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# Control of milk pasteurization process using model predictive approach

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## Abstract

A milk pasteurization process, a nonlinear process and multivariable interacting system, is 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 multi-variable control approach with model predictive control (MPC) is proposed in this study. The proposed algorithm was tested for control of a milk pasteurization process in three cases of simulation such as set point tracking, model mismatch, difference control and prediction horizons, and time sample. 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 and giving less drastic control action compared to the cascade generic model control (GMC) strategy.

**Keyword**: Model predictive control, Generic model control, Milk pasteurization process

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## 1. Introduction

Pasteurized milk, a dairy product, has a shelf life of 8 to 10 days in an unopened package. Food safety is a concren in milk temperature at every stage of the pasteurized milk process, especailly at the heat treatment process. It is clearly defined as above 72°C heating temperature at the outlet of the holding tube and below 4°C cooling temperature at the cooling stage of the plate pasteurizer (PP). Consequently, the control system has been designed to ensure the safety of pasteruized milk.

The control system in Thailand pasteurized milk plant, which was visited, has been used individually automaic control approaches at process equipment involved including utilities (Niamsuwan et al., 2011). The conventional on-off controllers have been applied to keep the water temperature in the boiler and the ripple plate, respectively. The simulation study validated by the real observation is illustrated in Fig. 1. In spite of the acceptable control performance achieved by the on-off controller, the fluctuated dynamic profiles of the water and milk temperature around the desired set points and the sudden movement control action are frequently presented. It has caused the pasteurized milk plant to insufficiently consume the energy.

The milk pasteurization process presents many challenging control problem, including: nonlinear dynamic behavior: multivariable interaction between manipulated and controlled variables and contraints on manipulated and state variables. A number of control approaches and algorithm that are able to handle some of the above problem have been presented in the acdamic literature. The single and multivariable controls with cascade standard PID (propotional-integral-derivative) controllers were proposed to eliminate the fluctuation of the milk temperature which was caused by disturbances such as inlet milk temperature, milk flowrate, hot water temperature, hot water flowrate etc (Negiz et al., 1996; Morison, 2005).

Both control algorithms gave good disturbance rejection at the PP. Practically, not only the temperature control but also the level control was required for several process equipments, such as storage tanks. A programmable logic controller known as PLC, programmed in ladder logic, can only be applied for both level and temperature control at a diary plant (Bylund, 1955). One literature has been reported the multivariable control system of milk pasteurization process by Negiz et al., 1998. They described the implementation of lethality-based control system for high temperature-short time (HTST) pasteurizer. It performed the significant improvement in control performance over single loop control.

The model predictive control (MPC), one of model-based control approachs, was developed by Culer at Shell Oil Company in 1979. The first approach called as the dynamic matrix control (DMC) based on linear models at that time. Recently, there are many frameworks developed under the predictive control strategy. Nonlinear MPC, a development of conventional MPC, used a nonlinear model (the first-principles mathematical models or semi-empirical models) to deal with nonlinearities in process dynamics and in objective functions (Manenti, 2011; Dones et al., 2010). Almost conventional MPCs compute the manipulated input values by minimizing the cost function based on optimal steady-state values. For a time-varying process operation, economic model predictive approaches have been developed by a reformulation of the quadratic cost functions in which the economics-based (not necessarily quadratic) cost function e.g. an estimator-based economic MPC, a Lyapunov-based economic MPC. (Heidarinejad et al., 2012; Chen et al., 2012). The MPC performed many potential applications in the process industry (Qin and Badgwell, 2003; Bauer and Craig, 2008), but only report of the DMC for HTST pasteurization process has been found (Ibarrola et al., 2002).

The MPC technique for multi-input multi-output (MIMO) system are studied in this paper for application to the milk pasteurization process which is commonly found in the dairy industries of Thailand. The highly nonlinear dynamic behavior, multivariable in nature, and interaction between unit processes cause this process to be difficult to control by conventional controllers. Therefore, the aim and contribution of this work is at showing the applicability of the nonlinear MPC on a multivariable process referring to a real industrial plant. To demonstrate the robustness of the predictive control strategy, tests involving set point tracking based on the real operation including model mismatch are performed in this study. Comparison is also made for the GMC approach.

## 2. Process Description

The milk pasteurization process can be briefly introduced. It consists of the unit process involved including utilities: PP, holding tube, boiler, cooling tower, ripple plate, and three water tanks as shown in Fig. 2. The mathematical models of milk pasteurization process have been studied here (Niamsuwan et al., 2013). The meaning of letters and symbols are given in nomenclature. The physical properties, geometry characteritics, and process data are summarized in Table 1.

$$\frac{dT_{mo}}{dt} = \frac{F_m\left(T_{mi} - T_{mo}\right)}{V_{pp,i}} \pm \frac{U_{pp,i}A_{pp,i}\Delta T_i}{\rho_m C_{pm} V_{pp,i}} \tag{1}$$

$$\frac{dT_{hi,1}}{dt} = \frac{\left(1 - u_1\right)F_h\left(T_{ho} - T_{hi,1}\right)}{V_{pp,2}} - \frac{U_{pp,2}A_{pp,2}\Delta T_2}{\rho_h C_{ph} V_{pp,2}} \tag{2}$$

$$\frac{dT_{ti}}{dt} = \frac{F_t\left(T_{to} - T_{ti}\right)}{V_{pp,3}} + \frac{U_{pp,3}A_{pp,3}\Delta T_3}{\rho_t C_{pt} V_{pp,3}} \tag{3}$$

$$\frac{dT_{ii}}{dt} = \frac{u_2 F_i\left(T_{io} - T_{ii}\right)}{V_{pp,4}} + \frac{U_{pp,4}A_{pp,4}\Delta T_4}{\rho_i C_{pi} V_{pp,4}} \tag{4}$$

$$T_{mo} = T_{mi} + \frac{4U_p\left(T_{mo} - T_a\right)}{\rho_m C_{pm} d_p} \tag{5}$$

$$\frac{dT_{to}}{dt} = \frac{F_t\left(T_{ti} - T_{to}\right)}{V_{ct}} - \frac{h_v E}{C_{pt} V_{ct}} + \frac{\rho_w C_{pw} F_w T_w}{\rho_t C_{pt} V_{ct}} - \frac{L_d F_c T_{ti} + h_A\left(T_{to} - T_a\right)}{\rho_t C_{pt} V_{ct}} \tag{6}$$

$$\frac{dT_{io}}{dt} = \frac{u_2 F_i\left(T_{ii} - T_{io}\right)}{V_{rp}} + \frac{\pi\left(u_4 n_s\right) d_f h_{fg} A_f}{60 \rho_i C_{pi} V_{rp} \nu} - \frac{U_{rp} A_{rp}\left(T_{io} - T_a\right)}{\rho_i C_{pi} V_{rp}} \tag{7}$$

$$\frac{dT_{ho}}{dt} = \frac{F_h\left(T_{hi} - T_{ho}\right)}{V_b} + \frac{u_3 m_f H_f - U_b A_b\left(T_{ho} - T_a\right)}{\rho_h C_{ph} V_b} \tag{8}$$

$$\frac{dT_{hi,2}}{dt} = \frac{u_1 F_h\left(T_{ho} - T_{hi,2}\right)}{V_h} - \frac{U_h A_h \Delta T}{\rho_h C_{ph} V_h} \tag{9}$$

## 3. Design of Controllers

The basis concept of the MPC is that it calculates future controls based on current measurements via the solution of predictive control strategy, but only the first element of controls is applied to the process (Kittisupakorn and Hussain, 2000). Therefore, the objective function of the predictive control strategy has been formed as follows:

$$\min_{u_n(k+1),\ldots,u_n(k+M)} \sum_{n=1}^{4} \sum_{l=1}^{P} \left[ W_1 \left[ Y_p(k+l) - Y_{sp}(k+1) \right]^2 + W_2 \left[ \Delta u_n \right]^2 \right] \tag{10}$$

Subject to process models (1) to (9)

$$u_{n,\min} < u_n(k+l) < u_{n,\max} \quad \text{for } l = 1, 2, \ldots, M \tag{11}$$

$$Y_{p,\min} < Y(k+l) < Y_{p,\max} \quad \text{for } l = 1, 2, \ldots, P \tag{12}$$

$$Y(k+p) = Y_{sp} \tag{13}$$

The objective function of the MPC (Eq. 10) is to minimize the sum of squares of the errors between the predicted outputs and the set point values and also the control movements evaluated over the prediction horizon. Bounded controls and controlled variable constraints are represented by Eqs. 11 and 12. Moreover, Eq. 13 is included to ensure that the controlled variables are forced to desired set points at the terminal time. The optimization problem is classified as multi-variables constraint optimization and solved by the sequential quadratic programming (SQP) in MATLAB software.

Fig. 3 shows the information flowchart of the MPC algorithm. A control trajectory u(k) referring to set point (k) for an entire horizon is computed on-line based on current state. The initial value of controls is implemented to the system. This means that the control action at time (k+1) is the control u(1) referring to set point (1) of future controls calculate at time k. Some feedback control is provided by measurements of the state at the next interval and repeating the calculation. Otherwise, measurements are compared to a set point or predicted value. The error between the measurements and set points can be utilized within the MPC algorithm. The MPC produces the future controls, which minimizes this error.

## 4. Control Implementation

### 4.1 Case Study

The main purpose of this simulation study is to evaluate the control performance of the MPC compared to the GMC approach. Here, the MPC algorithm has been studied to keep the milk temperature at the PP ($T_{mo}$) to the plant's requirements, as well as the hot and iced water temperature ($T_{ho}$ and $T_{io}$) to the desired set points. These are controlled by adjusting the hot and iced water flowrate at the PP ($u_1$ and $u_2$), liquefied petroleum gas (LPG) feeding rate at the boiler ($u_3$), and electrical current at the ripple plate ($u_4$), respectively. The simulations are made corresponding to the daily plant production capacity of 10 tons based on the real operation. After the production time over 33 minutes, the raw milk is delivered from the silo tank to the PP unit it is empty. It has caused the milk temperature at inlet of the PP to disturb as displayed in Fig. 4.

## 4.2 Simulation Result

The MPC strategy is initially applied to control the milk temperature, the hot water temperature, and the iced water temperature to desired values by adjusting the manipulated variables of $u_1$, $u_2$, $u_3$, and $u_4$, respectively. The simulation presents several cases of control study, which are set point tracking case and model mismatch case.

As for the set point tracking case, the MPC is designed to bring the milk temperature as well as the hot and iced water temperature to desired set points from initial values. The desired set points of the temperature are also set at 76˚C for the holding tube, 3˚C for the cooling stage, 92˚C for the boiler, and 2˚C for the ripple plate, respectively. The control of the temperature using the conventional MPC ($M = 6$ and $P = 12$) can be seen in Fig. 5 and Fig. 6. It can be seen that the MPC has been found to drive the process responses to the following set points without overshoot and oscillations and with less drastic control actions. The satisfactory performance obtained is due to the accurate representation of the process models and the anti-ringing term of the predictive control strategy corresponding to the selection of the MPC tuning parameters: control and prediction horizon ($M \leq P$) and weighting factors ($W_1 > W_2$).

For comparison, the GMC controller is considered. Four GMC controllers including cascade control strategy have been designed into two cascade-GMC loops (the detail as given in appendix). The GMC controllers are designed using the method presented by Lee and Sullivan (1988) and with subsequent fine tuning. The control of temperature using the GMC shows performance as displayed in Fig. 7 and Fig. 8. It can be found that the GMC provided slow response of controlled variables with a bit overshoot and also gradually adjustment control action, similar to the MPC.

For the model mismatch case, the overall heat transfer coefficient at each stage of the PP is taken into account as the model mismatch in parameter. The model mismatch is introduced by randomly increasing and decreasing the overall heat transfer coefficient from its nominal value by 10%. Fig. 9 and 10 show the results of the MPC and GMC control in this case. Fig. 9 illustrates that the MPC still brought the milk temperature at the holding tube and the cooling stage to the desired set points with smooth and without overshoot control response by the gradually adjustment flow rate of hot and iced water at the PP. As illustrated in Fig. 10, it clearly shows that the GMC including cascade control strategy brought the milk temperature to the desired set points by rigorous adjustment of LPG feeding rate causing slow and overshoot in the process response, especially at the holding tube of the PP. Table 2 shows the IAE values of MPC and GMC for holding tube of PP, and cooling stage of PP. They indicate that the MPC gives less error and better performances than the GMC, when the disturbances are introduced into the system. These results also show the robustness of the mathematical models in dealing with disturbances.

For the difference control horizon ($M$) and prediction horizons ($P$), the simulation study of the MPC has been made based on set points tracking under nominal disturbances. It can be seen in Fig. 11 that increasing both control horizon and prediction horizon will slightly smoothen the control action compared with Fig. 12 for the boiler, the ripple plate, the holding tube of PP, and the cooling stage of PP. Nevertheless, the MPC with $M = 12$ and $P = 24$ performed more computation time per cycle of 8-10 times than the conventional MPC ($M = 6$ and $P = 12$).

Comparison is also made for the MPC using the difference sampling time. The sampling time of the conventional MPC ($M = 6$ and $P = 12$) increased at about twice is considered for set points tracking under nominal disturbances. The results in Fig. 13 show that the smooth control action for the boiler, the ripple plate, the holding tube of PP, and the cooling stage of PP will be given, similar to the case of the difference control horizons and prediction horizons.

## 5. Conclusions

One of model based-control strategy namely MPC is dicussed and explained, since the milk pasteurization process is multivariable interacting system, which make it difficultly to control by the conventional control system. A proposed controller performed well in keeping the milk temperature and water temperature at the desired set points without any oscillation and overshoot. This is becasue of the accurated process model in this controller. On account of a predictive control strategy, control response for MPC was less dratic control action compared to that by the GMC. Comparison of performance with the GMC indicates that the MPC was more robust than the GMC and gave the better results in case involving model mismatches. These results can be convincingly used to propose the applicability of the studied nonlinear MPC to stakeholders relevant to pasteurization process.

## Acknowledgements

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## Appendix

### Appendix A: Generic control model

Generic model control (GMC), one of model-based control approach, is developed by Lee and Sullivan (1988). The GMC uses non-linear process model to determine the control action and two tuning parameters to obtain the desired response. Advantages of the GMC making a good framework are that the process model appears directly in the control algorithm and does not need to be linearized before use (Aziz, Hussain and Mujtaba, 2000).

The GMC control algorithm can be written as.

$$\frac{dY}{dt} = K_1\left(Y_{sp} - Y\right) + K_2\int_0^{t_f}\left(Y_{sp} - Y\right)dt \tag{A-1}$$

The first term in the algorithm is to bring the process response back to steady state owing to change in *dY/dt*. The second term is introduced to make the process response with zero offset. Detail of the GMC method can be found in Lee and Sullivan (1988).

## Appendix B: Cascade Control

The conventional feedback control can be compensated the disturbance. Sometimes, the response of controlled variable is slow because the controlled variable is disturbed before the feedback controller can respond. A cascade control algorithm, one of the most successful methods for enhancing single-loop control performance, is introduced to improve the control performance, reducing both the maximum deviation and the integral error of disturbance response.

In this work, the cascade GMC approach is applied to control the milk temperature at the outlet of holding tube and cooling stage of PP. Fig. B-1 shows the control algorithm of cascade GMC. The first cascade loop GMC is designed to the primary GMC keeping the milk temperature at the outlet of holding tube by computing the manipulated variable. It becomes the set point for the secondary GMC that maintains the hot water temperature at the boiler. For the second cascade loop GMC, the primary GMC is used to maintain the milk temperature at the outlet of cooling stage by calculating the set point for the secondary GMC, which is also designed to control the iced water temperature at the ripple plate.

## Nomenclature

| | |
|---|---|
| $A_{pp1}, A_{pp2}, A_{pp3}, A_{pp4}$ | Transferred area at each stage of PP |
| $A_b, A_{rp}$ | Surface area at boiler and ripple plate |

| | |
|---|---|
| $A_h$ | Transferred area for heating coil at water storage tank |
| $A_f$ | Peripheral flow area of ripple plate’s compressor |
| $C_{pm}, C_{ph}, C_{pi}, C_{pt}$ | Heat capacity for milk, hot water, iced water, and tap water |
| $d_f$ | Impeller’s diameter for compressor at ripple plate |
| $d_p$ | Diameter of holding tube |
| $E$ | Evaporation rate for cooling tower |
| $F_m$ | Volumetric flowrate of milk |
| $F_h, F_{h1}$ | Volumetric flowrate of hot water |
| $F_i$ | Volumetric flowrate for iced water |
| $F_t, F_c, F_w$ | Volumetric flowrate for tap water, circulation water, and makeup water at cooling tower |
| $h_A$ | Heat transfer coefficient at water surface |
| $h_{fg}$ | Latent heat vaporization of refrigerant at ripple plate |
| $h_v$ | Latent heat vaporization of water |
| $K_1, K_2$ | Tuning constants for GMC |
| $L_d$ | Mechanical drift loss at cooling tower |
| $H_f$ | Heating value of fuel |
| $m_f$ | Fueling rate at boiler |
| $M, P$ | Control and prediction horizon for MPC |
| $n$ | Sample the process outputs |
| $n_s$ | Impeller’s rotation speed for compressor at ripple plate |

| | |
|---|---|
| $T_{mi}, T_{mo}$ | Temperature of milk at inlet and outlet |
| $T_{hi}, T_{ho}$ | Temperature of hot water at inlet and outlet |
| $T_{ii}, T_{io}$ | Temperature of iced water at inlet and outlet |
| $T_{ti}, T_{to}$ | Temperature of tap water at inlet and outlet |
| $T_w$ | Temperature of makeup water at cooling tower |
| $t$ | Time |
| $t_f$ | Terminal time of horizon |
| $u_1, u_2, u_3, u_4$ | Manipulated variable |
| $U_{pp1}, U_{pp2}, U_{pp3}, U_{pp4}$ | Overall heat transfer coefficient between both sides at each stage of PP |
| $U_p$ | Overall heat transfer coefficient at surface of holding tube |
| $U_b, U_{rp}$ | Overall heat transfer coefficient at surface for boiler and ripple plate |
| $U_h$ | Overall heat transfer coefficient at surface for heating coil at water storage tank |
| $V_b, V_{rp}, V_{ct}$ | Water volume for boiler, ripple plate, and cooling tower |
| $V_{pp1}, V_{pp2}, V_{pp3}, V_{pp4}$ | Fluid volume for each side at each stage of PP |
| $V_h$ | Water volume inside heating coil at water storage tank |
| $W_1, W_2$ | Weighting factors for MPC |
| $Y$ | Measured variables |
| $Y_{sp}$ | Desired set points |

Greek Letter

| | |
|---|---|
| $\rho_m, \rho_h, \rho_i, \rho_t$ | Density for milk, hot water, iced water, and tap water |
| $v$ | Specific volume of refrigerant at the exit |

$\Delta T$ Temperature difference between both fluids

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**Table 1.** The physical properties and process data for the simulation study.

| | | | |
|---|---|---|---|
| Heat transfer area ($m^2$) | | Overall heat transfer coefficient ($W/m^2 \cdot K$) | |
| - Regenerative stage of PP; $A_{pp1}$ | 1.89 | - Regenerative stage of PP; $U_{pp1}$ | 940 |
| - Heating stage of PP; $A_{pp2}$ | 1.89 | - Heating stage of PP; $U_{pp2}$ | 940 |
| - Pre-cooling stage of PP; $A_{pp3}$ | 1.89 | - Pre-cooling stage of PP; $U_{pp3}$ | 950 |
| - Cooling stage of PP; $A_{pp4}$ | 3.99 | - Cooling stage of PP; $U_{pp4}$ | 1,000 |
| - Heating coil in water tank; $A_h$ | 0.5067 | - Heating coil in water tank; $U_h$ | 490 |
| Water volume ($m^3$) | | Characteristic for cooling tower | |
| - Boiler; $A_b$ | 1.20 | - Convective heat transfer coefficient (W/K) ; $h_A$ | 2,000 |
| - Ripple plate; $A_{tp}$ | 0.50 | - Latent heat of vaporization (kJ/kg) ; $h_v$ | 2,410 |
| - Cooling tower; $A_{ct}$ | 0.05 | - Circulation water ($m^3/s$) ; $F_c$ | $4.80\times10^{-3}$ |
| Diameter of holding tube (m) ; $d_p$ | $3.81\times10^{-2}$ | - Drift loss (%) ; $L_d$ | 2 |
| Length of holding tube (m) ; $L_p$ | 12 | Water make up temperature (°C) ; $T_w$ | 27 |
| Flowrate ($m^3/s$) | | Ambient air temperature (°C) ; $T_a$ | 30 |
| - Milk at PP; $F_m$ | $4\times10^{-4}$ | Specification for ripple plate compressor | |
| - Hot water at PP; $F_h$ | $1.60\times10^{-3}$ | - Rotating speed (rpm) ; $n_s$ | 5,000 |
| - Tap water at PP; $F_t$ | $4.80\times10^{-3}$ | - Diameter of impeller (m) ; $d_f$ | 0.40 |
| - Iced water at PP; $F_i$ | $1.92\times10^{-3}$ | - Periphereal flow area ($m^2$) ; $A_f$ | 0.002 |
| - Hot water (returned to boiler) ; $F_{h1}$ | $3.20\times10^{-3}$ | Specification for refrigerant | |
| Characteristic for boiler | | - Heat vaporization (kJ/kg) ; $h_f$ | 217 |
| - LPG consumption (kg/s) ; $m_f$ | $1.80\times10^{-3}$ | - Specific volume at the exit; $\nu$ | 0.50 |
| - LPG heating value (kJ/kg) ; $H_f$ | 49,888 | | |

**Table 2.** Performance comparison between MPC and GMC under the model mismatch case.

| Unit | IAE values | |
|---|---|---|
| | MPC | GMC |
| Holding tube of PP | $3.267\times10^3$ | $9.571\times10^3$ |
| Cooling stage of PP | $6.160\times10^3$ | $7.204\times10^3$ |

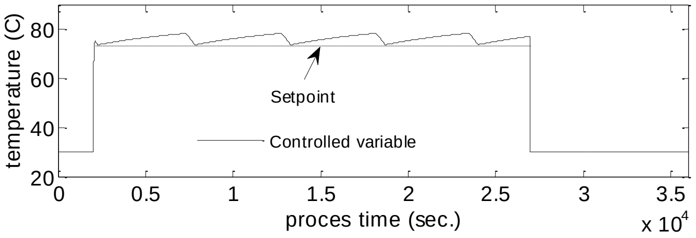


**Fig. 1.** Temperature profiles for the milk at the outlet of holding tube controlled by with the conventional controller

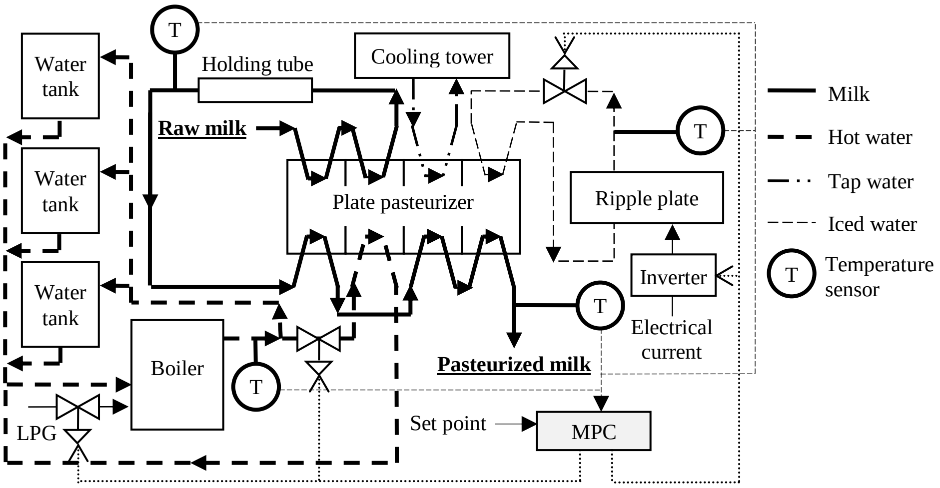


**Fig. 2.** The MPC control system in the milk pasteurization process

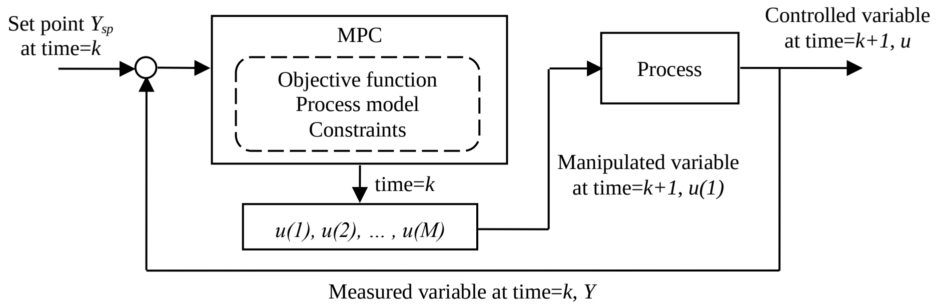


**Fig. 3.** Information flowchart of the MPC algorithm

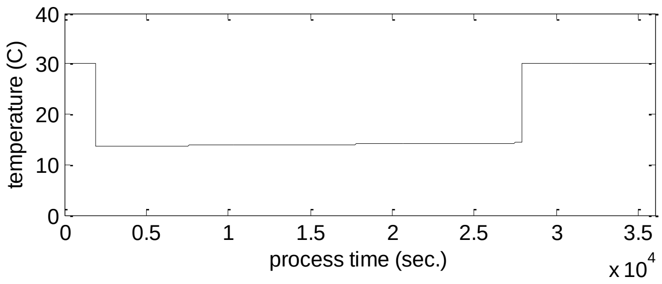
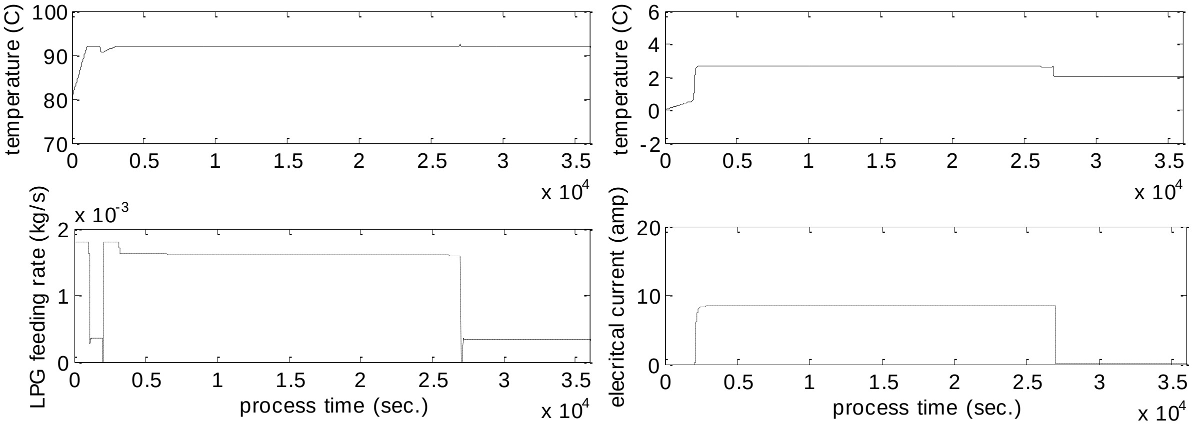
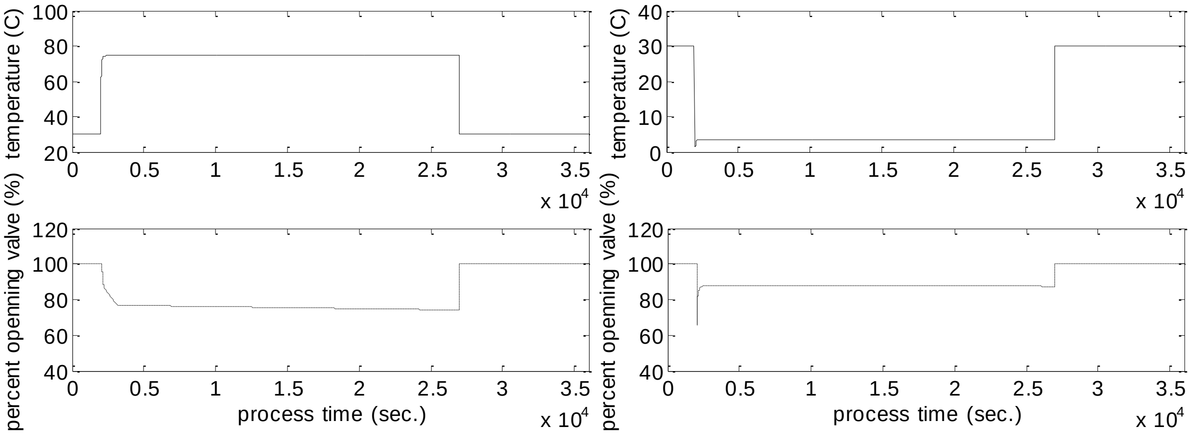


**Fig. 4.** Disturbances based on actually process operation



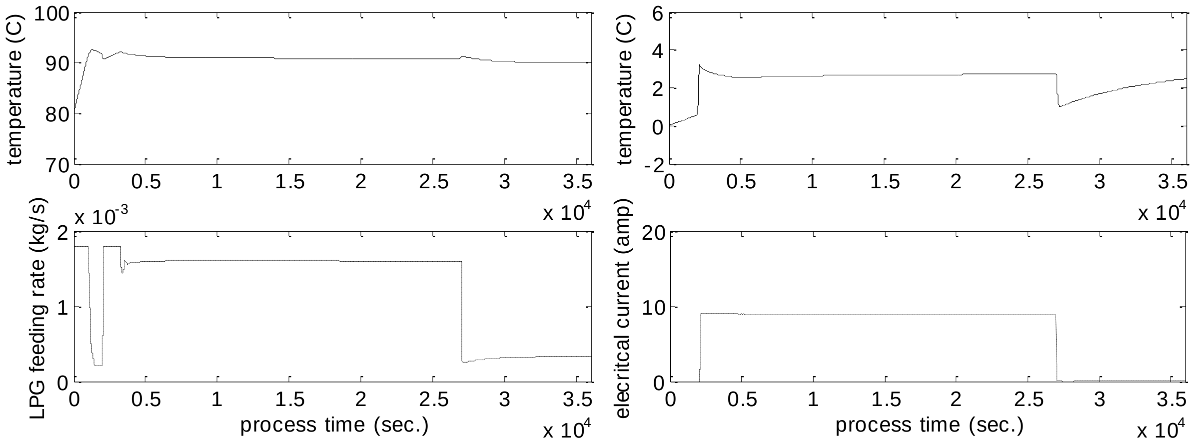
A) boiler B) ripple plate

**Fig. 5.** Set point tracking with MPC for hot and iced water temperature under nominal conditions (M = 6 and P = 12): (A) boiler and (B) ripple plate.



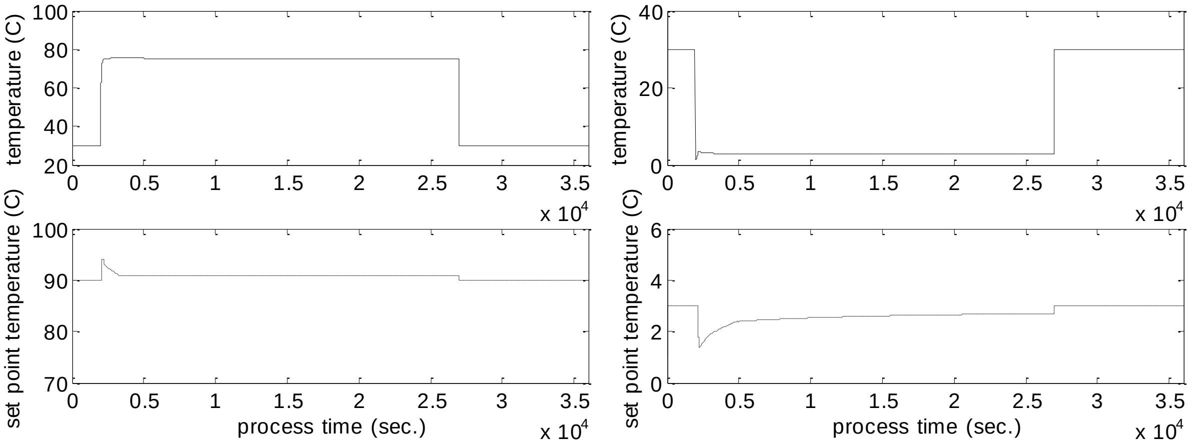
A) holding tube of PP B) cooling stage of PP

**Fig. 6.** Set point tracking with MPC for milk temperature under nominal conditions (M = 6 and P = 12): (A) holding tube of PP and (B) cooling stage of PP.



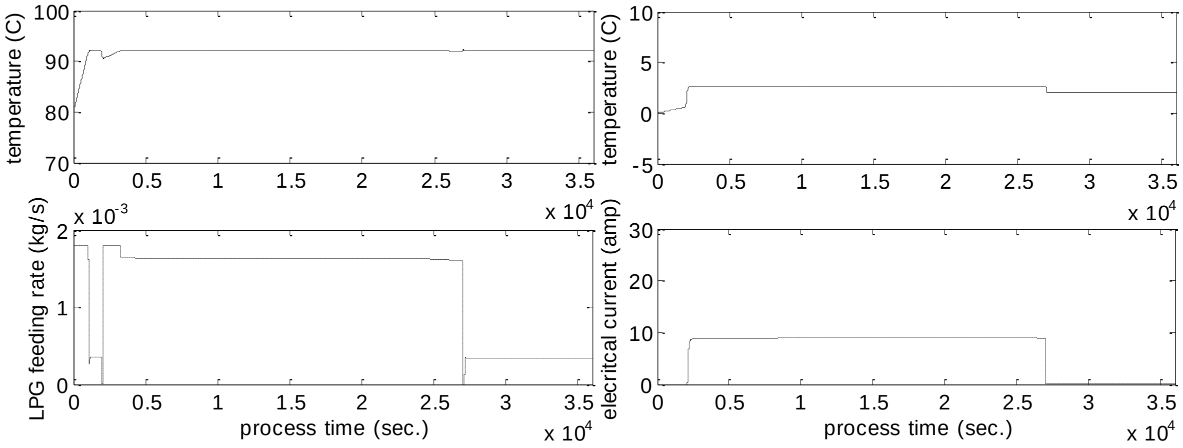
A) boiler B) ripple plate

**Fig. 7.** Set point tracking with GMC for hot and iced water temperature under nominal conditions: (A) boiler and (B) ripple plate.

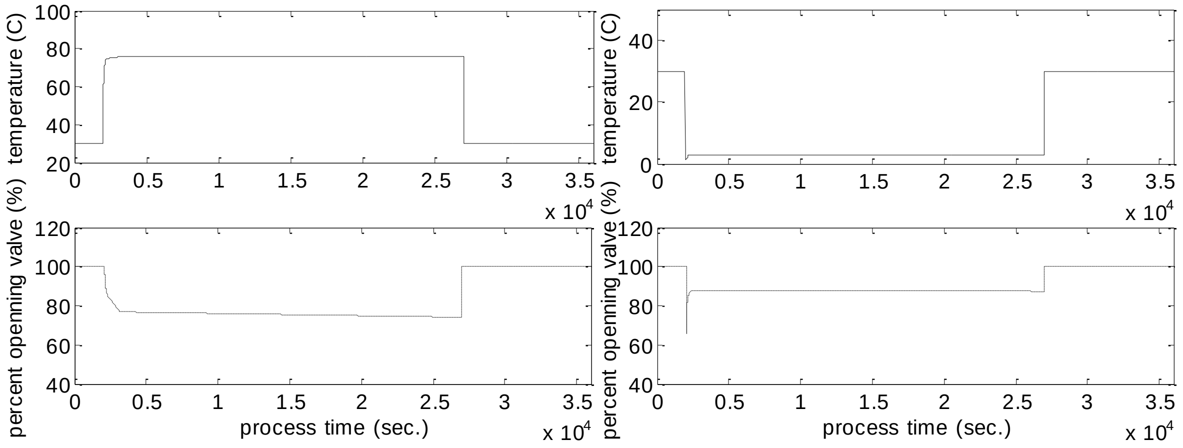


A) holding tube of PP B) cooling stage of PP

**Fig. 8.** Set point tracking with GMC for milk temperature under nominal conditions: (A) holding tube of PP and (B) cooling stage of PP



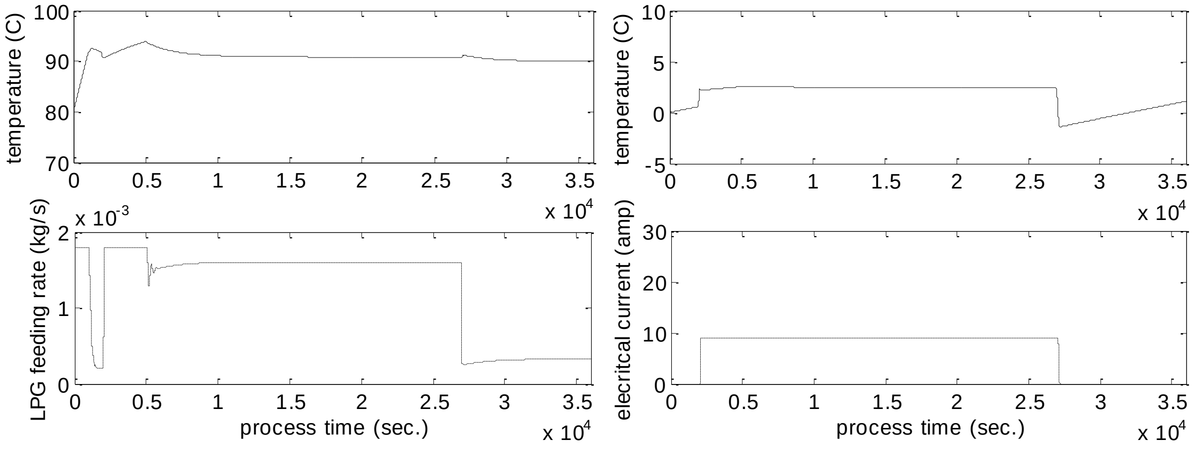
A) boiler B) ripple plate



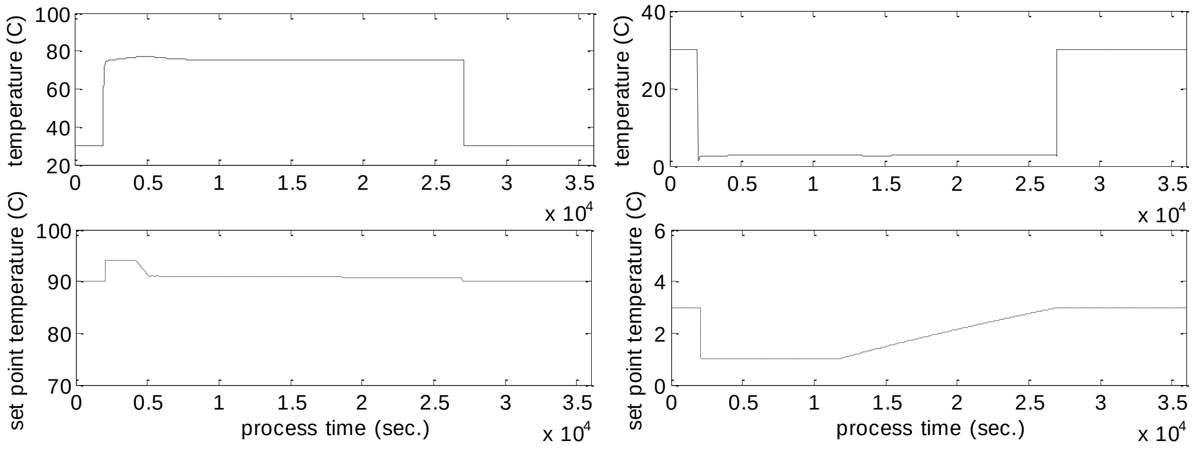
C) holding tube of PP D) cooling stage of PP

**Fig. 9.** Control response for MPC under model mismatch case:

(A) boiler, (B) ripple plate (C) holding tube of PP and (D) cooling stage of PP.



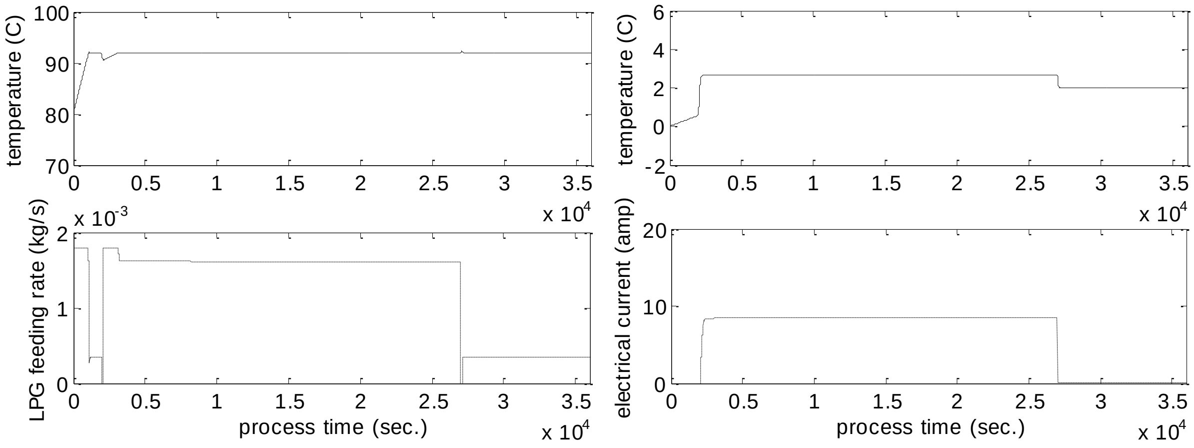
A) boiler B) ripple plate



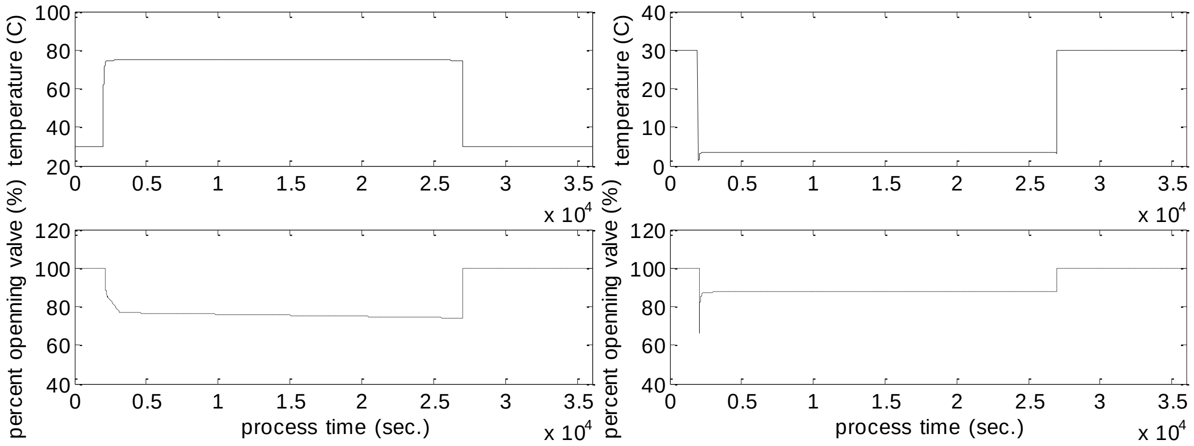
C) holding tube of PP D) cooling stage of PP

**Fig. 10.** Control response for GMC under model mismatch case:

(A) boiler, (B) ripple plate, (C) holding tube of PP and (D) cooling stage of PP.



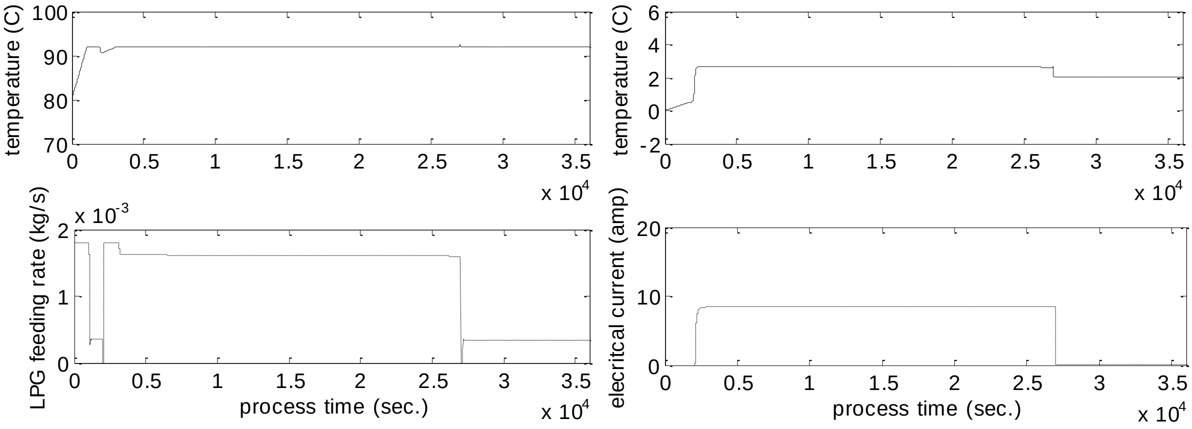
A) boiler B) ripple plate



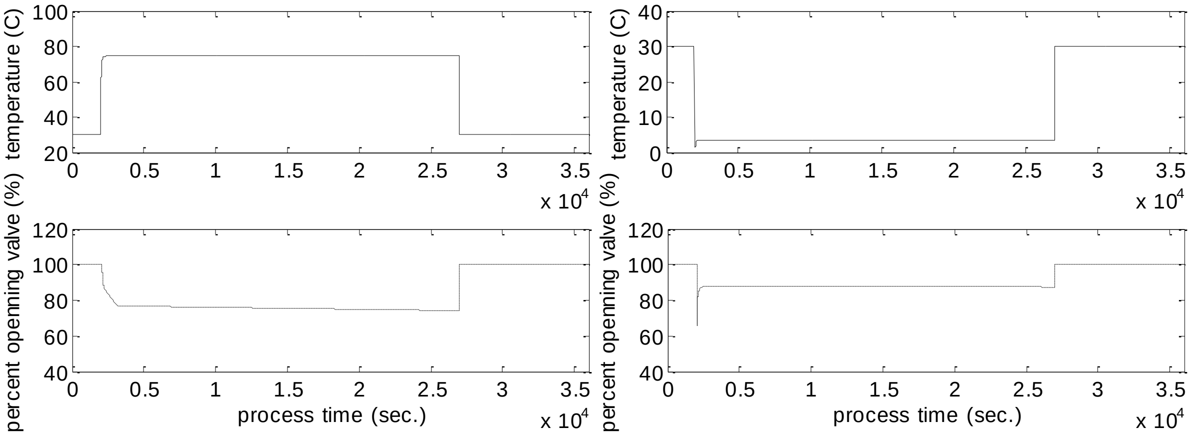
C) holding tube of PP D) cooling stage of PP

**Fig. 11.** Control response for MPC with $M = 12$ and $P = 24$

(A) boiler, (B) ripple plate, (C) holding tube of PP and (D) cooling stage of PP.



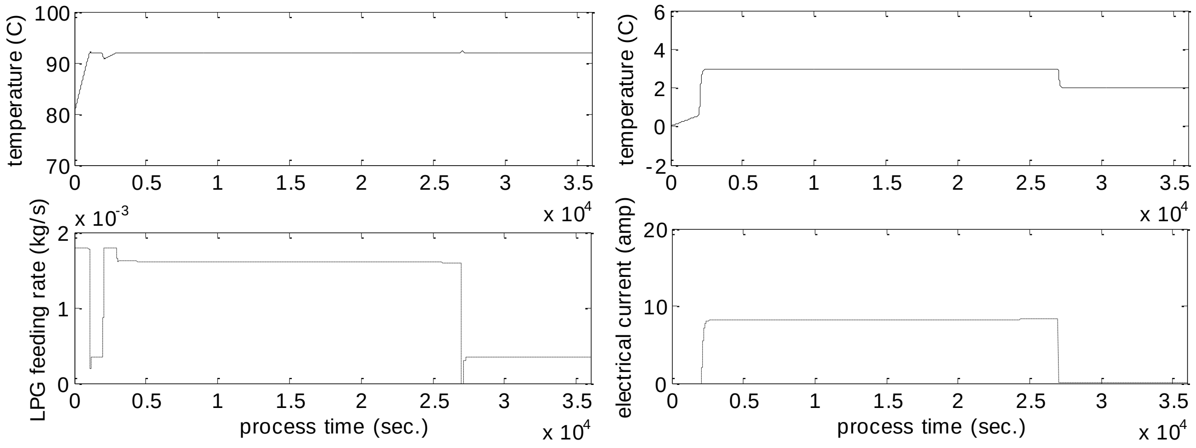
A) boiler B) ripple plate



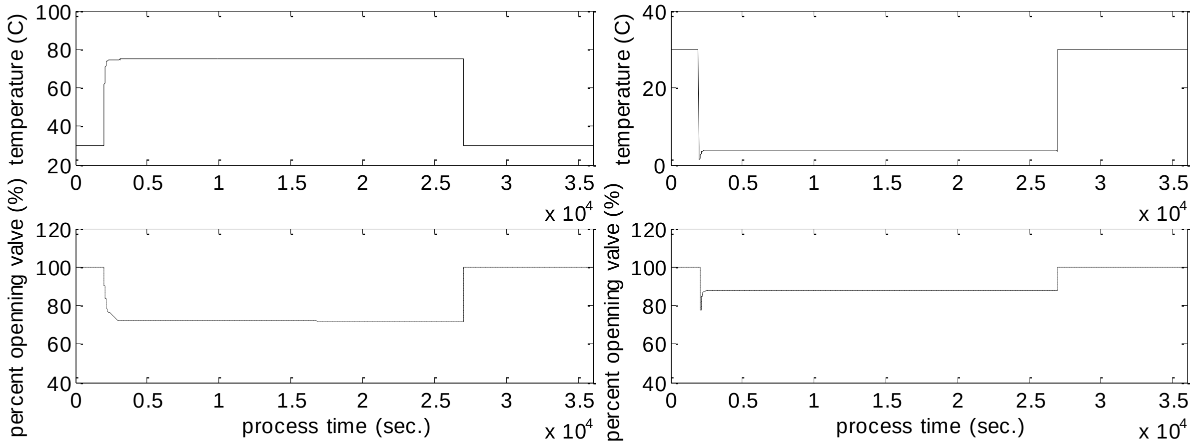
C) holding tube of PP D) cooling stage of PP

**Fig. 12.** Control response for MPC with $M = 6$ and $P = 12$

(A) boiler, (B) ripple plate, (C) holding tube of PP and (D) cooling stage of PP.



A) boiler B) ripple plate



C) holding tube of PP D) cooling stage of PP

**Fig. 13.** Control response for MPC with increasing sampling time (A) boiler, (B) ripple plate, (C) holding tube of PP and (D) cooling stage of PP.

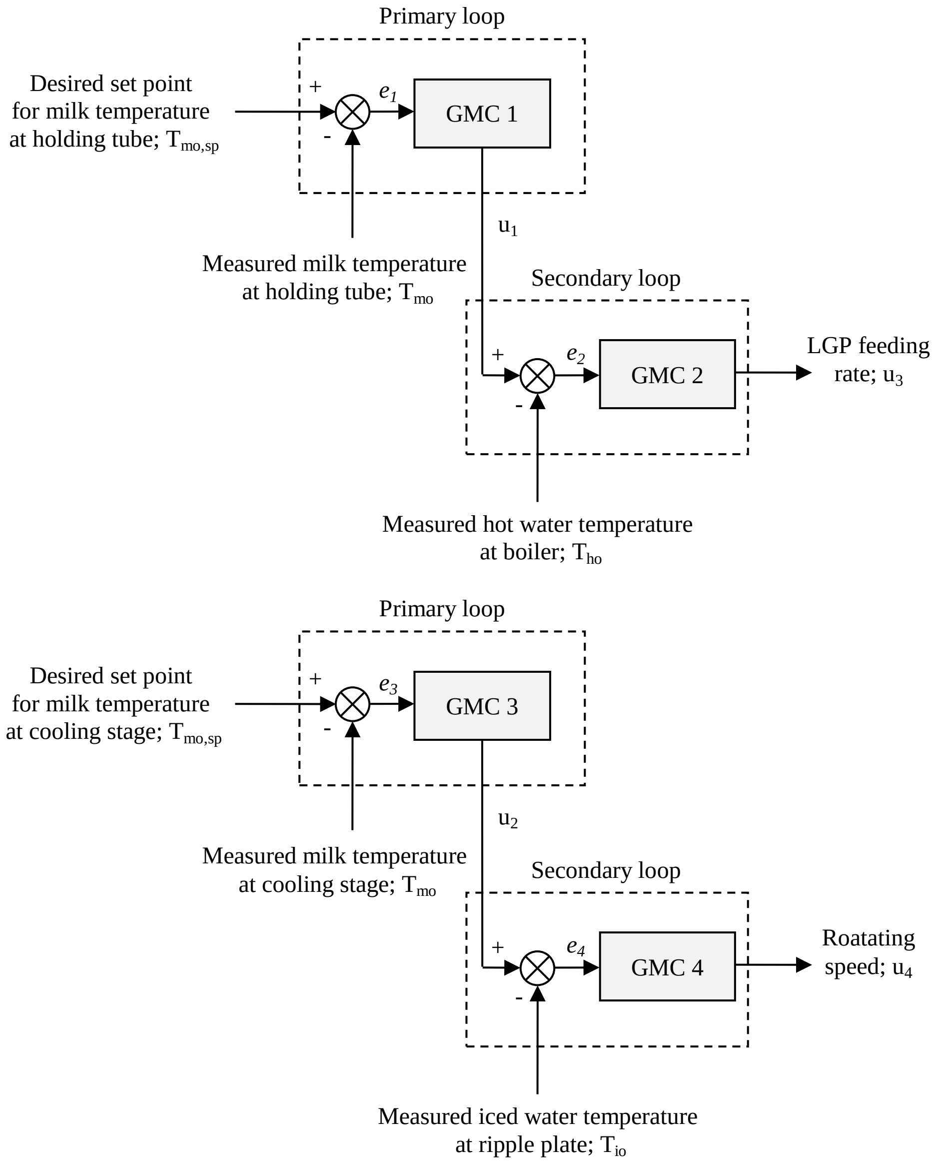


**Fig.B-1.** The application of the cascade GMC controllers in the milk pasteurization process