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CHAPTER 4

Vapor-Chain Concentration Control in a Three-Effect Milk Evaporator Simulator

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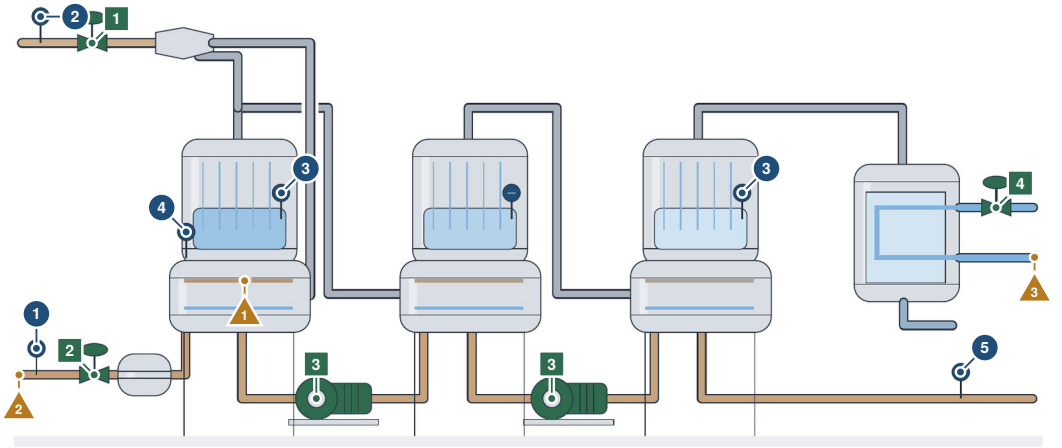
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CHAPTER 4

Vapor-Chain Concentration Control in a Three-Effect Milk Evaporator Simulator



The controller moves 1 motive steam to the steam jet 2 milk fed to the train 3 pumps between the effects 4 cooling water to the condenser

The controller reads 1 feed flow and feed solids 2 motive steam flow 3 sump levels 4 first-effect temperature 5 densitometer at the end of the product line

What disturbs it 1 deposits on the tubes 2 feed solids 3 warmer cooling water

The vapor of each effect heats the next within two minutes, while the concentrate reaches the only product reading at the end of the line minutes later. Illustration, not to scale.

IN PLAIN TERMS Steam Used Three Times, Judged at the End

The main idea. An evaporator thickens skim milk by boiling water out of it under a vacuum. Steam heats the first of three boiling stages, and the vapor from each stage heats the next one.

The challenge. The only gauge of the thick milk sits at the end of a long pipe, so it sees a steam change minutes late. The thickness can be fixed with the steam or with the milk flow, while deposits slowly push the first stage toward its heat limit.

Why it matters. The handle chosen decides whether the plant pays in steam or in milk, and how long it runs before it stops for cleaning.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	the first page, the fact on steam per pound of water in the Introduction, the history of the sugar pan that held its own concentration (Section 4.2), the two try-its and the fact on level tuning (Section 4.6) and the key points
Study	55 min	the whole chapter with its three pause points and the twelve exercises at its end
Practice	20 min	the first page, the results (Section 4.6), Technology in Practice (Section 4.7), Limitations (Section 4.8) and the two open challenges

The control question A densitometer at the end of a three-effect train reads the concentrate minutes after a steam move has reached every effect. Should the product solids be held with the steam or with the feed, how tightly should the sumps between the effects be held, and what ends a run when fouling spends the temperature margin of the first effect?

Learning objectives

- Explain why a steam step reaches the three vapors within two minutes and the densitometer only after about six.
- Compute the steam a feed-solids change needs from the mass balance, and the share a ratio built on the average economy leaves to the trim.
- Use the temperature budget to predict how the condenser and the deposits of each effect move the first effect's temperature.
- Compare steam and feed pairing at equal loop gain, and state what each costs in steam or in milk processed.
- Choose between tight and averaging level loops from the flow variation they pass to the dryer.

Prerequisites Sections 1.4.3 (throughput manipulator), 1.4.8 (averaging level control), 1.6.2 (velocity-form PID) and 1.6.4 (scenarios and data). Section 1.6.3 is needed only for the predictive supervisor.

The app https://apmonitor.com/apps/multi-effect-evaporator/

See also Volume 4, Chapter 4 for a feed rate cut by engine and rotor overrides when a limit binds, and Volume 4, Chapter 5 for torque and pressure overrides beneath a throughput supervisor on a product judged downstream.

4.1 Introduction

Milk powder is made by removing water twice. A falling-film evaporator first concentrates skim milk by boiling it under vacuum, and a spray dryer then removes most of what remains, so the evaporator decides both how much steam it spends and what concentrate the dryer receives. Energy use and energy efficiency have been analyzed along the whole route from fluid milk to milk powder [1]. The evaporator saves energy by reusing it. Its effects boil at successively lower pressures, the vapor boiled from the milk in one effect heats the next, and a thermal vapor recompressor (TVR), a steam jet, returns part of the first effect's vapor to that effect's own steam chest. Falling-film trains of this kind have been modeled from first principles and identified from plant data [2, 3], and their dynamics and control have been analyzed with mechanical vapor recompression [4].

In the train modeled here, 20 t/h of skim milk at 9.0 % solids leave the third effect as 3.75 t/h of concentrate at 48.0 %. The 3.39 t/h of motive steam that drive the thermocompressor entrain 5.30 t/h of the first effect's vapor, and with 0.18 t/h of steam to the preheater they evaporate 16.25 t/h of water, a steam economy of 4.56 kg/kg. Heat and concentration travel through the train at different speeds. After a 0.10 t/h step of the motive steam, the vapor made in the three effects shows half of its change after 16, 75 and 82 s, while the densitometer at the end of the product line needs 380 s.

The simulator is built against two beliefs. The first is that an evaporator's steam economy is fixed by its design, so that every extra kilogram of steam evaporates as much water as the average one. Here the average kilogram of motive steam evaporates 4.80 kg of water and the next one 2.4 kg, because a hotter steam chest makes the thermocompressor entrain less. The second is that the temperature of the first effect, which must stay below a product limit, is a matter of the first effect. It rests on the condenser and on the temperature drops of the effects below it, so deposits in the second and third effects spend its margin while deposits in the first spend economy. A transfer function from steam to densitometer carries neither. The class of problem is general. A quality measured at the end of a chain of thermally coupled units, a fast handle that costs energy against a slow one that costs throughput, buffers whose level tuning decides how flows propagate, and a hard limit approached by slow degradation are shared by the sugar evaporators where multiple effects began [5], by black

liquor trains [6], by multiple-effect desalination [7], and by any plant that must choose where its throughput is set [8] and whether its inventories are held tight or allowed to average [9].

> ✦ DID YOU KNOW? **Steam per Pound of Water, Effect by Effect**
>
> To evaporate one pound of water, a dairy evaporator with one effect needs 1.2 pounds of steam, one with two effects 0.6, one with four 0.3 and one with seven less than 0.1. Trains with thermal vapor recompression have a typical steam economy of 4 to 8 [10]. The train modeled here runs at 4.56 kg/kg.

Evaporator studies model a particular plant in order to identify or control it [2, 3, 11], and a first course in process control meets feedforward, level control and override control one loop at a time [12]. This chapter puts them on one train, on which the vapor chain can be watched while fouling spends the temperature margin. The effect balances, the thermocompressor energy balance, ratio feedforward, averaging level control, override control and the throughput supervisor are standard practice. Two measured results stand out. The marginal economy of the motive steam is half of its average, and at the deposits of a twenty-hour run the first effect's own deposit costs 1.19 K of temperature margin and 0.38 kg/kg of economy where those of the other two cost 4.20 K and 0.16 kg/kg. The model has 28 plant states and 26 ledger states whose water, solids and energy balances close to round-off, with a densitometer delay keyed to the product volume and a steady state solved by Newton's method, all written out here. The app carries eight cases and one graded shift, which set the vapor path against the liquid path, a steam pairing against a feed pairing and a buffer against a tight level loop, and a further case adds predictive supervision. Section 4.2 follows the domain's history, Section 4.3 builds the model and Section 4.4 reads its vapor chain and temperature budget. Section 4.5 describes the controller, Section 4.6 reports what the cases measure, with the predictive supervisor in Section 4.6.8, Section 4.7 describes the real instruments, final elements and controllers, and Section 4.8 states the limitations.

4.2 From the Sugar House to the Dairy Train

Evaporation in several effects entered industry through the sugar house. Norbert Rillieux's United States patents of 1843 and 1846, for improvements in sugar-works and in sugar-making, placed vacuum pans in series so that the vapor boiled from the juice in one heated the next, and both are reproduced in a documentary history of technology [5, 13]. The principle outgrew sugar. Seawater desalination by multiple-effect evaporation is analyzed effect by effect for its thermal performance [7], and the black liquor of the pulp mill is concentrated in falling-film effects whose plates have been modeled as distributed-parameter systems [6].

Two later developments shaped the dairy train. The first is vapor recompression. A steam jet compresses part of the vapor a train makes and returns it to the first effect, and an investigation of ejector design by analysis and experiment was published in 1950 [14]. The second is the falling film, which transfers heat at small temperature differences with a short residence, at the price of a film that has to cover the whole tube wall. Criteria for the breakup of thin liquid layers flowing over solid surfaces were set out in 1964 [15], and in falling-film evaporators a broken film has been identified as a cause of fouling [16].

Milk brought constraints of its own, a product that must not be overheated and deposits that grow on every heated surface. The fouling of heat exchangers in the dairy industry has been reviewed [17], and a dairy evaporator runs from one cleaning to the next rather than indefinitely. Control of these trains moved from single loops toward models. Process identification and physical modeling were compared for falling-film evaporators in 1994 [2], and the same authors placed a four-effect falling-film evaporator under multivariable supervisory control [11]. The dynamics and control of falling-film evaporators with mechanical vapor recompression were analyzed in 1999 [4], and dynamic models of an evaporation process were compared in 2000 [3]. Two structural decisions recur there and in plantwide control at large, which variable sets the throughput [8] and whether the inventories

Table 4.1 Variables of the Evaporator, Grouped by Role, at the Reset of Case 2

Variable	Role	Design value	Range
w_{AT}	CV, AT-301	48.0 % SP	40–52
F	CV, FT-200	20.0 t/h SP	6–26
$\dot{m}_m$	CV, FT-100	3.39 t/h	0–6
T_1	CV, TT-101, ceiling	69.5 °C SP	60–70
ℓ_1, ℓ_2, ℓ_3	CVs, LT-101 to 103	50 % SP	20–80
T_{pre}	CV, TT-400	67.0 °C SP	55–70
P_3	CV, PT-500	110 mbar SP	80–160
u_F, x_s	MVs, feed pump, spindle	66.7, 56.4 %	0–100
u_{p1}, u_{p2}, u_{p3}	MVs, pumps	50.5, 46.6, 46.9 %	0–100
x_p, x_c	MVs, preheat, cooling water	24.8, 40.9 %	0–100
R_1, R_2, R_3	MVs, recirculation	0 t/h	0–8
w_F	DV, feed solids	9.0 %	7–11
$T_{cw,t}$	DV, tower water	25 °C	12–36
P_m	DV, steam header	8.0 bar	4–10
ϕ	DV, fouling rate	1	0–4
T_{in}	DV, feed to preheater	62 °C	40–66
β_3	DV, LT-103 bias, unmeasured	0 %	±20
M_1, M_2, M_3	states, liquid	600, 400, 250 kg	
S_1, S_2, S_3	states, solids	97.1, 96.6, 120.0 kg	
H_i, as T_i	states, stored heat	65.32, 57.66, 49.52 °C	
$T_{w,i}$	states, tube walls	70.53, 63.53, 56.12 °C	
$R_{f,i}$	states, deposits	0	
E_s, E_{pre}	states, as θ_s, T_{pre}	72.14, 67.00 °C	
T_{cw}	state, water at condenser	25.0 °C	
$F, L_i, R_i, x_{s,p,c}$	states, actuators	as the MVs	

between units are held tightly or allowed to average [9]. The simulator puts both decisions, the thermocompressor and the fouling cycle on one train, and it logs what no plant can, the true solids of each tonne that leaves for the dryer.

> **HISTORY 1843: A Sugar Pan That Held Its Own Concentration**
>
> A United States patent to Norbert Rillieux of New Orleans, dated August 26, 1843, claimed four improvements in evaporating sugar juices. The fourth regulated the concentration of the sirup with a differential thermometer. One metal element sat in the sirup leaving the last evaporator, the other was acted on only by its vapor, and together they turned the spindle of a throttle valve in the juice supply. When the regulator showed the concentration too great, the valve opened and admitted more juice to the first evaporator. A simple thermometer would not do, the patent explains, because a sirup boiled in a vessel exhausted by an air pump changes its temperature with the pressure, while the difference between the sirup and its vapor indicates the concentration under all pressures [18]. The concentration was held with the feed, the pairing of case 3.

4.3 The Evaporator as Modeled

The simulated train is laid out in Figure 4.1. Skim milk passes a live-steam preheater and falls as a film down the tubes of effect 1, whose steam chest takes the thermocompressor's discharge. The liquid of each effect collects in its separator and sump and is pumped to the top of the next calandria, and the vapor of each effect condenses in the shell of the next, except that the thermocompressor draws part of effect 1's vapor back to the chest and effect 3's vapor goes to a condenser on cooling water. The product pump sends the concentrate along a product line, past the densitometer AT-301, to the dryer.

Table 4.1 groups the variables by role. The 54 entries of the state vector are 28 plant states and 26 cumulative ledgers of the water, solids and energy streams, for the whole plant and for each effect. One integration step advances ledgers and plant together, and because every held quantity is linear in the states, each balance closes from the state vector alone. The model works in SI units with absolute pressures, and because the engine's clock is the minute, every rate is multiplied by 60 on its way out.

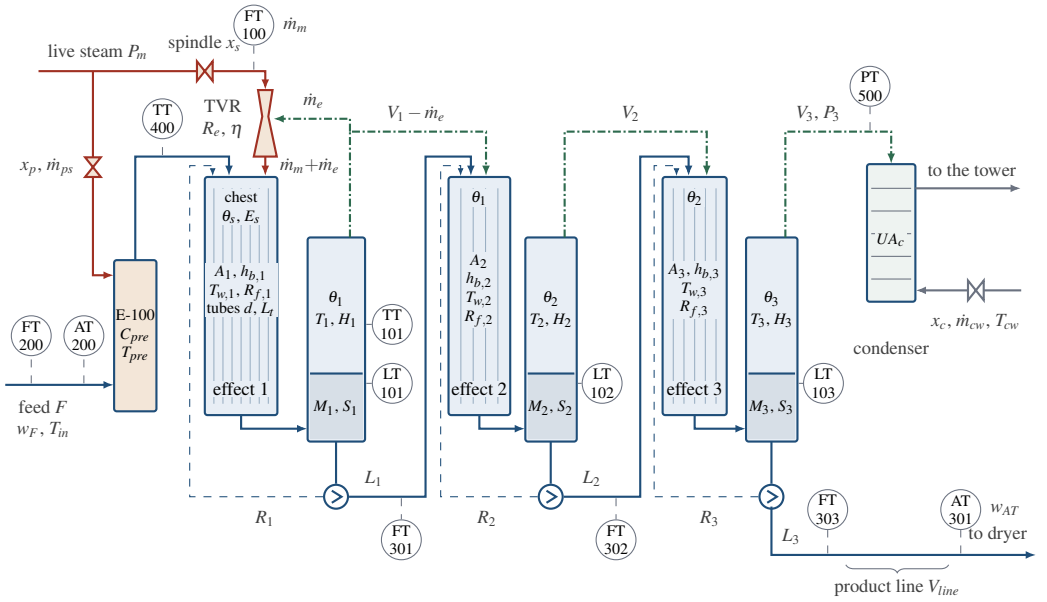


Figure 4.1 Three-effect falling-film evaporator as modeled. Live steam at P_m passes the spindle x_s and FT-100 into the thermocompressor (TVR), which entrains $\dot{m}_e$ of effect 1's vapor and discharges into the steam chest at θ_s, and a branch through x_p heats the preheater E-100. Feed F at w_F and T_{in} passes FT-200 and AT-200 to the top of effect 1. Each calandria of area A_i holds tubes of bore d and length L_t, a wall at $T_{w,i}$ and a deposit $R_{f,i}$, and each separator holds the liquid M_i and solids S_i at T_i under vapor at θ_i. Pumps move L_1 to L_3, thin dashed lines are the recirculation R_i, dash-dotted green lines are vapor, and effect 3's vapor V_3 condenses at P_3 against cooling water $\dot{m}_{cw}$ at T_{cw} through x_c. The product travels the line V_{line} to AT-301.

4.3.1 Mass, Solids and Stored Heat

Each effect is one well-mixed liquid, film, sump and piping together, whose mass and solids follow Equation (4.1).

$$\begin{aligned} \frac{\mathrm{d}M_i}{\mathrm{d}t} &= L_{in,i} - L_i - V_i \\ \frac{\mathrm{d}S_i}{\mathrm{d}t} &= L_{in,i}\, w_{in,i} - L_i\, w_i, \qquad w_i = S_i/M_i \end{aligned} \tag{4.1}$$

where $L_{in,1} = F$ with $w_{in,1} = w_F$, $L_{in,i} = L_{i-1}$ with $w_{in,i} = w_{i-1}$ for the other two, L_i is the flow each pump delivers and V_i the vapor the effect makes. No solids leave with the vapor. The level is $\ell_i = (M_i - M_{min,i})/M_{sump,i}$, and a pump delivers the flow of its first-order actuator times $\min(1, \max(0, \ell_i/0.02))$, so it starves below 2 %. The heat held by the liquid and by the steel at the boiling temperature, the separator, the vapor duct and the next calandria's shell, follows Equation (4.2).

$$\begin{aligned} \frac{\mathrm{d}H_i}{\mathrm{d}t} &= L_{in,i} h_{in,i} + Q_{b,i} - L_i c_p(w_i) T_i \\ &\quad - V_i h_{v,i} - UA_{loss}(T_i - T_{amb}) \\ T_i &= \frac{H_i}{c_w M_i - (c_w - c_s) S_i + C_{sep,i}} \\ \theta_i &= T_i - \mathrm{BPE}(w_i) \\ h_{v,i} &= c_w \theta_i + \lambda(\theta_i) + c_{pv}\mathrm{BPE}(w_i) \end{aligned} \tag{4.2}$$

where $h_{in,1} = c_p(w_F)T_{pre}$, $h_{in,i} = c_p(w_{i-1})T_{i-1}$ for the other two, $c_p(w) = c_w(1-w) + c_s w$, and $\lambda(T) = 2.501 \times 10^6 - 2370\,T$ in J/kg with T in °C, within 0.15 % of the steam tables between 40 and 80 °C. The liquid boils, so its vapor space sits at the saturation temperature θ_i, one boiling-point elevation below T_i, and θ_i is the temperature at which that vapor condenses in the next calandria. Saturation follows the Antoine equation $p_{sat}(T) = 133.322 \times 10^{8.07131 - 1730.63/(233.426+T)}$ in Pa. The elevation is an illustrative correlation, as shown in Equation (4.3).

$$\mathrm{BPE}(w) = 1.2x + 0.9x^4 \ \mathrm{K}, \qquad x = \frac{w}{1-w} \tag{4.3}$$

It is 0.23, 0.39, 1.76 and 2.54 K at 16, 24, 48 and 52 %, steep above 40 %.

4.3.2 Heat Through the Walls and the Vapor Chain

Every calandria wall sits between a condensing side on its whole area and a boiling film on its wetted share only, as shown in Equation (4.4).

$$\begin{aligned} C_w A_i \frac{\mathrm{d}T_{w,i}}{\mathrm{d}t} &= \underbrace{h_c A_i(\theta_{h,i} - T_{w,i})}_{Q_{c,i}} - \underbrace{U_{b,i} A_i f_{wet,i}(T_{w,i} - T_i)}_{Q_{b,i}} \\ \frac{1}{U_{b,i}} &= \frac{1}{h_{b,i}} + R_{f,i} \end{aligned} \tag{4.4}$$

where the heating temperature is $\theta_{h,1} = \theta_s$ in the steam chest, $\theta_{h,2} = \theta_1$ and $\theta_{h,3} = \theta_2$. An effect makes exactly the vapor that the next calandria condenses, plus, for effect 1, what the thermocompressor draws, and effect 3's vapor goes to the condenser, as shown in Equation (4.5).

$$\begin{aligned} V_i &= \frac{Q_{c,i+1}}{\lambda(\theta_i) + c_{pv}\mathrm{BPE}_i} + \dot{m}_e\,\delta_{i1}, \qquad i = 1,2 \\ V_3 &= \frac{\varepsilon_c \dot{m}_{cw} c_w(\theta_3 - T_{cw})}{\lambda(\theta_3) + c_{pv}\mathrm{BPE}_3}, \qquad \varepsilon_c = 1 - \mathrm{e}^{-UA_c/(\dot{m}_{cw}c_w)} \end{aligned} \tag{4.5}$$

with $\dot{m}_{cw} = x_c \dot{m}_{cw,max}$, the condenser duty taken as zero if $\theta_3 < T_{cw}$, and $P_3 = p_{sat}(\theta_3)$. The vapor inventories are neglected, but the heat stored at each boiling temperature is a state, so the chain is not an algebraic loop. A steam move reaches effect 3 through three stored heats in series.

4.3.3 Thermocompressor and Steam Chest

The thermocompressor is an illustrative energy balance. A fraction η of the motive steam's isentropic enthalpy drop from P_m to the suction pressure P_s compresses motive and entrained vapor together to the chest's pressure P_d, which gives the entrainment ratio of Equation (4.6).

$$\begin{aligned} R_e &= R_{e,max}\tanh(r/R_{e,max}) \\ r &= \max\left(0,\ \eta\,\Delta h_m/\Delta h_c - 1\right) \\ \Delta h_m &= c_{p,g}(T_m + 273.15)\left[1 - (P_s/P_m)^{\kappa}\right] \\ \Delta h_c &= c_{p,g}(T_1 + 273.15)\left[(P_d/P_s)^{\kappa} - 1\right] \end{aligned} \tag{4.6}$$

where $P_s = p_{sat}(\theta_1)$, $P_d = p_{sat}(\theta_s)$, T_m is the saturation temperature of the header, $\kappa = 0.3/1.3$ and $c_{p,g} = 1.3R_v/0.3$ for an ideal gas with $\gamma = 1.3$. The motive flow is $\dot{m}_m = x_s \dot{m}_{m,max} P_m/P_{m0}$ and the entrained flow $\dot{m}_e = R_e \dot{m}_m$. At the design point the jet compresses 25.05 kPa to 34.08 kPa, a ratio of 1.36, and entrains 1.566 kg/kg. The steam chest holds only its steel's heat, $E_s = C_{sh}\theta_s$, and condenses everything it receives at θ_s, as shown in Equation (4.7).

$$\frac{\mathrm{d}E_s}{\mathrm{d}t} = \dot{m}_m h_g(T_m) + \dot{m}_e h_{v,1} - (\dot{m}_m + \dot{m}_e)c_w\theta_s - Q_{c,1} \tag{4.7}$$

where $h_g(T) = c_w T + \lambda(T)$. A hotter chest raises P_d and lowers R_e, which is the mechanism behind both the marginal economy of Section 4.4 and the loss of economy to fouling.

4.3.4 Fouling and the Wetting Floor

Deposits grow faster in thicker concentrate, on hotter walls and on dry tubes, by the illustrative law of Equation (4.8).

$$\begin{aligned} \frac{\mathrm{d}R_{f,i}}{\mathrm{d}t} &= k_{f,i}\,\phi\left(\frac{w_i}{0.3}\right)^{n_w} \mathrm{e}^{\frac{E_f}{R}\left(\frac{1}{343.15}-\frac{1}{T_{w,i}}\right)} \\ &\quad \times \left[1 + k_{dry}(1 - f_{wet,i})\right] \\ f_{wet,i} &= \min\left(1,\ \frac{\Gamma_i}{\Gamma_{min}}\right), \qquad \Gamma_i = \frac{L_{in,i} + R_i}{A_i / L_t} \end{aligned} \tag{4.8}$$

where $T_{w,i}$ is absolute in the exponent, ϕ multiplies every rate, and A_i/L_t is the wetted perimeter of the tube bundle, 30.0, 12.5 and 17.5 m, the equivalent of 208, 87 and 121 tubes. Below the wetting floor the dry share of the tubes transfers no heat and fouls 31 times as fast. The constants make the deposits grow at 5.1, 5.8 and 8.5×10^{-6} m^2 K/W per hour at the clean design point, and a cleaning in place (CIP) resets them to zero at once. At the design point the three films run at 2.31, 3.09 and 1.48 times the floor, so effect 3, which needs 5.04 t/h to stay wet, is the first to break at turndown.

4.3.5 Preheater, Condenser Water and Actuators

The preheater is one liquid heat capacity heated by live steam, as shown in Equation (4.9).

$$\begin{aligned} C_{pre}\frac{\mathrm{d}T_{pre}}{\mathrm{d}t} &= F c_p(w_F)(T_{in} - T_{pre}) + \dot{m}_{ps}\lambda_{pre} \\ \dot{m}_{ps} &= x_p \dot{m}_{ps,max} P_m / P_{m0} \end{aligned} \tag{4.9}$$

The feed, the three pumps, the three recirculation pumps, the spindle and the preheat and cooling-water valves follow their commands through first-order lags of $\tau_p = 2$ s, and the water reaching the condenser follows the tower through $\tau_{cw}\,\mathrm{d}T_{cw}/\mathrm{d}t = T_{cw,t} - T_{cw}$.

4.3.6 Economy and Its Bound

The steam economy counts the water evaporated per kilogram of live steam, motive and preheat together, and it is bounded by one kilogram per effect plus the thermocompressor's recycle, with every kilogram of steam counted at the heat it gives up, as shown in Equation (4.10).

$$\varepsilon = \frac{V_1 + V_2 + V_3}{\dot{m}_m + \dot{m}_{ps}} < (N + R_e)\,\frac{\dot{m}_m q_m + \dot{m}_{ps}\lambda_{pre}}{\lambda(\theta_1)(\dot{m}_m + \dot{m}_{ps})} \tag{4.10}$$

with $N = 3$ effects, while $q_m = h_g(T_m) - c_w\theta_s$ is the heat a kilogram of motive steam gives up in the chest, 2.51 MJ/kg at the design point. The economy is 4.56 kg/kg there against a bound of 4.85 kg/kg.

4.3.7 Design Point

At the reset of case 2 the flows into, between and out of the effects are 20.00, 11.12, 7.46 and 3.75 t/h, the solids 9.0, 16.19, 24.14 and 48.00 %, and the holdups 600, 400 and 250 kg, residences of 3.2, 3.2 and 4.0 min. The effects boil at 65.32, 57.66 and 49.52 °C under vapor at 65.09, 57.27 and 47.76 °C, the chest is at 72.14 °C, and the temperature differences through the three calandrias are 6.82, 7.43 and 7.75 K. The effects make 8.88, 3.66 and 3.71 t/h of vapor with duties of 5.77, 2.33 and 2.41 MW, the condenser takes 2.46 MW from 147 t/h of cooling water warmed from 25.0 to 39.4 °C, and the preheater lifts the feed from 62 to 67 °C with 0.11 MW. The clean overall coefficients are 2352, 2095 and 1478 W/(m^2 K).

4.3.8 Initialization and Numerical Integration

Table 4.2 lists the parameters. A case starts from the steady state that belongs to its own configuration, with the feed, the levels, the preheat and the pressure of effect 3 at their setpoints and the free handle, the motive steam on steam pairing or the feed on feed pairing, placing the product on its solids

Table 4.2 Parameters of the Evaporator, Marked Visible Where the Show Model Dialog Offers a Slider and Hidden Where It Does Not

Symbol	Meaning	Value	Class
A_1, A_2, A_3	heating areas	360, 150, 210 m^2	visible
$h_{b,i}$	film and wall, W/(m^2 K)	3075, 2650, 1735	visible
h_c	condensing coefficient	10 000 W/(m^2 K)	hidden
C_w	tube wall per area	6 kJ/(m^2 K)	hidden
$C_{sep,i}$	steel at T_i, MJ/K	4.0, 3.0, 3.0	hidden
C_{sh}	steam chest steel	3.0 MJ/K	hidden
UA_{loss}, T_{amb}	loss per effect	500 W/K, 25 °C	hidden
d, L_t	tube bore, length	46 mm, 12 m	hidden
Γ_{min}	minimum wetting rate	0.08 kg/(m s)	visible
$M_{min,i}$	film and pipe holdup	350, 200, 120 kg	hidden
$M_{sump,i}$	sump, 0 to 100 %	500, 400, 260 kg	visible
F_{max}	feed pump	30 t/h	hidden
$L_{max,i}$	transfer, product pumps	22, 16, 8 t/h	hidden
R_{max}	recirculation pump, each	8 t/h	hidden
τ_p	actuator lag	2 s	hidden
$\dot{m}_{m,max}$	motive steam, full spindle	6 t/h	visible
P_{m0}	design header pressure	8 bar	hidden
η	ejector efficiency	0.28	visible
$R_{e,max}$	entrainment ceiling	3 kg/kg	hidden
UA_c	condenser	171 kW/K	visible
$\dot{m}_{cw,max}$	cooling water, full valve	360 t/h	hidden
τ_{cw}	cooling-water circuit	15 min	visible
C_{pre}	preheater liquid	590 kJ/K	hidden
$\dot{m}_{ps,max}$	preheat steam, full valve	0.72 t/h	hidden
λ_{pre}	preheat steam latent heat	2200 kJ/kg	hidden
$k_{f,i}$	fouling rates, 10^{-9} m^2 K/J	3.4, 3.8, 3.8	visible
E_f, n_w	fouling activation, exponent	80 kJ/mol, 1.5	hidden
k_{dry}	fouling on dry tubes	30	hidden
V_{line}	product line to AT-301	73 L	visible
T_{max}	product temperature limit	70 °C	visible
t_0	hours since CIP at reset	0 h	visible
ν	instrument noise scale	1	visible
c_w, c_s, c_{pv}	water, solids, vapor, J/(kg K)	4187, 1400, 1900	fixed
R_v	gas constant of steam	461.5 J/(kg K)	fixed

setpoint. Newton's method solves the nine unknowns the mass balances do not give explicitly, θ_s, θ_1 to θ_3, the three wall temperatures, the free handle and the cooling-water valve, while a fixed point on the mass balances gives the flows and the solids. At the reset of case 2 the residual is 5.5×10^{-13} after 12 iterations, and no plant state other than the deposits moves by more than 1×10^{-9} per minute. Below the design feed a second steady state exists, with effect 3 under its wetting floor, so the solver walks the feed down from 20 t/h in steps of at most 1.44 t/h to stay on the wet branch. A start that does not converge, needs an actuator beyond its range or leaves a film below its floor, as a feed setpoint of 13 t/h chosen before the run would, gives way to the case's own steady state, from which the loops then move the plant. The plant advances by classical fourth-order Runge-Kutta steps of 0.5 s on the engine of Section 1.6.1, the loops execute every 5 s, a row is logged every 5 s (14 400 rows in the 20 h case), and every random sequence is seeded at 20261103, so a noisy run replays identically. The tube walls are the fastest states, with time constants $C_w/(h_c + h_{b,i})$ of 0.46 to 0.51 s, inside the stability limit of the method at this step, and halving the step moves the temperatures and solids of case 1 at 11 min by less than 1×10^{-3}. Over the 480 min challenge and over a 300 min fouling run with a CIP the water, solids and energy ledgers close below 1×10^{-9} relative, one of the 37 checks the application passes. The speed selector spans 0.25 to 300 simulated minutes per second of real time, 5 by default, and leaves the trajectory unchanged.

4.3.9 Assumptions

Each effect is one well-mixed liquid at its boiling point, while a real falling film is plug flow down the tubes and often split into passes, so the model's residence-time distribution is too broad and its three- to four-minute holdups stand for the whole train's residence. The vapor inventories are neglected and the pressure of each vapor space follows the heat stored at its boiling temperature, which holds while the vapor spaces are small against the stored heat and fails for a fast pressure transient. Swell and shrink of the boiling sumps and the flash of condensate between calandrias are not modeled.

The elevation, the fouling law, the wetting floor with its linear loss of wetted area and the thermocompressor characteristic are illustrative. The thermocompressor is an energy balance with ideal-gas enthalpies and a smooth ceiling rather than a manufacturer's map, and real ejectors break down above a critical compression ratio, which the model does not reproduce. The Antoine equation is used beyond the range it was fitted for in the motive steam, where it gives 169.7 °C at 8 bar. Viscosity does not lower the film coefficient, so U falls only by fouling and by dry tubes, and recirculation changes the wetting of a lumped effect but not its composition.

The condenser is an ε-NTU exchanger with a fixed UA_c, no non-condensable gas and no vacuum pump. The densitometer turns density into solids exactly, with no temperature or fat error, CIP is instantaneous, and mechanical vapor recompression is not included, because a fan across effect 1 would only replace the thermocompressor's recycle and one across the whole train would need about 25 K of lift. The 70 °C limit, the 69.5 °C ceiling and all sizes and capacities are teaching values, not a design basis.

4.4 The Vapor Chain and the Temperature Budget

4.4.1 Two Paths Through One Train

Heat and concentration leave the steam chest by different routes. Heat travels as vapor and needs only to raise the temperatures that drive it through each calandria. Concentration travels as liquid, through the holdups of the three effects and then along 73 L of product line, 85 s at the design flow, to a densitometer that reports every 5 s. The step of case 1 separates the two, as shown in Figure 4.2. With the noise off, and read at every 0.5 s step, the vapor made in effect 1 shows half of its tenth-minute change after 16 s, because the thermocompressor draws more of that vapor as soon as its motive flow rises. The second and third effects follow at 75 and 82 s, and AT-301, which first moves by 0.01 % after 150 s, at 380 s. The vapors overshoot their tenth-minute values by 12 to 17 % at about four minutes, because the solids building up in each effect raise its boiling-point elevation and take back part of the temperature difference the heat had gained. With the elevation held at its design values, in a copy of the model outside the application, the overshoot shrinks to 2 to 4 %.

> **TRY IT IN THE APP** **1 · Step the Steam, Time the Chain**
>
> Load the scenario, press Run and watch the stopwatch beside the staircase. At one minute the motive steam rises by 0.10 t/h and nothing corrects it. The vapor of effect 1 arrives first, after about 20 s, effects 2 and 3 after about 75 and 70 s, and the densitometer AT-301 last, after about 400 s.

What delays the second and third effects is storage rather than transport. The condenser holds the bottom of the staircase, so a larger duty through each calandria needs a larger temperature difference, and the liquid and the steel of the chest and the effects must be heated to it. Their heat capacities at the boiling temperature are 3.0, 6.24, 4.41 and 3.71 MJ/K, with 2.16, 0.90 and 1.26 MJ/K more in the tube walls. The step brings 70 kW of extra heat once FIC-100 has moved the motive flow, 95 % of the way after 53 s, and of the 7.11 MJ it has supplied two minutes after the move, 5.35 MJ have gone into raising those temperatures rather than into vapor for the next effect.

Pause. Try Exercise 4.1 before reading on.

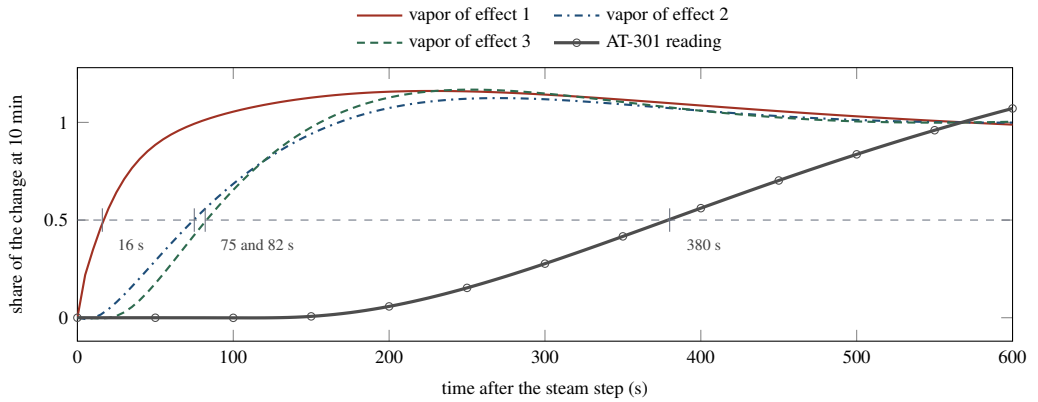


Figure 4.2 Vapor chain after a 0.10 t/h step of the motive steam in case 1, with the solids loop off and the instrument noise off. Each trace is the change since the step as a share of its mean over the tenth minute, 0.096, 0.062 and 0.055 t/h for the vapor of the three effects (solid, dash-dotted and dashed) and 1.80 % for the AT-301 reading (very thick, open circles), and the ticks mark where each crosses one half.

4.4.2 The Marginal Kilogram of Steam

The economy of the train is an average, and the thermocompressor makes the margin dearer than the average. At the design point the live steam evaporates 4.56 kg of water per kilogram and the motive steam alone 4.80 kg. Solved at steady state with the feed and the levels fixed, 0.10 t/h more motive steam evaporates 0.24 t/h more water, a marginal economy of 2.41 kg/kg, and 0.20 t/h more evaporates 0.45 t/h, 2.23 kg/kg. The extra steam heats the chest from 72.14 to 73.15 °C, which raises the pressure the jet must reach and lowers its entrainment from 1.566 to 1.530 kg/kg, so each added kilogram of motive steam brings less recycled vapor with it. The size of the effect belongs to the illustrative characteristic of Equation (4.6), in which the entrainment falls as the compression ratio rises. The bound of Equation (4.10) counts that recycle, and the train reaches 94.0 % of it at the design point, 92.6 % after 20 h of fouling (4.14 against 4.47 kg/kg) and 95.5 % at 13 t/h (5.37 against 5.62 kg/kg).

4.4.3 The Temperature Budget of the First Effect

The product temperature limit applies to the first effect, but the first effect's temperature is set below it. Reading the staircase upward from the condenser gives Equation (4.11).

$$T_1 = \theta_3 + \mathrm{BPE}_3 + \Delta T_3 + \mathrm{BPE}_2 + \Delta T_2 + \mathrm{BPE}_1 \tag{4.11}$$

where $\Delta T_i = \theta_{h,i} - T_i$ is the temperature difference through calandria i. At the design point this is $47.76 + 1.76 + 7.75 + 0.39 + 7.43 + 0.23 = 65.32\,^{\circ}\mathrm{C}$, 4.18 K below the 69.5 °C ceiling. The drop through effect 1 and its deposit do not appear, because they lie above T_1 and lift the steam chest instead. Fouling therefore spends the margin through the second and third effects, as shown in Figure 4.3. When the ceiling binds in case 7 at 14.9 h, $\Delta T_2 + \Delta T_3$ has grown from 15.18 to 19.29 K, while θ_3 is still 47.77 °C and the three elevations total 2.34 K against 2.39.

Table 4.3 separates the two consequences of fouling at the deposits reached after 20 h. The deposit in effect 1 alone lifts T_1 by 1.19 K, because a hotter chest entrains less and sends more of effect 1's vapor down the train, and it costs 0.38 kg/kg of economy. The deposits in effects 2 and 3 lift T_1 by 4.20 K and cost 0.16 kg/kg. With all three in place, holding 48 % at 20 t/h needs $T_1 = 71.10\,^{\circ}\mathrm{C}$, above the 70 °C limit, so late in the cycle the evaporator can cut its feed, run hot or leave the product thin, and nothing else.

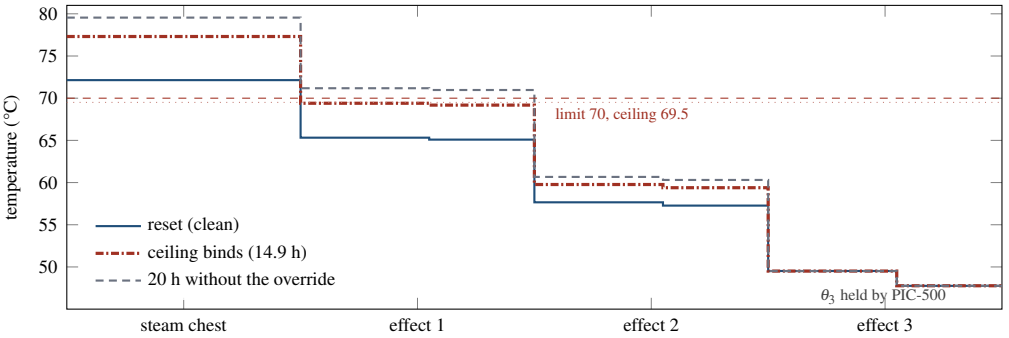


Figure 4.3 Temperature staircase of case 7 read from the engine. Each effect is drawn as its boiling product at T_i and then its vapor at θ_i, one boiling-point elevation lower, at the reset (solid), when the ceiling binds (dash-dotted) and at 20 h without the override (dashed), and the drops between the steps are the temperature differences through the calandrias. From the reset to the moment the ceiling binds, the drops through effects 2 and 3 widen from 15.2 to 19.3 K over a bottom held at 47.8 °C, and without the override the first effect reaches 71.18 °C at 20 h.

Table 4.3 Steady State at 20 t/h and 48 % With the Deposits of 20 h Placed in One Effect at a Time

Deposits in	T_1 (°C)	θ_s (°C)	R_e (kg/kg)	$\dot{m}_m$ (t/h)	ε (kg/kg)
none	65.32	72.14	1.566	3.39	4.56
effect 1	66.51	74.78	1.187	3.71	4.18
effects 2 and 3	69.52	76.40	1.509	3.51	4.40
all three	71.10	79.44	1.130	3.86	4.03

R_f = 1.27, 1.38 and 1.89 × 10^{-4} m^2 K/W, the values of case 7 at 20 h.

🕮 **Pause.** Try Exercise 4.3 before reading on.

4.5 Implemented Controller

Every $\Delta t_c = 5$ s, once per ten physics steps and first at 5 s after a priming execution at the reset, the controller executes ten PI loops, a ratio station, a wetting-floor function and a supervisor, and the integrals advance by that interval. Within a physics step a scripted event that is due comes first, then the controller when a scan is due, then the integration, then the checks for dry-out, sump levels and the temperature limit, and last the outputs and the logged row.

4.5.1 Instruments

No loop sees the state directly. Each transmitter follows its true value through an exact first-order lag, and colored noise, itself filtered to first order and refreshed at every control step, is added to the result. FT-200 and FT-100 lag 1 s with 0.3 % and 0.5 % of reading, the effect thermometers lag 5 s with 0.04 K, the level transmitters are damped 5 s with 0.5 % of span, FT-301 to FT-303 lag 1 s with 0.5 %, PT-500 lags 1 s with 0.15 mbar, TT-400 lags 3 s with 0.04 K, and the refractometer AT-200 lags 30 s with 0.02 % solids. LT-103 may carry an unmeasured bias. The densitometer AT-301 is the framework's shared sampled analyzer fed by a transport delay keyed to the cumulative product volume $\int L_3/\rho(w_3)\,\mathrm{d}t$, with $\rho(w) = 1/[(1-w)/1000 + w/1600]$ in kg/m^3, so the concentrate it sees left effect 3 one line volume earlier. It draws a sample every 5 s, publishes it 5 s later with 0.04 % of white noise and holds it, so at the design flow its reading is about 90 s old. One parameter scales all of the noise.

Table 4.4 Pairing, Direction and Shipped Tuning of Each Loop

Tag	CV	MV	a	K_c	τ_I, output
FIC-200	F	u_F	+1	2	0.1 min, 0–100
FIC-100	$\dot{m}_m$	x_s	+1	5	0.1 min, 0–100
AIC-301 steam	w_{AT}	trim a	+1	0.04	10 min, $-ff$ to $C-ff$
AIC-301 feed	w_{AT}	F_{SP}	−1	0.12	12 min, 6–30
TIC-601	T_1	steam limit	+1	0.1	3 min, 0 to D
FY-700	w_{AT}	feed limit	−1	0.12	6 min, 6 to F_{dem}
LIC-101 to 103	ℓ_i	u_{pi}	−1	0.6	20 min, 0–100
TIC-400	T_{pre}	x_p	+1	5	0.5 min, 0–100
PIC-500	P_3	x_c	−1	2	1 min, 0–100

Gains in % per t/h, % per t/h, t/h per %, t/h per %, t/h per K, t/h per %, % per %, % per K and % per mbar, in the order of the rows. Flow outputs in t/h. The tight level alternative is $K_c = 6$ with $\tau_I = 1$ min.

4.5.2 The PI Algorithm

All ten loops use the shared velocity-form PID law of Section 1.6.2, Equations (1.11) to (1.14), with no derivative action, so the running sum equals the proportional term. The action a is -1 for the loops whose actuator must rise with the measurement, the three level loops, PIC-500, the feed-paired AIC-301 and FY-700, and $+1$ for the others. Windup is removed from the integral term alone, by back-calculation whose tracking time equals τ_I, and every loop here has integral action. The clamp limits what is emitted and nothing else, and no loop here uses the shared law's optional slew limit. A loop in MANUAL tracks the operator's value, so the change back to AUTO is bumpless. Table 4.4 gives each loop's pairing, direction and shipped tuning.

4.5.3 The Steam Demand

On steam pairing, AIC-301 trims a steam-to-feed ratio. FFC-302 turns the measured feed into the motive steam the mass balance asks for, as shown in Equation (4.12).

$$\begin{aligned} ff &= F_m\,(1 - w_{F,m}/w_{SP})/\hat{\varepsilon} \\ D &= \mathrm{clamp}(ff + a,\ 0,\ \dot{m}_{m,max}) \end{aligned} \tag{4.12}$$

where F_m is FT-200, $w_{F,m}$ is AT-200 with the feed-solids compensation on and the design 9 % without it, $\hat{\varepsilon} = 4.8$ kg/kg of water per kilogram of motive steam, a is AIC-301's output and D the steam demand, with $ff = 0$ when the ratio is off. The estimate is the design economy of the motive steam, $16.25/3.39 = 4.80$, so at the design point the ratio alone asks for 3.39 t/h and the trim rests at zero. Because it is an average, a drop of the feed solids from 9.0 to 8.4 % makes the ratio add 0.052 t/h where the steady state needs 0.076 t/h. The trim is limited to $-ff$ and the steam cap C less ff, switching the ratio on or off moves its term into the integral so the demand does not jump, and a change of pairing, or of the solids loop's state, makes the loop track for one step. On feed pairing AIC-301's output is the feed setpoint and the motive steam is its own setpoint. The feed then becomes the throughput manipulator of Section 1.4.3, moved by a quality loop.

4.5.4 The Ceiling and the Throughput Supervisor

TIC-601 is a high limit on the steam demand. Its setpoint is the ceiling $T_{lim} = 69.5\,^{\circ}$C, its measurement TT-101, and its output is clamped between zero and D, so while the product is cool it rests on the clamp at the demand and its own back-calculation keeps it from winding up. FIC-100 receives $\min(D, u_O)$. The override counts as limiting once its unclamped output falls 0.002 t/h below the demand, and it stops once that output returns to 0.03 t/h above it. FY-700 then acts on the feed in the same way. While the steam is capped, by the override or at 6 t/h, a second solids loop with its setpoint 0.3 % below w_{SP} computes a feed limit between 6 t/h and the operator's throughput F_{dem}, which

approaches the feed setpoint at 0.5 t/h per minute, and FIC-200 receives $\min(F_{dem}, u_T)$. Once the cap is released the limit walks back up at the loop's own pace. The supervisor declares CIP due while the override is limiting and either the feed cut exceeds 5 % or AT-301 reads more than 1 % below its setpoint, counted by a leaky timer that must reach 300 s, so a brief release does not restart the count. A feed rate cut by a selector when an equipment limit binds is also the structure of the engine and rotor overrides in Volume 4, Chapter 4, and Volume 4, Chapter 5 pairs torque and die-pressure overrides with a throughput supervisor of the same kind.

4.5.5 Levels, Preheat, Condenser and the Wetting Floor

LIC-101 to LIC-103 set the three pumps from the sump levels. The sumps hold 500, 400 and 260 kg between empty and full, 2.7, 3.2 and 4.2 min of outflow at the design point, so proportional action alone would return the levels with time constants of 2.3, 2.5 and 3.3 min at the averaging gain and of 14, 15 and 20 s at the tight one. Section 1.4.8 shows why the PI form of such a loop passes flow variation on, enlarged near its natural frequency. TIC-400 holds the preheated feed at 67 °C with the preheat steam, and PIC-500 holds effect 3 at 110 mbar, a saturation temperature of 47.8 °C, with the cooling water. FY-800 is protection logic, live in both modes when it is switched on, which sets each recirculation to $R_i = \mathrm{clamp}[(1+m)\Gamma_{min}A_i/L_t - L_{in,i,m},\ 0,\ R_{max}]$ with $m = 15\,\%$ and the inflow measured by FT-200, FT-301 or FT-302.

4.5.6 What Each Model Knows

The equations of Section 4.3 form the simulation model. The classical solids loop has no fitted dynamic model. Its process paths were measured here by open-loop steps from the reset state of case 1, with the solids loop off and the noise and the fouling off. By a two-point fit at 28.3 and 63.2 % of the change after 89 min, a 0.10 t/h step of the motive steam moves the true solids at AT-301 by 33.0 % per t/h with a time constant of 6.1 min and an apparent dead time of 4.3 min. For the feed, with its setpoint ramp at the 10 t/h per minute maximum so that the step is complete in 6 s, the gain is −8.3 % per t/h from a 1 t/h cut and −7.1 % per t/h from a 1 t/h increase, with 5.9 and 5.0 min for the cut. The two paths differ far more in gain than in time. The steam raises the evaporation of all three effects within two minutes, while a feed change concentrates effect 1 at once and reaches the others through the liquid, and with tight level loops the feed path's apparent dead time falls to 1.3 min. The shipped tunings give loop gains KK_c of 1.32 on steam and 1.0 on feed. The classical controllers use the mass balance with an average economy in Equation (4.12), the wetting requirement of FY-800 and the 0.3 % offset of FY-700, and none of them contains the falling entrainment of Section 4.4.

4.5.7 Model Predictive Control

A separate supervisory model predicts AT-301 and TT-101 from motive steam and feed requests, within the MPC option that Section 1.6.3 describes in general. Multivariable evaporator supervision motivates this comparison [11], while the receding-horizon form follows industrial MPC [19]. Central steps of $\pm 0.02\,\mathrm{t/h}$ steam and $\pm 0.2\,\mathrm{t/h}$ feed were applied after 120 min with clean calandrias, noise off, averaging levels and the quality and protective supervisors off. Four first-order paths were fit over 60 min. In output order (reported solids, first-effect temperature) and input order (steam, feed), their coefficients are

$$K = \begin{bmatrix} 33.454 & -8.465 \\ 8.239 & -1.121 \end{bmatrix}, \qquad \tau = \begin{bmatrix} 6.078 & 5.463 \\ 6.031 & 5.347 \end{bmatrix},$$
$$\theta = \begin{bmatrix} 4.234 & 5.264 \\ 0 & 5.548 \end{bmatrix}, \qquad G_{ij}(s) = \frac{K_{ij} e^{-\theta_{ij} s}}{1 + \tau_{ij} s}. \tag{4.13}$$

Gains have units of percentage points or kelvin per t/h, and times are in minutes. The fitted RMS errors are 0.0114 % and 0.0467 % for solids, and 0.00281 and 0.006 27 K for temperature. The implemented

model rounds the steam delay to 4 min for solids and the shared feed delay to 5.5 min, giving four lag states and nineteen delay cells. Independent replay gives solids RMS errors of 0.0125 and 0.0481 % for these rounded paths. This approximates the measured paths, including transport and reporting. It does not reconstruct the true composition.

Every 0.5 min, measured flows advance the discrete model about the flows and readings at activation. Fast flow tracking is assumed when future requests enter those same paths. A bias b_i for each output is updated as $b_i^+ = b_i + 0.2(y_{i,m} - \hat{y}_i - b_i)$, with $y_{i,m}$ the current instrument reading and $\hat{y}_i$ its nominal prediction. This corrects output offsets, without the general disturbance-model guarantees discussed in [20]. Changing plant parameters does not change K, τ or the delay cells. Neither feed composition nor a future disturbance enters this predictor.

The plan covers 30 min in sixty steps and twelve blocks of $(1,1,1,1,2,2,3,4,6,9,15,15)$ steps. For steam and feed requests u_s, u_f in t/h, the objective is

$$\begin{aligned} J = \sum_{k=1}^{60} \big[& (\hat{w}_k - w_{SP})^2 + 0.001(u_{s,k} - u_{s,0})^2 \\ & + 0.5(u_{f,k} - F_{SP})^2 \big] \\ + \sum_{j=1}^{12} & \big[2(\Delta u_{s,j})^2 + 0.1(\Delta u_{f,j})^2 \big] \\ + 10^5 \sigma_T^2 & + 10^4 \sigma_T , \end{aligned} \tag{4.14}$$

where $\hat{w}$ is biased predicted solids in percent, $u_{s,0}$ is the activation steam flow, F_{SP} is requested throughput, and $\sigma_T \geq 0$ is one temperature slack shared by the entire horizon. The weights apply to these engineering units. The predicted band is $\hat{T}_{1,k} \leq T_{lim} + \sigma_T$. Steam requests lie between zero and 6 t/h, feed between 6 t/h and the smaller of 30 t/h and F_{SP}, and block changes cannot exceed 0.10 and 0.25 t/h, respectively. Reduced run capacities replace the command maxima. If requested feed is below 6 t/h, it also lowers the feed minimum. A 10^{-8} diagonal ridge regularizes the quadratic program.

The plan replaces AIC-301's steam demand and can lower the feed request. All inner loops and selectors remain. AIC-301 tracks the applied steam request. A failed, nonoptimal, malformed, nonfinite or out-of-range plan is rejected, including invalid later moves. The first failed scan retains both applied requests, then feed returns at its existing ramp while the tracked PI controls steam. The next valid plan resumes supervision. The optimizer is active only in Auto with steam pairing and solids supervision enabled.

4.6 Cases and Their Measured Outcomes

The original eight cases and the shift appear in Table 4.5. Those original cases start from one reference configuration, steam pairing with averaging levels, the override and FY-700 on, and the ratio and recirculation off, and each departs from it only where its row says. Fouling runs at the design rate in every case, so every steam value read after an hour carries it. An hour of fouling at the design point needs 0.019 t/h more motive steam, or at fixed steam and feed would take the solids from 48.0 to 47.38 %. Every number in this section was read from the engine itself, run without its interface at the default seed, with each setting that departs from a case changed at $t = 0$ before the run starts, as a reader does before pressing Run (Section 1.6.4), and Table 4.6 gathers the scorecard's tiles case by case.

4.6.1 The Chain and the Two Handles

Case 1 prints the chain of Section 4.4 on the stopwatch beside the staircase, which scans every 5 s with the noise on and reads 20, 75, 70 and 400 s. Effects 2 and 3 arrive together or a scan apart, in either order depending on the noise, and over seeds 1 to 5 AT-301 arrives after 375 to 390 s. Ten

Table 4.5 Cases, Their Events and What Each Teaches

#	Case and event	Lesson
1	Solids loop off, steam +0.10 t/h at 1 min	vapor against liquid
2	On steam, w_{SP} 48 to 49 % at 5 min	delay sets the pace
3	On feed, the same step	throughput as the MV
4	w_F 9.0 to 8.4 % at 5 min	feed forward what moved
5	Tight levels, LT-103 +10 % at 10 min	sumps as buffers
6	Tower 25 to 32 °C at 5 min	the staircase lifts
7	20 h from clean	ceiling, cut, CIP due
8	Feed 16 to 13 t/h at 5 min, ratio on	the wetting floor
9	Feed 20 to 22 t/h, steam/feed MPC	delayed-output plan
10	480 min shift	graded challenge

Table 4.6 Scorecard Tiles at the End of Each Run, Which Lasts 60 min Except 12 min for Case 1, 30 min for Case 5, 120 min for Cases 4 and 6 and 20 h for Case 7

Case and configuration	Feed (t)	Off (t)	Worst (%)	Hottest (°C)	ε	Dry (s)
1 as shipped	4.0	0.26	2.28	67.03	4.50	0
2 as shipped	20.0	0.26	0.84	67.04	4.53	0
2 K_c 0.08, τ_I 5	20.0	2.00	2.52	67.04	4.53	0
2 K_c 0.02, τ_I 20	20.0	0.30	0.97	67.04	4.54	0
3 as shipped	19.9	0.30	0.96	67.04	4.54	0
3 K_c 0.16, τ_I 10	19.8	0.28	0.92	67.04	4.54	0
4 as shipped	40.0	0.35	1.18	67.05	4.51	0
4 ratio	40.0	0.35	1.19	67.05	4.51	0
4 ratio and compensation	40.0	0	0.38	67.05	4.51	0
5 tight	10.0	0	0.58	67.03	4.55	0.5
5 averaging	10.0	0	0.09	67.03	4.55	0
6 as shipped	40.0	0	0.74	67.67	4.48	0
6 12 h into the cycle[a]	39.2	1.49	1.24	69.64	4.24	0
7 as shipped	397.2	0	0.80	69.50	4.31	0
7 FY-700 off	399.9	17.39	5.86	69.46	4.31	0
7 override off	399.9	0	0.36	71.18	4.29	0
8 as shipped	13.6	0.61	1.94	67.06	5.25	2670
8 recirculation	13.6	0.75	2.49	67.06	5.28	0

Off: product outside ±1 % of the setpoint. Worst: largest error of the true solids at AT-301 after 10 min. ε: economy since reset, kg/kg.
[a] Hours since CIP at reset set to 12 before the run.

minutes after the move the chest and the three effects stand 0.81, 0.69, 0.54 and 0.40 K warmer and the true solids at AT-301 have climbed from 48.1 to 50.1 %, and to 51.3 % by 30 min, with nothing correcting them. Stepping the motive steam back down by 0.10 t/h once the case has settled, at 60 min, gives arrivals of 20, 75, 80 and 390 s on the same stopwatch, with effects 2 and 3 again within a scan of each other and AT-301 again last.

In case 2 the solids setpoint moves from 48 to 49 % at 5 min. On steam, with 0.04 t/h per % and 10 min, the true solids reach 48.9 % after 9.3 min and peak at 49.13 %, with a scorecard IAE of 11.9 % min over the hour, while the motive steam rises from 3.39 to 3.43 t/h, of which 0.030 t/h is the step's steady-state requirement and the rest mostly the hour's fouling. Doubling the gain and halving the integral time reaches 48.9 % after 6.0 min but swings between 46.48 and 51.31 % and has not settled by 60 min (IAE 61.3), and 0.02 t/h per % with 20 min reaches only 48.67 % in the hour (IAE 29.5). The delay and the holdups set the pace, and the gain chooses how the loop behaves inside it. The crossing time moves with the instrument noise, from 9.6 to 11.8 min over seeds 1 to 5 and 10.1 min with the noise off.

Case 3 pairs AIC-301 with the feed at 0.12 t/h per % and 12 min. The same step reaches 48.9 %

after 12.9 min, peaking at 49.01 % (IAE 16.1), and the feed settles near 19.85 t/h, so the hour processes 19.86 t of milk against 19.97 t in case 2. Most of the difference in speed is the tuning. At the steam loop's loop gain and integral time, 0.16 t/h per % and 10 min, the feed-paired loop reaches 48.9 % after 9.7 min, 0.3 min behind steam pairing, and peaks at 49.27 % against 49.13, while a gain of 0.25 reaches it after 7.8 min and overshoots to 49.63 %. The 0.3 min lies inside the spread the noise gives either loop, and with the noise off the two cross at 10.3 and 10.1 min. The cost does not go away. At steady state one more percent of solids costs 0.12 t/h of feed at fixed steam or 0.030 t/h of motive steam at fixed feed, and the feed pairing also cuts the feed for the fouling, which is why case 3 ends the hour 0.15 t/h below the design feed.

> **TRY IT IN THE APP** **3 · The Same Loop on Feed Rate**
>
> Load the scenario and press Run. At 5 min the solids setpoint moves from 48 to 49 %, and AIC-301 moves the feed instead of the steam. The true solids reach 48.9 % after 12.9 min and peak at 49.01 %, while the feed settles near 19.85 t/h, below the design 20 t/h.

4.6.2 Feed Solids and the Ratio

In case 4 the feed solids fall from 9.0 to 8.4 % at 5 min. More water must now leave each tonne of feed, 16.50 t/h in all against 16.25, which at steady state needs 3.46 t/h of motive steam against 3.39. Without a feedforward the loop waits for AT-301 and the true solids fall to 46.82 % at 17.3 min. The ratio alone follows the feed flow, which did not change, and gives the same run to within the flow transmitter's noise, a fall to 46.81 %. With the feed-solids compensation the ratio raises the steam as soon as AT-200 sees the thinner milk, the product dips only to 47.62 % at 21.1 min and nothing goes off specification, the IAE falling from 28.2 to 15.3 % min. Before the dip the product barely rises, to 48.01 % at 12.3 min, because the steam acts before the thinner milk has reached effect 3. The trim still supplies about a third of the steam change, because the ratio's average economy asks for 0.052 t/h of the 0.076 t/h the plant needs.

Pause. Try Exercise 4.2 before reading on.

4.6.3 Tight Against Averaging

Case 5 starts with tight level loops and a steady feed. In the first 10 min each loop turns its transmitter's boiling noise into pump speed, the transfer flows vary with standard deviations of 0.78 and 0.74 t/h, the product pump runs between 25 and 62 %, and the product flow to the dryer swings between 2.06 and 4.89 t/h around its 3.75, a standard deviation of 0.60 t/h (0.44 to 0.50 t/h over seeds 1 to 5). The swings reach the concentrate, which wanders between 47.45 and 48.60 %, and at 19.8 min they take effect 3's film below its floor for one 0.5 s step. When LT-103 starts to read 10 % high at 10 min, the tight product pump drains effect 3's sump at once, reaching its 7.97 t/h limit at 10.2 min. With the averaging tuning the product flow's standard deviation is 0.023 t/h and that of the true solids 0.056 % (0.012 to 0.034 % over seeds 1 to 5), and the same bias drains the sump slowly, peaking at 4.23 t/h. Either way the true level settles near 39 % while LT-103 reads about 49, because no level loop can see its own transmitter's bias. The variation a tight loop passes on grows along a chain of inventories, which Chapter 11 measures stage by stage for ordering rules.

> ✦ DID YOU KNOW? **Tight Level Loops Spoil the Concentrate**
>
> From the simulator: in case 5, tight level loops leave a worst solids error of 0.58 % and 0.5 s of broken film, while averaging loops leave 0.09 % and none. Holding the sumps exactly passes the boiling noise on as flow (Table 4.6).

4.6.4 A Warm Condenser

In case 6 the cooling tower warms from 25 to 32 °C at 5 min, and the water reaching the condenser follows through its 15 min lag. PIC-500 opens the cooling water until the valve saturates at 28.0 min, and from then on the pressure of effect 3 floats up to 120.9 mbar. After two hours the chest and the three effects stand 2.54, 2.35, 2.11 and 1.85 K warmer, the entrainment has fallen from 1.57 to 1.49 kg/kg, the economy from 4.56 to 4.42, the motive steam has risen from 3.39 to 3.49 t/h, and the product dipped to 47.26 % at 40.2 min while the effects took up the heat for their new temperatures. The growth of the rise toward the top of the staircase is the fouling of those two hours. With the fouling off the same warming lifts the chest and the three effects by 1.76, 1.72, 1.72 and 1.73 K, the entrainment falls only to 1.54 kg/kg, the economy to 4.48 and the motive steam rises to 3.45 t/h, so the condenser moves every step together, as Equation (4.11) requires. On a clean evaporator the first effect ends at 67.7 °C. The hours since CIP are a start-up parameter, and setting them to 12 h before the run starts the case twelve hours into a fouling cycle, with T_1 at 68.21 °C. The same lift then puts the first effect on the override at 32.0 min, the feed is cut to 19.15 t/h, the product dips to 46.76 % and 1.49 t go off specification.

4.6.5 Twenty Hours of Fouling

Case 7 runs 20 h from clean at 20 t/h. At 6, 12 and 15 h the calandrias keep 91 to 92, 82 to 84 and 78 to 81 % of their clean film coefficients, the chest climbs from 72.1 to 74.0, 76.1 and 77.3 °C, the entrainment falls from 1.57 to 1.45, 1.31 and 1.24 kg/kg, the economy from 4.56 to 4.42, 4.25 and 4.17, and the motive steam rises from 3.39 to 3.49, 3.64 and 3.71 t/h. The first effect climbs from 65.3 to 66.8 and 68.4 °C and meets the 69.5 °C ceiling at 14.9 h, when the motive steam has peaked at 3.74 t/h of its 6, so the steam supply is not what runs out. From there TIC-601 holds the steam, lowering it to 3.51 t/h by 20 h, the product never passes 69.50 °C, and FY-700 cuts the feed to keep the solids in specification, never below 47.20 %. Once the cut has stayed beyond 5 % for five minutes the supervisor declares CIP due, at 19.6 h, and at 20 h the feed is 18.88 t/h, while the economy of 4.14 and the calandrias' 72, 73 and 75 % of their film coefficients appear in Figure 4.4.

Holding 48 % at 20 t/h this late in the cycle is infeasible within the temperature limit, and the two ways of pretending otherwise are both measured. Without FY-700 the product falls to 42.1 % by 20 h and 17.4 t go off specification, with CIP declared on the solids at 15.8 h. Without the override the first effect passes 70 °C at 16.7 h and reaches 71.18 °C, close to the temperature Table 4.3 gives for the 20 h deposits at the full rate (71.10 °C). The same trade between temperature and throughput appears in the crude preheat train of Volume 11, Chapter 3, where a saturated fuel valve leaves the charge rate as the last handle on the column inlet temperature.

Lowering the bottom of the staircase works the other way, as Equation (4.11) predicts. With the effect 3 pressure setpoint at 100 mbar, set before the run, the case starts with θ_3 at 45.88 °C, the first effect peaks at 68.27 °C, the override never acts and the full 20 t/h is processed for the 20 h, with an economy since reset of 4.41 against 4.31.

4.6.6 Turndown Into the Wetting Floor

Case 8 starts at 16 t/h with the ratio and its compensation on, where effect 3's film runs at 1.14 times its floor of 0.08 kg/(m s), and lowers the feed setpoint to 13 t/h at 5 min, ramping at 0.2 t/h per minute. Effect 3's film breaks at 15.3 min, when the feed has fallen to 13.93 t/h, and stays broken for 2670 s of the hour, at as little as 0.85 of the floor, so the dry share fouls fast and effect 3 ends the hour at 0.961 of its clean film coefficient. With recirculation FY-800 returns 1.12 t/h to the top of effect 3 at the end

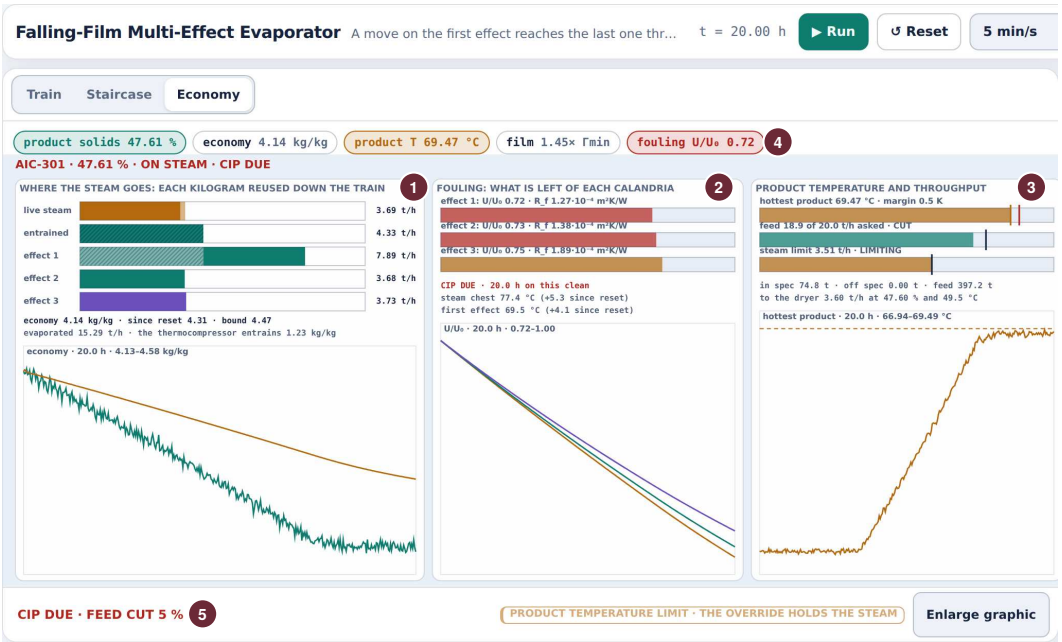


Figure 4.4 The evaporator in case 7, "Twenty hours of fouling," at $t = 20.00$ h with no control changed, in the Economy view. The steam ladder shows 3.69 t/h of live steam, 4.33 t/h of effect 1's vapor entrained at 1.23 kg/kg, and 7.89, 3.68 and 3.73 t/h made by the three effects, 15.29 t/h in all, for an economy of 4.14 kg/kg against 4.31 since reset and a bound of 4.47, and its sparkline falls through the run. The fouling panel gives 0.72, 0.73 and 0.75 of the clean film coefficients, with the chest at 77.4 °C and the first effect at 69.5 °C, 4.1 K above its reset. The product panel gives the hottest product at 69.47 °C, 0.5 K from the limit, the feed cut to 18.9 of the 20.0 t/h asked and the steam limited to 3.51 t/h, with 74.8 t in specification and none off of 397.2 t fed, and its sparkline sits on the preheater's 67 °C until the first effect overtakes it, then rises and flattens on the 69.5 °C ceiling. The badges add the worst film at 1.45 times its floor, and the status line reads CIP DUE · FEED CUT 5 %. The screen is cropped to its header and plant view. Callouts: (1) the steam ladder, (2) the fouling panel, (3) the product panel, (4) the badges and (5) the status line.

of the hour, the film never falls below 1.12 times the floor, and effect 3 keeps 0.988. Recirculation protects the heat transfer, not the concentration. After the ramp the solids wander between 47.06 and 49.94 % as shipped and between 46.79 and 50.49 % with recirculation, because the economy rises from 4.99 to 5.37 kg/kg at the lower load as the thermocompressor entrains more. The ratio, built on 4.8, asks at 60 min for 2.20 t/h of motive steam where 1.84 t/h suffice, and the trim has to take back 0.37 t/h.

4.6.7 The Shift Challenge

The challenge runs 480 min at 20 t/h from clean. The feed solids drop to 8.4 % at 1 h and the tower warms from 25 to 31 °C from 3 h, and the shift starts on feed pairing with tight level loops and no feedforward. The target asks for the true solids within 48 ± 1 % from 10 min on, at least 158 t of feed, a product never above 70 °C, an economy since reset of at least 4.35 kg/kg and no film below the floor. The configurations measured on the shift are compared in Table 4.7.

As shipped the product swings between 46.51 and 48.79 %, a worst error of 1.49 %, only 155.5 t of feed are processed because the loop cuts the feed whenever the product runs thin, and the tight loops break effect 3's film for 13 s. The suggested configuration holds 47.38 to 48.06 %, a worst error

Table 4.7 Configurations Measured on the Eight-Hour Shift

Configuration	Solids (%)	Off (t)	Feed (t)	Hottest (°C)	ε	Dry (s)
as shipped	46.51–48.79	0.64	155.5	67.05	4.49	13
suggested[a]	47.38–48.06	0	160.0	69.35	4.40	0
steam, averaging, no feedforward	46.77–48.06	0.45	160.0	69.36	4.40	0
steam, averaging, ratio alone	46.77–48.06	0.45	160.0	69.35	4.40	0
steam, feedforward, tight	46.94–48.87	0.02	160.0	69.34	4.40	0.5
feed, averaging	46.52–48.05	0.62	155.5	67.05	4.49	0

[a] steam pairing, ratio with feed-solids compensation, averaging levels.

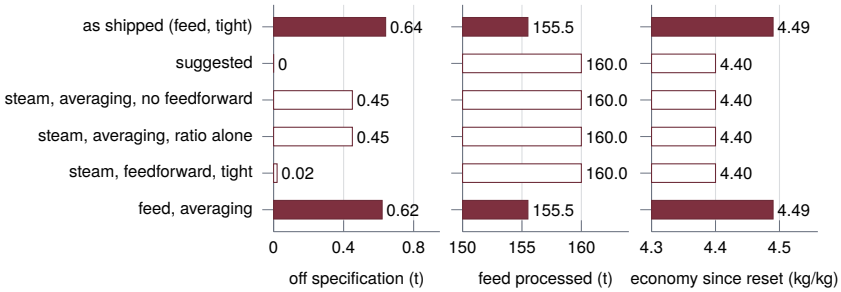


Figure 4.5 The eight-hour shift under the six configurations of Table 4.7. Dark bars hold the solids with the feed and white bars with the steam. The feed and economy axes start at 150 t and 4.3 kg/kg. Notice that both feed-paired runs show the higher economy and process less milk, while the suggested configuration alone sends nothing off specification.

of 0.62 %, processes all 160.0 t, peaks at 69.35 °C and ends at 4.40 kg/kg. Each of its three changes is needed on its own. Without the compensation, or without any feedforward, the product falls to 46.77 %, with tight levels to 46.94 % while effect 3's film breaks for 0.5 s (0 to 6.5 s over seeds 1 to 5), and on feed pairing even averaging levels leave only 155.5 t. The extra 4.4 t of milk cost 1.42 t of steam for 3.7 t more water, 2.6 kg/kg at the margin, so the shipped configuration's higher economy is throughput it gave up. Over seeds 1 to 5 the suggested configuration's worst error stays between 0.52 and 0.79 % and the shipped one's between 1.41 and 1.82 %. Figure 4.5 sets the six configurations side by side.

4.6.8 Steam and Feed Planned Through the Delayed Measurement

Case 9 requests 22 t/h instead of 20 t/h after 5 min, with averaging levels, compensated feedforward and recirculation. Identical seeds, measurements, limits and events are used for both structures. Table 4.8 reports 120 min runs, except 1200 min for fouling and 480 min for the suggested shift. Solids IAE uses the same reported measurement as the scorecard. Steam travel sums changes of the applied steam request after its selector, which differs from demand travel when the override binds.

On the throughput move, MPC reduces IAE from 54.92 to 20.28 % min and off-specification product from 1.123 to 0.199 t, with 43.689 versus 43.730 t processed. It plans around the delayed concentration response, as shown in Figure 4.6. The 22.40 versus 4.10 t/h steam-travel comparison also contains the cost of noisy feedforward. Disabling feedforward gives classical travel of 3.05 t/h, but IAE rises to 138.90 % min. MPC ignores that channel and its response is unchanged. Among nine hindsight classical settings ($K_c = 0.02, 0.04, 0.08$, $\tau_I = 5, 10, 20$ min), the smallest IAE is 44.57 % min at 0.08 and 10 min. This finite search establishes no global tuning optimum. Halving the physics step retains IAE 54.92070 versus 20.276 14 % min.

The predictive model omits AT-200's feed-composition compensation. On the suggested shift it therefore produces 0.466 t off specification, with worst error 1.225 %, and does not meet the

Table 4.8 Matched Classical and Predictive Supervision

Case, law	IAE (% min)	Travel (t/h)	Feed (t)	Off (t)	Plans
Throughput, Loops	54.92	22.40	43.730	1.123	0
Throughput, MPC	20.28	4.10	43.689	0.199	240
Setpoint, Loops	18.24	2.79	39.967	0.255	0
Setpoint, MPC	17.89	3.44	39.959	0.026	240
Feed solids, Loops	28.18	2.75	39.967	0.347	0
Feed solids, MPC	29.40	3.10	39.959	0.412	240
Warm water, Loops	25.90	2.75	39.967	0.000	0
Warm water, MPC	25.88	3.12	39.959	0.000	240
Fouling, Loops	236.71	19.85	397.249	0.000	0
Fouling, MPC	198.74	35.43	397.054	0.000	2400
Shift, suggested, Loops	66.79	82.92	159.962	0.000	0
Shift, suggested, MPC	89.64	12.43	159.924	0.466	960

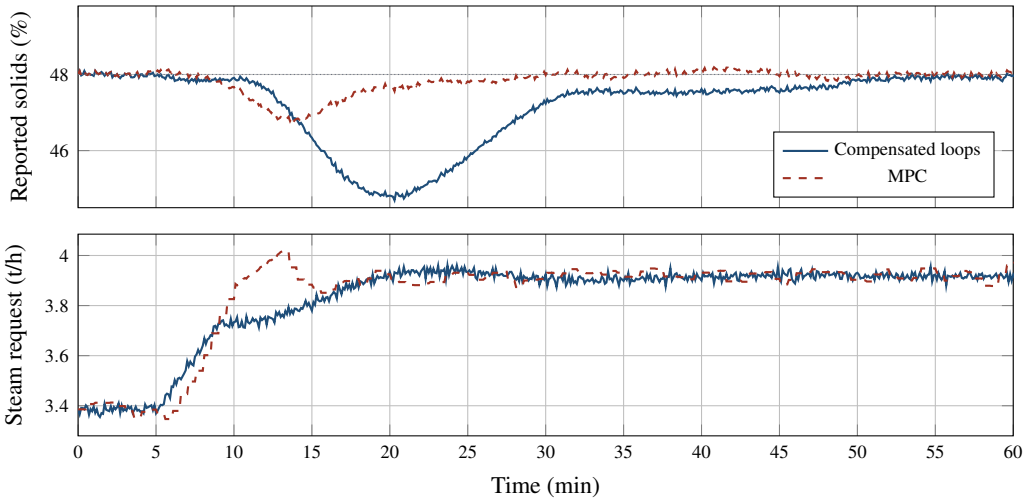


Figure 4.6 Concentration and steam requests after the throughput increase, compensated loops solid and MPC dashed, with the setpoint dotted. The first hour of the matched runs is shown.

unchanged challenge criterion. The suggested classical structure passes with no off-specification product and worst error 0.617 %. Selecting MPC on the as-loaded shift does not activate it because that case uses feed pairing. That run remains the original failure, rather than evidence of predictive control.

On fouling, the smaller IAE costs 35.43 t/h rather than 19.85 t/h of steam-request travel and 0.195 t of feed. Peak temperature is 69.546 °C versus 69.495 °C, with 65.6 versus 0 min above the 69.5 °C supervisory ceiling. Both stay below 70 °C. The fixed clean model and shared temperature slack do not guarantee the actual ceiling. The warm-water result is essentially tied, while the feed-solids case has greater IAE and off-specification mass under MPC.

No plan is rejected in these comparisons. Chrome averages 3.88 ms per solve over 240 plans, or 0.776 % of one core at unit playback. At the nominal 300 setting, solves alone require 2.33 cores. Actual playback on the test host reaches 117.6 simulated min/sec at 8.16 frames/sec, compared with 1.02 min/sec at 60.4 frames/sec at the unit setting. The highest setting is consequently a requested acceleration rather than a guaranteed rate.

4.7 Technology in Practice

What Measures It

The product is judged by its density. The vibrating-tube meter measures density so precisely that such meters often serve mainly as density meters and only secondarily as flowmeters, and the same instrument reports mass flow and the temperature of its tubes [21]. The other readings of the train are flows, temperatures, levels and one pressure, with the feed solids read by the refractometer AT-200. In the chapter AT-301 is the framework's shared sampled analyzer behind a transport delay keyed to the product volume, so at the design flow its reading is about 90 s old.

> **TECHNOLOGY** **Sensor: The Vibrating-Tube Density Meter**
>
> A vibrating-tube meter, the Coriolis flowmeter, keeps its tubes oscillating at their resonant frequency with a force coil. A denser fluid gives the tubes more mass, so they vibrate at a lower frequency, while the phase shift between two pickups gives the mass flow. A resistance thermometer on the tubes compensates the effect of temperature on the metal. Gas bubbles trapped in bent tubes spread the mass unevenly and cause errors in density and flow, and bent tubes may hold product in a way that is unacceptable in hygienic service, where straighter tubes fare better [21]. AT-301 in the chapter turns density into solids exactly, with 0.04 % of noise and a delay keyed to the product line.

What Moves It

Four kinds of final element act on the train. The spindle of the thermocompressor sets the motive steam, the feed pump sets the throughput, the transfer and product pumps move the liquid from sump to sump, and one valve sets the cooling water to the condenser. In the model every one of them follows its command through a first-order lag of 2 s, without stiction.

> **TECHNOLOGY** **Final Element: The Steam Jet and Its Spindle**
>
> An ejector drives a high-velocity gas or vapor such as steam through a tapered tube, which produces a vacuum at its throat [21]. In thermal vapor recompression, high-pressure steam compresses the vapor leaving an evaporator in such an ejector, and the mixture returns to the same unit as its heating medium. Part of the vapor must leave to keep the mass balance of the steam entering the unit [10]. In the chapter the spindle sets the motive flow under FIC-100 through a 2 s lag, and at the design point the jet compresses 25.05 kPa to 34.08 kPa. Real ejectors break down above a critical compression ratio, which the model does not reproduce.

Where the Controller Runs

Industrial loops are often nested or cascaded, so that the setpoint of one loop comes from another, and supervisory and lower-level loops run with cycle times from milliseconds to minutes. A distributed control system adds a supervisory level that oversees the controllers of local processes [22]. In the conventional structure of a processing unit, the dynamic constraint control above the basic loops combines PID algorithms, lead-lag blocks and high and low select logic, executed about every minute over basic controls executed every second, and model predictive control replaces that combination with a single controller [19]. The chapter's structure is of that conventional kind. Ten PI loops, a ratio station, a wetting-floor function and a supervisor execute every 5 s over a plant integrated every 0.5 s, and the low selects on the steam and the feed are its select logic. The optional predictive supervisor replaces only the steam demand of AIC-301 and leaves every inner loop and selector in place. Figure 4.7 draws the solids loop on its devices.

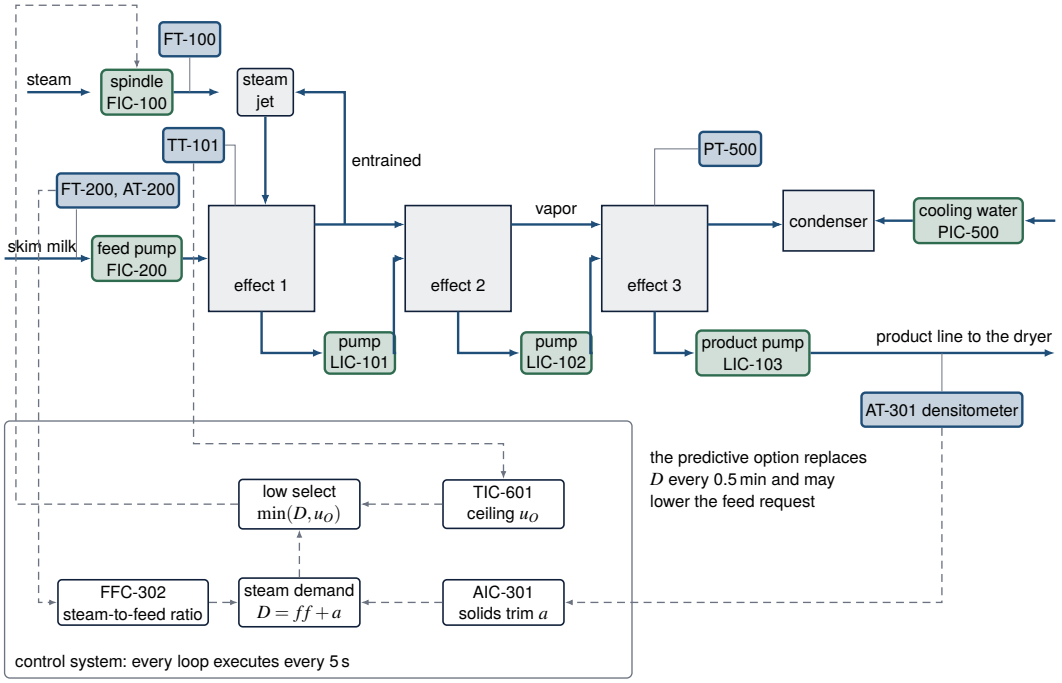


Figure 4.7 The solids loop on plant hardware. The ratio station turns the measured feed into the motive steam the mass balance asks for, AIC-301 trims it from the densitometer at the end of the product line, and the low select lets TIC-601 hold the steam down when the first effect reaches its ceiling. FIC-100 then moves the spindle of the steam jet. The feed, the three sumps and the pressure of effect 3 are held by their own loops on the feed pump, the transfer and product pumps and the cooling-water valve. Notice that the only reading of the product is the last device on the train, behind three effects and the product line.

> ⚠ **IN PRACTICE** **What Keeps an Evaporator Efficient**
>
> A dairy energy guide lists the common sources of inefficiency in evaporators: excessive venting, losses by radiation and convection, poor vacuum system performance, air and water leaks, fouling and poor separator efficiency. Its maintenance program prevents air leaks, because air does not condense and must be vented, cleans the heat transfer surfaces, stops water leaks that dilute the product and keeps the pressure profile at the optimum, since excess pressure raises the boiling point [10]. The chapter's condenser has no non-condensable gas and no vacuum pump, and case 6 shows how a warmer bottom lifts every step of the staircase.

What Is Modernizing It

Vapor recompression is done either by a mechanical compressor or by a steam jet ejector [23]. In mechanical vapor recompression the vapors are compressed by centrifugal compressors or turbo fans and a small amount of steam makes up the condensate formed during compression. Its steam economy can range from 10 to 30, against a typical 4 to 8 for thermal recompression, and it is most economical where electricity is cheap, while the steam jet is most economical where high-pressure steam is cheap. Membranes are a second direction. Reverse osmosis and ultrafiltration can concentrate a product before it reaches the evaporator, which lowers the water the evaporator must remove and so its energy [10]. The same guide puts the savings of process control at around 5 % or more for plants without updated control systems [10]. The chapter models neither a fan nor a membrane, and a fan across effect 1 would only replace the thermocompressor's recycle.

4.8 Limitations

The effects are well mixed, so the model's residence-time distribution is broader than a falling film's plug flow, and the vapor inventories, the swell of the boiling sumps and the flash of condensate are left out. The boiling-point elevation, the fouling law, the wetting floor and the thermocompressor characteristic are illustrative, the thermocompressor has no critical compression ratio, and the film coefficient does not fall with the viscosity of the concentrate.

The densitometer is exact apart from its delay and noise, with no laboratory check, and the pumps and valves are linear first-order actuators without stiction. Cleaning in place is an instantaneous reset, and mechanical vapor recompression is not modeled. The feedforward's economy estimate is fixed, so it over-steams at turndown, and the limits, sizes and capacities are teaching values for one train.

> **OPEN CHALLENGE** **Evaporation Without Live Steam**
>
> A 2022 industrial decarbonization roadmap of the United States Department of Energy names the electrification of evaporation and pasteurization as an important opportunity for food and beverage manufacturing, where these processes mostly run below 200 °C. It asks for studies of how a change of technology affects the final product, so that safety and quality are kept. Mechanically driven heat pumps such as vapor recompression already suit low-grade heat, but research is needed to extend them to higher temperatures [24]. The train of this chapter runs on live steam through a thermocompressor. Progress would be evaporation driven by electricity with a product shown to be unchanged.

The predictive supervisor uses one clean operating point and fixed delays, although product-line residence changes with flow. Output-bias correction does not estimate fouling-dependent gains or supply the omitted composition signal. The shift loss and the 65.6 min above the fouling ceiling quantify these restrictions.

> **OPEN CHALLENGE** **A Predictive Model That Ages With the Deposits**
>
> A survey of industrial model predictive control found a lack of methods to verify whether an identified model is adequate for control, or whether it has deteriorated significantly since the controller was commissioned. Only two adaptive algorithms had reached the market despite a strong incentive for a self-tuning controller, which the survey reads as the difficulty of adaptive control in the real world [19]. The predictive supervisor of this chapter keeps one clean model through a fouling cycle and spends 65.6 min above the supervisory ceiling. Progress would be a supervisor that detects when deposits have aged its model and updates it without losing the limit.

4.9 Conclusion

A three-effect milk evaporator is a train in which heat and concentration travel at different speeds, and the simulator records the true solids next to the densitometer's reading, which makes the gap between them measurable. With the design settings, 3.39 t/h of motive steam and 0.18 t/h of preheat steam evaporate 16.25 t/h, an economy of 4.56 kg/kg against a bound of 4.85. A steam step reaches half of its change in the vapor of the three effects after 16, 75 and 82 s and in the densitometer after 380 s, and the next kilogram of motive steam evaporates 2.4 kg against an average of 4.80. The first effect's temperature rests on the condenser and on the drops through the effects below it, so the deposits of a twenty-hour run lift it by 4.20 K from effects 2 and 3 and by 1.19 K from effect 1, which instead costs 0.38 kg/kg of economy. Over twenty hours the ceiling binds at 14.9 h and the supervisor declares CIP due at 19.6 h rather than run the product above 69.50 °C or off its solids. At equal loop gain the two pairings reach 48.9 % within 0.3 min of each other, inside the spread the instrument noise gives, and the feed pairing pays in milk. The shift improves from 0.64 t off specification and 155.5 t processed to none off and 160.0 t. The effects are well mixed and the fouling, wetting and thermocompressor laws are illustrative. Predictive supervision lowers throughput-step IAE from 54.92 to 20.28 % min, but produces 0.466 t off specification on a shift the compensated loops pass. Further work would

add plug flow in the tubes, a film coefficient that falls with viscosity, an ejector map with its critical compression ratio and a cleaning cycle with its hours offline. A concentration measured at the end of a chain has to be controlled through the whole chain.

KEY POINTS

- A steam move reaches the three vapors within two minutes, and the concentrate reaches the densitometer at the end of the product line only after about six.
- The next kilogram of motive steam evaporates 2.4 kg against an average of 4.80.
- The deposits of a twenty-hour run in effects 2 and 3 lift the first effect by 4.20 K, those in effect 1 by 1.19 K.
- At equal loop gain the steam and feed pairings reach 48.9 % within 0.3 min of each other, and the feed pairing pays in milk.

Where else this applies. Volume 4, Chapter 4 and Volume 4, Chapter 5 cut a feed rate when an equipment limit binds, and Volume 11, Chapter 3 trades temperature against throughput in the same way.

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4.10 Exercises

4.1 ⌕ Concept check · 1 min

In case 1 the motive steam steps up by 0.10 t/h with the solids loop off. The vapor made in effect 1 shows half of its change after 16 s, and the vapors of effects 2 and 3 after 75 and 82 s. Why does effect 1 answer first?

(a) Effect 1 holds the least liquid, so its boiling temperature rises fastest

(b) AIC-301 reads the densitometer and moves effect 1 before the others

(c) The thermocompressor draws more of effect 1's vapor as soon as its motive flow rises

(d) PIC-500 holds the pressure of effect 1, so its vapor follows the steam at once

4.2 ⌕ Concept check · 2 min

In case 4 the feed solids fall from 9.0 to 8.4 %. With the steam-to-feed ratio on and its feed-solids compensation off, the true solids fall to 46.81 %, the same run as with no feedforward. Why does the ratio alone not help?

(a) Its economy estimate of 4.8 kg/kg is too high, so its correction is too small

(b) It moves the motive steam, whose effect reaches AT-301 only after six minutes

(c) AIC-301 limits its trim to cancel the ratio's output after the disturbance

(d) It follows the measured feed flow, and the feed flow did not change

4.3 ⌕ Concept check · 2 min

Table 4.3 places the deposits of a twenty-hour run in one effect at a time. Those of effects 2 and 3 lift the first effect by 4.20 K, while the deposit of effect 1 alone lifts it by 1.19 K. Which statement explains the difference?

(a) The first effect sits on the condenser and the drops of effects 2 and 3, and its own drop lies above it

(b) Effects 2 and 3 have more heating area, so their deposits hold more resistance in total

(c) Deposits in effects 2 and 3 raise the boiling-point elevations of the concentrate

(d) The deposit of effect 1 lowers the entrainment, which cools the first effect's liquid

4.4 Theory and calculation · 6 min

The evaporator takes 20 t/h of skim milk to 48.0 % solids, and no solids leave with the vapor.

(a) Find the product flow and the water evaporated with feed at 9.0 %, and again with feed at 8.4 %. *Checkpoint:* 3.75 and 16.25 t/h, then 3.50 and 16.50 t/h.

(b) Find the motive steam that the compensated ratio of Equation (4.12) asks for at each feed solids, with $\hat{\varepsilon} = 4.8\,\mathrm{kg/kg}$, and its change. *Checkpoint:* 3.385 and 3.438 t/h, a change of 0.052 t/h.

(c) At steady state the thinner feed needs 0.076 t/h more motive steam. Find the water evaporated per added kilogram of motive steam for this disturbance, and the share of the steam change left to the trim of AIC-301. *Checkpoint:* About 3.3 kg/kg, and about one third.

4.5 Theory and calculation · 7 min

Use Equations (4.3) and (4.11) and the design point of Section 4.3.

(a) Find the boiling-point elevation of the product at 48 % solids. *Checkpoint:* 1.76 K.

(b) Add up the temperature budget of the first effect at the design point, with $\theta_3 = 47.76\,^{\circ}\mathrm{C}$, $\Delta T_3 = 7.75\,\mathrm{K}$, $\Delta T_2 = 7.43\,\mathrm{K}$ and elevations of 0.39 and 0.23 K in effects 2 and 1, and find the margin to the 69.5 °C ceiling. *Checkpoint:* 65.32 °C and 4.18 K.

(c) The effect 3 pressure setpoint is lowered from 110 to 100 mbar. Find the new θ_3 from the Antoine equation of Section 4.3. Without the override, case 7 at 110 mbar takes the first effect to 71.18 °C at 20 h. Estimate its peak at 100 mbar if every step of the staircase moves with the bottom, and say whether the ceiling would bind. *Checkpoint:* 45.88 °C, and about 69.30 °C, just under the ceiling.

4.6 Theory and calculation · 6 min

Effect 3's sump holds 260 kg between empty and full, and the product pump passes 8 t/h at full speed. Its design duty is 3.75 t/h, a command of 46.9 %. LIC-103 runs at 0.6 %/% with 20 min (averaging) or 6 %/% with 1 min (tight).

(a) Find the time constant with which proportional action alone would return the level, $M_{sump}/(K_c L_{max})$, for each tuning. *Checkpoint:* 3.25 min and 19.5 s.

(b) At 10 min in case 5 LT-103 starts to read 10 % high. Find the immediate change of the pump command from the proportional term, and the product flow it asks for, for each tuning. *Checkpoint:* Averaging: +6 %, 4.23 t/h. Tight: +60 %, the full 8 t/h.

(c) Once the loop has brought LT-103 back to its setpoint, find the true level and the concentrate drained from the sump. *Checkpoint:* About 40 %, and 26 kg.

4.7 App challenge · 8 min

Load scenario 1, Step the steam, time the chain, at the default seed and a speed of 1. The motive steam steps from 3.39 to 3.49 t/h at 1 min with the solids loop off.

(a) Run to 12 min and read the four half-change times that the vapor chain panel prints ten minutes after the move. *Checkpoint:* 20, 75, 70 and 400 s.

(b) Run on to 30 min and read the true solids at AT-301, the `product_solids_pct` column of the exported file. *Checkpoint:* 51.3 %.

(c) Run on to 60 min, set the Motive steam setpoint on the FIC-100 card back to 3.39 t/h, run to 72 min and read the panel again. *Checkpoint:* 20, 75, 80 and 390 s.

Accept times within one 5 s scan and solids within 0.05 %. Say why AT-301 always comes last.

4.8 App challenge · 8 min

Use the default seed and a speed of 5, and read the true solids from the "true at AT-301" trace or the `product_solids_pct` column. The solids setpoint steps from 48 to 49 % at 5 min.

(a) Load scenario 2, Solids loop on live steam, and run to 60 min as shipped. Read how long after the step the true solids first reach 48.9 %, their peak, and the Feed processed tile. *Checkpoint:* About 9.3 min, 49.13 % and 20.0 t.

(b) Load scenario 3, The same loop on feed rate, set the Solids gain on feed to 0.16 t/h per % and the Solids integral time on feed to 10 min before Run, and run to 60 min. Read the same three values. *Checkpoint:* About 9.7 min, 49.27 % and 19.8 t.

Accept crossing times within 0.2 min and peaks within 0.02 %. Compare the loop gains of the two runs and say what the feed pairing costs.

4.9 App challenge · 8 min

Load the last scenario, Challenge, an eight-hour shift, and run the full 480 min at the default seed and a speed of 60. Read the scorecard tiles Worst solids error, Feed processed, Hottest product, Economy since reset and Dry-out at the end.

(a) Run the shift as shipped, with feed pairing, tight level loops and no feedforward. *Checkpoint:* 1.49 %, 155.5 t, 67.05 °C, 4.49 kg/kg, 13 s.

(b) Reload the scenario. Before Run, set Solids held by to Live steam, turn the Steam-to-feed ratio and the Feed-solids compensation On, and set the three Level gains to 0.6 % per % and the three Level integral times to 20 min. Run the shift again. *Checkpoint:* 0.62 %, 160.0 t, 69.35 °C, 4.40 kg/kg, 0 s.

Accept the tiles as displayed. Say which targets the first run misses and what the second run's higher steam buys.

4.10 Application area · 4 min

At the design point 3.39 t/h of motive steam gives up 2.51 MJ/kg in the chest, 0.18 t/h of preheat steam gives up 2.20 MJ/kg, effect 1's vapor condenses at 65.09 °C and the jet entrains 1.566 kg/kg. The train evaporates 16.25 t/h.

(a) Find the latent heat $\lambda(\theta_1)$ and the bound of Equation (4.10), and compare it with the economy. *Checkpoint:* 2.347 MJ/kg, 4.85 kg/kg against 4.56 kg/kg.

(b) Find the bound with no thermocompressor ($R_e = 0$) and the same heat per kilogram of steam, and the live steam that a train at that bound would need for the same water. *Checkpoint:* 3.19 kg/kg and about 5.1 t/h.

4.11 Application area · 4 min

A falling film needs at least $\Gamma_{min} = 0.08\,\mathrm{kg/(m\,s)}$ of liquid per meter of wetted perimeter, and the tube bundle of effect 3 has 17.5 m of perimeter. FY-800 keeps each film 15 % above the floor by recirculation.

(a) Find the flow effect 3 needs to stay wet, and its margin at the design inflow of 7.46 t/h. *Checkpoint:* 5.04 t/h and 1.48 times the floor.

(b) At the end of case 8 with recirculation on, FY-800 returns 1.12 t/h to the top of effect 3. Find the inflow FT-302 measures and the share of the floor the film would receive without recirculation. *Checkpoint:* About 4.68 t/h, about 0.93 of the floor.

4.12 Review the agent · 5 min

An engineer asks an AI assistant whether the solids loop can be slowed down for thinner milk, and it replies as follows. "The live-steam economy is 4.56 kg/kg. The thinner feed of case 4 needs 0.25 t/h

more water evaporated, which takes $0.25/4.56 = 0.055\,\mathrm{t/h}$ of steam. The compensated ratio already adds 0.052 t/h, within 6 %. Detune AIC-301 to 0.02 t/h per % and 20 min, and the feedforward will carry the disturbance.” Find the flaw and say how to check it.