INTERACTIVE CONTROL ENGINEERING
Principles and Applications

Volume 8 Batch, Run-to-Run, and Hybrid Control

CHAPTER 13

Milk Pasteurizer Simulator for Product History, Regeneration and Flow Diversion

Pages 309–329

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How to cite this chapter. "Milk Pasteurizer Simulator for Product History, Regeneration and Flow Diversion," in *Batch, Run-to-Run, and Hybrid Control*, John D. Hedengren, Ed., vol. 8 of *Interactive Control Engineering: Principles and Applications*. Advanced Process Solutions, LLC, 2026, ch. 13, pp. 309–329.

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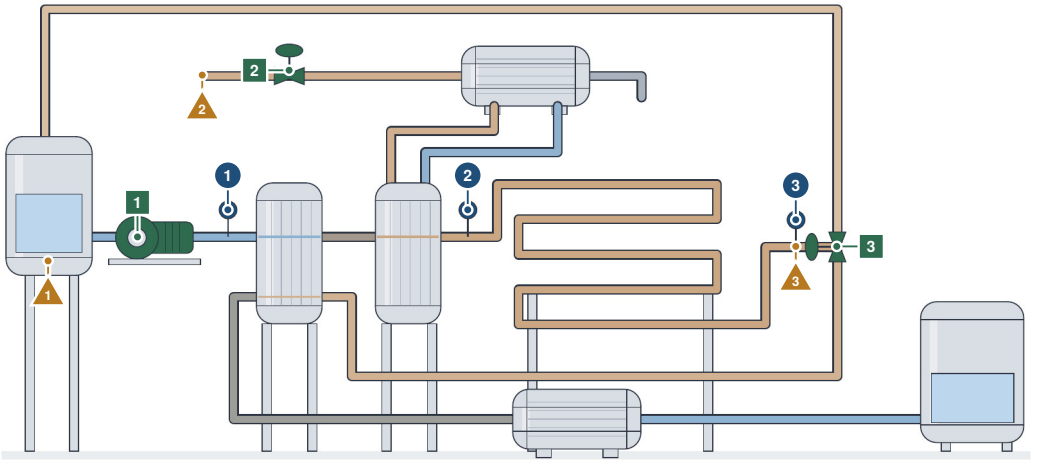
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CHAPTER 13

Milk Pasteurizer Simulator for Product History, Regeneration and Flow Diversion



The controller moves 1 the pumps that move and time the milk (one is drawn)
2 the steam valve that heats the hot water 3 the flow diversion valve, forward or back to the tank

The controller reads 1 the flow meter after the pump 2 the milk temperature leaving the heater
3 the recorder and indicating thermometers at the end of the tube

What disturbs it 1 colder raw milk in the balance tank 2 a sag in the steam supply
3 both end-of-tube thermometers drifting high

Raw milk is warmed by treated milk, heated, held in a long tube and then sent on or back by one valve, so notice that the only judge of each parcel is the thermometer pair just before that valve. Illustration, not to scale.

IN PLAIN TERMS Hot Enough, Long Enough, and Proven

The main idea. A dairy heats raw milk to kill germs and keeps it hot for a set time in a long pipe. A valve at the end of the pipe sends the milk on only when the thermometers say it was treated, and sends it back to be heated again otherwise.

The challenge. The controller sees the thermometers but never the milk itself. Faster flow cuts the time in the pipe while the milk stays hot, and two thermometers that drift together can pass untreated milk while every check looks fine.

Why it matters. Milk that has gone on cannot be called back, so the plant must be sure of every part of it before it leaves.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	the first page, the fact in the Introduction, the history in Section 13.2, the two try-its and the fact in Section 13.6, and the key points
Study	45 min	the whole chapter with its three pause points and the twelve exercises at its end
Practice	15 min	the first page, the results (Section 13.6), Technology in Practice (Section 13.7), Limitations (Section 13.8) and the open challenge

The control question A pasteurizer is judged on the time and temperature each parcel of milk received, which no controller measures. What can the temperature cascade, the diversion supervisor and its instruments guarantee about that history, and what can none of them see?

Learning objectives

- Compute the holding time and the legal flow from the tube volume and the recipe.
- Derive the regenerator's effectiveness and its recycle gain, and use them to explain why the plant is slow and sensitive to steam.
- Explain how conditional integration on the outer loop shortens the return from a diversion.
- Distinguish a fault that a comparison of two thermometers catches from one it cannot see.
- Choose a setpoint margin, a feedforward and a tuning that ride out a campaign without a diversion or excess heat.

Prerequisites Sections 1.4.2 (the dose as a guard), 1.4.7 (switching, latch and persistence), 1.6.2 (the PI algorithm and its anti-windup) and 1.6.4 (scenarios, scorecard and data).

The app https://apmonitor.com/apps/food-pasteurization/

See also Volume 3, Chapter 2 for matching a loop structure to where a disturbance enters, Volume 3, Chapter 3 for the speed a cascade's inner loop must reach, and Volume 5, Chapter 7 for diverting the product of a continuous line on a residence time.

13.1 Introduction

A process controller is usually judged by how closely a measured variable follows its setpoint. A pasteurizer is judged by something no controller measures, the time and temperature that each unit of product actually received, and the plant is allowed to send product back whenever that is in doubt. Thermal processing of foods is full of this shape. Retorts for canned foods are controlled on line during sterilization [1], high-temperature short-time (HTST) milk systems have been studied with control strategies built on the lethality delivered [2], and an automated HTST pasteurizer has been run with its flow diversion valve driven by a lethality controller [3].

The HTST milk pasteurizer is the familiar industrial case. Raw milk from a constant-level balance tank is warmed in a regenerator by milk that has already been treated, brought to the recipe temperature with hot water, and held in a tube sized so that the product spends the recipe time in it. A flow diversion valve (FDV) at the end of the tube then sends each part of the stream forward to be cooled, or back to the balance tank. The stringency of the time and temperature standards was set on the heat resistance of *Coxiella burnetii* [4, 5]. The simulator assumes a recipe of 72 °C held for 15 s, which its briefing takes from the U.S. Pasteurized Milk Ordinance minimum for milk (161 °F, rounded up). The same ordinance sets the standards against which the holding time of an HTST plant is checked [6].

DID YOU KNOW? From Fifteen Seconds to a Hundredth

The ordinance accepts more than one recipe for continuous flow. Milk held at 72 °C for 15 s is pasteurized, and so is milk held at 89 °C for 1.0 s or at 100 °C for 0.01 s. The temperature rises by 3 °C for a product with ten percent fat or more, eighteen percent total solids or more, or added sweeteners [7].

Three properties separate this plant from a temperature loop with a dead time. The holding time is the tube volume divided by the flow, so a flow increase shortens the treatment of every parcel while the temperature trend looks unchanged, and a real holding tube passes a spread of residence times whose fastest particle decides compliance [6, 8]. The regenerator returns heat from the product to the product, which makes the plant slow and sensitive to its heat input, and the return stops the moment product is diverted. The diversion itself rests on instruments that lag, drift and can fail together, while product that has passed them cannot be recalled. Product can also be contaminated after the tube,

since over 16 000 culture-confirmed cases of salmonellosis in Illinois were traced to pasteurized milk from a single dairy plant, with evidence suggesting that the strain had persisted in the plant and contaminated milk after pasteurization [9].

The simulator addresses the belief that product at its temperature setpoint is treated product. The class of problem is general, since a retort must also deliver a sterilizing treatment that is a history rather than a reading [1], and any continuous process adds a residence that follows the throughput. Volume 5, Chapter 7 routes the product of a continuous drug-substance line to a divert tank on the same question of which material an upset touched. A transfer function whose dead time is a constant represents neither. However, predictive control studies of pasteurizers address the temperature loop [10, 11] rather than the routing of the product and the record of what it received. The record is the dose idea of Section 1.4.2 applied to every parcel of a continuous stream.

This chapter presents a regenerative HTST milk pasteurizer simulator in which the product moves as parcels that each keep their own record, so that the holding time follows the flow, the regenerator exchanges heat parcel against parcel, and the supervisor that routes the product can be compared with what the product actually received. HTST pasteurization, cascade control with feedforward, conditional integration and diversion logic are standard practice. The simulator rests on a parcel model with an exactly conservative counterflow regenerator and a truth log kept apart from the instruments, and the chapter gives enough detail to rebuild it. Eight cases and a challenge separate what the controller, the supervisor and the instruments can and cannot guarantee.

Section 13.2 reviews the standards, the holding-time checks and earlier computer control of HTST plants. Section 13.3 sets out the parcel model: its sections, heat transfer, hot-water circuit, pressure differential, parcel records and parameters. Section 13.4 treats the regenerator as a filter and a recycle, and Section 13.5 gives the instruments, the cascade with feedforward and the supervisor as implemented. Section 13.6 measures the eight cases, the supervisor's margins and the challenge. Section 13.7 describes the real thermometers, diversion device and controllers of a plant, Section 13.8 states the limitations, Section 13.9 concludes, and the exercises of Section 13.10 run the cases.

13.2 Pasteurization, Holding Time and Diversion

The history of milk pasteurization and of the standards that govern it has been reviewed [12]. The standards name a temperature and a time. Their stringency was set on the requirements for *Coxiella burnetii*, regarded as the most heat-resistant organism of public health significance, and the review that traced this choice also questioned it [5]. The pasteurization of milk containing the organism of Q fever had been studied in 1957 [4]. The history cited above judges the present standards adequate for public health, with the exception of the endospores of *Bacillus cereus*, provided good manufacturing practices are followed [12], which places as much of the burden on the plant as on the recipe.

> ⧖ HISTORY **1924 to 2025: A Model Ordinance for Milk**
>
> Studies by the United States Public Health Service at the turn of the century on the role of milk in spreading disease led to research on sanitary measures, including studies that improved the pasteurization process. In 1924 the Service developed a model regulation, the Standard Milk Ordinance, for voluntary adoption by state and local agencies, and a Code published in 1927 gave the details of compliance. Its successor, the Grade "A" Pasteurized Milk Ordinance, reached its 34th revision in 2025. In 1938 milkborne outbreaks were 25 % of all outbreaks traced to infected foods and contaminated water, and milk and fluid milk products are now associated with less than 1 % of them [7].

Continuous flow turned the time half of the recipe into a flow problem. A method for checking the holding time of short time high temperature pasteurizers appeared in 1939 [13], and the residence time of milk products in HTST holding tubes was measured in 1968 [8]. Tracer tests on a pilot-scale HTST pasteurizer, run to establish whether it met the Pasteurized Milk Ordinance standards, found the fastest moving particle leaving a nominal 21.5 s holding section after 18.6 s, with the section

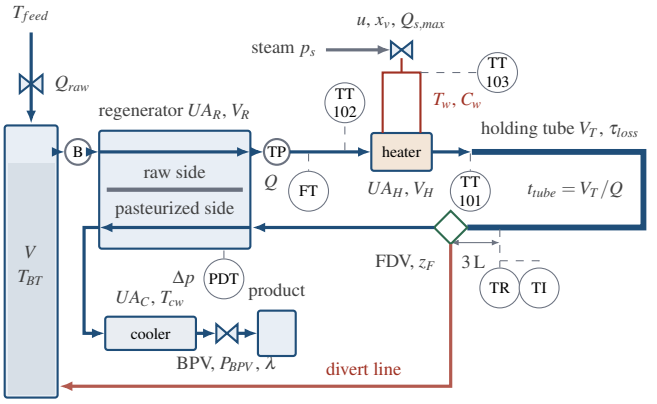


Figure 13.1 Regenerative HTST pasteurizer as modeled. Raw milk at T_{feed} enters the balance tank through a float valve (Q_{raw}), passes the booster pump B, the raw side of the regenerator, the timing pump TP that sets the flow Q, the flow meter FT and TT-102, and is heated by hot water at T_w fed by the steam valve at position x_v. TT-101 reads the heater outlet at the tube inlet. The recorder TR and the indicating thermometer TI read the product 3 L before the FDV, which sends it back through the pasteurized side of the regenerator, the cooler and the back-pressure valve BPV to the product tank, or along the divert line to the balance tank. PDT measures the pressure differential Δp across the regenerator plates.

45 % back-mixed [6]. Compliance is therefore judged on the fastest particle rather than on the mean residence.

Computer control of HTST pasteurizers was evaluated against the regulated instruments. A computer-based system controlled the hot-water temperature, the flow through a centrifugal timing pump and the diversion of underprocessed product, compared single-loop, cascade and multivariable strategies, drove the flow diversion valve with a lethality controller, and logged temperatures within ±0.1 °C of the safety thermal limit recorder [3]. Lethality-based control strategies for HTST systems followed [2], and model predictive control of the pasteurization temperature has been demonstrated [10, 11]. On the equipment side, dynamic models of plate heat exchangers follow milk fouling through the channels [14]. Milk fouling involves protein denaturation and aggregation, is reduced by lower surface temperatures and higher velocities, and costs billions of dollars every year [15].

13.3 Parcel Model of the Pasteurizer

The simulated plant processes 9000 L/h of milk at 6 °C through a 45 L holding tube, an 18.0 s hold, with a 900 kW steam valve on the hot-water circuit. The balance tank, the regenerator with its raw and pasteurized sides, the timing pump, the heater and hot-water circuit, the two passes of the holding tube, the FDV, the cooler and every instrument are shown in Figure 13.1.

Table 13.1 lists the variables by role. Eight lumped states are integrated together with the temperatures of the parcels, which occupy 128 state slots of which 96 are in use at the design flow. The positions, routes and records of the parcels are discrete plant state, updated after each integration step.

13.3.1 Parcels and Sections

The milk is a chain of parcels of volume $\Delta V = 2\,\text{L}$. Each parcel i has a center s_i, measured in liters along its path, a temperature T_i and a record. Three paths exist, the line from the balance tank to the FDV, the forward path from the FDV to the product tank and the divert line back to the balance tank. After every step of length Δt the parcels on the first path advance by $Q\Delta t$, those on the forward path advance by the same amount only while the FDV points forward, and those on the divert line only while it points to divert. A parcel reaching the FDV joins the path the valve points to, a parcel

Table 13.1 Roles and Design Values of the Pasteurizer Variables

Variable	Role	Design value	Range
T_{101}	CV, TT-101	73.5 °C SP	72–78
T_w	inner CV, TT-103	77.0 °C	60–95
u	MV, steam valve	12.5 %	0–100
$T_{w,SP}$	MV of TIC-101	77.0 °C	60–95
FDV	MV of the supervisor	forward	or divert
Q_{SP}	timing pump setpoint	9000 L/h	6000–12 000
T_{feed}	DV, raw feed	6 °C	1–20
p_s	DV, steam supply	100 %	0–110
r_f	DV, fouling rate	0 %/min	0–5
b_R, b_I	DV, thermometer biases	0 °C	±3
λ_{set}	DV, BPV spring loss	0 %	0–60
Q, V	states, flow, tank volume	9000 L/h, 140 L	—
VT_{BT}	state, tank heat content	$T_{BT} = 6$ °C	—
T_w, x_v	states, hot water, valve	77.0 °C, 0.125	—
R_f, Δp, λ	states	0, 25.0 kPa, 0	—
T_i	states, parcels	128 slots	—

reaching the product tank is delivered, a diverted parcel reaching the balance tank is mixed into it, and new parcels leave the tank at its temperature T_{BT}. Residence time is therefore whatever the flow makes it, parcel by parcel.

Each section X (heater, tube, regenerator side or cooler) occupies an interval $[X_0, X_1]$ of its path, and a parcel feels it in proportion to its overlap, as shown in Equation (13.1).

$$w_{X,i} = \frac{\left|\left[s_i - \frac{\Delta V}{2},\, s_i + \frac{\Delta V}{2}\right] \cap [X_0, X_1]\right|}{\Delta V} \tag{13.1}$$

The weights and the regenerator pairs below are frozen through one integration step, an eighth of the 0.8 s a parcel takes to move its own length at 9000 L/h.

13.3.2 Heat Transfer on Each Parcel

On the line from the balance tank, a parcel is heated in the heater and loses heat in the tube, and on the forward path it is chilled in the cooler, as shown in Equation (13.2).

$$\begin{aligned} \frac{\mathrm{d}T_i}{\mathrm{d}t} &= w_{H,i}\, k_H\, (T_w - T_i) + \frac{w_{T,i}}{\tau_{loss}}\, (T_{amb} - T_i) + \dot{T}_{R,i} \\ \frac{\mathrm{d}T_j}{\mathrm{d}t} &= w_{C,j}\, k_C\, (T_{cw} - T_j) - \dot{T}_{R,j} \end{aligned} \tag{13.2}$$

where i is a raw-side parcel, j a forward parcel, $k_H = UA_H/[(1+R_f)\,\rho c_p V_H]$ and $k_C = UA_C/(\rho c_p V_C)$ are rate constants in s^{-1}, R_f is the fouling resistance as a fraction of the clean heater resistance, T_{amb} the room temperature and T_{cw} the ice water. Parcels on the divert line neither gain nor lose heat. Evaluated at steady flow, the heater term reproduces the familiar outlet relation $T_{out} = T_w - (T_w - T_{in})\,\mathrm{e}^{-NTU_H}$ with $NTU_H = UA_H/[(1+R_f)\rho c_p Q]$, which is 1.38 at the design flow.

The regenerator couples every raw parcel i to every pasteurized parcel j that overlaps it along the exchanger, as shown in Equation (13.3).

$$\dot{T}_{R,i} = \sum_j k_R\, \ell_{ij}\, (T_j - T_i), \qquad \dot{T}_{R,j} = \sum_i k_R\, \ell_{ij}\, (T_j - T_i) \tag{13.3}$$

Here $k_R = UA_R/(\rho c_p \Delta V)$, and ℓ_{ij} measures the overlap of the two parcels as a fraction of the regenerator length, with both measured from the raw inlet so that the pasteurized parcels run in

counterflow. Because the two parcels of a pair have the same volume, the heat one side gains is exactly what the other loses, and energy is conserved pair by pair. At balanced flow the arrangement approaches the counterflow effectiveness of Equation (13.4) [16].

$$\varepsilon = \frac{NTU_R}{1+NTU_R}, \qquad NTU_R = \frac{UA_R}{\rho c_p Q} \tag{13.4}$$

At 9000 L/h, $NTU_R = 5.67$ and $\varepsilon = 0.850$, and the parcel regenerator delivers 0.847 at the settled steady state of the first case, within the 1 % that the application's own check requires.

13.3.3 Hot Water, Steam, Pump and Balance Tank

The hot-water circuit is one well-mixed capacitance heated by steam and cooled by the parcels in the heater, as shown in Equation (13.5).

$$\begin{aligned} C_w \frac{\mathrm{d}T_w}{\mathrm{d}t} &= Q_{s,max}\, x_v \frac{p_s}{100} - Q_h - UA_{wl}(T_w - T_{amb}) \\ Q_h &= \rho c_p \Delta V \sum_i w_{H,i}\, k_H\, (T_w - T_i) \end{aligned} \tag{13.5}$$

Here $Q_{s,max}$ is the heat the fully open valve passes at design supply pressure, $x_v \in [0,1]$ the valve position and p_s the supply pressure in percent of design, so that a pressure loss removes heat at an unchanged valve position. The valve, the timing pump and the balance tank follow Equation (13.6).

$$\begin{aligned} \tau_v \frac{\mathrm{d}x_v}{\mathrm{d}t} &= \frac{u}{100} - x_v, \qquad \tau_p \frac{\mathrm{d}Q}{\mathrm{d}t} = Q_{SP} - Q \\ \frac{\mathrm{d}V}{\mathrm{d}t} &= Q_{raw} - Q, \qquad \frac{\mathrm{d}(VT_{BT})}{\mathrm{d}t} = Q_{raw} T_{feed} - Q\, T_{BT} \\ Q_{raw} &= \mathrm{clamp}\big(K_{fv}(V_{set} - V),\, 0,\, Q_{raw,max}\big) \end{aligned} \tag{13.6}$$

where Q_{raw} is the flow through the float valve. A diverted parcel arriving at the tank adds ΔV to V and $\Delta V\, T_i$ to VT_{BT} at once, so a long diversion fills the tank with hot product and closes the float valve. Fouling grows at the rate set by the disturbance slider, $\mathrm{d}R_f/\mathrm{d}t = r_f/6000$ with r_f in percent of the clean resistance per minute, so that the heater keeps $1/(1+R_f)$ of its clean UA_H.

13.3.4 Pressure Differential and the Diversion Valve

The pasteurized side of the regenerator is held above the raw side by the back-pressure valve and the friction downstream of the regenerator, while the booster pump pressurizes the raw side. The differential follows its algebraic target through a one-second lag, given by Equation (13.7).

$$\begin{aligned} \tau_{\Delta p} \frac{\mathrm{d}\Delta p}{\mathrm{d}t} &= \Delta p^* - \Delta p, \qquad q = Q/Q_0 \\ \Delta p^* &= P_{BPV}(1-\lambda) + \phi\, P_f\, q^2 \\ &\quad - \beta\left(P_B - P_d\, q^2\right) - (1-\beta)\, P_{suc} \end{aligned} \tag{13.7}$$

where $Q_0 = 9000\,\mathrm{L/h}$, $\phi = 1$ in forward flow and 0 otherwise, $\beta = 1$ while the booster runs and 0 when it is stopped, and the spring loss creeps toward its disturbance value by $\tau_{cr}\,\mathrm{d}\lambda/\mathrm{d}t = \lambda_{set} - \lambda$. At the design flow $\Delta p = 25.0\,\mathrm{kPa}$, and with the booster stopped during a diversion it is 90.0 kPa. The FDV position z_F moves toward 1 (forward) or 0 (divert) at a rate of $1/\tau_{FDV}$ and routes a crossing parcel forward while $z_F \geq 0.5$.

13.3.5 The Parcel Record and the Truth Log

Each parcel carries two clocks for the holding tube. In every step the fraction of the step its center spends inside the tube is $f_i = |[s_i, s_i + Q\Delta t] \cap [T_0, T_1)|/(Q\Delta t)$, exact for steady flow, and the clocks

Table 13.2 Parameters of the Pasteurizer. The Parameter Panel Shows and Adjusts the Visible Ones and Omits the Hidden Ones

Symbol	Meaning	Value	Class
T_{rec}, t_{hold}	recipe	72.0 °C, 15 s	visible
Δp_{min}	interlock trip	6.9 kPa	visible
V_T	holding tube	45 L	hidden
τ_{loss}	tube heat loss	3000 s	visible
UA_H, V_H	heater, clean	14.0 kW/K, 12 L	vis., hid.
UA_R, V_R	regenerator, per side	57.4 kW/K, 30 L	vis., hid.
UA_C, V_C	cooler	25.3 kW/K, 20 L	hidden
T_{cw}, T_{amb}	ice water, room	1.5, 20 °C	hidden
C_w	hot-water capacity	400 kJ/K	visible
$Q_{s,max}$, τ_v	steam valve	900 kW, 3 s	visible
UA_{wl}	hot-water loss	100 W/K	hidden
V_{set}, K_{fv}	float valve	150 L, 0.25 s^{-1}	hidden
$Q_{raw,max}$, τ_p	float capacity, pump	21 600 L/h, 2 s	hidden
P_{BPV}, P_B	BPV, booster	80, 80 kPa	visible
P_f, P_d, P_{suc}	friction, droop, suction	20, 5, −10 kPa	hidden
$\tau_{\Delta p}$, τ_{cr}	pressure, creep	1, 60 s	hidden
τ_{FDV}	FDV travel	0.5 s	visible
τ_{101}, τ_R, τ_{TI}	thermometer lags	2, 1.5, 2 s	visible
τ_{102}, τ_{103}	thermometer lags	2, 3 s	hidden
τ_{FT}, τ_{PDT}	flow, Δp lags	1, 0.5 s	hidden
—	plausibility tolerance	0.5 °C	visible
ρ, c_p	milk	1030 kg/m^3, 3.93 kJ/(kg K)	fixed
ΔV	parcel, slots	2 L, 128	fixed

advance as shown in Equation (13.8).

$$t_{T,i} \leftarrow t_{T,i} + f_i \Delta t, \qquad t_{h,i} \leftarrow t_{h,i} + f_i \Delta t \ \text{ if } T_i \geq T_{rec} \tag{13.8}$$

where $t_{T,i}$ is the time in the tube and $t_{h,i}$ the continuous hold. One step below T_{rec} sets $t_{h,i}$ to zero for good. At the FDV the parcel is treated if $t_{h,i} \geq t_{hold}$, and otherwise underprocessed, by temperature if its hold was broken and by time if it was not. The time in the tube is therefore $t_{tube} = V_T/Q$, 18.0 s at 9000 L/h, and the largest flow that still holds every parcel for the recipe time is $Q_{legal} = V_T/t_{hold} = 10\,800\,\text{L/h}$. Two more records are kept. The heat above the recipe, $E_i = \int \max(0, T_i - T_{rec})\,dt$ over the whole path in °C s, measures overprocessing without quality kinetics, and a forward parcel inside the pasteurized side of the regenerator while $\Delta p < 0$ is flagged as a raw-contact risk, since a pinhole would then leak raw milk into it. No leak is simulated. The scorecard counts these records, not the instruments, and the controller never reads them.

13.3.6 Numbers, Geometry and Initialization

The parameters are listed in Table 13.2. The fixed pipe runs are 4 L from the balance tank to the regenerator, 6 L from the regenerator to the heater with TT-102 at their middle, 3 L from the heater to the tube with TT-101 at the tube inlet, 6 L from the FDV to the pasteurized side, 8 L from there to the cooler, 4 L on to the product tank and 24 L in the divert line. The recorder and the indicating thermometer sit 3 L before the FDV, inside the end of the tube, so that the 1.2 s of travel from them to the valve covers most of the recorder's lag and the valve's travel. Every scenario starts from the closed-form balanced steady state of the line, with linear profiles in the regenerator, the balance tank at $V = V_{set} - Q/K_{fv} = 140\,\text{L}$ and the steam valve at the position that balances the heater duty, 12.29 %. Integration is classical fourth-order Runge-Kutta with a 0.1 s step. Halving the step moves the steady heater inlet by 0.004 °C at 400 s of the first case, inside the 0.02 °C that one of the application's 36 passing checks allows.

13.3.7 Assumptions

Plug flow holds in every section, so each parcel moves at the mean velocity and its time in the tube is exactly V_T/Q. A real holding tube has a velocity profile, and its fastest particle can leave well before the mean residence [6, 8], so the model overstates the hold of a real tube at the same flow.

Heat transfer is lumped per section with constant milk properties, one well-mixed hot-water temperature and no heat capacity in the plates. Plate metal would slow the loss of preheat after a diversion without preventing it, and a channel-by-channel model is available where that detail matters [14].

Fouling is a prescribed growth of resistance, not a deposition model. Real milk fouling depends on the surface temperature [15], which the cascade raises as it compensates, so a real run fouls faster toward its end.

The recipe is one temperature and one time. No microbial kinetics (decimal reduction times and z values) are modeled, so a parcel held at 71.9 °C counts as fully underprocessed.

Pressures are algebraic with a one-second settling, and a raw-contact risk is a flag rather than a contamination. The instruments are first-order lags with colored noise and an additive bias, with no failed-open or failed-shut modes, and the timing pump is a first-order drive with no pump curve.

13.4 Regeneration as a Recycle

The regenerator does three things at once, and each shapes the control problem. Averaged from 60 to 300 s of case 1, it transfers 576 kW against 107 kW in the heater, 84 % of the heating. The steam supplies 112.8 kW, of which 5.7 kW is lost from the hot-water circuit, and the plant uses 12.5 kWh of steam per 1000 L while the milk takes up about 76 kWh per 1000 L on its way from 6 to 73.5 °C.

It is a filter for feed disturbances. With the product temperature fixed, a change at the raw inlet reaches the heater inlet multiplied by $1-\varepsilon = 0.15$.

It is also a recycle. A change in the heater outlet T_{101} travels through the tube, the FDV and the pasteurized side and returns to the heater inlet about 24 s later at 9000 L/h, multiplied by ε and the tube loss, and the heater passes $\mathrm{e}^{-NTU_H} = 0.251$ of its inlet to its outlet. With the measured effectiveness the loop gain is therefore $g = \varepsilon\,\mathrm{e}^{-NTU_H}\,a_T = 0.211$, with $a_T = \mathrm{e}^{-V_T/(Q\tau_{loss})} = 0.994$, and the steady gain from the hot water to the product rises from the heater's own $1-\mathrm{e}^{-NTU_H} = 0.749$ to Equation (13.9).

$$\begin{aligned} \frac{\partial T_{101}}{\partial T_w} &= \frac{1-\mathrm{e}^{-NTU_H}}{1-g} = 0.950 \\ \frac{\partial T_{101}}{\partial T_{feed}} &= \frac{\mathrm{e}^{-NTU_H}(1-\varepsilon)}{1-g} = 0.0486 \end{aligned} \tag{13.9}$$

The recycle matters most to the hot water. With the valve fixed, the heater draws $\rho c_p Q(1-\mathrm{e}^{-NTU_H}) = 7.6\,\mathrm{kW/K}$ from the circuit, which with the circuit's own loss would let it settle in about 52 s, with 1.17 °C of hot water for each percent of valve. Most of that heat comes back through the regenerator, and only the heat that leaves with the product, the tube loss and the circuit's own loss is really removed, 1.61 kW/K in all. In manual, a 1 % step of the steam valve from 12.5 to 13.5 %, taken as the difference from an identical run without the step so that the slow drift of a valve held just below its settled balance of 12.53 % cancels, raises the hot water 0.82 °C in the first minute, 2.82 °C in five minutes and 5.57 °C in the end, with 63 % of the rise taking 429 s, and the energy balance of the step closes to within 0.01 kW of the added 9 kW. The regenerator makes the plant almost five times as sensitive to steam and about eight times slower. The same property makes a small manual error persist, since a valve held at 12.4 % instead of 12.53 % lets the product settle 0.67 °C low over about 40 min.

The recycle is broken by the routing. In a diversion nothing flows through the pasteurized side, the raw milk reaches the heater at the balance-tank temperature, and the heater must supply $\rho c_p Q(T_{SP} - T_{BT})$ by itself, 683 kW from a 6 °C tank. The 900 kW valve was sized for that duty.

13.5 Implemented Controller

The loops and the supervisor run on every third 0.1 s physics step, a control period $\Delta t_c = 0.3\,\mathrm{s}$, and the integrals advance with that value. A priming call seeds them at $t = 0$, and they then execute at 0.3, 0.6, 0.9 s and so on. Within each step any scripted event that is due is applied first, then the controller when its period is due, then the integration, then the parcel motion and routing, the order of the engine step in Section 1.6.1. The historian logs at 2 Hz, and the speed runs from 1 to 60 s of simulated time per second of real time, 5 by default.

13.5.1 Instruments

No loop reads a parcel. Every measurement is the true value at a fixed point of the line passed through an exact first-order lag, updated at each controller execution, plus colored noise with a 0.5 s correlation time and, for the recorder and the indicating thermometer, an additive bias. The lags are 2 s for TT-101 and TT-102, 3 s for TT-103, 1.5 s for the recorder, 2 s for the indicating thermometer, 1 s for the flow meter and 0.5 s for the PDT. The noise has a standard deviation of 0.03 °C on TT-101 and TT-102, 0.05 °C on TT-103, 0.02 °C on the two tube thermometers, 0.3 % of reading on the flow meter and 0.3 kPa on the PDT. The recorder and the indicating thermometer read the same point, so only their lags, their noise and their biases differ.

13.5.2 Cascade, Feedforward and the PI Algorithm

TIC-101 holds the heater outlet by setting the hot-water setpoint, and TIC-102 holds the hot water by moving the steam valve. With feedforward on, TIC-101 adds the hot-water temperature that the clean heater needs at the measured flow Q_m and heater inlet $T_{102,m}$, as shown in Equation (13.10).

$$T_{w,ff} = \frac{T_{SP} - T_{102,m}\,\mathrm{e}^{-N_m}}{1 - \mathrm{e}^{-N_m}}, \qquad N_m = \frac{UA_H}{\rho c_p Q_m} \tag{13.10}$$

clamped to 20–130 °C. The feedforward knows nothing of fouling, the recycle or the losses, and the integral trims what it misses. Both loops are PI controllers in the velocity form of Section 1.6.2, executed every Δt_c with no derivative term and no rate limit. In Equation (1.16) the output bias u_b is $T_{w,ff}$ for TIC-101 and zero for TIC-102, and the back-calculation of Equation (1.17) uses the tracking time $T_t = \tau_I$. The limits are 60–95 °C on the hot-water setpoint and 0–100 % on the valve. Each loop is reverse acting under the ISA convention, since a product below its setpoint must raise the hot-water setpoint and a cold hot-water circuit must open the valve. The defaults are $K_c = 1.0\,^\circ\mathrm{C}$ per °C and $\tau_I = 20\,\mathrm{s}$ for TIC-101, and $K_c = 6\,\%$ per °C and $\tau_I = 30\,\mathrm{s}$ for TIC-102.

The outer loop has a second anti-windup mechanism. While the valve command sits at 100 % with the product below its setpoint, or at zero with the product above it, TIC-101 runs with $\tau_I = \infty$ for that scan, so its integral term stops while the proportional term still acts. This is conditional integration against the saturation of the inner loop, the remedy for cascade windup [17]. In manual the operator sets the valve, TIC-102 tracks the operator's valve position as in Section 1.6.2, and TIC-101 tracks the measured hot water, so the return to automatic is bumpless. In local mode TIC-102 holds the operator's hot-water setpoint and TIC-101 tracks it. Switching the feedforward shifts the integral by the old minus the new feedforward, so the hot-water setpoint does not jump. The timing pump receives the flow setpoint directly, and there is no flow loop.

13.5.3 The Supervisor

The FDV is commanded by the state machine shown in Figure 13.2, a hybrid automaton in the sense of Section 1.4.7. Forward flow requires that the recorder read at least $T_{rec} + \delta$, 72.2 °C with the default $\delta = 0.2\,^\circ\mathrm{C}$, that the measured flow not exceed Q_{legal}, that the Δp interlock be untripped, and that the two tube thermometers not disagree by more than 0.5 °C for 3 s, a persistence that keeps the difference between their lags during a fast swing from counting as a fault. Any failure diverts at once. When all four conditions hold again the supervisor keeps diverting in recovery until $n_{flush} V_T$, 90 L at

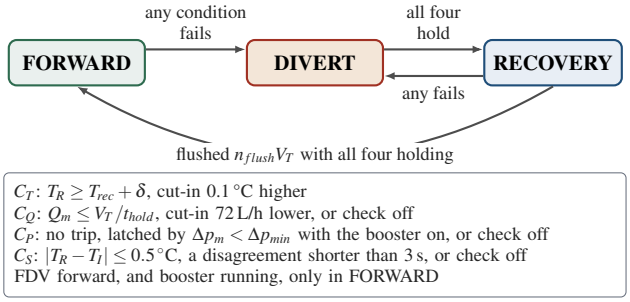


Figure 13.2 Supervisor that routes the product. The four conditions are evaluated on the instruments every 0.3 s, and only the transition from forward to divert counts a diversion. A Δp trip also stops the booster and stays latched until an operator reset, and the flush is counted with the measured flow.

the default of two tube volumes, has passed, so parcels that were in the tube during the fault never go forward on a later good reading. The Δp trip, set below 6.9 kPa while the booster runs, stops the booster, which drops the raw side to suction, and clears only on an operator reset, a latch in the sense of Section 1.4.7.

13.5.4 Simulation, Control and Internal Models

The parcel model of Section 13.3 is the simulation model. The controller's internal model is Equation (13.10), the clean heater alone, with no regenerator, no fouling and no losses. The supervisor's only model is the legal flow V_T/t_{hold}. No model is identified inside the application, but step tests on it give the control model the tuning faces. Through the inner loop in local mode, a 1 °C step of the hot-water setpoint, taken as the difference from an identical run without the step, leaves the heater inlet within 0.001 °C of its old value for 24.4 s, and the product settles 0.950 °C higher, 0.749 °C of it from the heater and the rest returned by the regenerator. The hot water overshoots to 1.32 °C above its old value at 20 s on the way.

13.6 Scenarios and Measured Results

The eight cases and the challenge are listed in Table 13.3. Every case starts from the reference configuration, feedforward and outer-loop anti-windup on, a 73.5 °C product setpoint, two flush volumes and every check on, apart from the changes named. Each change a case names is made after the case is loaded and before the run starts. Reset keeps the reader's settings (Section 1.6.1), and the app gives one run whether a setting is chosen before the run or carried through Reset. All values below were read from headless runs of the engine at the default seed, with times in seconds of simulated time. Values that move with the measurement noise are averages over the stated window, and events are timed to the 0.1 s step.

13.6.1 Stable Production and a Colder Feed

In the first case the regenerator warms the milk from 6 to 62.9 °C, and the heater, with hot water at 77.0 °C and the valve at 12.5 %, adds the last 10.6 °C. Each parcel spends 18.0 s in the tube, 3 s more than the recipe, and reaches the recorder 0.30 °C cooler, at 73.20 °C. A parcel that makes the whole trip carries 30.0 °C s of heat above the recipe, and the scorecard's mean over the parcels delivered by 300 s is 29.9 °C s, since the parcels already in the line at $t = 0$ start with the heat records of the steady profile.

When the feed switches from 10 to 2 °C at 60 s, the balance tank passes 6 °C after 39 s, and the heater inlet falls only from 63.55 °C to 62.31 °C by 480 s, a drop of 1.24 °C. The heater attenuates that again, and the heater outlet departs from its setpoint by at most 0.08 °C with the cascade and feedforward and 0.10 °C without the feedforward. The heater duty rises from 101 to 113 kW, and the

Table 13.3 Scenario Sequence

#	Scenario and event	Teaching point
1	Stable production	where the heat comes from
2	Feed 10 to 2 °C at 60 s	the regenerator filters
3	10 500 L/h, then 11 500 L/h	a flow limit is a time limit
4	Steam to 60, then 15 %	inner-loop headroom
5	Fouling at 3 %/min	a controller hides decline
6	Recorder, then both, +1.5 °C	what redundancy cannot see
7	BPV spring creeps	the interlock and its margin
8	40 s steam trip, no anti-windup	the return is the upset
9	1800 s campaign	graded challenge

Table 13.4 Outcomes of the Cases at the Default Seed

Case	Measured outcome
1, mean 60–300 s	regenerator 576, heater 107, steam 112.8 kW
1, per parcel	hold 18.0 s, tube loss 0.30 °C, 30.0 °C s
2, heater inlet	63.55 °C to 62.31 °C by 480 s
2, product departure	cascade 0.08, no FF 0.10, local 0.25 °C
3, 10 500 L/h	hold 15.4 s, dip 0.66 °C, no diversion
3, 11 500 L/h	divert 241.6 s, low 64.9 °C, forward 447.4 s
3, same	576 L diverted, heater peak 682 kW
3, flow check off	134 parcels (268 L) held 14.1 s
4, 60 % steam	valve 12.5 to 20.9 %, dip 0.66 °C
4, 15 % steam	divert 268.6 s, low 52.5 °C, 284 L
4, no outer anti-windup	456 L diverted
5, 1200 s	UA_H 62.5 %, T_w 77.0 to 81.1 °C
5, product	within 0.13 °C, integral 4.0 °C
6, recorder drift	divert 62.8 s, 382 L, forward 216.1 s
6, common drift	128 parcels (256 L) by 540 s, undetected
6, check off, one drift	27 parcels by 180 s
7, BPV creep	trip 103.9 s at 6.61 kPa, 506 L
7, interlock off	reversal 132.2 s, 151 parcels (302 L)
8, no anti-windup	3 diversions, 506 L, 45.6 °C s
8, anti-windup on	1 diversion, 236 L, 33.5 °C s

product leaving the cooler falls from 3.0 to 2.4 °C. With the cascade opened (Local) the hot water holds its 77.0 °C default rather than the 76.8 °C the cascade was asking for, so the product has risen to 73.60 °C when the feed switches, on its way to the 73.66 °C that the same hot water holds without the switch. It then settles at 73.27 °C, the 0.39 °C below that level that the recycle gain of Equation (13.9) predicts for the 8 °C change, and bottoms 0.25 °C below its setpoint at 282 s. The colder feed is a small upset by physics, because it enters before the regenerator. The case serves to locate where a disturbance enters rather than to test the loop, the question Volume 3, Chapter 2 asks of every loop structure.

13.6.2 Flow and the Holding Time

A flow step to 10 500 L/h at 60 s shortens the hold from 18.0 to 15.4 s and dips the product 0.66 °C without a diversion. At 240 s production asks for 11 500 L/h, where the hold would be 14.1 s however hot the product is, and the flow condition diverts at 241.6 s. The diversion is expensive. With nothing flowing through the pasteurized side, the heater inlet falls to 12.0 °C, the heater duty rises to 682 kW and the heater outlet sinks to 64.9 °C. After production returns to 9000 L/h at 330 s, the supervisor enters recovery at 342.7 s, falls back to divert twice as the loops restore the temperature, and returns to forward flow at 447.4 s, with 576 L diverted. With the flow check off, no diversion occurs and 134 parcels, 268 L, go forward by 330 s at the right temperature and held only 14.1 s.

🕮 **Pause.** Try Exercise 13.1 before reading on.

13.6.3 Steam Loss and Fouling

A sag of the steam supply to 60 % at 60 s is ridden out by the inner loop. The valve opens from 12.5 to 20.9 %, passing 20.5 % at 74.1 s, the product dips 0.66 °C, and the recorder never reads below 72.56 °C. At 240 s the supply falls to 15 %, where the valve needs about 80 % to give the heater its 107 kW. The hot water cools while the valve travels, and the FDV diverts at 268.6 s, before the valve reaches 80 % at 272.1 s. The diversion removes the regenerator's hot side, and by 300 s the heater is taking 385 kW against the 135 kW a wide-open valve can give, so the heater outlet has sunk to 53.9 °C when the supply returns at 300 s and reaches 52.5 °C at 302.4 s. Forward flow resumes at 382.0 s after 284 L. With the outer-loop anti-windup off the same event costs 456 L and forward flow resumes at 451.3 s.

Fouling at an accelerated 3 % per minute leaves the heater with less than 70 % of its clean UA_H from 857 s and 62.5 % after 1200 s. The cascade raises the hot water from 77.0 to 81.1 °C to push the same heat through the poorer surface, the product stays within 0.13 °C of its setpoint, and the valve stays between 11.9 and 13.5 % because the duty has not changed. The feedforward still assumes a clean heater and stays at 77.0 °C, and the integral of TIC-101 carries 4.0 °C. The approach, hot water minus product, grows from 3.5 °C in the first 30 s to 7.6 °C in the last 30 s, and it is the only trend that shows the deposit. A fouling rate of this size would not occur in a dairy, but it serves to compress a production run into twenty minutes. Volume 2, Chapter 4 follows fouling on a steam-heated exchanger.

13.6.4 What the Instruments Cannot See

When the recorder alone reads 1.5 °C high at 60 s, the plausibility check diverts at 62.8 s with the product at 73.17 °C. A comparison of two instruments can say that one of them is wrong but never which one, so good product is lost, 382 L by the time the recorder is recalibrated at 180 s and forward flow resumes at 216.1 s. At 360 s both thermometers read 1.5 °C high together, they agree, and the check has nothing to compare. At 390 s the operator trims the setpoint to 72.0 °C to bring the recorder back to its usual reading. The product at the recorder falls below 72 °C at 419.5 s, and the first underprocessed parcel goes forward at 421.3 s. At 500 s, as shown for the recorder and the product in Figure 13.3, the recorder reads 73.17 °C and the indicating thermometer 73.10 °C while the product is at 71.76 °C, and by 540 s 128 parcels, 256 L, have gone forward underprocessed, every one while all four conditions held. With the plausibility check off and the same trim made at 120 s, the single drifting recorder passes 27 parcels by 180 s. Redundancy catches independent faults and not common ones.

> **TRY IT IN THE APP 6 · Sensor Bias**
>
> Load the scenario and press Run. Watch the FDV and the tube strip of the trends. When the recorder alone reads high at 60 s the plant diverts. After 360 s both thermometers read high together, the FDV stays forward, and the product trace falls below the recipe line while both thermometer traces stay above it. By 540 s 128 parcels have gone forward underprocessed.

Pause. Try Exercise 13.2 before reading on.

13.6.5 The Pressure Differential

The differential starts at 25.0 kPa. At 60 s the back-pressure valve spring begins to creep toward 45 % below its setting, and the interlock trips at 103.9 s, when the transmitter reads 6.56 kPa and the true differential is still 6.61 kPa. The booster stops, the raw side drops to suction and the FDV diverts. The trip latches through the repair at 240 s until the operator reset at 270 s, and forward flow resumes at 306.1 s after 506 L. With the interlock off the differential reverses at 132.2 s, and 151 parcels, 302 L, sit in the regenerator with the raw side at the higher pressure and go on to the product tank, 150 of

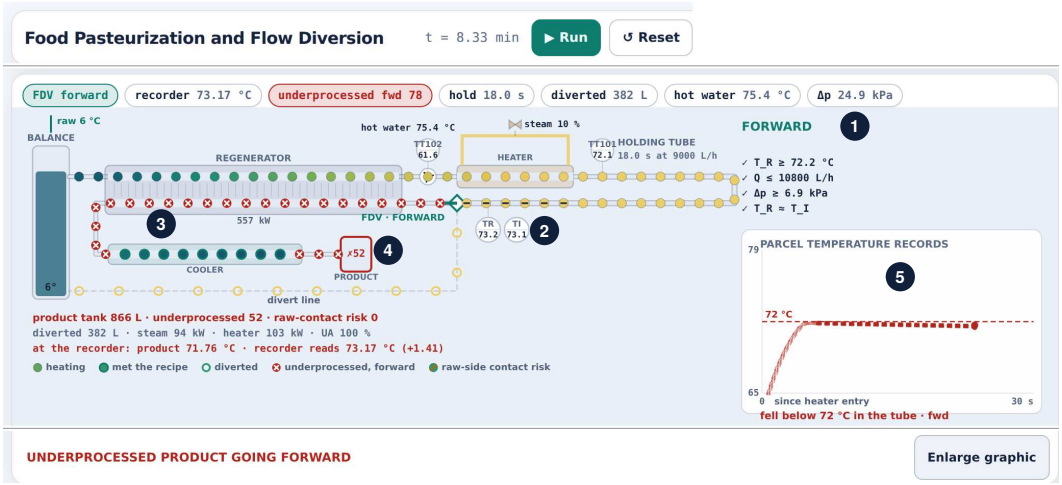


Figure 13.3 The pasteurizer application in case 6, sensor bias, at $t = 8.33$ min (500 s), 140 s after both tube thermometers began reading 1.5 °C high and 110 s after the setpoint was trimmed to 72.0 °C. The picture is a composite of the app's header, plant view and status strip, and the control panel, the trends and the Learn panel are cut. (1) The FDV is forward and the supervisor's four conditions are all ticked, while the tally under the scene gives the product at the recorder as 71.76 °C against a recorder reading of 73.17 °C at (2) the recorder and the indicating thermometer. The six parcels in the last 11 L of the holding tube carry the bar of a record already broken, (3) crossed red parcels fill the pasteurized side of the regenerator and surround nine treated parcels in the cooler, (4) the product tank counts 52 of the 78 underprocessed parcels forwarded so far, and (5) the parcel records run just below the 72 °C line. The status strip reads underprocessed product going forward, and the tally shows 382 L diverted, 866 L delivered and no raw-contact risk.

them by the repair and the last 0.1 s after it, while the differential recovers. The margin between the 6.9 kPa trip and zero is what turns a slow mechanical failure into a safe diversion.

13.6.6 Coming Back From a Diversion

Case 8 trips the steam for 40 s at 30 s with the outer-loop anti-windup off, and the FDV diverts at 56.5 s. When the steam returns at 70 s the valve is wide open, the hot water overshoots to 98.3 °C at 105.4 s, and the heater outlet peaks at 77.7 °C at 110.4 s, while the plant is still diverting. Recovery begins at 115.0 s and forward flow resumes at 151.3 s. Then the regenerator restarts with a balance tank at 56.1 °C, the heater outlet rises to 75.96 °C at 168 s, and the valve stays below 0.5 % from 168.6 to 214.5 s, because the hot water can cool only as fast as the milk carries heat out of it. Without anti-windup the integral of TIC-101 keeps pushing the hot-water setpoint down, to 70.3 °C, and when the tank refills with cold milk the product falls below the cut-out, with second and third diversions at 230.5 and 398.8 s and 506 L diverted by 420 s. With the anti-windup on, the setpoint bottoms at 71.5 °C and one diversion of 236 L is the whole cost, while the heat above the recipe per delivered parcel falls from 45.6 to 33.5 °C s. The largest overshoot of the case therefore belongs to the diversion, and the upset that causes the later diversions is the smaller one after the return.

Table 13.5 Supervisor and Plant Margins. Runs Last 600 s for Case 3, 420 s for Case 8, 1800 s for the Challenge, and 900 s With the Smaller Valve

Configuration	Diversions	Diverted	Under
case 3, flush 0 volumes	8	478 L	0
case 3, flush 1 volume	8	786 L	1
case 3, flush 2 volumes (default)	1	576 L	0
case 3, flush 3 volumes	1	622 L	0
case 8, cut-out margin 0 °C	3	494 L	1
challenge as shipped, margin 0 °C	4	1524 L	6
case 3, 500 kW valve	4	1058 L	0
case 4, 500 kW valve	3	932 L	0

TRY IT IN THE APP 8 · Recovery From Diversion

Load the scenario and press Run. With the outer-loop anti-windup off the steam trip costs 3 diversions and 506 L by 420 s. Press Reset, set Outer-loop anti-windup to On on the TIC-101 card before pressing Run, and run again: one diversion of 236 L is the whole cost.

Pause. Try Exercise 13.3 before reading on.

13.6.7 The Supervisor's Margins

What the defaults of the supervisor and the plant protect against is measured in Table 13.5. The counts of underprocessed parcels depend on the measurement noise, so every configuration was also run at seven other seeds, and the spread is given below. With no flush, case 3 returns to forward flow the moment the recorder recovers and cycles through 8 diversions, which forwards no underprocessed parcel at the default seed but up to 2 at others. One tube volume still cycles 8 times, diverts 786 L and forwards one underprocessed parcel (none at the other seven seeds). Two volumes return in one diversion of 576 L with none forwarded at any seed, and three add 46 L without improving safety. Without the 0.2 °C cut-out margin, the recorder's 1.5 s lag lets 1 underprocessed parcel through in case 8 (1 to 4 over the seeds) and 6 in the shipped challenge (3 to 7), while a 0.5 s recorder lets none through in either (at most one at other seeds). With a 500 kW valve, set in the parameter panel before the run, the heater cannot replace the regenerator during a diversion, and case 3 is still diverting at 900 s after 4 diversions and 1058 L. At four of the eight seeds it regains forward flow near 572 s after 2 diversions, 125 s later than with the full valve. Moving the recorder to 0.5 L before the valve in a copy of the model, with everything else unchanged, forwards 3 underprocessed parcels in case 3 with a one-volume flush (2 to 4 over the seeds), where the 3 L position forwards 1 (0 or 1). Neither position forwards one in the shipped challenge at the default seed, and the 0.5 L position forwards one at a single other seed.

13.6.8 The Campaign Challenge

The challenge runs 1800 s with two silo switches, four production-rate changes and two sags of the steam supply, starting from a detuned cascade (K_c 0.5 and 60 s outside, 3 and 60 s inside) with no feedforward, no outer anti-windup and a 73.0 °C setpoint. It is met with no underprocessed or raw-contact-risk parcel forwarded, at most 100 L diverted, and at most 40 °C s of heat above the recipe per delivered parcel. The measured configurations are listed in Table 13.6. As shipped the plant stays safe but diverts 4 times, 1554 L in all, and delivers 3220 L for 83.8 kWh, 26.0 kWh per 1000 L. The suggested configuration never diverts, keeps the heater outlet between 72.84 and 74.90 °C and the tube outlet above 72.59 °C, and delivers 4774 L for 63.9 kWh, 13.4 kWh per 1000 L, with 34.9 °C s per parcel, 5.1 °C s inside the limit. Each element pays for itself. A higher setpoint alone avoids every diversion but overheats the product, the suggested tuning at the old setpoint diverts 7 times (6

Table 13.6 Challenge Configurations Over 1800 s. Heat Is the Mean Heat Above 72 °C per Delivered Parcel

Configuration	Div.	Diverted	Heat	Delivered
as shipped	4	1554 L	74.2	3220 L
suggested[a]	0	0	34.9	4774 L
setpoint 74.5 °C only	0	0	49.9	4774 L
suggested at 73.0 °C	7	2084 L	25.6	2688 L
suggested, no feedforward	1	304 L	39.7	4470 L
suggested, no anti-windup	0	0	34.8	4774 L

[a] feedforward and anti-windup on, 1.0 and 20 s, 6 and 30 s, 73.8 °C

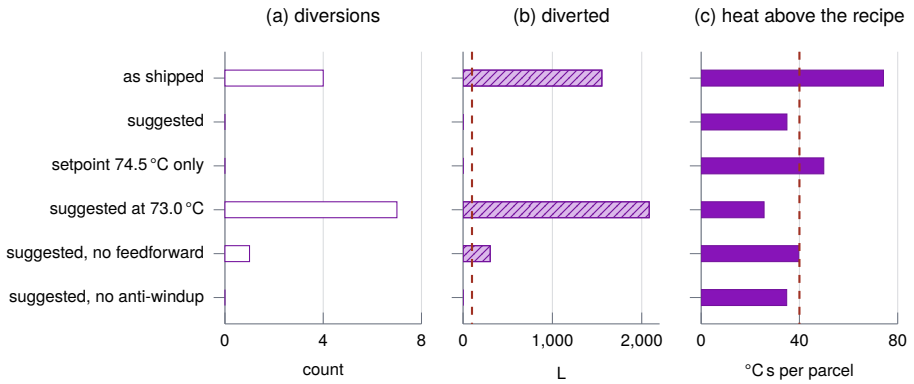


Figure 13.4 The campaign challenge of Table 13.6 in its six configurations: (a) diversions, (b) volume diverted and (c) heat above the recipe per delivered parcel, with the challenge limits dashed. The table prints the values. Notice that no tuning buys the margin that the setpoint gives, and that the margin is paid for in heat: the higher setpoint alone never diverts but overheats, and the suggested tuning at the old setpoint diverts most of all.

or 7 over eight seeds), and dropping only the feedforward costs one diversion of 304 L. The outer anti-windup changes little in the suggested run, because the valve command sits at zero only from 906.4 to 914.8 s, after the cut to 8000 L/h, and the frozen integral moves the mean heat by 0.1 °C s. Figure 13.4 draws the diversions, the volume diverted and the heat of each configuration against the limits.

> ✦ **DID YOU KNOW? Better Tuning, More Diversions**
>
> From the simulator: the suggested tuning, run at the shipped 73.0 °C setpoint, diverts 7 times and sends 2084 L back, where the detuned plant as shipped diverts 4 times and 1554 L. The setpoint, not the tuning, buys the margin (Table 13.6).

13.7 Technology in Practice

What Measures It

In a real HTST plant the sensor of the thermal-limit controller sits at the outlet of the holding tube. It is set and sealed so that forward flow cannot start unless the temperature there is above the pasteurization temperature, nor continue once it falls below, and no milk may bypass it [7]. That is the cut-out of Figure 13.2, read by the chapter's TR. The time half of the recipe is held by a positive-displacement timing pump or by a timing system built on a magnetic flow meter [7], the TP and FT of Figure 13.1.

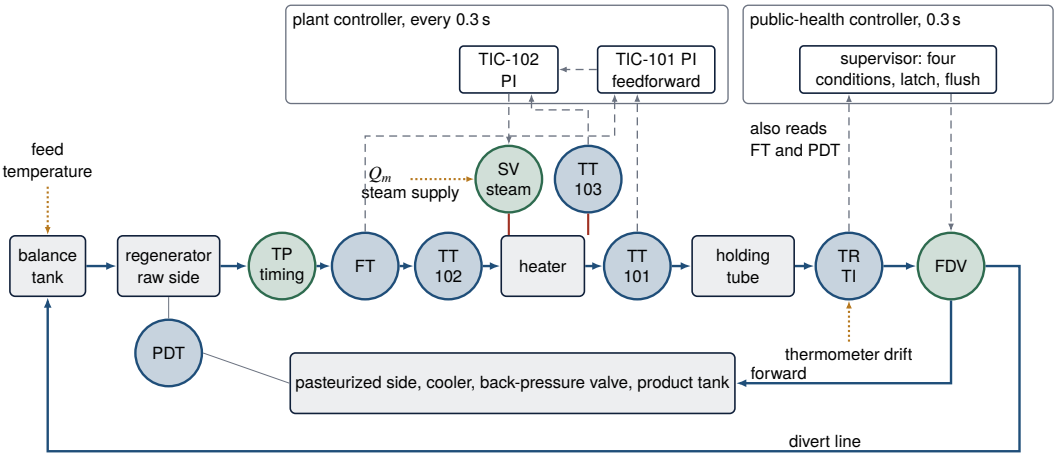


Figure 13.5 The loops of the pasteurizer drawn on plant hardware, with the chapter's tags. Sensors are drawn blue, final elements green and disturbances dotted. The temperature cascade (TIC-101 on TT-101 sets the setpoint of TIC-102 on TT-103, which moves the steam valve) runs on the plant controller, and the supervisor that commands the FDV runs on its own controller, as the ordinance requires of a public-health computer. Notice that the cascade never reads TR and TI, and the supervisor never moves the steam.

> **TECHNOLOGY** **Sensor: A Recorder-Controller and Its Witness**
>
> The ordinance asks for two thermometers at the end of the holding tube. The recorder-controller must read within 0.5 °C near the temperature at which it diverts, and a digital sensor may drift no more than 0.5 °C in three months against a certified source. Its self-diagnostic circuits blank the reading on a failed component. The indicating thermometer must read within 0.2 °C, and in a bath test its reading must climb from 11 °C to 4 °C below the bath in four seconds or less [7]. TR and TI of Section 13.5 model the pair as lags of 1.5 and 2 s with a bias each, and a common bias is the fault the pair cannot see.

What Moves It

Three final elements act on the milk: the steam valve of the hot-water circuit, the timing pump and the flow diversion device. The booster pump on the raw side is a fourth, switched rather than modulated. The ordinance lets it run only while the timing pump runs, the diversion device is forward and the pasteurized milk is at least 6.9 kPa above the most the booster can develop [7]. The chapter's interlock trips at the same 6.9 kPa (Table 13.2) and stops the booster. Figure 13.5 draws the loops on this hardware.

> **TECHNOLOGY** **Final Element: The Flow Diversion Device**
>
> The flow diversion device sits downstream of the holding tube and diverts the milk automatically in response to a sub-legal condition. A failure of its motive power must divert the flow, so the valve fails safe. A leak-escape on the forward side of the seat carries any leakage outside or back to the balance tank, and the flow-control sensor sits at most 46 cm upstream of the valve inlet. Motive pumps must stop when the milk is below the pasteurization temperature and the valve is not fully diverted [7]. The chapter's FDV is a two-position valve with a 0.5 s travel.

Where the Controller Runs

Computers commonly manage the public-health devices of a pasteurizer, and the ordinance treats such a computer as a replacement for hard wiring. A computer or programmable logic controller used for public-health control is dedicated to one pasteurizer, cannot be commanded by any other

computer, puts every public-health output in its fail-safe position on loss of power, and keeps its program sealed. It must monitor all inputs and update all outputs at least once every second [7]. The chapter's supervisor scans every 0.3 s, inside that limit. Read as plant hardware, the cascade of TIC-101 and TIC-102 belongs in the plant controller, which may only request a device, and the four conditions, the latch and the flush belong in the public-health controller.

> **IN PRACTICE** **Cut-In, Cut-Out and the Salt Test**
>
> At the start of each day the operator finds the cut-in and cut-out temperatures on the indicating thermometer and enters them on the recorder chart, and checks the recorder against the indicating thermometer, adjusting it to read no higher. The holding time is the flow time of the fastest particle. It is tested at maximum flow by timing a salt solution injected into water through the tube, on installation, at least every six months, after any change that may affect it, and whenever the seal on the timing pump's speed is broken [7].

What Is Modernizing It

Three developments touch this plant. Many pasteurization systems time the hold with a magnetic flow meter. Its flow alarm diverts whenever the flow would make the hold shorter than the legal time, and once the legal flow returns a delay keeps the device diverted for at least 15 or 25 seconds, depending on the product [7]. The chapter's supervisor has both, as its flow condition and its flush. Electronic collection and storage of data can replace the circular chart recorder, provided the records keep the purpose of their paper counterparts [7]. In-line fouling sensors and predictive models aim to time cleaning-in-place from the state of the surface [18], the trend that the approach of case 5 stands in for.

13.8 Limitations

Plug flow gives every parcel the mean residence. A real holding tube is judged on its fastest particle, which the model does not represent [6].

The recipe is a threshold with no microbial kinetics, so the model cannot credit extra lethality at higher temperature or grade a short excursion by its effect. The overprocessing measure, heat above the recipe in °C s, stands in for quality kinetics.

The fouling rate is prescribed rather than tied to the surface temperature [15], and no leak is simulated behind the raw-contact flag. The instruments drift only through the bias sliders and the scenario events.

> **OPEN CHALLENGE** **Seeing the Deposit Before It Matters**
>
> Fouling still cuts the efficiency of dairy heat treatment, raises its energy use and complicates its cleaning, and in severe cases a plant can fail to meet its required thermal profile. Cleaning is usually decided from a fall in heat transfer or a rise in pressure drop, which sees fouling late, and cleaning systems cannot tell when the deposit is gone, so they nearly always overclean. Acoustic, ultrasonic, electrochemical and spectroscopic sensors and learned predictors exist, but most remain at the experimental or prototype stage [18]. Progress would be in-line sensing on real exchangers that sets the cleaning schedule. Case 5 shows the gap: only the approach reveals the deposit.

13.9 Conclusion

A regenerative HTST pasteurizer is a plant in which the controlled variable is not the thing that must be guaranteed, and the simulator described here keeps the two apart by carrying the milk as parcels with their own records. The regenerator supplies 84 % of the heat, and the recycle it creates raises the steady gain of the hot water to 5.57 °C per percent of valve with a 429 s response, against 1.17 °C per percent and 52 s without it, while a diversion removes it and asks the heater for up to 682 kW. A flow of 11 500 L/h holds each parcel 14.1 s, and without the flow check 134 parcels go forward at the right temperature. Two thermometers drifting together pass 128 underprocessed parcels while every

condition holds. Conditional integration on the outer loop cuts the return from a steam trip from 3 diversions and 506 L to 1 and 236 L, and the challenge moves from 4 diversions and 1554 L to none. The model assumes plug flow, a threshold recipe and prescribed fouling. A fuller model would add a residence time distribution with a fastest particle, microbial kinetics for the recipe, a fouling law driven by the wall temperature and a simulated leak. The application is an accessible browser plant for learning where a temperature loop ends and a certified treatment begins.

KEY POINTS

- A pasteurizer must guarantee the time and temperature each parcel of milk received, which no controller measures.
- The regenerator supplies 84 % of the heat, and its recycle makes the plant almost five times as sensitive to steam and about eight times slower.
- The holding time is the tube volume divided by the flow, so at 11 500 L/h every parcel is held 14.1 s however hot it is.
- Two thermometers drifting together pass 128 underprocessed parcels while every condition of the supervisor holds.
- Conditional integration on the outer loop cuts the return from a steam trip from 3 diversions and 506 L to 1 and 236 L.

Where else this applies. The cut-out margin above the recipe, sized to the recorder's lag (Table 13.5), is a guard band of the same kind as the one that narrows the fill limits before a vial is accepted in Chapter 9.

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13.10 Exercises

13.1 Concept check · 2 min

In Scenario 3 production asks for 11 500 L/h at 240 s. With the flow check off, the cascade keeps the product near its setpoint and the recorder never reads below the recipe temperature. Is the milk that goes forward pasteurized?

(a) Yes, because every parcel stays at or above 72 °C all the way through the holding tube

(b) Yes, provided the feedforward raises the hot water to match the higher flow

(c) No, because the tube now holds each parcel 14.1 s, under the 15 s of the recipe

(d) No, because the regenerator recovers less heat at the higher flow and the product cools

13.2 Concept check · 2 min

In Scenario 6 both tube thermometers start reading 1.5 °C high at 360 s, and the operator trims the setpoint to 72.0 °C at 390 s. Underprocessed parcels go forward from 421.3 s while all four conditions of the supervisor hold. Why does the plausibility check not divert?

(a) Its 3 s persistence filters out a drift as gradual as this one

(b) The trim of the setpoint switches the check off until the next recalibration

(c) The recorder's lag hides the drift until the product has left the tube

(d) The two thermometers agree, so a comparison between them has nothing to detect

13.3 Concept check · 1 min

In Scenario 8 the outer-loop anti-windup is off. After forward flow resumes at 151.3 s the steam valve stays shut while the product runs hot, and two more diversions follow by 420 s. What does the outer-loop anti-windup change?

(a) It freezes the product loop's integral while the valve is pinned, so the hot-water setpoint is not driven down

(b) It limits how fast the steam valve may open when the steam returns at 70 s

(c) It keeps the FDV in divert until the balance tank has cooled to the feed temperature

(d) It narrows the hot-water setpoint range so that the hot water cannot overshoot

13.4 Theory and calculation · 4 min

The holding tube holds $V_T = 45\,\text{L}$, the recipe asks for 15 s at 72.0 °C, and the parcels move in plug flow.

(a) Find the time in the tube at 9000 L/h, 10 500 L/h and 11 500 L/h. *Checkpoint:* 18.0 s, 15.4 s and 14.1 s.

(b) Find the legal flow Q_{legal}, and the flow below which the flow condition holds again after a trip, given its cut-in 72 L/h lower. *Checkpoint:* 10 800 L/h and 10 728 L/h.

(c) With all four conditions holding, how long does the default flush of two tube volumes take at 9000 L/h? Compare with Scenario 6, where the recorder is recalibrated at 180 s and forward flow returns at 216.1 s. *Checkpoint:* 36 s, as measured.

13.5 Theory and calculation · 7 min

The regenerator has $UA_R = 57.4\,\mathrm{kW/K}$ and the clean heater $UA_H = 14.0\,\mathrm{kW/K}$. Milk has $\rho = 1030\,\mathrm{kg/m^3}$ and $c_p = 3.93\,\mathrm{kJ/(kg\,K)}$, the flow is 9000 L/h, and the tube loss has $\tau_{loss} = 3000\,\mathrm{s}$ (Equations (13.4) and (13.9)).

(a) Find $\rho c_p Q$, NTU_R, ε, NTU_H and e^{-NTU_H}. *Checkpoint:* 10.12 kW/K, 5.67, 0.850, 1.38 and 0.251.

(b) With the parcel effectiveness 0.847, find a_T, the recycle loop gain g and the steady gains of T_{101} to the hot water and to the feed. Derive the second from a balance on the heater and the regenerator. *Checkpoint:* 0.994, 0.211, 0.950 and 0.0486.

(c) In Scenario 2 with the cascade opened (Local), the hot water holds 77.0 °C while the feed falls 8 °C. Predict the steady fall of the product. *Checkpoint:* 0.39 °C, as measured (73.66 to 73.27 °C).

13.6 Theory and calculation · 7 min

Each percent of the 900 kW steam valve adds 9 kW at design pressure. The hot-water circuit has $C_w = 400\,\mathrm{kJ/K}$ and loses $UA_{wl} = 100\,\mathrm{W/K}$, and the heater passes $1 - \mathrm{e}^{-NTU_H} = 0.749$ of the difference between the hot water and its inlet to the milk (Section 13.4).

(a) Ignore the recycle, so that the heater inlet stays fixed. Find the heat the circuit loses per kelvin of hot water, the steady rise per percent of valve and the time constant of the hot water. *Checkpoint:* 7.68 kW/K, 1.17 °C per percent, 52 s.

(b) With the recycle, a kelvin of hot water raises T_{101} by 0.950 and the heater inlet by εa_T times that, with $\varepsilon = 0.847$ and $a_T = 0.994$. Find the net heat lost per kelvin and the steady rise per percent, and compare with the measured 5.57 °C. *Checkpoint:* 1.62 kW/K and 5.6 °C per percent.

(c) In a diversion the heater must bring 6 °C milk to 73.5 °C by itself. Find the duty, and compare it with what the wide-open valve passes at full steam pressure and at 15 % of it. *Checkpoint:* 683 kW against 900 kW and 135 kW.

13.7 App challenge · 7 min

Open Scenario 3, "3 · Flow increase", at the default seed, and run at 30× (30 s of plant time per wall second).

(a) Run it as loaded to 600 s (20 s of wall time). Read the Diversions and Diverted tiles. *Checkpoint:* 1 diversion, 576 L, both fixed once forward flow returns at 447.4 s.

(b) Press Reset, set Divert above the legal flow to Off on the Timing pump card, and run to 400 s. Read Underprocessed forwarded and Diverted. *Checkpoint:* 142 parcels, 0 L. The count is fixed from 336 s.

(c) The chapter counts 134 parcels by 330 s. Explain where the other parcels come from. *Checkpoint:* 8 parcels in the tube when production returned to 9000 L/h.

13.8 App challenge · 7 min

Open Scenario 8, "8 · Recovery from diversion", at the default seed, and run at 10×.

(a) Run it as loaded, with Outer-loop anti-windup Off, and pause between 490 and 560 s. Read the Diversions and Diverted tiles, and the lowest hot-water setpoint on the product trend after forward flow resumes at 151.3 s. Tolerance 0.2 °C. *Checkpoint:* 3 diversions, 670 L, lowest setpoint 70.3 °C.

(b) Press Reset, set Outer-loop anti-windup to On on the TIC-101 card, and run to the same time. Read the same values. *Checkpoint:* 1 diversion, 236 L, lowest setpoint 71.5 °C.

(c) Run the first case on past 560 s. What happens, and why does the chapter quote 506 L by 420 s? *Checkpoint:* A fourth diversion at 568 s. The third diversion is still under way at 420 s.

13.9 App challenge · 8 min

Open the challenge, "Challenge · variable-feed campaign", at the default seed, and run at 60× (30 s of wall time). Pause at 1800 s. The counts and volumes do not change between 1740 and 1860 s. Read the heat at 1800 s, to within 1 °C s.

(a) Run it as loaded. Read Underprocessed forwarded, Diversions, Diverted and Excess heat. *Checkpoint:* 0 parcels, 4 diversions, 1554 L, 74.2 °C s. Target not met.

(b) Press Reveal suggested tuning, then Reset, and run again. Read the same tiles. *Checkpoint:* 0 parcels, 0 diversions, 0 L, 34.9 °C s. Target met.

(c) Set Product temperature setpoint to 73.0 °C, press Reset and run again. Read the same tiles and explain the result. *Checkpoint:* 0 parcels, 7 diversions, 2084 L, 25.6 °C s.

13.10 Application area · 4 min

Tracer tests on a pilot HTST pasteurizer found the fastest particle leaving a nominal 21.5 s holding section after 18.6 s (Section 13.2). Assume the tube of this chapter has the same ratio of fastest to nominal time.

(a) Find the hold of the fastest particle at 9000 L/h and at the legal flow of 10 800 L/h. *Checkpoint:* 15.6 s and 13.0 s.

(b) Find the largest flow at which the fastest particle is still held 15 s, or the tube volume that would allow 10 800 L/h. *Checkpoint:* About 9340 L/h, or about 52 L.

13.11 Application area · 5 min

In Scenario 5 fouling grows at 3 % of the clean resistance per minute, so R_f rises by $r_f/6000$ each second and the heater keeps $1/(1+R_f)$ of its clean UA_H. The heater inlet stays near 62.9 °C because the duty does not change.

(a) Find when the heater falls below 70 % of clean, and what is left at 1200 s. *Checkpoint:* 857 s and 62.5 %.

(b) From the outlet relation with $NTU_H = 1.38/(1+R_f)$, find the hot water that holds the product at 73.5 °C when clean and at 1200 s, and compare with the run. *Checkpoint:* 77.0 °C and 81.2 °C, against 77.0 and 81.1 °C.

(c) The hot-water setpoint is limited to 95 °C. At what share of the clean UA_H does the cascade run out of room, and when would that happen at this rate? Say what an operator should watch. *Checkpoint:* About 29 %, after about 82 min. The approach.

13.12 Review the agent · 5 min

An AI assistant reviews the challenge with the suggested tuning at a 73.0 °C setpoint and writes: "The 7 diversions come from the 0.2 °C cut-out margin, which trips the FDV on good milk. Set Cut-out margin above the recipe to 0 °C. The recorder then diverts only below the 72.0 °C of the recipe, the run drops to 3 diversions and 686 L, the heat falls to 21.6 °C s, and nothing underprocessed can pass, since the recorder still enforces the recipe." Find the flaw, and say how you would check it in the app.