Adaptive Feedback Control for a Pasteurization Process

Emil D.J. Rasmussen [1], Massimiliano Errico [1] and Stefania Tronci [2],*

[1] Department of Chemical Engineering, Biotechnology and Environmental Technology,
    University of Southern Denmark, Campusvej 55, DK-5230 Odense M, Denmark;
    emira15@student.sdu.dk (E.D.J.R.); maer@kbm.sdu.dk (M.E.)

[2] Dipartimento di Ingegneria Meccanica, Chimica e dei Materiali, Università degli Studi di Cagliari,
    Via Marengo 3, 09123 Cagliari, Italy

* Correspondence: stefania.tronci@dimcm.unica.it; Tel.: +39-070-675-5050

Abstract: The milk pasteurization process is nonlinear in nature, and for this reason, the application of linear control algorithms does not guarantee the obtainment of the required performance in every condition. The problem is here addressed by proposing an adaptive algorithm, which was obtained by starting from an observer-based control approach. The main result is the obtainment of a simple PI-like controller structure, where the control parameters depend on the state of the system and are adapted online. The proposed algorithm was designed and applied on a simulated process, where the temperature dependence of the milk's physical properties was considered. The control strategy was tested by simulating different situations, particularly when time-varying disturbances entered the system. The use of the adaptive rule reduces the variance generally introduced by the PI or PID controller.

Keywords: pasteurization; milk; modeling; adaptive control

1. Introduction

Pasteurization has been used industrially to produce safe and stable dairy products since the late 1800s. The method is based on the observation that fermentation could be prevented through heating at a specific temperature for a defined amount of time. In particular, the method targets the destruction of vegetative pathogenic bacteria, such as *Mycobacterium tuberculosis*, *Coxiella burnetii*, salmonellas, *Listeria monocytogenes*, campylobacters, and *Escherichia coli* O157:H7 [1].

During the 1900s, technology progressed fast in developing different pasteurization techniques [2]. The dominant technology in the first half of the 1900s was the holding method or vat pasteurization. This technique is based on heating the milk in batch mode at about 63 °C for 30 min. However, high-temperature short-time (HTST) continuous techniques were rapidly accepted at an industrial scale already in the early 1940s [3].

Over the years, different temperature-application times have been proposed, following the technological evolution of the process. Ohmic heating, microwave heating, pulse electric field, and ultrasound are some of the indirect or nonthermal alternative methods to heating processes [4–7]. Nevertheless, not all of them were industrially accepted compared to traditional heating procedures, and in some cases, their efficiency in reducing the bacterial count was lower than standard pasteurization [8].

Nowadays, HTST is a widely accepted technology for milk pasteurization and it is usually performed in plate heat exchangers.

A modern pasteurization plant consists of different heating and cooling sections that ensure that the milk reaches the required temperatures. Generally, the milk flows from the storage tank into the

regeneration section where it is heated at 57–68 °C using pasteurized milk as a heating agent, allowing a heat recovery of up to 93% [9]. The preheated milk is then transferred to the heating section where it is heated up and reaches the final pasteurization temperature. A coiled pipe, called the holding tube, is placed after the heating section and is used to ensure that the milk is held at the pasteurization temperature for the required time [10]. The pasteurized milk passes through a cooling section where an external cooling agent is used to return it to the storage temperature.

Two important research branches have been developed within HTST processes applied to milk pasteurization. The first is related to the optimization of the energy consumption. This branch is related to the availability of process simulators with models that are able to include the milk properties, nutritional indexes, and the thermal inactivation of the microorganisms [11]. This problem was assessed by Arteaga et al. [12], through the study of the optimal time-temperature profiles of the milk heat treatment. The second research branch is related to the control of the process. According to Eurostat (2020), 172.2 million tons of raw milk were produced in 2018. This massive production must result in products that are safe for consumption [13].

The use of a proper control scheme can be a valid tool to improve process performances, reduce costs, and reject disturbances that may significantly move the system from the desired conditions. The control of a HTST pasteurization system includes typical behaviors of many industrial processes, such as complex dynamical models with nonlinearities, making the development of the controller a difficult task. The regulation of both utilities and milk temperatures using a model predictive approach was reported in Niamsuwan et al. [14], where good results were obtained with respect to other control techniques, such as the cascade generic model control (GMC) strategy. Other studies propose different model predictive control (MPC) approaches, with the objective of minimizing the energy consumption [15,16]. Kayalvizh et al. [17] developed individual cascade controllers to maintain the temperature of the milk in the heating and cooling stages of the milk pasteurization process at optimum levels. Pour et al. [18] presented three strategies to design MPC controllers using linear parameter varying models. More recently, the same authors proposed an improved health-aware economic MPC strategy aimed at minimizing the damage of components in a pasteurization plant [19].

In the present paper, the model proposed by Niamsuwan et al. [14] was extended in order to take into account temperature dependence of the density and heat capacity of the milk, using the relationships proposed by Munir et al. [20]. The main variables of the process, which are temperature at the exit of the holding tube and the milk temperature at the end of the pasteurization plant, are controlled by means of two adaptive PI (proportional-integral) controllers, designed using an observer-based structure [21]. The main characteristic of this approach is the systematic tuning design and antiwindup. The performance of the proposed control design was assessed by considering set-point changes and disturbance rejections. The process was designed taking into account the EU legislation that requires a heat treatment of at least 72 °C for 15 s [22].

2. Process Model

On the basis of the milk pasteurization system described in Niamsuwan et al. [14,16], a HTST pasteurization system consisting of a sequence of four heat exchangers was considered. According to the scheme presented in Figure 1, in the heat exchanger sequence it is possible to identify the general sections within a pasteurization unit: regeneration, heating, and cooling. To assure proper heating and cooling of the milk, hot and cold utilities were provided in the form of a boiler and a cooling tower, respectively. Moreover, a ripper plate cooling system was used for the final cooling step. Water was used as heating or cooling media.
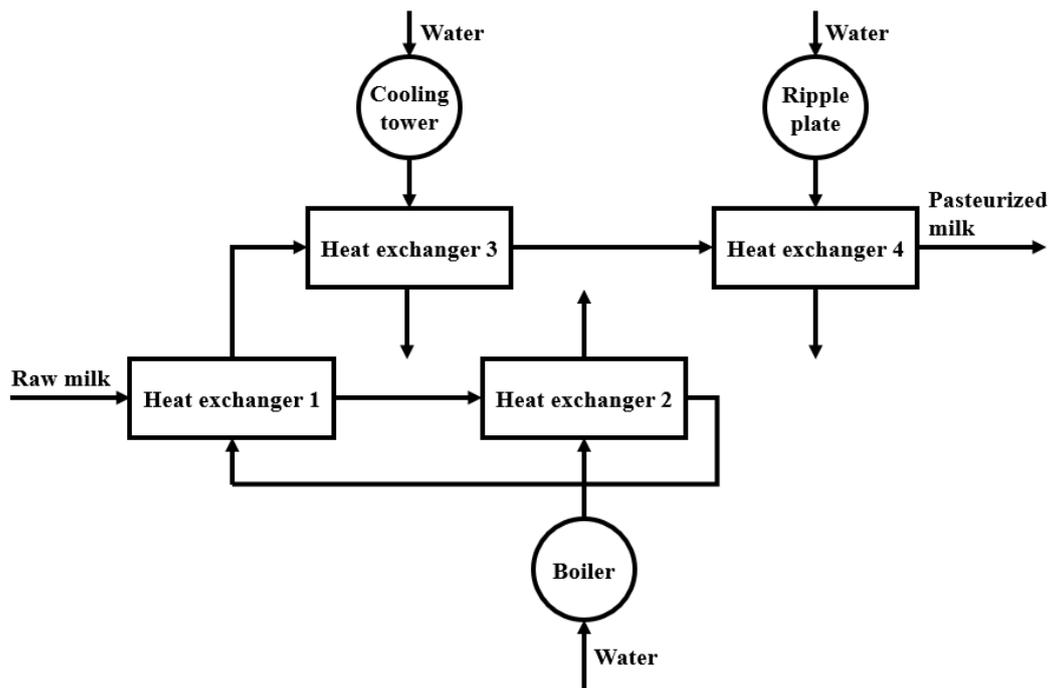
Figure 1. Schematic flow diagram for the pasteurization process considered.

The flow arrangement of the heat exchangers is countercurrent for heat exchanger 1, cocurrent for heat exchanger 2, and countercurrent for the two cooling steps in heat exchangers 3 and 4. In heat exchanger 2, a cocurrent flow was chosen to reduce the thermal stress of the milk.

On the basis of the system depicted in Figure 1, first order differential equations describing the temperature change within each unit of the pasteurization system were defined. These are based on the general mass and energy balances of each unit.

The models are based on the following assumptions:

1. Perfectly mixed conditions;
2. Physical and chemical properties of liquids, such as density and heat capacity, are constant, apart from the properties of milk, which are modeled as function of temperature and milk composition;
3. Negligible variation of volume on both sides of the plate heat exchanger, the heating coil of the water tank, the boiler, the ripple plate, and the cooling tower;
4. Well-insulated piping for hot and iced water of the boiler and ripple plate, meaning omitted temperature drop at the piping surface throughout the length of the piping.

Heat exchanger:
$$\frac{dT_{m,o}}{dt} = \frac{F_m(T_{m,i} - T_{m,o})}{V_{pp,i}} \pm \frac{U_{pp,i}A_{pp,i}\Delta T_{lm}}{\rho_m C_{p,m} V_{pp,i}} \tag{1}$$

Boiler:
$$\frac{dT_{h,i}}{dt} = \frac{F_h(T_{h,i} - T_{h,o})}{V_b} + \frac{\dot{m}_f H_f - U_b A_b(T_{h,o} - T_a)}{\rho_h C_{p,h} V_b} \tag{2}$$

$$\frac{dT_{h,o}}{dt} = \frac{F_h(T_{h,i} - T_{h,o})}{V_{pp,2}} - \frac{U_{pp,2}A_{pp,2}\Delta T_{lm}}{\rho_h C_{p,h} V_{pp,2}} \tag{3}$$

Cooling tower:
$$\frac{dT_{t,i}}{dt} = \frac{F_t(T_{t,i} - T_{t,o})}{V_{ct}} - \frac{h_v E}{C_{p,t} V_{ct}} + \frac{\rho_w C_{p,w} F_w T_w}{\rho_t C_{p,t} V_{ct}} - \frac{L_d F_c T_{t,o} + h_A(T_{t,o} - T_a)}{\rho_t C_{p,t} V_{ct}} \tag{4}$$

$$\frac{dT_{t,o}}{dt} = \frac{F_t(T_{t,i} - T_{t,o})}{V_{pp,3}} - \frac{U_{pp,3}A_{pp,3}\Delta T_{lm}}{\rho_t C_{p,t} V_{pp,3}} \tag{5}$$

Ripple plate:

$$\frac{dT_{i,i}}{dt} = \frac{F_i(T_{i,o} - T_{i,i})}{V_{rp}} + \frac{\pi n_s d_f h_{fg} A_f}{60\rho_i C_{p,i} V_{rp} v} - \frac{U_{rp} A_{rp}(T_{i,i} - T_a)}{\rho_i C_{p,i} V_{rp}} \tag{6}$$

$$\frac{dT_{i,o}}{dt} = \frac{F_i(T_{i,i} - T_{i,o})}{V_{pp,4}} - \frac{U_{pp,4}A_{pp,4}\Delta T_{lm}}{\rho_i C_{p,i} V_{pp,4}} \tag{7}$$

Holding tube:

$$T_{m,o} = \frac{\rho_m C_{p,m} F_m T_{m,i} + T_a U_p 2\pi d_p L_p}{\rho_m C_{p,m} F_m U_p 2\pi d_p L_p} \tag{8}$$

The temperature dependence of the density and heat capacity of the milk were considered. The models used to determine the properties were based on the correlations reviewed in Munir (2015).

$$\rho_m\left(T, X_{fat}\right) = \left(1040.7 - 2.665 \cdot 10^{-1}\, T - 2.3 \cdot 10^{-3}\, T^2\right) \\ - X_{fat}\left(1.011 + 9.76 \cdot 10^{-3}\, T - 4.81 \cdot 10^{-5}\, T^2\right)\left[\frac{kg}{m^3}\right] \tag{9}$$

$$C_{p,m}\left(T, X_{fat}\right) = 4.0283 \\ + [0.0304 \cdot \exp\left(-0.0069(T - 19.2424)^2\right) + 0.0071 \\ \cdot \exp\left(-0.0686(T - 34.1363)^2\right)]X_{fat} \cdot 10^2 - 0.0182 \cdot X_{fat} \cdot 10^2 \left[\frac{J}{g\,K}\right] \tag{10}$$

where T is in °C and X_{fat} is the milk fat fraction, which was set equal to 0.015.

The properties were evaluated for each heat exchanger by taking the average of the property evaluated at the inlet and outlet port temperature. This estimates the property change throughout the heat exchanger. Parameter values and nominal condition used in the simulation of the process are reported in Table 1.

Table 1. Physical properties and process data for the simulation.

Heat Transfer Areas [m²]		Boiler Characteristics	
Regenerative stage; A_1	2	Fuel rate [kg/s]; m_f	1.8×10^{-3}
Heating stage; A_2	2.2	Fuel heating value [kJ/kg]; H_f	49888
Precooling stage; A_3	1	Heat transfer area $\left[m^2\right]$; A_b	2.3
Cooling stage; A_4	5.0		
Overall Heat Transfer Coefficients $\left[\mathbf{W/m^2 \cdot K}\right]$			
Regenerative stage; U_1	940	Cooling tower characteristics	
Heating stage; U_2	940	Heat transfer coefficient [W/K]; h_A	2000
Precooling stage; U_3	950	Heat of vaporization [kJ/kg]; h_v	2410
Cooling stage; U_4	1000	Circulation water $\left[m^3/s\right]$; F_c	4.8×10^{-3}
Boiler; U_b	227	Drift loss [%]; L_d	2
Flowrates $\left[\mathbf{m^3/s}\right]$		**Make-up Water Temperature [°C]; T_w**	**27**
Milk; F_m	4×10^{-4}	Evaporation rate [m³/s]; E	1.7×10^{-5}
Hot water; F_h	1.6×10^{-3}		
Tap water; F_t	4.8×10^{-3}	Specifications for ripple plate compressor	
Ice water; F_i	1.92×10^{-3}	Rotating speed [rpm]; n_s	5000
Volumes $\left[\mathbf{m^3}\right]$		**Diameter of Impeller [m]; d_f**	**0.4**
Regenerative stage; V_1	0.3803	Peripheral flow area [m²]; A_f	0.002
Heating stage; V_2	0.4079	Heat transfer area $\left[m^2\right]$; A_{rp}	2.5
Precooling stage; V_3	0.2873		
Cooling stage; V_4	0.4565	Specifications for refrigerant	
Boiler; V_b	1.2	Heat of vaporization [kJ/kg]; h_f	217
Cooling tower; V_{ct}	0.05	Specific volume at the exit; v	0.5
Ripple plate; V_{rp}	0.5	Overall heat transfer $\left[W/m^2 \cdot K\right]$; U_{rp}	1120
Ambient air temperature [°C]; T_a	30		

3. Impact of Process Disturbances and Control Strategy

The effect of disturbances on the pasteurization process is important to evaluate, in order to find the best control strategy that guarantees adherence to the desired conditions. Following the analysis reported in Morison [23], and using the model proposed by Niamsuwan et al. [14], two possible disturbances were introduced in the system using simple step-variations. The analysis considers the effect of the variations of inlet milk temperature and ambient temperature variations on the milk temperature at the exit of the holding tube, and on the cold milk temperature at the end of the fourth heat exchanger. Conditions and results are reported in Table 2 in deviations variables, where the initial values are calculated at the nominal conditions.

Table 2. Effects of input changes on steady-state conditions of the pasteurization process.

Disturbance Variable	Disturbance Amount	Change in Temperature at the Exit of Holding Tube	Change in Temperature at the Exit of Fourth Heat Exchanger
Milk feed temperature	+4 °C	+2.6 °C	+0.94 °C
	−4 °C	−2.6 °C	−0.92 °C
Environment temperature	+4 °C	+1.48 °C	3.05 °C
	−4 °C	−1.47 °C	−3.04 °C

In order to avoid unnecessary heat exposure of proteins and enzymes, which can lead to a product of poorer quality, variations of no more than about +0.5 °C are allowed for the milk in the holding tube [14]. On the contrary, if the temperature does not reach 72 °C, the milk will be rejected and must be treated once more. The results reported in Table 2 show that such conditions are always exceeded when the inlet milk temperature or the ambient temperature are increased. Furthermore, the effects on cold milk leaving the pasteurizer are not negligible and a controller to reject them is essential for the product quality and the process economy.

Considering the effect of disturbances, two feedback controllers were designed. One was used to control the temperature at the exit of the holding tube, as it is related to the safety of the milk and the product quality. The manipulated input is the fuel flow rate at the boiler. The second controlled variable is the temperature of cold milk that exits the pasteurizer, using the rotating speed at the ripple plate. A low outlet temperature is required to diminish the growth rate of microorganisms still present after the pasteurization, avoiding recontamination of the product downstream in the pasteurizer. The controller is also useful to prevent the outlet temperature becoming lower than the required value, thus reducing energy waste.

4. Control Design

As evidenced by Niamsuwan et al. [14], the sluggish dynamics and the nonlinear behavior make the pasteurization process difficult to control by means of a simple feedback action. Nevertheless, operators in the industry are most familiar with traditional PID controllers and such a scheme is usually preferred. Model-based feedback control can be a valid alternative to the use of the linear model-free PI algorithm, and the use of adaptive parameters along the process motions could represent a possible solution for controlling nonlinear time-variant processes [24]. The algorithm proposed in the present paper uses the observer-based controller method [21], but it differs from the original approach, because the parameters of the control action are adjusted as a function of the process conditions.

4.1. Observer-Based Control

The adaptive algorithm proposed here is derived from the control law proposed by Castellanos-Sahagun et al. [21]. The original algorithm is based on the nonlinear constructive theory and passivity concepts and it has the following characteristics: (i) systematic tuning design and

(ii) antiwindup capability, which is obtained by the observer-based structure with linear decentralized PI components.

The linearized form of the equation describing the generic controlled output (y) and the manipulated input (u) is considered as reported in Equations (11) and (12):

$$\frac{dy}{dt} = au + b \tag{11}$$

$$a = \left.\frac{\partial f}{du}\right|_o \tag{12}$$

where the coefficient a is the derivative of the vector field f describing the dynamic of y, and in the original form of this approach, it is calculated at a reference condition.

The control problem can be solved for u if a reference trajectory is set for the output y, as reported in Equation (12):

$$\frac{dy}{dt} = -K_c y \tag{13}$$

where K_c is a constant gain.

Using Equation (11) in Equation (13), u can be obtained as reported in Equation (14):

$$u = \frac{-(K_c y + b)}{a} \tag{14}$$

The variable b in Equation (14) is unknown and it represents the modeling errors, or more specifically, the nonlinear part of the model and the effect of disturbances [25]. The variable b can be estimated using the measured input u and the measured output y as reported in Equation (15):

$$\frac{d\hat{b}}{dt} = K_o(b - \hat{b}) = K_o\left(\frac{dy}{dt} - au - \hat{b}\right) \tag{15}$$

where K_o is the observer gain. It is better to avoid the use of derivative in the algorithm, therefore a coordinate change is introduced in Equations (16) and (17):

$$\chi = \hat{b} - K_o y \tag{16}$$

$$\frac{d\chi}{dt} = -K_o \chi - K_o(au + K_o y) \tag{17}$$

The controller can be easily tuned using the rules proposed by Castellanos-Sahagun et al. (2005), reported in Equations (18) and (19):

$$K_c = 1 \div 2\omega \tag{18}$$

$$K_o = 5 \div 10 K_c \tag{19}$$

The controller gain in Equation (18) represents the characteristic frequency of the controller, which should be equal or twice as large as the characteristic frequency ω of the system. In order to obtain high efficiency, the estimator should converge more quickly than the controller.

4.2. Adaptive Scheme

In this work, the algorithm proposed by Castellanos-Sahagun et al. [21] is modified by updating the value of the parameter a in Equation (12) at each sampling time. Indicating with a_1 the parameter used in the adaptive PI controller of the holding tube temperature, the approximated equation reported in Equation (20) is used to adjust the gain of the controller at the varying conditions.

$$a_1 = \frac{\partial f_{m_{o,2}}}{\partial m_f} \cong \frac{\partial f_{m_{o,2}}}{\partial T_{h,o}} \frac{\partial T_{h,o}}{\partial m_f} \tag{20}$$

where $f_{m_{o,2}}$ indicates the function describing the dynamics of the milk at the exit of the second heat exchanger, $T_{h,o}$ is the hot water temperature at the exit of the boiler, and m_f is the fuel rate.

The same dependence can be obtained for the cold milk temperature at the outlet of the fourth heat exchanger. Such output is controlled by manipulating the rotating speed at the ripple plate and the adjustment of the controller gain is calculated with Equation (21):

$$a_2 = \frac{\partial f_{m_{o,4}}}{\partial n_s} \cong \frac{\partial f_{m_{o,4}}}{\partial T_{i,o}} \frac{\partial T_{i,o}}{\partial n_s} \tag{21}$$

where $f_{m_{o,4}}$ is the function describing the dynamics of the cold milk, $T_{i,o}$ is the iced water at the outlet of the ripple plate, and n_s indicates the rotating speed.

The two coefficients a_1 and a_2 are updated at each sampling time of the controller, in order to take into account the changes in the process characteristics due to the nonlinear behavior.

The controller scheme is reported in Figure 2, where $y = (T_{mo2d}, T_{mo4})$ represents the controlled output vector, (T_{mo2d}) is the milk temperature at the exit of the holding tube, T_{mo4} is the outlet milk temperature, $y_r = \left(T^r_{mo2d}, T^r_{mo4}\right)$ is the vector of the reference trajectories, $u = \left(m_f, n_s\right)$ is the manipulated input vector, $x = (T_{mo1}, T_{mo2}, T_{hi}, T_{h0}, T_{ii}, T_{io}, T_{mo3})$ is the auxiliary measurements vector, and e is the mismatch between set-points and controlled outputs. The block "Observer" indicates the integration of Equation (15).
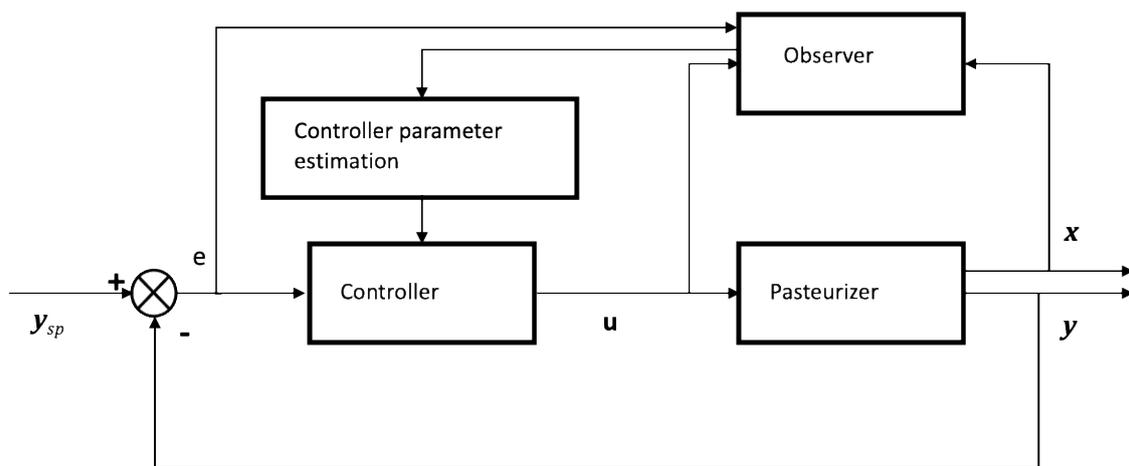
Figure 2. Block diagram of the adaptive control scheme.

5. Results

The effect of disturbances in the plant can impact the properties of the product (pasteurization temperature) and the consumption of energy, both for heating and cooling the milk. For this reason, the presence of controllers in the plant can improve the efficiency of the process and guarantee the desired pasteurization conditions. As reported in the previous section, two control loops were designed. A one-way interaction was present between the two control loops, because changes in the ripple plate do not affect the pasteurization temperature. Nevertheless, when the temperature of the hot milk was changed by the controller, all downstream temperatures were affected.

A decentralized MIMO (multi input-multi output) system was used to control the pasteurization process, using the observer-based approach with adaptive gain described in the previous section. Different simulations were performed in order to evaluate the controller performances.

First, set-point tracking in the absence of input disturbances is reported in Figure 3. The temperature at the exit of the holding tube was first set to 72 °C, then to 74 °C, and again to 72 °C. The temperature of the outlet milk was set first to 8 °C and then to 4 °C. The two controllers manipulated the fuel flow rate (m_f) and the rotating speed of the riple plate (n_s) and were able to track the system to the

desired conditions. In this simulation, the ambient temperature was set equal to 30 °C, according to the nominal conditions in Niamsuwan et al. [14].
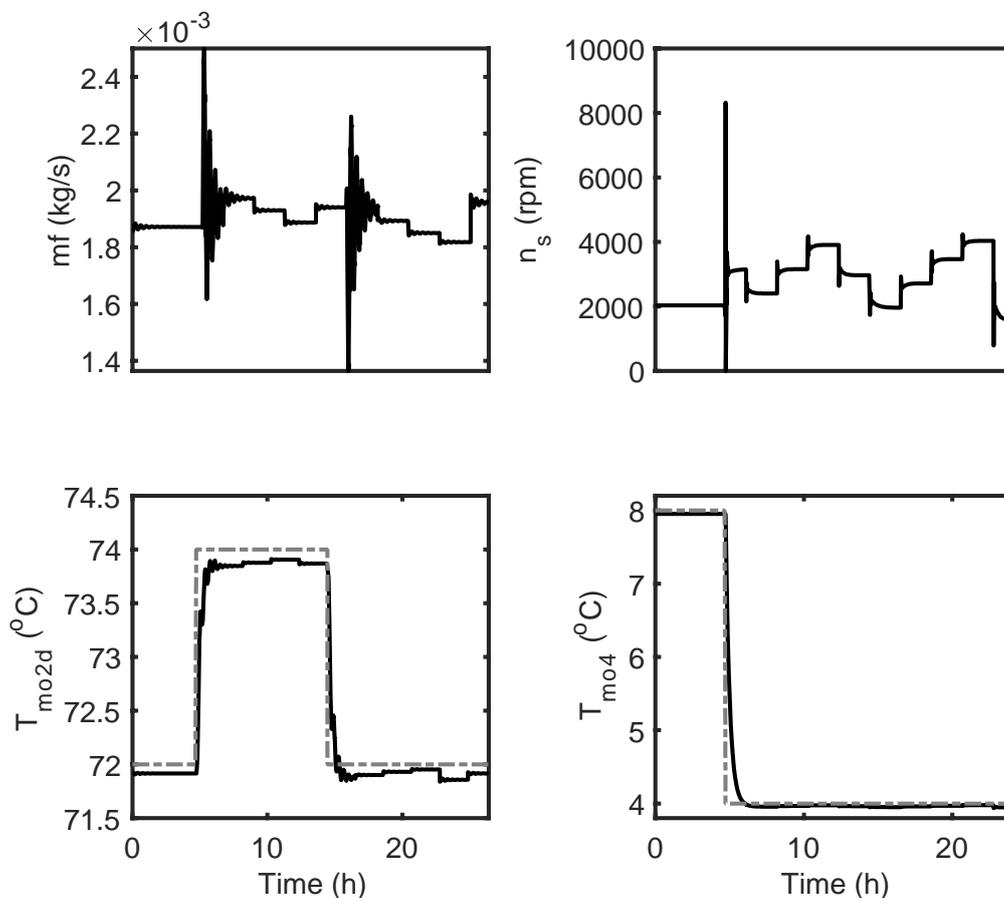
Figure 3. Controlled outputs are the temperature at the outlet of the holding tube, T_{mo2d} (**bottom left panel**) and milk temperature at the outlet of the fourth heat exchanger, T_{mo4} (**bottom right panel**). Set-points for both T_{mo2d} and T_{mo4} are reported with a grey dash-dotted line; manipulated inputs are fuel flow rate at boiler, m_f (**top left panel**), and rotating speed at the refrigeration rate, n_s (**top right panel**).

In order to evaluate the system in a more demanding situation, a colder scenario with respect to the previous situation was considered, applying the ambient temperature variation reported in the top panel of Figure 4. Set-point changes were also applied to make the test more challenging for the controllers: milk temperature at the exit of the holding tube was first set to 74 °C, then to 72 °C. Outlet milk temperature was set first to 4 °C and then to 8 °C. The performance was still satisfactory and, even if a small offset was present due to the impossibility to completely reject the disturbances, the mismatch was always within +/−0.5 °C. A more aggressive controller could eliminate the offset, but it led to large overshoots in the holding tube temperature response and this behavior can be detrimental to the quality of the product.

A further test was conducted by varying the input milk temperature, using step changes, as reported in the top panel of Figure 5. The responses for the holding tube and exit milk temperature are shown in Figure 5, showing a good performance in terms of response rate and very small offsets. The impact on the cold milk temperature is very low, and a small amount of work of the controller is able to guarantee the desired conditions, which are 72 °C for the milk temperature leaving the holding tube and 8 °C for the outlet milk temperature.
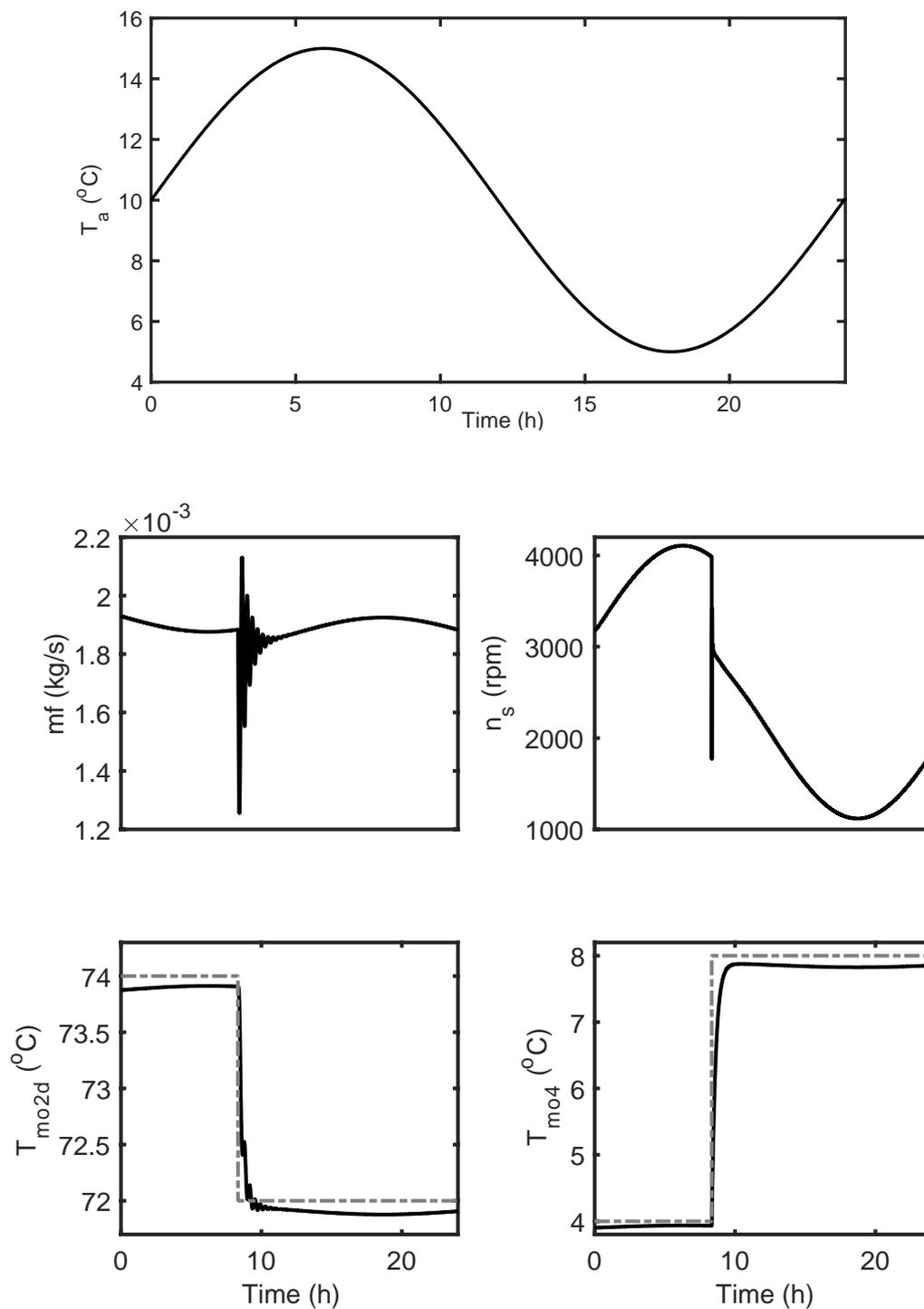
Figure 4. Process disturbance is the ambient temperature, T_a (**top panel**). Controlled outputs are the temperature at the outlet of the holding tube, T_{mo2d} (**bottom left panel**) and milk temperature at the outlet of the fourth heat exchanger, T_{mo4} (**bottom right panel**). Set-points for both T_{mo2d} and T_{mo4} are reported with a grey dash-dotted line; manipulated inputs are fuel flow rate at boiler, m_f (**middle left panel**), and rotating speed at the refrigeration rate, n_s (**middle right panel**).
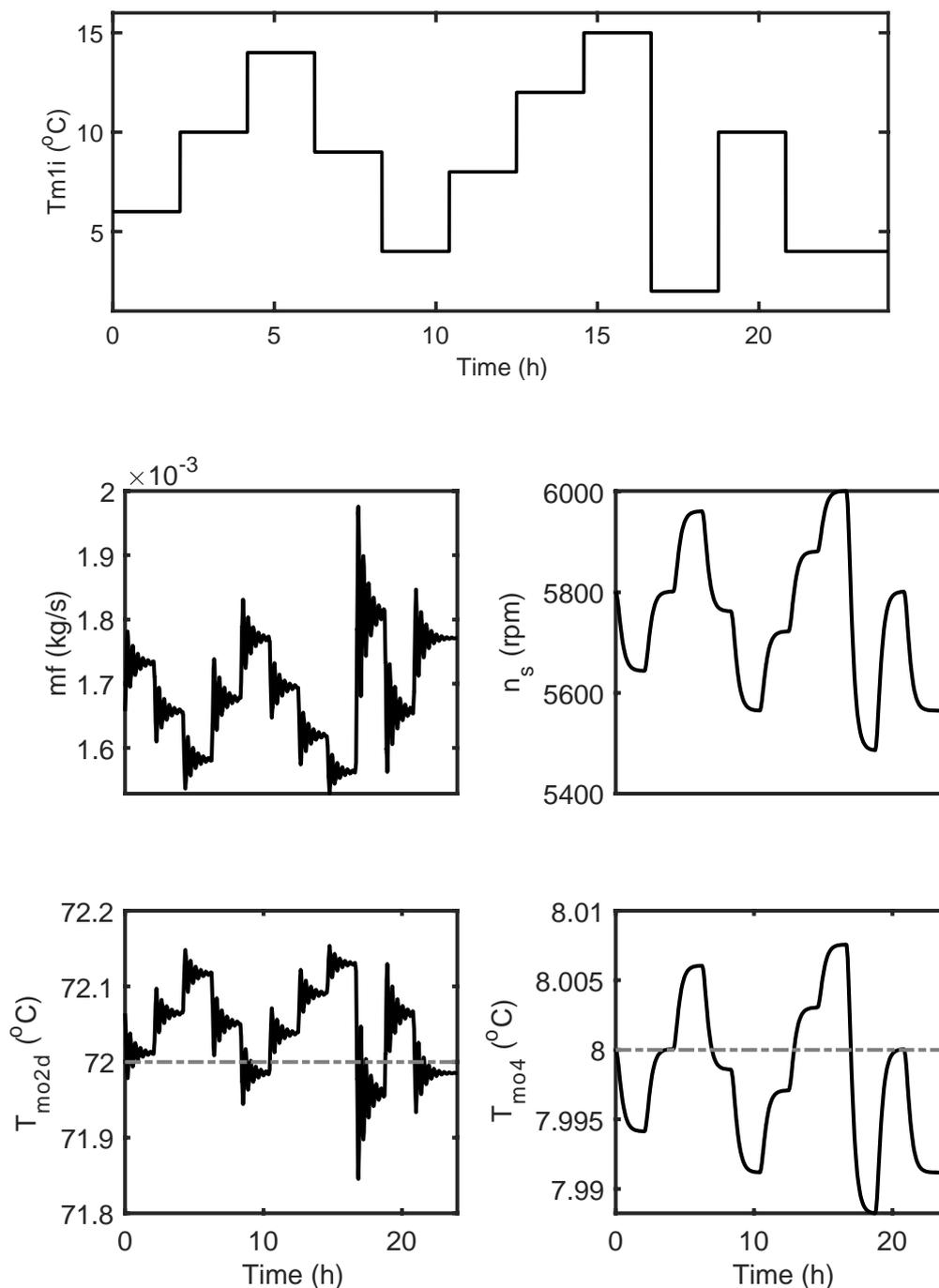
Figure 5. Process disturbance is the inlet milk temperature, T_{m1i} (**top panel**). Controlled outputs are the temperature at the outlet of the holding tube, T_{mo2d} (**bottom left panel**) and milk temperature at the outlet of the fourth heat exchanger, T_{mo4} (**bottom right panel**). Set-points for both T_{mo2d} and T_{mo4} are reported with a grey dash-dotted line; manipulated inputs are fuel flow rate at boiler, m_f (**middle left panel**), and rotating speed at the refrigeration rate, n_s (**middle right panel**).

6. Conclusions

The control problem of a milk pasteurization process was addressed by means of an adaptive PI control algorithm. In particular, the proposed control strategy was applied to a simulation model proposed in the literature, where the dependence on temperature of the milk's physical parameters was introduced, in order to obtain a more realistic representation of the process. Two feedback control

loops were designed in order to reduce disturbance effects on pasteurization temperature and milk temperature leaving the pasteurizer. The main purpose was to avoid process conditions that can damage the product, reduce microbial risks, and avoid energy consumption in the cooling phase of the product. Since the process has a nonlinear behavior, the gains of the two feedback controllers were adapted online, such that the performances of the systems were also maintained when the distance from the nominal conditions was large. The proposed approach also has the advantage of being characterized by a systematic tuning procedure and antiwindup properties. The obtained control system was evaluated in the presence of large variations of disturbances and set-point changes, and it is important to note that it was possible to reject them with very small oscillations of the controlled variables.

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Nomenclature

A_{pp}, A_b, A_f, A_{rp}	Heat exchanger area (plate pasteurizer), boiler, peripheral flow area of ripple plate compressor and ripple plate [m^2]
$C_{p,m}, C_{p,h}, C_{p,t}, C_{p,i}, C_{p,w}$	Heat capacity at constant pressure of milk, hot water, tap water and ice water [J kg^{-1} °C^{-1}]
d$_f$	Impeller diameter at ripple plate compressor [m]
d$_p$	Diameter of holding tube [m]
E	Evaporation rate for cooling tower [m^3 s^{-1}]
F$_m$, F$_h$, F$_t$, F$_i$, F$_w$, F$_c$	Volumetric flow of milk, hot water, tap water, ice water, make-up water and circulation water [m^3 s^{-1}]
H$_f$	Heating value of fuel [kJ kg^{-1}]
h$_v$	Latent heat of vaporization of water [kJ kg^{-1}]
h$_A$	Heat transfer coefficient at water surface [W K^{-1}]
h$_{fg}$	Latent heat of vaporization of refrigerant at ripple plate [kJ kg^{-1}]
L$_d$	Mechanical drift loss at cooling tower [%]
L$_p$	Length of holding tube [m]
$\dot{m}_f$	Fueling rate at boiler [kg s^{-1}]
n$_s$	Impeller rotational speed at ripple plate compressor [rpm]
$T_{m,i}, T_{m,o}$	Temperature of milk at inlet or outlet of heat exchanger [°C]
$T_{h,i}, T_{h,o}$	Temperature of hot water at inlet or outlet of heat exchanger [°C]
$T_{t,i}, T_{t,o}$	Temperature of hot water at inlet or outlet of heat exchanger [°C]
$T_{i,i}, T_{i,o}$	Temperature of hot water at inlet or outlet of heat exchanger [°C]
T_w	Temperature of make-up water [°C]
T$_a$	Ambient temperature [°C]
t	Time [s]
ΔT_{lm}	Logarithmic mean temperature difference [°C]
U$_{pp}$, U$_b$, U$_{rp}$, U$_p$	Overall heat transfer coefficient of heat exchanger, boiler, ripple plate and holding tube [W m^{-2} K^{-1}]
$V_{pp}, V_b, V_{ct}, V_{rp}$	Water volume for heat exchanger, boiler, cooling tower and ripple plate [m^3]
$\rho_m, \rho_h, \rho_t, \rho_i, \rho_w$	Density of milk, hot water, tap water, ice water and make-up water [kg m^{-3}]

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