heat) \tag{2}$$

$$Heat\ retained\ = m_m C_m \frac{dT_{mx}}{dt} \tag{3}$$

By applying the energy conservation principle, we get (4) and (5).

$$Heat In = \ Heat\ Out + Heat\ retained \tag{4}$$

$$h_s \dot{m}_{s(t)} = \dot{m}_m C_m \big(T_{mx(t)} - T_{mn(t)}\big) + m_m C_m \frac{dT_{mx(t)}}{dt} \tag{5}$$

A first order linear differential equation is (5), whereas the $T_{mx(t)}$ is a dependent variable. To convert this equation into an algebraic expression to be used for block diagram in control system design, its Laplace transformation is computed and expressed in (6).

$$h_s \dot{m}_s(s) = \dot{m}_m C_m \big(T_{mx}(s) - T_{mn}(s)\big) + m_m C_m S * T_{mx}(s) \tag{6}$$

$$h_s \dot{m}_s(s) + \dot{m}_m C_m T_{mn}(s) = \dot{m}_m C_m T_{mx}(s) + m_m C_m S * T_{mx}(s) \tag{7}$$

$$h_s \dot{m}_s(s) + \dot{m}_m C_m T_{mn}(s) = (\dot{m}_m C_m + m_m C_m S) * T_{mx}(s) \tag{8}$$

$$T_{mx}(s) = \left(\frac{h_s}{m_m C_m S + \dot{m}_m C_m} \dot{m}_s(s) + \frac{\dot{m}_m C_m}{m_m C_m S + \dot{m}_m C_m} T_{mn}(s) \right) \tag{9}$$

$$G_1 = \frac{h_s}{m_m C_m S + \dot{m}_m C_m} \qquad G_2 = \frac{\dot{m}_m C_m}{m_m C_m S + \dot{m}_m C_m} \tag{10}$$

G_1 is the transfer function for the heat exchanger and G_2 is the disturbance transfer function for inlet temperature disturbance.

$$T_{mx}(s) = (G_1 \dot{m}_s(s) + G_2 T_{mn}(s)) \tag{11}$$

In the current study, the following design parameters were used. Considering the first order system plus time delay in (11) becomes (12).

$$T_{mx}(s) = (G_1 \dot{m}_s(s) + G_2 T_{mn}(s)) e^{-ts} \tag{12}$$

Time delay, t is assumed as 4 seconds; this value defines the delay in steam activation and the corresponding change in outlet temperature of the heat exchanger. By considering the parameter values from Table 1 we get G_1 and G_2 transfer functions as (13).

$$G_1 = \frac{2065.35}{39.3s + 3.93} \qquad G_2 = \frac{1}{10s + 1} \tag{13}$$

Considering both transfer functions and time delay, the complete expression is attained as given in (14).

$$T_{mx}(s) = \left(\frac{2065.35}{39.3s + 3.93} \dot{m}_s(s) + \frac{1}{10s + 1} T_{mn}(s) \right) e^{-4s} \tag{14}$$

Figure 3 depicts the block diagram of the developed transfer function of the UHT system. This diagram provides a basis for the control system design that encompasses two transfer functions, two input variables, and one controlled variable. In open-loop control architecture, the control of the system is independent of the error between the setpoint and the controlled variable. The output can only be changed manually by the operator's input. We know that the outlet temperature T_{mx}(t) is directly related to the steam flow rate. Increasing the steam flow rate will increase the outlet temperature.

Table 1. Basic design parameters

Parameter	Design Value	Units
Mass flow rate of milk $\dot{m}_m$	1	[Kg/s]
Mass Retained in Heat Exchanger m_m	10	Kg
Specific Heat of Milk C_m	3.93	[KJ/kg/K]
Steam Latent Heat h_s	2065.35	[KJ/kg]
Steam Pressure	6	bar

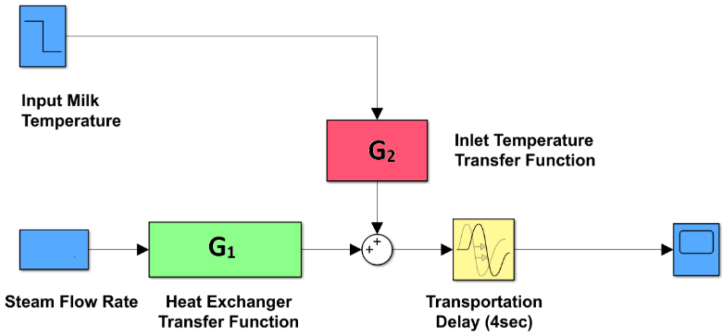

Figure 3. Control block diagram of heat exchanger

The gain for the open loop transfer function is set to 1/1,200. This gain is calculated by using the energy balance equation on a steady-state heat exchanger with an inlet temperature of 80 °C and an outlet at 140 °C. In steady state conditions in (5) becomes

$$\text{Gain } = \frac{\dot{m}_{s(t)}}{T_{mx(t)}} = \frac{0.1141}{140} = \frac{1}{1226}$$

All parameters and transfer functions were programmed in a Simulink environment and the developed model is shown in Figure 4. The temperature set point is the input control variable to the system and the steam flow rate is calculated by the gain function. Output is monitored on an oscilloscope and sent to the MATLAB environment for plotting purposes.

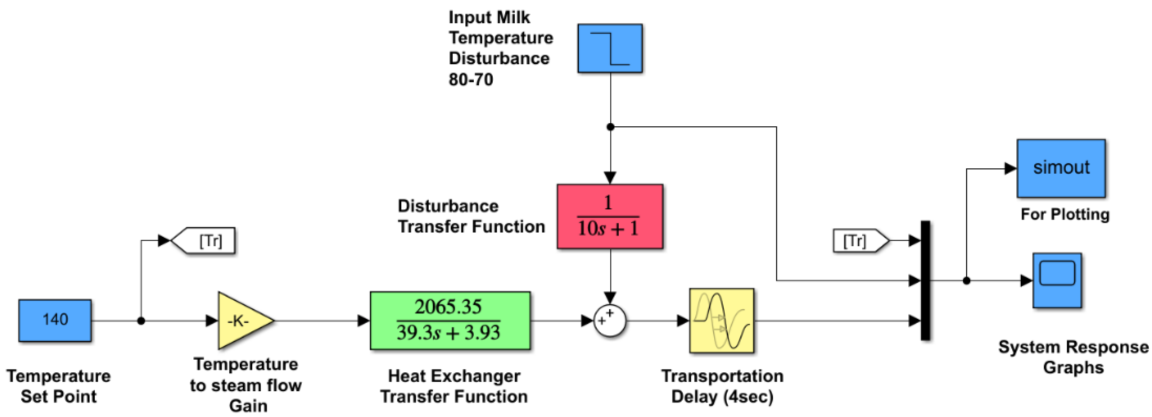

Figure 4. Open loop control system in Simulink

2.2. Feedforward controller design

The controller design is a vital step in control system design to meet the design specifications of the complete system. The insertion of a feedforward controller in the disturbance path adequately reduces the disturbance variable effect on the controlled variable. For its implementation, the first disturbance is measured, then it is processed by the feedforward transfer function and its output is then added to the forward path. For the calculation of this feedforward controller transfer function for UHT, Figure 5 is drawn. From here by setting the reference value steam flowrate $\dot{m}_s = 0$, the transfer function between the controlled variable (outlet temperature) and disturbance signal (inlet temperature) is established.

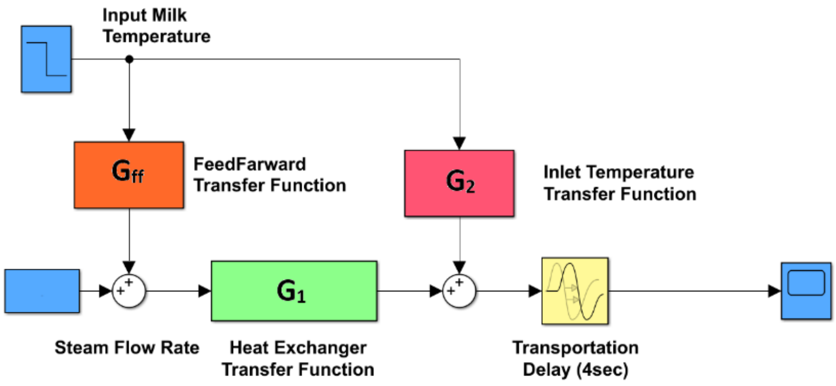

Figure 5. Control block diagram for feedforward function

Consider when steam flowrate $\dot{m}_s = 0$ then milk inlet temperature equal to milk outlet temperature from Figure 3. The feedforward controller transfer function is in (17). It will be placed in the path of the disturbance signal and its output will be added to the manipulated signal.

$$(\dot{m}_s + G_{ff})G_1 + G_2 = 0 \quad (15)$$

$$G_{ff} = -\frac{G_2}{G_1} \quad (16)$$

$$G_{ff} = \frac{-39.3 * s \ - 3.93}{20653.5 * s + 2065.35} \quad (17)$$

2.3. PID feedback controller

A conventional PID controller is used to process the error signal (i.e., the difference between the reference value and the actual measured value). Its output is then used to drive the actuator. In Figure 6, the PID feedback controller is placed before the heat exchanger transfer function. Depending on the PID values and the error signal strength, a control decision is taken that dictates the amount for steam flow rate. As discussed above due to FOSTD, there will be a delay of 4 sec from inlet to outlet gain, so the response will be a delayed function. In the PID controller, proportional integral and derivative constants are obtained from the MATLAB PID auto-tuner function. The placement of the PID controller along with the complete Simulink block diagram is shown in Figure 6.

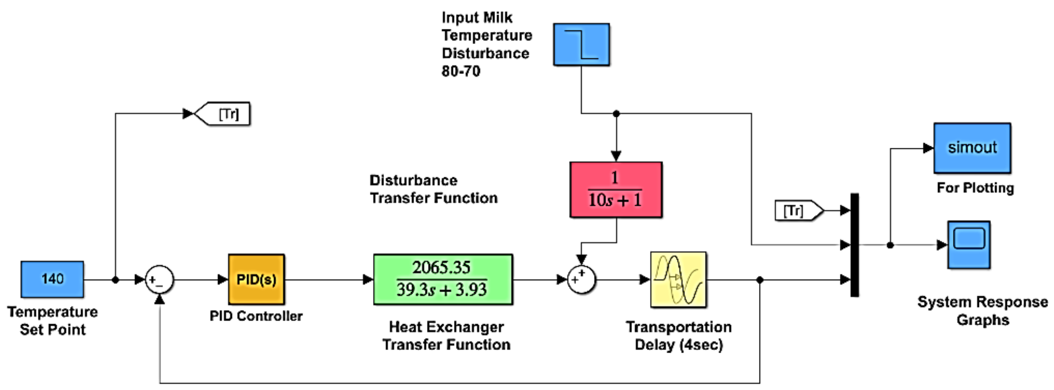

Figure 6. PID feedback controller

2.4. Feedforward-PID hybrid control

The concatenation of the PID feedback controller and feedforward controller is a favorable combination to track the reference value and to negate the effect of the disturbance signal on the controlled variable to attain the design specifications. Figure 7 depicts the inclusion of both controllers with a complete Simulink diagram. The reference value is compared with the feedback signal and an error signal is produced that is provided to the PID controller to conduct control action using its output. On the other hand, the disturbance signal is measured and provided to the feedforward controller, and its output is added to the response of the PID controller. The combined effect of these both controllers is used to drive the actuator (steam valve). For the UHT application, the set point provided at the reference signal is 140°, whereas the disturbance signal changes its value from 80° to 70°. The feedforward controller transfer function is developed from the physics-based model of the whole system and is described in the previous section.

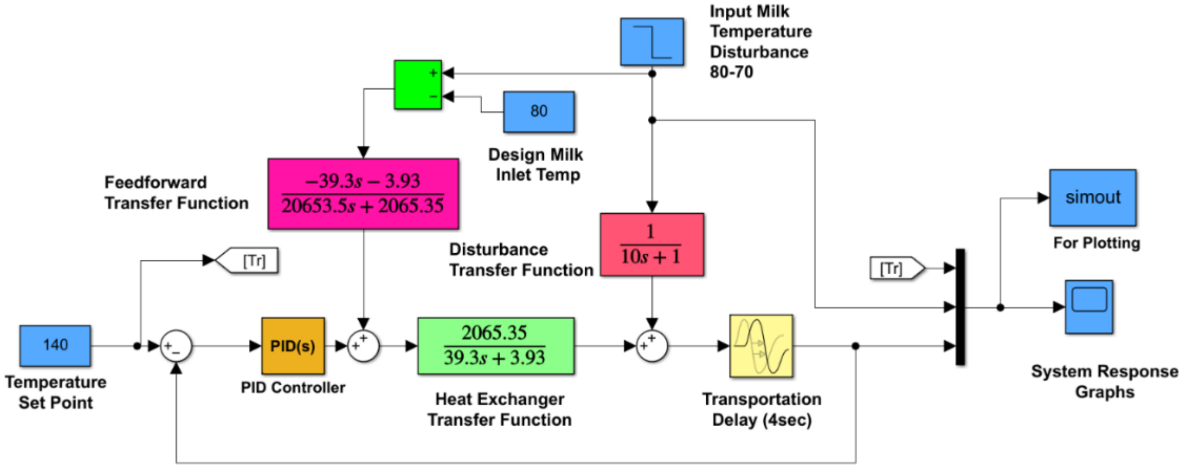

Figure 7. Feedforward-PID hybrid control

2.5. Fuzzy-PID hybrid control

Using both controllers (feedforward and PID feedback) exhibits promising results to control the output variable. An important step in designing the feedforward controller is to have complete knowledge of system differential equations and their associated transfer functions. Once the system is complex due to the interaction of various subsystems, it might be difficult to come up with a complete system model. To cope with such scenarios, soft computing controllers (fuzzy logic, genetic algorithm) may be a good choice to conduct the control action. In this section, a hybrid fuzzy feedforward controller with PID feedback control is proposed as shown in Figure 8. The function of the fuzzy feedforward controller is to negate the effect of the disturbance signal on the output temperature. The PID values in this control scheme are the same as those used in the above models.

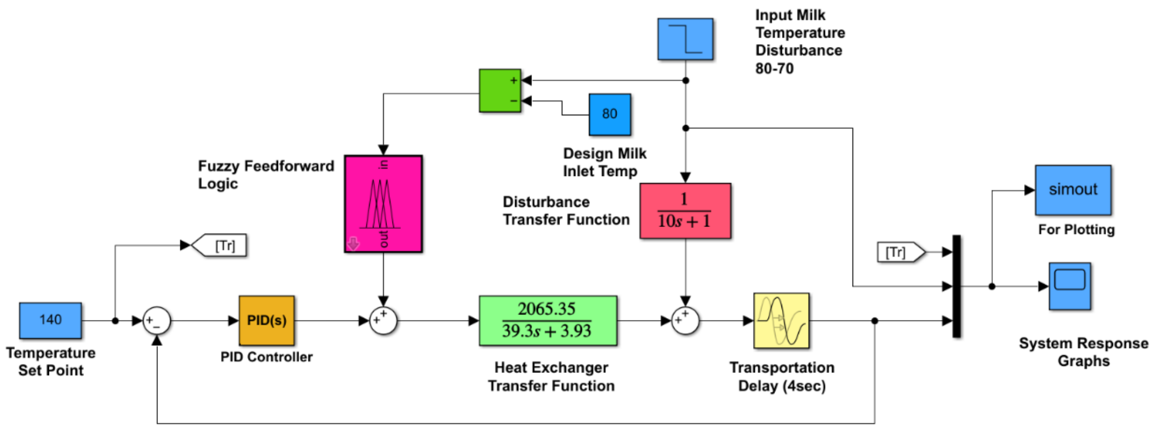

Figure 8. Fuzzy-PID hybrid control

The membership functions for temperature variation (input) are negative, zero, and positive. Similarly for steam flow rate (output), the membership functions are negative, zero, and positive as presented in Figure 9. The above-mentioned fuzzy rules and associated membership functions result in the fuzzy surface which is shown in Figure 10. From this surface, it is evident that, when the disturbance temperature is increasing (+ve disturbance), less steam is required to drive the actuator, so the steam flow rate is reduced. When the disturbance is negative, meaning the disturbance temperature is decreasing, more steam is required to compensate for this disturbance. These fuzzy rules are implemented as feedforward controllers and its complete Simulink diagram is shown in Figure 10.

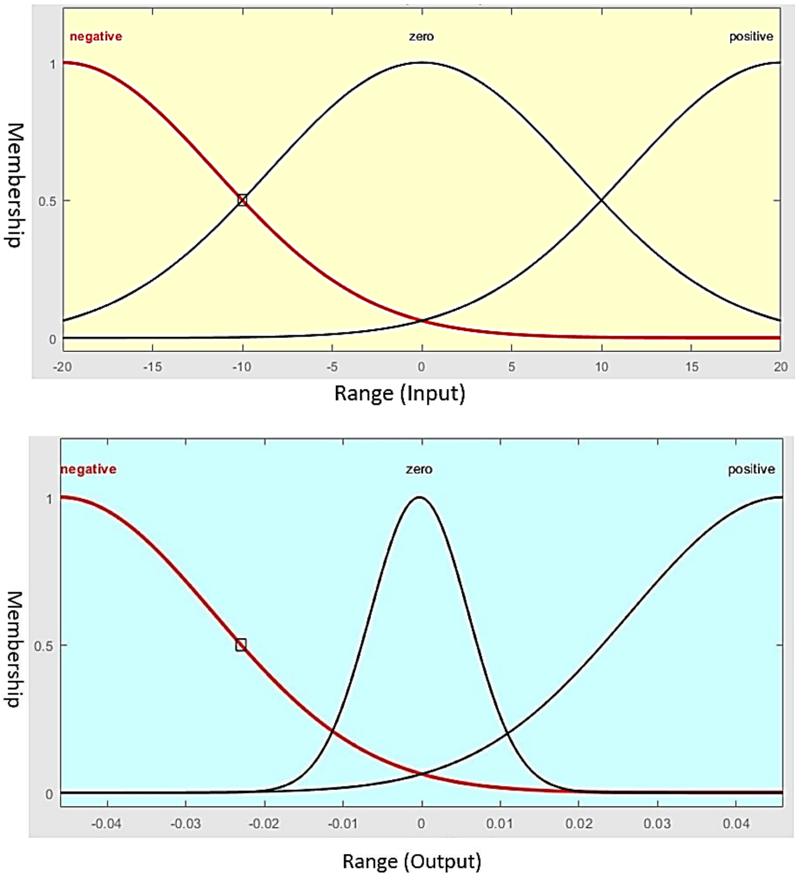

Figure 9. Membership function for temperature variation (input) and steam flow rate (output)

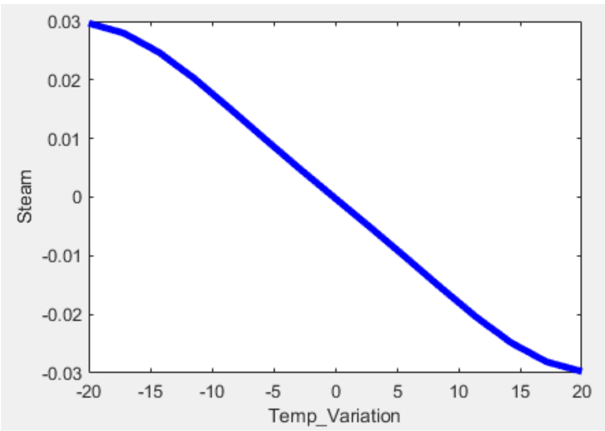

Figure 10. Fuzzy surface for steam flow rate (output) and temperature (input)

3. RESULTS AND DISCUSSION

The developed Simulink models for the UHT control system were set for the simulation by providing the simulation parameters. Simulation time was provided as 180 sec with a step of 0.1 sec and the ODE45 solver was selected due to its fast convergence and robust computation. All the results were imported to the MATLAB environment for plotting and post-processing purposes. The reference signal (desired temperature) is set at 140° by the constant block function of MATLAB. Another input, disturbance signal is applied, and it changes its value from 80 to 70 °C when the time is 100 sec. Simulations for all control systems were conducted and the responses of open loop system, PID feedback, PID with feedforward, and hybrid fuzzy feedforward with PID feedback controller were computed and plotted on one graph for their relative comparison and performance analysis. Figure 11 shows all the control system responses of the above-mentioned control strategies.

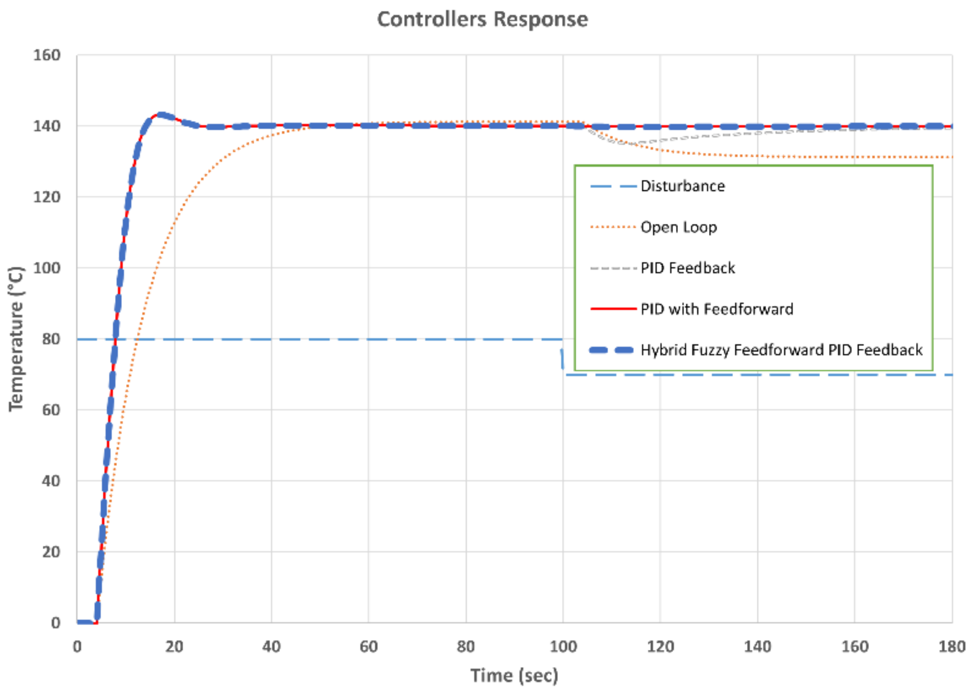

Figure 11. Various control system responses

In an open-loop control system, we do not have any measurement of controlled variables (feedback signal), and the system is operated directly by the actuator. Actuator input is applied at the start of the simulation. In the open loop response, the process temperature starts increasing at t=4 sec, because of the time delay function in the model. In the response plot, the rise time is 21.7 sec and a steady state error of 1.3 °C is observed initially. The rise time is calculated as the time taken by the controller from 10% to 90% of the output which corresponds to 14 to 126 °C. Steady-state error is a common problem in open-loop response that dictated the need for feedback control system design [15]. Steady-state error in the output temperature is not a desirable quality of any temperature control system. After the disturbance was introduced at t=100 sec the steady state error increased drastically from 1.3 to 8.7 °C and the output settled at 126 °C. It should be noted that the output temperature of 126.3 °C is below 135 °C, the critical limit of a UHT process, and the minimum temperature to achieve the lower limit of the bacteriological index of 1. It is clear from the simulation results that an open loop controller is not a suitable controller for the UHT temperature control system.

To attain better performance, a PID controller is incorporated to process the error signal. In the response of this system, the rise time has significantly reduced from 21.7 to 6.7 sec in comparison to the open loop, and the steady state error is reduced to zero after 40 seconds. However, the disturbance signal at 100 seconds results in a drop in output temperature from 140 to 135.2 °C. It should be noted that the lower limit for UHT is 135 °C. Such conditions will drop the bacteriological index to the critical limit, and a further drop in the temperature will result in an unsterile product in food processing equipment. For PID feedback control, it took 60 seconds to reach the desired 140 °C after the injection of the disturbance signal. The inability of the

PID feedback controller to negate the effect of disturbance makes the PID controller an inefficient controller where the disturbance in the UHT system cannot be neglected.

Further enhancement of the system response is attained by using the combined effect of the PID feedback controller with the feedforward controller. In this configuration, the initial response of the whole system (i.e., rise-time and settling time) are driven by the PID feedback controller. The positive impact of the feedforward controller is seen when the system is subjected to a disturbance at t=100 sec. The effect of disturbance in inlet temperature was negated by feedforward action and no change in output temperature is observed. The steady-state error remains zero as it was before the disturbance injection. In this configuration, the feedforward controller was obtained by a mathematical model, and it perfectly negates the effect of the disturbance signal on the controlled variable. In some cases, if the system is complicated and the interconnection of various subsystems, it seems impossible to acquire the feedforward transfer function in a mathematical expression. Soft computing techniques like fuzzy logic-based fuzzy feedforward controllers are used in conjunction with PID feedback controllers. This configuration provides a similar initial response as PID feedback control with a transfer function-based feedforward controller. Moreover, the impact of change in inlet temperature (at t=100 sec from 80 to 70 °C) is negated by the fuzzy logic controller completely as evidenced in Figure 11. The advantage of using a hybrid fuzzy feedforward controller over a transfer function-based controller is its development and deployment without a detailed mathematical model of the system.

4. CONCLUSION

In this work, a detailed mathematical model of a heating control system for UHT application is developed from a heat transfer equation and then a control system block diagram is developed by identifying various systems and signals. The developed model was imported to Simulink. The open loon step response of the system shows high rise time and steady-state error, and it necessitates the controller design to attain the control performance parameters. Using the PID controller, the rise time has significantly reduced from 21.7 to 6.7 sec in comparison to the open loop, and the steady state error is reduced to zero after 40 seconds. However, the disturbance signal at 100 seconds results in a drop in output temperature from 140 to 135.2 °C. In the fuzzy-PID hybrid controller, the initial response of the whole system (i.e., rise-time and settling-time) are driven by the PID feedback controller. The positive impact of the fuzzy controller is seen when the system is subjected to a disturbance at t=100 sec. The effect of disturbance in inlet temperature was negated by fuzzy control action and no change in output temperature is observed. The steady-state error remains zero as it was before the disturbance injection. The findings of the simulation indicate that a fuzzy-PID hybrid controller combines the benefits of two control methods. PID controller processes the error signal and tracks the setpoint whereas the feedforward controller (transfer function or fuzzy) effectively rejects the disturbance signal's effect. In summary, the fuzzy-PID hybrid controller performs better than the individual PID or fuzzy controller.

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