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CHAPTER 10

Inferential Moisture Control Near the Sticky Point of a Milk Powder Spray Dryer

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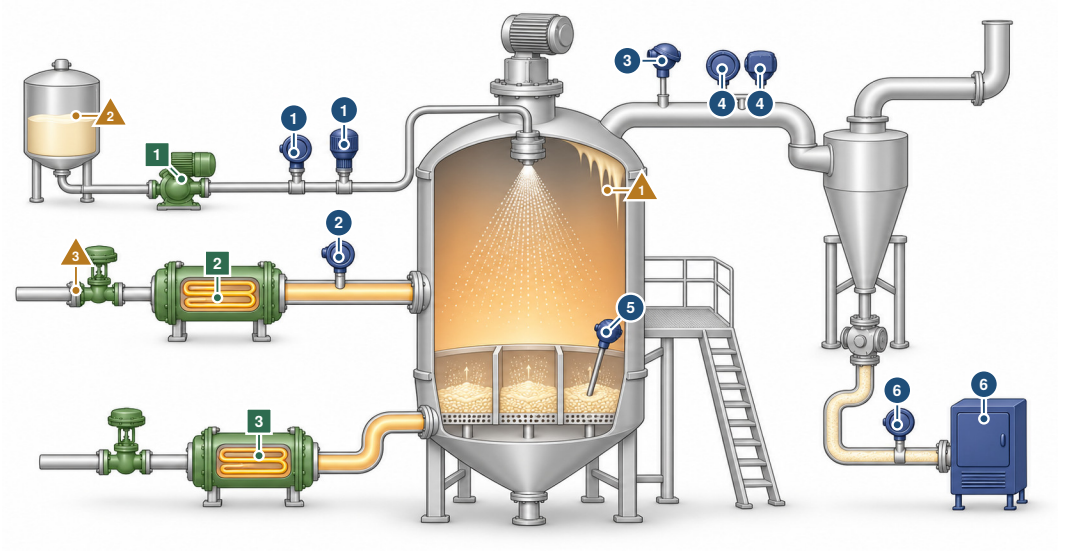
The app for this chapter
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CHAPTER 10

Inferential Moisture Control Near the Sticky Point of a Milk Powder Spray Dryer



The controller moves 1 feed pump for the milk concentrate 2 heater of the drying air 3 heater of the fluid bed air

The controller reads 1 feed flow and feed solids 2 inlet air temperature
3 exhaust temperature, held by the main loop 4 exhaust humidity and carbon monoxide 5 fluid bed temperature
6 powder sampled for the laboratory

What disturbs it 1 deposit on the hot roof 2 weaker concentrate from the evaporator 3 humid intake air

The exhaust temperature (3) answers within seconds, while the moisture of the powder reaches the laboratory (6) most of an hour later. Illustration, not to scale.

IN PLAIN TERMS Drying Milk by a Stand-In Temperature

The main idea. A spray dryer sprays thick milk into hot air, and the drops dry into powder in seconds. The plant steers by the temperature of the air leaving the dryer, because that reading comes at once.

The challenge. What matters is the water left in the powder, and the laboratory reports it most of an hour late. When the milk or the weather changes, the same air temperature means wetter powder, and powder that is too wet and hot sticks to the walls.

Why it matters. Sticky powder piles up on the hot roof of the dryer, where it can catch fire.

THREE WAYS TO READ THIS CHAPTER

Explore	11 min	the first page, the fact on the moisture rule (Section 10.1), the two history segments (Section 10.2), the try-it on the weaker concentrate and the try-it on the laboratory correction (Section 10.6), the fact on the laboratory alone and the key points
Study	65 min	the whole chapter with its three pause points and the twelve exercises at its end
Practice	25 min	the first page, the results (Section 10.6), Technology in Practice (Section 10.7), Limitations (Section 10.8) and the open challenge

The control question A spray dryer is steered by an exhaust temperature that answers in seconds and judged on a powder moisture that its laboratory reports most of an hour later, while its throughput is bounded by a sticky point that no instrument measures. When does the outlet temperature stand for the powder, and what do a soft sensor, a late laboratory, feedforward and overrides recover when it does not?

Learning objectives

- Explain why an outlet temperature held on its setpoint stops standing for the powder moisture when the concentrate or the intake air changes, and read the feedforward gains from the steady map.
- Compute the glass transition and the sticky margin of the particles leaving the chamber from the Gordon–Taylor rule.
- Trace how a laboratory result, sampled every 30 min and reported 40 min later, corrects a biased soft sensor, and what the bias leaves uncorrected.
- Compare feedforward, moisture feedback, overrides and a throughput optimizer on the campaign's tonnage, sticky margin and energy.
- Judge whether a model predictive controller's gain comes from its model or from its speed.

Prerequisites Sections 1.4.5, 1.4.7, 1.4.8, 1.6.2 and 1.6.4, with 1.6.3 for case 9.

The app https://apmonitor.com/apps/spray-dryer/

See also Volume 4, Chapter 6 for another dryer whose throughput a constraint bounds, Volume 4, Chapter 5 for a food product judged downstream under overrides, Volume 4, Chapter 4 for throughput pushed against limits measured late, and Volume 9, Chapter 4 for offset-free predictive control with an estimated bias.

10.1 Introduction

Spray drying is the preferred way to take the water out of many liquid foods, and it leaves a free-flowing powder [1]. The main difficulty in controlling the process is to meet the residual moisture specification while keeping the powder from sticking to the chamber walls [2]. In the two-stage dryer simulated here, a milk concentrate from an evaporator is atomized into hot air at the top of a chamber, dries in seconds and is finished in a fluid bed below. At the design point 12 000 kg/h of air heated to 190 °C turns 1001 kg/h of skim-milk concentrate at 48 % solids into 498 kg/h of powder at 3.50 % moisture, with the exhaust at 80.0 °C and the particles leaving the chamber 2.93 K inside their sticky limit.

DID YOU KNOW? Five Percent by Federal Rule

United States rules for dairy plants define nonfat dry milk as pasteurized skim milk with only its water removed, holding not more than 5 percent moisture and not more than 1.5 percent milkfat by weight. The powder must be cooled to no more than 110 °F before packaging [3]. The 3.5 % ± 0.3 % specification of this chapter sits inside that ceiling.

The dryer measures its air and sells its powder. The exhaust temperature falls 5.9 K within 2 min of a 10 % step in the feed, while the powder leaving the fluid bed takes 4.0 min to cross its 3.8 % upper limit, and the laboratory, which samples every 30 min and reports each sample 40 min after it was drawn, first reports the change 65 min after the step. The moisture is controlled by holding the outlet temperature with the feed, and the outlet stands in for the moisture for as long as the concentrate and the intake air stay as they were. When the evaporator upstream sends 44 % solids instead of 48 %, the outlet loop keeps the exhaust within 0.39 K of 80 °C while the powder rises to 3.85 %. When the afternoon intake climbs from 8 toward 18 g/kg of water per kilogram of dry air, the powder reaches 4.10 % and the particles leaving the chamber cross their sticky line.

This chapter sets out to dislodge the habit of reading an outlet temperature on its setpoint as powder in specification. Holding a secondary variable in place of an unmeasured quality is the plainest form of inferential control [4] (Section 1.4.8), and the weakness it carries is general. For a simulated industrial debutanizer whose conventional policy held one stage temperature at its setpoint,

a static estimator built from four to six tray temperatures improved the steady-state control of the bottoms quality by as much as 400 % under feed composition disturbances [5]. The structure appears in any plant in which a fast measurement stands for a slow analysis, which is why that study posed the estimator as a general design problem. The dryer adds a second inferred quantity to the first. Its throughput is limited by the stickiness of the particles leaving the chamber, which no instrument measures, and a hotter inlet that buys more powder moves the particles toward that limit while every temperature loop holds its setpoint. A transfer function from feed to exhaust temperature carries neither the moisture nor the margin.

Control studies of spray dryers compare linear and economically optimizing model predictive control with conventional PID and PI strategies on first-principles models [1, 2], and control in drying as a whole has been reviewed across 71 publications [6]. This chapter works with a plant on which the outlet loop can be watched holding its setpoint while the powder leaves its specification, and on which the soft sensor, the laboratory correction and the constraint handling that repair the fault are then added one at a time. The plant is a two-stage milk powder dryer that keeps the true moisture, the true sticky margin and the true roof deposit apart from what its controllers estimate, and closes its water, solids and energy balances to round-off. Psychrometrics, drying curves, the glass transition, soft sensors, bias updating, feedforward and override control are all established practice. The model has 33 states with IAPWS-IF97 saturation pressures, the soft sensor solves the plant's own drying equations at the measured air states, the laboratory is the framework's shared sampled analyzer, and the deposit ignites by a declared rule, all described completely enough to be rebuilt. Nine cases and a graded campaign separate a proxy from the quality it stands for, a model from its bias, and a constraint from the loops that approach it.

Section 10.2 follows the domain from energy surveys to predictive control. Section 10.3 sets out the model, and Section 10.4 reads from its steady states what the outlet temperature stands for. Section 10.5 describes the controller: the PI loops, the soft sensor and its laboratory bias, the feedforward, the overrides, the throughput optimizer and an optional model predictive controller. Section 10.6 reports what the nine cases and the campaign measure, Section 10.7 sets the loops on plant hardware, Section 10.8 states the limitations, Section 10.9 draws the conclusions, and the exercises of Section 10.10 work through the cases.

10.2 Energy, Stickiness, Deposits and the Outlet Loop

Spray dryers burn a great deal of fuel. A survey commissioned in 2000 by the United Kingdom government's energy efficiency program found specific energy consumptions from around 3 to 20 GJ per tonne of water evaporated among spray dryers in the chemicals, foods and ceramics industries, with an average of 4.87 GJ/t, and estimated that about 29 % of the energy supplied to them was wasted [7]. The design of fluid bed and spray dryers for low energy consumption had been treated as one subject in 1984 [8], and the simulated plant pairs the two, a chamber that leaves the powder slightly wet and a bed that finishes it. At its design point it spends 4175 kJ of heat per kilogram of water evaporated, 4.18 GJ/t.

> ⧖ HISTORY **1872: A Patent That Led to Milk Powder**
>
> Spray drying turns a liquid into dry particles by spraying it into a hot gas. Its first observation dates from 1860, and Samuel Percy patented a primitive spray dryer in the United States in 1872. The early devices lacked efficiency and safety. Once those problems were overcome the method suited the food industry, and by the 1920s it was making milk powder, which has remained one of its most important uses. The Second World War, with its need to cut the weight and volume of the food to be carried, pushed the method further, and after the war it reached the pharmaceutical, chemical, ceramic and polymer industries [9].

The drying law in the model descends from the characteristic drying curve, a normalized rate that equals one while the particle surface is wet and falls with the free moisture below a critical value,

whose basis was examined in 1974 [10]. A characteristic drying curve for milk powder was assessed in 2001 for use in computational fluid dynamics modeling [11].

Stickiness has a thermodynamic explanation. Water plasticizes amorphous sugars, and in dehydrated sugar solutions used as models of amorphous foods the glass transition, crystallization and melting temperatures all fell as the moisture rose, with the glass transition of a sucrose and fructose model slightly below the empirical sticky point at every moisture studied [12]. The mixing rule now used to predict the glass transition of a sugar and water mixture from its two components was derived in 1952 for binary copolymers [13]. For skim milk powder, the sticky point measured by the cohesive force between stirred particles in a heated flask followed the predicted glass transition of lactose shifted up by 23.3 K, between 25 and 95 °C [14]. Sticky powder is what stays on the walls. In a pilot-scale co-current dryer the wall deposition flux of skim milk powder was highest, 16 g/(m^2 h), when the outlet particle temperature was furthest above the sticky-point temperature, which happened at the lowest of the three inlet temperatures tested, 170 °C, and the highest product moisture [15].

A deposit is also fuel. An investigation of a series of dryer fires, told in the history segment below, found that such deposits could ignite by themselves [16]. The simulator's rule, a layer of 3 mm on a roof held at 158 °C or more for 20 min, belongs to that line of reasoning but is a teaching value, not a calculated one. The application names the sources of real thresholds, layer-ignition tests to ISO/IEC 80079-20-2 and the dryer guidance of NFPA 61 and VDI 2263.

> ⧖ HISTORY **1984: Fires Traced to the Dryer's Own Deposits**
>
> A company operating a spray dryer for skimmed milk and fat-filled powders asked the Fire Research Station to find the cause of a series of fires. The investigation, reported in 1984, showed that the powders could ignite spontaneously in certain circumstances. It calculated the thickness of powder deposit on the dryer walls needed for a risk of self-ignition and found it close enough to the thicknesses met in practice to suggest that self-ignition was a real problem. It also put forward how fires could start in fluid-bed instantizers and suggested preventive measures [16].

Control came late to drying. A review of 71 publications on control in drying found that control tools began to appear in drying applications only in 1979 and that more advanced concepts followed from about 1998 [6]. For milk powder, a review of modern process control techniques in 2005 described advanced control under development and named models for stickiness and thermodynamic models of spray drying among the developments to come [17]. Predictive control followed. Against a conventional PID strategy, a linear model predictive controller on a two-stage spray dryer raised the production rate by 7.9 %, the profit by 8.2 % and the energy efficiency by 4.1 % over an industrially recorded disturbance scenario [2], and an economically optimizing nonlinear controller improved the cost of drying by 26.7 % against conventional PI control in simulation [1]. The simulator's shipped structure stays between those two ends, with conventional loops, a soft sensor under laboratory correction, feedforward, overrides and a constraint pusher, which is the ground a student covers before a predictive controller can be judged against it, and an optional linear predictive controller, Section 10.5.6, is judged against it in case 9.

10.3 The Dryer as Modeled

The simulated plant dries skim-milk concentrate in a chamber with a rotary atomizer and finishes it in an external fluid bed, as shown in Figure 10.1. The chamber is two well-mixed cells of air, the upper one against the roof around the hot-air disperser and the lower one against the cylinder wall, and each carries one well-mixed population of particles with its own residence. The bed has a drying section blown with heated air and a cooling section blown with room air, and the powder crosses a weir between them. Moisture is written X on a dry basis (kilograms of water per kilogram of solids) and $w = X/(1+X)$ on a wet basis, and the percentages quoted for the powder are wet basis.

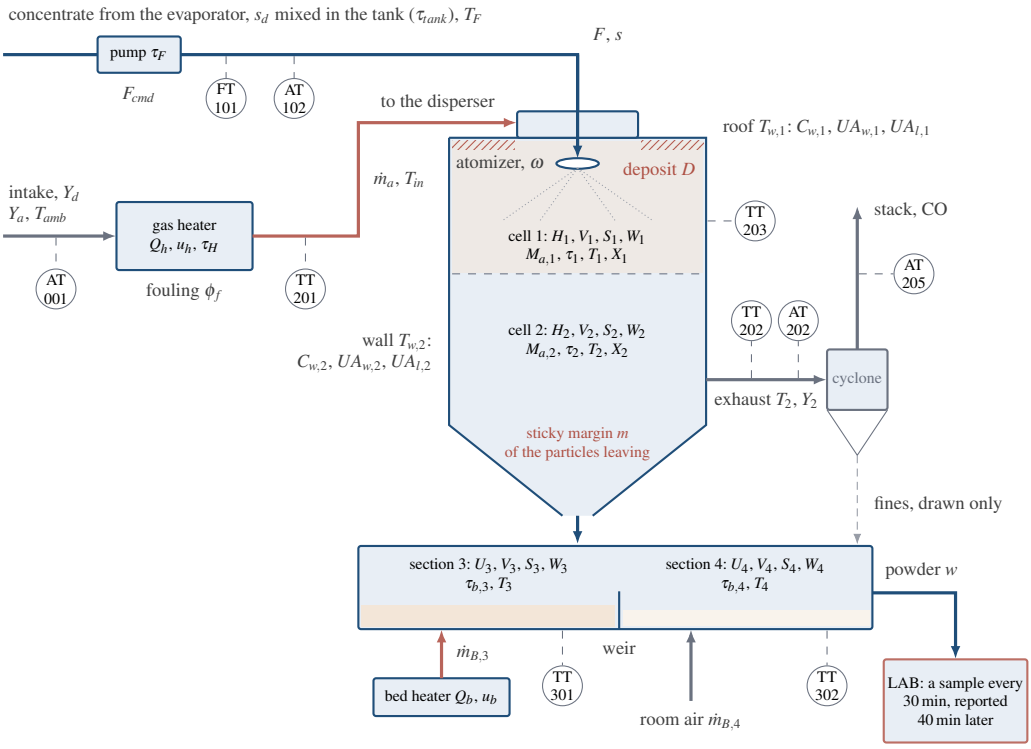


Figure 10.1 Two-stage milk powder dryer as modeled. Intake air at T_{amb} and Y_a passes the gas heater (Q_h, output u_h) and TT-201 and enters the roof through the disperser at $\dot{m}_a$ and T_{in}. Concentrate of solids s, mixed from the evaporator's s_d in a balance tank, is pumped at F past FT-101 and the densitometer AT-102 to the atomizer. Chamber cells 1 and 2 hold air enthalpy H and vapor V and particle solids S and water W, the roof $T_{w,1}$ carries the deposit D, and the exhaust passes TT-202, AT-202, a cyclone that is drawn but not modeled, and the CO analyzer AT-205. Bed sections 3 and 4, joined by a weir, are fed with heated air $\dot{m}_{B,3}$ from the bed heater (Q_b, u_b) and room air $\dot{m}_{B,4}$, and the laboratory samples the powder at the discharge. Dashed lines are measurements.

Table 10.1 gives the controlled, manipulated and disturbance variables beside the 33 states. Each chamber cell carries the enthalpy H_i and water vapor V_i of its air, the solids S_i and water W_i of its particles and one wall temperature, and each bed section carries its energy U_j, the vapor V_j in the air above it and the solids and water of its powder. Six more states hold the two heater duties, the feed flow, the feed solids, the intake humidity and the roof deposit, and the last nine are running totals of the water, solids and energy that enter and leave, the heater energy and the powder made. Because the totals advance with the plant in every integration step, the balances can be checked against the state vector at any instant.

10.3.1 Humid Air

Enthalpies are per kilogram of dry air and referred to dry air and liquid water at 0 °C. The psychrometric relations shared by the plant, the soft sensor and the scene are Equation (10.1).

$$\begin{aligned} h(T,Y) &= c_a T + Y(\lambda_0 + c_v T), \qquad T = \frac{h - Y\lambda_0}{c_a + Y c_v} \\ Y &= \frac{\varepsilon\, p_v}{P - p_v}, \qquad \varphi = \frac{p_v}{p_{sat}(T)} \\ h(T,Y) &+ \big[Y_s(T_{wb}) - Y\big] c_w T_{wb} = h\big(T_{wb}, Y_s(T_{wb})\big) \end{aligned} \tag{10.1}$$

Table 10.1 What Each Variable Does in the Loops, and Its Design-Point Value

Variable	Role	Design value	Range
T_2 (TT-202)	CV, TIC-202	80.0 °C SP	65–100
T_{in} (TT-201)	CV, TIC-201	190 °C SP	150–240
T_3 (TT-301)	CV, TIC-301	55.0 °C SP	40–90
$\hat{w}$ (AY-401)	CV, AIC-400	3.50 % SP	2.5–4.5
$\hat{m}$ (AY-401)	constraint, UIC-205	2.93 K, SP 0.5	0–6
Y_{202} (AT-202)	constraint, AIC-206	49.6 g/kg, 58 max	40–90
F_{cmd}	MV, feed pump	1001 kg/h	0–1500
u_h, u_b	MVs, heaters	74.9, 27.4 %	0–100
$T_{out,SP}$	MV of AIC-400	80.0 °C	65–100
$T_{in,SP}$	MV of FY-500, overrides	190 °C	150–240
s_d	DV, evaporator	48 %	44–52
Y_d	DV, weather	8 g/kg	4–22
T_F, ϕ_f	DVs, feed, fouling	50 °C, 0	35–70, 0–50 %
ω, t_{lab}	DVs, wear, lab	0, 40 min	0–25 %, 20–90
H_i, V_i, S_i, W_i	states, cells 1, 2	see text	—
$T_{w,1}$, $T_{w,2}$	states, roof, wall	147.4, 66.0 °C	—
U_j, V_j, S_j, W_j	states, sections 3, 4	see text	—
Q_h, Q_b	states, heaters	561.5, 22.0 kW	—
F, s, Y_a, D	states	1001, 48, 8, 0	—
w, m	truth, powder, margin	3.50 %, 2.93 K	—

Here Y is the humidity ratio, p_v the vapor pressure, φ the relative humidity, Y_s the saturation humidity and T_{wb} the adiabatic-saturation (wet-bulb) temperature, with $c_a = 1006$, $c_v = 1860$ and $c_w = 4186\,\mathrm{J/(kg\,K)}$, $\lambda_0 = 2.501\,\mathrm{MJ/kg}$, $P = 101\,325\,\mathrm{Pa}$ and $\varepsilon = 0.621945$. The saturation pressure is the IAPWS-IF97 region-4 equation [18], and the wet bulb is found by a Newton iteration kept inside a bracket. The application's checks put p_{sat} within a relative 4.4×10^{-5} of 2.3392 kPa at 20 °C and 101.418 kPa at 100 °C, give air at 30 °C and 50 % relative humidity 13.31 g/kg of water and a wet bulb of 22.0 °C, and agree with a bisection for the wet bulb to 1.6×10^{-12} K from 0 to 250 °C.

10.3.2 The Chamber Cells

Each chamber cell $i = 1, 2$ holds a fixed mass of dry air $M_{a,i}$, so its temperature follows from its two air states through Equation (10.1), and its balances are Equation (10.2).

$$\begin{aligned} \frac{\mathrm{d}H_i}{\mathrm{d}t} &= \dot{m}_a(h_{i-1} - h_i) + P_{i-1} - P_i - Q_{w,i} \\ \frac{\mathrm{d}V_i}{\mathrm{d}t} &= \dot{m}_a(Y_{i-1} - Y_i) + E_i \\ \frac{\mathrm{d}S_i}{\mathrm{d}t} &= \frac{S_{i-1}}{\tau_{i-1}} - \frac{S_i}{\tau_i}, \qquad \frac{\mathrm{d}W_i}{\mathrm{d}t} = \frac{W_{i-1}}{\tau_{i-1}} - \frac{W_i}{\tau_i} - E_i \\ C_{w,i}\frac{\mathrm{d}T_{w,i}}{\mathrm{d}t} &= Q_{w,i} - UA_{l,i}(T_{w,i} - T_{amb}) \end{aligned} \tag{10.2}$$

where $h_i = H_i/M_{a,i}$ and $Y_i = V_i/M_{a,i}$, the particles leave cell i with the enthalpy $P_i = (S_i c_s + W_i c_w)T_{p,i}/\tau_i$ at their own temperature $T_{p,i}$, and E_i is the water they evaporate. The inlet to cell 1 is the heated air, $h_0 = h(T_{amb}, Y_a) + Q_h/\dot{m}_a$ and $Y_0 = Y_a$, and the feed, $S_0/\tau_0 = \dot{s} = Fs$, $W_0/\tau_0 = F(1-s)$ and $P_0 = [\dot{s}c_s + F(1-s)c_w]T_F$, with $c_s = 1500\,\mathrm{J/(kg\,K)}$ for milk solids. The roof exchanges heat with a film at the mean of the inlet and cell temperatures, $Q_{w,1} = UA_{w,1}[(T_{in} + T_1)/2 - T_{w,1}]$, and the cylinder wall with the lower cell, $Q_{w,2} = UA_{w,2}(T_2 - T_{w,2})$. Evaporation adds vapor to the air without adding enthalpy, and that is the whole mechanism by which the spray cools it. The air holdups of 60 kg and 90 kg are 18 and 27 s of flow.

10.3.3 The Drying Curve and the Equilibrium Moisture

The particles in a cell dry at the rate $E_i = S_i k (T_i - T_{wb,i}) f(X_i)$, with $X_i = W_i / S_i$ and $T_{wb,i}$ the wet bulb of the cell's air, through the illustrative characteristic drying curve of Equation (10.3).

$$
\begin{aligned}
f(X) &= \begin{cases} 1, & X \geq X_{cr} \\ \left(\dfrac{X - X_e}{X_{cr} - X_e} \right)^n, & X_e < X < X_{cr} \\ 0, & X \leq X_e \end{cases} \\
T_p &= T_{wb} + (T - T_{wb})(1 - f) \\
X_e &= \frac{X_m C K a_w}{(1 - K a_w)(1 - K a_w + C K a_w)}
\end{aligned}
\tag{10.3}
$$

Here $C = C_0 \mathrm{e}^{H_C / T^*}$ and $K = K_0 \mathrm{e}^{H_K / T^*}$ with T^* the absolute temperature, and a_w is the relative humidity of the cell's air, capped at 0.98. The particle temperature is quasi-steady. It sits at the wet bulb while the surface is wet and rises toward the air as the rate falls, and the heat a chamber particle stores is neglected because the cells hold 3.3 kg of solids against 150 kg of air, although the enthalpy the particles carry is counted. The equilibrium moisture X_e is a GAB isotherm with illustrative constants for skim milk, 5.59 % on a dry basis at 25 °C and a water activity of 0.30 and 2.68 % at 80 °C and 0.17. Atomizer wear ω, in percent of droplet diameter, divides the chamber constant by $(1 + \omega/100)^2$, because the time to evaporate a droplet grows with the square of its size.

10.3.4 The Fluid Bed

Each bed section $j = 3, 4$ is well mixed. Its powder, its steel and the air above it share one temperature, which follows from the section's energy, and its balances are Equation (10.4).

$$
\begin{aligned}
T_j &= \frac{U_j - V_j \lambda_0}{C_b + S_j c_s + W_j c_w + M_{fb} c_a + V_j c_v} \\
\frac{\mathrm{d}U_j}{\mathrm{d}t} &= \dot{m}_{B,j} \left[h_{B,j} - h(T_j, Y_j) \right] + P_{j-1} - P_j \\
&\quad - U A_b (T_j - T_{amb}), \qquad Y_j = V_j / M_{fb} \\
\frac{\mathrm{d}V_j}{\mathrm{d}t} &= \dot{m}_{B,j} (Y_a - Y_j) + E_j \\
\frac{\mathrm{d}S_j}{\mathrm{d}t} &= \sigma_{j-1} - \sigma_j, \qquad \frac{\mathrm{d}W_j}{\mathrm{d}t} = \sigma_{j-1} X_{j-1} - \sigma_j X_j - E_j \\
\sigma_j &= \dot{s}_D \left(\frac{S_j}{\dot{s}_D \, \tau_{b,j}} \right)^{1.5}, \qquad P_j = \sigma_j (c_s + X_j c_w) T_j
\end{aligned}
\tag{10.4}
$$

where the chamber discharge enters section 3, $\sigma_2 = S_2 / \tau_2$ and $\sigma_2 X_2 = W_2 / \tau_2$ with the enthalpy P_2 of Equation (10.2), the drying section is blown with heated air, $h_{B,3} = h(T_{amb}, Y_a) + Q_b / \dot{m}_{B,3}$, and the cooling section with room air, $h_{B,4} = h(T_{amb}, Y_a)$. The powder leaves each section over a weir whose outflow grows as the holdup to the power 1.5, scaled by the design solids flow $\dot{s}_D = 480\,\mathrm{kg/h}$ and the design residences $\tau_{b,3}$ and $\tau_{b,4}$, so the residence rises when the rate falls. It dries on the curve of Equation (10.3) with the much smaller constant k_{bed} of internal diffusion and at the bed temperature, $E_j = S_j k_{bed} (T_j - T_{wb,j}) f(X_j)$.

10.3.5 Stickiness, the Roof Deposit and the Fire

Stickiness is judged on the particles leaving the chamber, as shown in Equation (10.5).

$$\begin{aligned} T_g(w) &= \frac{(1-w)T_{g,s} + k_{GT}\, w\, T_{g,w}}{(1-w) + k_{GT}\, w} \\ m &= \Delta T_{st} - \left[T_{p,2} - T_g(w_2)\right] \\ \frac{\mathrm{d}D}{\mathrm{d}t} &= r_{dep} \min\left[\max(0,-m),5\right] L - r_{clean}\frac{D}{D+0.05} \end{aligned} \tag{10.5}$$

The first line is the Gordon–Taylor rule [13] for amorphous lactose, $T_{g,s} = 101\,^{\circ}\mathrm{C}$, $T_{g,w} = -135\,^{\circ}\mathrm{C}$ and $k_{GT} = 6.7$, which gives 54.9 °C at 3.5 %. The margin m is how far the particles stay below the sticky line $T_g + \Delta T_{st}$, with $\Delta T_{st} = 20\,\mathrm{K}$, so it is positive while they are not sticky, and it is set to ΔT_{st} when the chamber carries less than 1 % of its design load. Sticky fines are taken to recirculate to the roof around the disperser, so the deposit D, in millimeters, grows only while $m < 0$, by up to 5 K of stickiness at $r_{dep} = 2\,\mathrm{mm}$ per kelvin-hour and the load $L = \min(1.5, \sigma_2/\dot{s}_D)$, and air hammers remove it at up to $r_{clean} = 0.3\,\mathrm{mm/h}$. A layer of at least $D_{\mathrm{fire}} = 3\,\mathrm{mm}$ on a roof at $T_{w,1} \geq T_{\mathrm{fire}} = 158\,^{\circ}\mathrm{C}$ held without a break for $t_{\mathrm{fire}} = 20\,\mathrm{min}$ ignites, and an interruption restarts the clock. After ignition the exhaust carbon monoxide rises as $\min[5000, \mathrm{e}^{k_{CO}(t-t_{ign})}]$ ppm with $k_{CO} = 0.5\,\mathrm{min}^{-1}$. The interlock reads the analyzer AT-205, raises an alarm at 15 ppm and shuts the dryer down at 40 ppm, the feed and heaters go to zero, and the run ends a minute later. The sticky criterion, the deposit law and the fire rule are all teaching values.

10.3.6 Actuators, Boundary Conditions and the Product

The heaters, the pump and the two slow boundary conditions all follow their targets to first order, in Equation (10.6).

$$\begin{aligned} \tau_H \dot{Q}_h &= (1-\phi_f)\, u_h Q_{h,max}/100 - Q_h \\ \tau_{Hb} \dot{Q}_b &= u_b Q_{b,max}/100 - Q_b \\ \tau_F \dot{F} &= \mathrm{clamp}(F_{cmd}, 0, F_{max}) - F \\ \tau_{tank}\dot{s} &= s_d - s, \qquad \tau_{amb}\dot{Y}_a = Y_d - Y_a \end{aligned} \tag{10.6}$$

Here ϕ_f is the fouled share of the gas heater, s_d the solids the evaporator sends and Y_d the humidity of the weather. Every kilogram of powder leaving the cooling section, at the rate $\sigma_4(1+X_4)$, is booked in specification while its true moisture is within 3.5 % ± 0.3 %, and off specification otherwise. The specific energy is the heater energy per kilogram of powder, $(Q_h+Q_b)/[\sigma_4(1+X_4)]$ now and $\int (Q_h+Q_b)\,\mathrm{d}t$ over the powder made since reset for the campaign.

10.3.7 Parameters, Initial State and Integration

Table 10.2 gives every parameter. Twenty-eight are shown in the Show Model panel and may be moved while the dryer runs, and 24 are hidden. The declared design point is 1000 kg/h of concentrate at 48 % solids, 190 °C at the inlet, 80 °C at the outlet and 3.5 % in the powder, and the illustrative drying constants were chosen so that the model reproduces it. Every scenario starts from a steady state computed at reset for the configuration in force, its own plus any setting the learner carries through a Reset. The solver finds each chamber cell's temperature and particle moisture by nested Illinois false-position roots, the feed that puts the outlet on its setpoint by a third, and each bed section's temperature and moisture the same way, and with the moisture controller on it also finds the outlet setpoint at which the controller's own reading equals its setpoint. At the design point it returns a feed of 1000.94 kg/h, a gas heater at 74.865 % of its rating and a bed heater at 27.442 %, and the largest relative derivative outside the ledgers at the stored state is 2.5×10^{-15}.

The plant is integrated by the classical fourth-order Runge–Kutta method at a fixed step of 0.5 s, the controllers run every 2 s, and a row goes to the historian every 5 s, so the eight-hour campaign fills 5760 rows. The fastest state is the particle moisture in the lower cell, which relaxes at $1.28\,\mathrm{s}^{-1}$ in

Table 10.2 Parameters of the Dryer. V Is a Value the Show Model Panel Displays and Lets the User Move, H One It Keeps Hidden

Symbol	Meaning	Value		Symbol	Meaning	Value	
$\dot{m}_a$	drying air, dry basis	12 000 kg/h	V	$T_{g,s}$, $T_{g,w}$	glass transition, solids, water	101, −135 °C	V, H
T_{amb}	room and intake air	25 °C	V	k_{GT}, ΔT_{st}	Gordon–Taylor, sticky criterion	6.7, 20 K	V
$M_{a,1}$, $M_{a,2}$	air in the upper, lower cell	60, 90 kg	H	r_{dep}, r_{clean}	deposit growth, cleaning	2.0 mm/(K h), 0.3 mm/h	V
τ_1, τ_2	particle residences	5, 20 s	V	D_{fire}, T_{fire}, t_{fire}	layer, roof, time to ignite	3 mm, 158 °C, 20 min	V
$UA_{w,1}$, $UA_{l,1}$	roof transfer, loss	1700, 150 W/K	H	k_{CO}	smolder growth	0.5 min^{-1}	H
$C_{w,1}$	roof heat capacity	1.5 MJ/K	H	—	CO alarm, shutdown	15, 40 ppm	V
$UA_{w,2}$, $UA_{l,2}$	wall transfer, loss	1000, 340 W/K	H	$\dot{m}_{B,3}$, $\dot{m}_{B,4}$	bed air, drying, cooling	2500, 1500 kg/h	V
$C_{w,2}$	wall heat capacity	2.5 MJ/K	H	$\tau_{b,3}$, $\tau_{b,4}$	powder residence at design	180, 120 s	V
k	drying constant, chamber	1.47×10^{-3} K^{-1} s^{-1}	V	C_b, UA_b	bed steel, loss per section	200 kJ/K, 20 W/K	H
X_{cr}, n	critical moisture, exponent	6.7 % d.b., 1	V	M_{fb}	air above each section	5 kg	H
k_{bed}	drying constant, bed	4.33×10^{-6} K^{-1} s^{-1}	V	$Q_{h,max}$, τ_H	gas heater rating, lag	750 kW, 30 s	V, H
X_m	GAB monolayer moisture	0.05 kg/kg	H	$Q_{b,max}$, τ_{Hb}	bed heater rating, lag	80 kW, 20 s	V, H
C_0, H_C	GAB constant C	0.1402, 1327 K	H	F_{max}, τ_F	feed pump capacity, lag	1500 kg/h, 3 s	V, H
K_0, H_K	GAB constant K	0.2793, 349 K	H	τ_{tank}, τ_{amb}	balance tank, weather lags	300, 1200 s	H
c_s	milk solids heat capacity	1500 J/(kg K)	fixed	w_{spec}, w_{tol}	moisture specification	3.5 % ± 0.3 %	V
$\dot{s}_D$	design solids flow	480 kg/h	fixed	—	lab interval, repeatability	30 min, 0.05 %	V, H

the falling-rate period at the design point, so the product of that rate and the step is 0.64, well inside the stability limit of the method. Halving the step moves the deposit of the push case at 90 min by 5.8×10^{-10} of its value and the humid case's moisture at 120 min by 1.3×10^{-11} points, because the controller scans and the scripted events fall on the same instants at either step. The water, solids and energy ledgers close to 1.5×10^{-13} of their throughput over the moisture-control, push and fire cases. Every noise sequence is seeded at 20261027, so a run replays to the bit, and the speed selector plays the dryer at 1, 5, 20, 60 or 300 minutes per second, five by default, at which the campaign plays in 96 s, without changing its trajectory (Section 1.6.1).

10.3.8 Assumptions

The chamber is two well-mixed air cells, each with one particle population of mean moisture. Real sprays have a size distribution and every particle a history, so some particles leave wetter and hotter than the mean, and those are the ones that stick. Atomizer wear enters only as a slower drying constant.

The particle temperature is quasi-steady, which fails close to the atomizer, where a droplet warms from the feed temperature before it reaches the wet bulb. The powder in each bed section shares one temperature with the steel and the air above it, and powder drier than its equilibrium moisture does not take water back, which matters in the cooling section, whose room air would hold the powder at 4.50 % on a dry basis while it is at 3.63 %.

The drying curve and the isotherm are illustrative constants fitted to the declared design point, not to a milk powder, and the application sets the critical moisture of 6.7 % on a dry basis lower than milk's so that the design particle sits off the sticky line. The sticky line is 20 K above the lactose glass transition, while the measured shift for skim milk powder is 23.3 K [14]. Stickiness depends on the

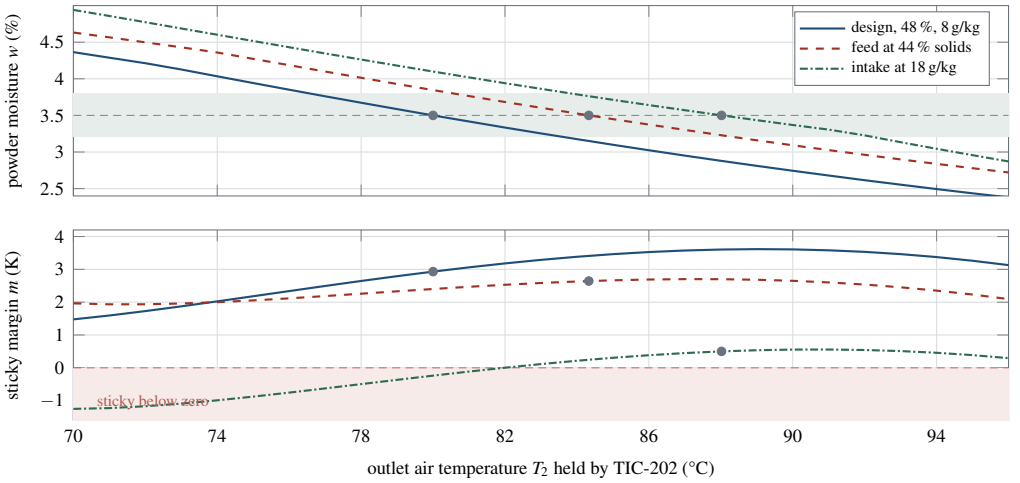


Figure 10.2 Steady-state powder moisture and sticky margin against the outlet temperature held by TIC-202, at a 190 °C inlet and a 55 °C bed. Solid lines are the design point, dashed lines a 44 % concentrate and dash-dotted lines 18 g/kg intake air. The upper band is the 3.2 % to 3.8 % specification, the lower band the sticky region below zero margin, and the dots mark the outlet that gives 3.5 %, 80.0 °C at the design point, 84.3 °C with a 44 % concentrate and 88.0 °C with 18 g/kg intake air.

particle surface rather than on its mean moisture, and the application notes that milk proteins raise the real sticky curve.

The deposit forms only on the roof, and the deposit law, the air-hammer cleaning, the ignition rule and the CO levels are teaching values, with no explosion, venting or suppression model. The air flow is fixed, the walls are two lumped heat capacities, and the cyclone and the ducts are drawn but carry no states. The concentrate arrives through a 5 min balance tank, and in the campaign its solids replay a declared dip of the kind the evaporator makes, one way, without coupling to a model of it. The three-effect milk evaporator of Volume 6, Chapter 4 holds those solids against its own delay. The laboratory has a repeatability of 0.05 % and no sampling error beyond it. All sizes, ratings and limits are teaching values for one product, not a design basis.

10.4 What the Outlet Temperature Stands For

At the design point the gas heater delivers 561.5 kW to the drying air and the bed heater 22.0 kW to the drying section, and the dryer evaporates 503.1 kg/h of water to make 497.9 kg/h of powder, 4219 kJ of heat per kilogram of powder. The upper cell runs at 126.4 °C and 31.8 g/kg, and its particles leave it still in the constant-rate period, at the wet bulb of 45.7 °C and 32.9 % moisture. The lower cell, the exhaust, runs at 80.0 °C, 49.6 g/kg and 15.8 % relative humidity, with a wet bulb of 45.2 °C. Its particles leave the chamber at 4.17 % moisture and a normalized drying rate of 0.44, at 64.8 °C against a glass transition of 47.7 °C, which is the margin of 2.93 K. The drying section at 55.0 °C, blown with air at 56.0 °C, finishes the powder to 3.50 %, and the cooling section brings it to 34.9 °C without drying it further. The walls lose 32.3 kW, 18.4 kW of it from the roof at 147.4 °C and 14.0 kW from the cylinder at 66.0 °C, and the bed loses 0.8 kW.

The outlet temperature is a good proxy only along one curve, as shown in Figure 10.2. Near the design point each kelvin of outlet takes 0.085 % of moisture off the powder and 1.42 % off the throughput, because at a fixed inlet a hotter exhaust carries more of the heat away unused. The curve that gives 3.5 % at 80.0 °C gives it at 84.3 °C when the feed is 44 % solids and at 88.0 °C when the intake carries 18 g/kg, and at a held 80 °C the moisture falls 0.079 % per point of feed solids and rises 0.067 % per g/kg of intake humidity. The horizontal shifts are the feedforward gains, 1.08 K

per point of solids below 48 % and 0.80 K per g/kg of humidity above 8 g/kg, which the application rounds to 1.1 and 0.8. They are not constant. Holding 3.5 % takes 76.8 °C at 52 % solids, 0.80 K per point on the strong side, and 90.3 °C at 22 g/kg, 0.74 K per g/kg.

🕮 **Pause.** Try Exercise 10.1 before reading on.

The two disturbances act on the constraint in different ways. A weaker concentrate at a held 80 °C sends the particles out at 4.71 % but cooler, at 59.9 °C, and their glass transition falls to 42.3 °C, so the margin drops only from 2.93 to 2.40 K. Humid intake air raises the wet bulb that the drying rate works against, the particles leave at 4.51 % and 64.5 °C with a glass transition of 44.3 °C, and the margin falls to −0.24 K. A hotter outlet does not always help. It dries the particles, which raises their glass transition, but it also heats them, and the design margin peaks at 3.61 K near 90 °C and then falls. In the humid case the margin is negative below an outlet of 82 °C, peaks at 0.56 K and is 0.50 K at the 88.0 °C that holds 3.5 %. At 22 g/kg, the top of the humidity slider, the outlet that holds 3.5 %, 90.3 °C, leaves the particles 0.55 K past the sticky line, so no outlet setpoint at a 190 °C inlet delivers both.

Throughput is bought with the inlet. At a held 80 °C outlet each kelvin of inlet brings 9.75 kg/h more feed, adds 0.40 g/kg to the exhaust and takes 0.121 K from the margin, and the design particle turns sticky at a steady inlet of 215.7 °C, with 1252 kg/h of feed and 624 kg/h of powder. The roof reaches the 158 °C of the fire rule sooner, at an inlet of 208.5 °C, so between the two a deposit already on the roof can ignite while the powder being made is not sticky.

10.5 Implemented Controller

Six PI loops, the soft sensor, the laboratory and the optimizer execute every $\Delta t_c = 2\,\mathrm{s}$, at the start of every fourth physics step and before its integration, after a priming call at reset. Inside a physics step a scripted event that is due is applied first, the controller runs next when a scan is due, and the integration, the checks for sticky powder, ignition and the CO interlock, the outputs and the historian follow in that order. The structure is drawn in Figure 10.3.

10.5.1 Instruments and the Laboratory

The controllers use the transmitter and laboratory readings, together with the initial deposit specified for the scenario. A transmitter reads the true value where it is mounted, passes it through an exact first-order lag and adds noise that is itself filtered to first order, with the standard deviation of Table 10.3. The laboratory is the framework's shared sampled analyzer, and Section 1.4.5 gives the age its results add to a loop. It draws a sample of the true powder moisture at the bed discharge every 30 min, reports it after the turnaround, 40 min by default, with white noise of 0.05 %, and holds the result until the next one. At reset a sample drawn 30 min earlier is already in analysis and reports at 10 min, so a fresh result arrives at 10, 40, 70 minutes and so on. The first sample drawn after an event at 5 min is reported 65 min after it.

10.5.2 The PI Law

The six loops share the framework's velocity-form PID of Section 1.6.2, written for a loop without derivative action in Equation (10.7).

$$\begin{aligned} e_k &= \gamma(r_k - y_k), \qquad p_k = K_c e_k \\ \Sigma_k &= \Sigma_{k-1} + (p_k - p_{k-1}), \qquad v_k = \Sigma_k + I_{k-1} \\ u_k &= \min\left[u_{max}, \max(u_{min}, v_k)\right] \\ I_k &= I_{k-1} + \left[\frac{K_c}{\tau_I} e_k + \frac{u_k - v_k}{\tau_I}\right]\Delta t \end{aligned} \tag{10.7}$$

In it r is the setpoint, y the measurement, $\gamma = \pm 1$ the action and Δt the execution period. It is Equations (1.16) to (1.18) without the derivative term and the slew limit, which no loop here uses.

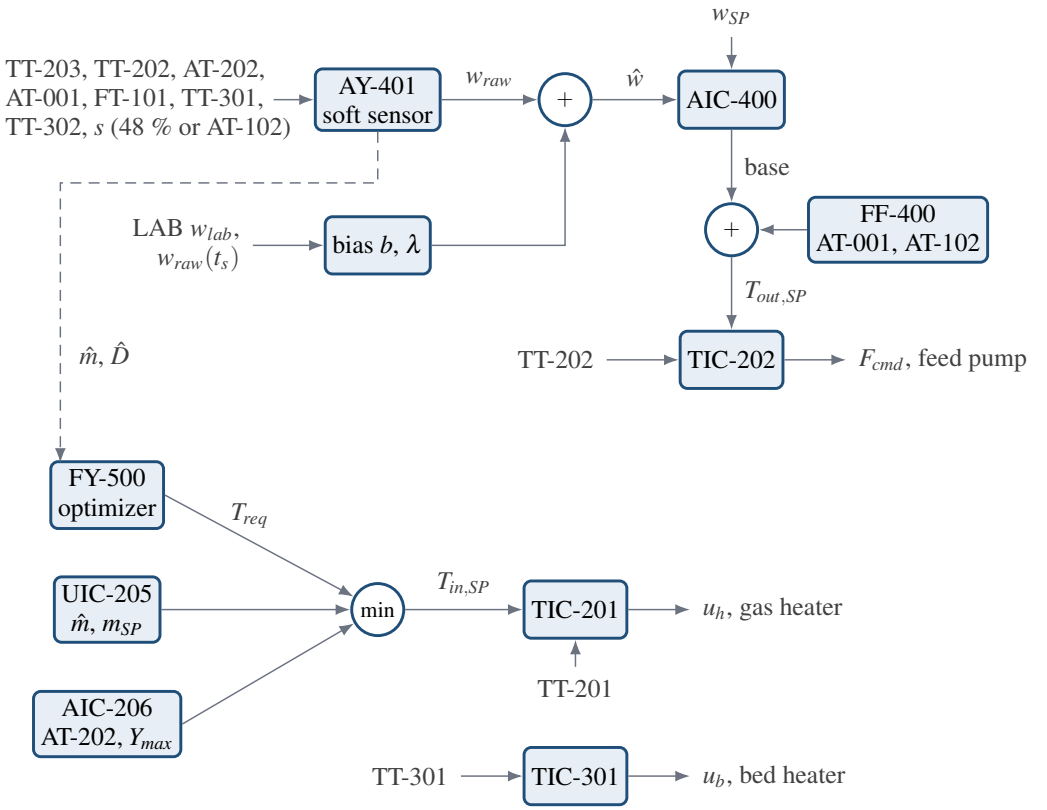


Figure 10.3 Control structure. The soft sensor AY-401, corrected by the laboratory bias, feeds AIC-400, whose outlet setpoint FF-400 biases before TIC-202 moves the feed. The optimizer's request and the two overrides meet in a minimum selector ahead of TIC-201, and the soft sensor's margin and deposit estimates reach the optimizer and UIC-205.

Table 10.3 Transmitters and the Laboratory. Each Noise Has the Correlation Time Shown, and FT-101's Is a Fraction of Its Reading

Tag	Measures	Lag	Noise 1σ, time
TT-201	inlet air	5 s	0.2 K, 3 s
TT-203	upper cell air	5 s	0.3 K, 3 s
TT-202	exhaust air	5 s	0.1 K, 3 s
AT-202	exhaust humidity	30 s	0.1 g/kg, 10 s
AT-001	intake humidity	60 s	0.05 g/kg, 20 s
FT-101	feed flow	1 s	0.3 %, 2 s
AT-102	feed solids	20 s	0.05 points, 10 s
TT-301, TT-302	bed sections	10 s	0.1 K, 5 s
AT-205	exhaust CO	20 s	0.2 ppm, 10 s
LAB	powder moisture	30, 40 min	0.05 points, white

The sum Σ_k always equals the present p_k, and windup is handled on the integral alone, by back-calculation toward the applied output with the time constant τ_I. The exception is AIC-400 on the laboratory alone, which tracks with the longer of τ_I and the time since the previous result. The clamp that follows the feedforward in Equation (10.9) is not one of AIC-400's limits, so a setpoint held there by the clamp does not unwind AIC-400's integral. In manual, or when a loop is not the one

Table 10.4 The Six PI Loops as Shipped. In the ISA Convention the Loops With $\gamma = -1$ Are Direct Acting and Those With $\gamma = +1$ Reverse Acting

Loop	PV	Output	γ	K_c	τ_I (min)	Limits
TIC-202	T_{202}	F_{cmd}	-1	30	1.0	0–1500
TIC-201	T_{201}	u_h	$+1$	1.0	0.5	0–100
TIC-301	T_{301}	u_b	$+1$	6	4	0–100
AIC-400	$\hat{w}$, w_{lab}	T_{base}	-1	5	8	65–100
UIC-205	$\hat{m}$	T_{SO}	-1	5	1	150–240
AIC-206	Y_{202}	T_{YO}	$+1$	1.2	1	150–240

K_c in kg/h per K, % per K, % per K, K per %, K per K and K per g/kg, limits in kg/h, %, %, °C, °C and °C.

selected, it tracks by setting $I_k = u_{op} - \Sigma_k$, so the emitted value is the one applied and the return to automatic is bumpless. At reset a priming call tracks every loop at the steady actuator values of the solved state. Table 10.4 gives each loop's pairing and shipped tuning.

TIC-202 is the classical loop. It raises the feed when the exhaust runs hot, because more water cools the air, and its shipped tuning of 30 kg/h per kelvin and 1.0 min settles an outlet step in under two minutes. TIC-201 holds the inlet with the gas heater and TIC-301 the drying section of the bed with the bed heater.

10.5.3 The Soft Sensor and Its Laboratory Bias

AY-401 infers the moisture now from the measured state of the air, with the plant's own drying curve and a new atomizer, as shown in Equation (10.8).

$$\begin{aligned} \hat{X}_0 - \hat{X}_1 &= \tau_1 k \big[T_{203} - T_{wb}(T_{203}, \hat{Y}_1)\big] f(\hat{X}_1) \\ \hat{Y}_1 &= Y_{001} + F_{101}\, \hat{s}\, (\hat{X}_0 - \hat{X}_1)/\dot{m}_a \\ \hat{X}_1 - \hat{X}_2 &= \tau_2 k \big[T_{202} - T_{wb}(T_{202}, Y_{202})\big] f(\hat{X}_2) \\ b &\leftarrow \mathrm{clamp}\big(b + \lambda\,[w_{lab} - w_{raw}(t_s) - b],\ \pm 2\big) \\ \hat{w} &= w_{raw} + b \end{aligned} \tag{10.8}$$

The feed carries $\hat{X}_0 = (1-\hat{s})/\hat{s}$ of water per kilogram of solids, with $\hat{s}$ either the operator's 48 % or the reading of the densitometer AT-102, subscripts name the transmitters, and each f takes its equilibrium moisture from the relative humidity of the air it is evaluated in. The chamber is solved quasi-steadily by false position at every execution, because a particle spends 25 s there, and the two bed sections are integrated from the chamber estimate by an explicit Euler step of 2 s at TT-301 and TT-302, because the powder spends about 5 min there. The raw estimate w_{raw} is the moisture leaving the modeled cooling section. The same solution gives an estimated margin $\hat{m}$ for the particles leaving the chamber, and the deposit law of Equation (10.5) run on $\hat{m}$ gives an estimated deposit $\hat{D}$. With exact inputs the soft sensor reproduces the plant's steady moisture to 6.9×10^{-18} at five operating points, because it solves the plant's equations. What it cannot know is what it is not told, the true feed solids unless it reads AT-102 and the wear of the atomizer. Chapter 11 infers the unmeasured core of a brick from a two-node model in the same way.

The bias follows the framework's shared update, an exponentially weighted average of the model's residual and the steady scalar filter of Equation (1.12), with $\lambda = 0.5$ and a clamp of ± 2 points, so a constant model error ε is learned as $\varepsilon[1-(1-\lambda)^n]$ after n results. Each result is compared with the raw estimate at the time t_s its sample was drawn, read from a ring buffer of 8192 values at the 2 s cycle, and not with the estimate of the moment, which would chase the plant's own response to the corrections (Equation (1.14)). With the correction switched off the residual is recorded and the bias does not move.

Pause. Try Exercise 10.2 before reading on.

10.5.4 Moisture Control and Feedforward

AIC-400 sets the outlet setpoint from the corrected estimate every 2 s. Feedforward from the intake humidity and the feed solids is added to its output, as shown in Equation (10.9).

$$\begin{aligned} T_{ff} &= K_Y\,(Y_{001} - 8) + K_S(48 - s_{102}) \\ T_{out,SP} &= \mathrm{clamp}(T_{base} + T_{ff},\ 65,\ 100) \end{aligned} \tag{10.9}$$

where T_{base} is AIC-400's output, or the operator's setpoint with the moisture controller off, Y_{001} is in g/kg and s_{102} in percent, each term is present only when its feedforward is switched on, and $K_Y = 0.8\,\mathrm{K}$ per g/kg and $K_S = 1.1\,\mathrm{K}$ per point come from the steady map of Figure 10.2. With the soft sensor set to laboratory only, AIC-400 executes once per laboratory result with Δt equal to the time since the previous result, 30 min, and holds its output in between.

10.5.5 Overrides and the Throughput Optimizer

The inlet setpoint that TIC-201 receives is the lowest of the requested inlet and the enabled overrides. UIC-205 lowers it when the estimated margin falls below its 0.5 K setpoint, and AIC-206 when AT-202 passes its 58 g/kg ceiling. The overrides act on the inlet because, with the outlet held, the inlet sets how much water the air has to carry. Cutting the feed at a fixed inlet heats the particles faster than it dries them. At a 225 °C inlet, a cut from 1343 to 1150 kg/h lifts the steady margin only to 0.03 K, and a cut to 950 kg/h takes it back to −3.46 K, with the particles at 98.9 °C. Each override that is not selected tracks the applied setpoint by external reset, so a change of selection is bumpless. The requested inlet is the operator's, or with FY-500 on it follows Equation (10.10).

$$\begin{aligned} \eta &= \min\Big[\hat{m} - m_{min},\ \frac{D_{max} - \hat{D}}{0.25},\ \frac{95 - u_h}{3}, \\ &\qquad \frac{Y_{max} - 2 - Y_{202}}{2},\ \frac{98 - T_{out,SP}}{2}\Big] \\ \frac{\mathrm{d}T_{req}}{\mathrm{d}t} &= r\,\mathrm{clamp}(\eta, -4, 1) \\ T_{in,SP} &= \min(T_{req}, T_{SO}, T_{YO}) \end{aligned} \tag{10.10}$$

Each headroom is measured in its own unit of caution, the humidity term is present only with that override on, and the last only with the moisture controller on. With $m_{min} = 1.5\,\mathrm{K}$, $D_{max} = 0.5\,\mathrm{mm}$ and $r = 0.5\,\mathrm{K/min}$, the request climbs at r while every headroom exceeds one, more slowly as the smallest approaches zero, and falls at up to 2 K/min when it is negative. It is kept no more than 2 K above the applied setpoint and between 150 °C and the ceiling $T_{in,max} = 225\,^{\circ}\mathrm{C}$, and while an override holds the inlet it may only descend. FY-500 is in effect an integrating controller on the worst normalized headroom, a constraint pusher rather than a model-based optimization, and it comes to rest where the binding headroom is zero. Volume 4, Chapter 6 pushes the line speed of another dryer toward its first binding limit with a model-based push.

Pause. Try Exercise 10.3 before reading on.

10.5.6 Model Predictive Control

A model predictive controller (MPC) is offered as an option for the feed and the inlet. All cases retain the loops as their initial structure apart from case 9, which starts on MPC. A quadratic program is solved at a period $T_s = 10\,\mathrm{s}$ (five control scans) for the inlet request T_{req} and the feed command F_{cmd} over $N = 90$ steps, or 15 min, with the block lengths $(1,1,1,1,2,2,3,4,6,9,15,45)$. The first planned values are applied for one decision period, the receding-horizon practice of Section 1.6.3 [19, 20]. The first plan is made on the priming call, so a run under the MPC logs it from $t = 0$. The request

Table 10.5 Response Shapes of the MPC's Model, Equation (10.11). Times in Seconds, Fit Residual RMS in Percent of the Change

Pair	a	θ	τ_1	τ_2	τ_s	Resid.
$F \to \hat{w}$	0.842	36.4	142.5	106.3	2199	0.17
$F \to T_{202}$	0.801	5.9	22.6	11.5	1876	0.12
$F \to Y_{202}$	1.017	10.6	30.5	30.5	1990	0.10
$F \to \hat{m}$	1.081	8.9	33.8	33.8	426	2.52
$T_{req} \to \hat{w}$	0.580	63.6	60.4	205.1	1489	0.20
$T_{req} \to T_{202}$	0.588	13.8	27.8	9.6	1482	0.52
$T_{req} \to Y_{202}$	0.582	81.0	50.3	9.2	1379	0.84
$T_{req} \to \hat{m}$	0.462	49.0	27.6	27.6	1360	3.25
$T_{req} \to u_h$	1	0	10	1	—	—

takes FY-500's place in the minimum selector of Equation (10.10), so UIC-205, AIC-206 and the heater clamp act above the plan as they act above the optimizer, and the feed goes to the pump in TIC-202's place. Meanwhile TIC-202's integral tracks the plan's feed and the outlet setpoint follows TT-202, so that AIC-400 also tracks and the loops stand ready to resume.

The controller's model has the handles $u = (T_{req}, F_{cmd})$ and five outputs, $y = (\hat{w}, T_{202}, Y_{202}, \hat{m}, u_h)$, the corrected moisture estimate, the exhaust temperature and humidity, the estimated margin and the gas heater output. Its gains K_{ij} come from the steady balance that AY-401 solves, evaluated with the declared parameters of Table 10.2, a 50 °C feed and a new atomizer, never with the run's values, and they are recomputed at every decision by forward differences of 1 K and 1 kg/h at the measured operating point (TT-201, the applied feed, TT-301, AT-001 and the solids the soft sensor is told). At the design point, per kg/h of feed and per kelvin of inlet, the moisture gains are 0.00631 and −0.0541 points, the outlet gains −0.0745 and 0.727 K, the margin gains −0.0101 and −0.0243 K, and the heater gains 0 and 0.454 points. Because the margin's feed gain changes sign near the sticky point, that path is omitted from the plan, as it is from the inlet-only overrides. The remaining paths follow Equation (10.11).

$$y_{ij}(t) = K_{ij}\Big[a_{ij}\, g_2(t-\theta_{ij};\tau_{1,ij},\tau_{2,ij}) + (1-a_{ij})\big(1-\mathrm{e}^{-t/\tau_{s,ij}}\big)\Big] \tag{10.11}$$

Here g_2 is the unit step response of two first-order lags in series and the parallel lag τ_s is the chamber walls. The shapes, in Table 10.5, were fitted to steps of 50 kg/h of feed and 5 K of inlet setpoint in both directions from case 2's design point with its event removed, TIC-201 and TIC-301 in automatic and the feed scripted, each against an unstepped run on the same seed over 120 min. At T_s each dead time becomes whole steps on a delay line of its input, the remainder joining τ_1, and the lags are discretized exactly, which gives 38 states (11 for the delays and 27 for the lags). With a constant input the model settles on the linearization $K\Delta u$ to within 1.4×10^{-10}.

Driven by the same steps with the noise off, the plan's model is within 3 % of the plant's change after 120 min for every output but the margin, which falls 0.161 K after the inlet step against a predicted 0.123 K, 31 % more, and whose gain differs by 33 % between steps up and down. The heater path uses nominal lags of 10 and 1 s rather than an independently fitted pair. Its prediction has an RMS error of 6.8 % of the step change, with the correct steady gain.

The optimized variables are increments of each handle, referenced to the currently applied input. A block shares one increment. Each plan minimizes Equation (10.12), in which j counts the blocks,

$\hat{y}_{i,k}$ is a predicted output and ε_i the one slack of output i.

$$\begin{aligned} \mathscr{J} = & -\sum_{k=1}^{N} \frac{F_{cmd,k}}{\mathrm{kg/h}} + \lambda \sum_{j=0}^{11} \left[\left(\frac{\Delta T_{req,j}}{1\,\mathrm{K}} \right)^2 + \left(\frac{\Delta F_{cmd,j}}{10\,\mathrm{kg/h}} \right)^2 \right] \\ & + \sum_{i=1}^{5} \left(\nu_i \varepsilon_i + \kappa_i \varepsilon_i^2 \right) \\ \text{s.t. } & \underline{y}_{i,k} - \varepsilon_i \le \hat{y}_{i,k} \le \bar{y}_{i,k} + \varepsilon_i, \quad \varepsilon_i \ge 0 \\ & 150\,^{\circ}\mathrm{C} \le T_{req,j} \le T_{in,max}, \quad 0 \le F_{cmd,j} \le F_{max} \\ & -4rT_s \le T_{req,j} - T_{req,j-1} \le rT_s \end{aligned} \tag{10.12}$$

The feed earns one unit per kg/h per step, and $\lambda = 1000$ prices moves. The soft limits are the loops' own. The moisture estimate stays under AIC-400's setpoint, 3.5 %, the margin estimate over the optimizer's floor $m_{min} = 1.5\,\mathrm{K}$, the heater under 95 %, the exhaust humidity under $Y_{max} - 2$ while AIC-206 is on, and the outlet inside the 65 to 100 °C that AIC-400 may ask for. The slack prices (ν_i, κ_i) are $(2 \times 10^5, 2 \times 10^6)$ per point of moisture, $(10^5, 10^6)$ per kelvin of margin, $(2 \times 10^4, 2 \times 10^5)$ per point of heater, $(3 \times 10^4, 3 \times 10^5)$ per g/kg and $(10^4, 10^5)$ per kelvin of outlet, each far above the 90 units a kg/h of feed earns over the horizon. When the initial prediction violates a band, its bound tightens linearly toward the specified limit, taking 60 steps for moisture, 3 for the heater and 6 for each remaining output. The handle limits are hard. At the default ceiling of 225 °C and rate r, the request rises at most 0.083 K and falls at most 0.333 K per block. It cannot rise above the applied setpoint while the deposit estimate exceeds D_{max}. Energy is not priced. The move price was set once on case 9, before any comparison, as the largest λ within 1 % of the best powder in specification among values that reject no plan, leave no sticky minute and move the feed no more than the loops. The model's states are advanced by the inputs actually applied over each period, under either structure, and each output carries an additive bias, the period's mean measurement less the model's present output, held over the horizon. This output-disturbance model makes the plan offset-free on what the transmitters and AY-401 read [21], and no Kalman filter is involved (Section 1.4.7). The offset-free MPC of Volume 9, Chapter 4 carries its disturbance in a Kalman estimator instead. The moisture the plan reads is AY-401's corrected estimate, so the laboratory reaches it only through the bias of Equation (10.8), and it never sees the true moisture, the true solids or a laboratory result before the report. No preview of any event reaches either structure.

The program has 24 input values and 5 slacks and is solved by the shared dual active-set method [22]. Acceptance requires an optimal status, finite values and inputs within their bounds. Otherwise the tracked loops resume control until a subsequent plan passes these checks. Three forced rejections with the noise off hand over with a feed step of 0.011 kg/h and an inlet setpoint step of 0.004 K, and none of the 178740 plans measured below was rejected. The minimum selector still acts at every scan, and a forced ignition in case 7 shuts off the feed and heaters. Manual mode starts at the inlet setpoint after the protective overrides. The MPC reads only what the loops read and the declared values, and nine copies of the controller altered to hand it one truth value or run parameter all fail the application's checks. A warmed plan takes 3.3 ms in Chrome, so the plans need more than a core at the two top speeds, and under the MPC each frame stops stepping after 25 ms, which leaves the logged rows unchanged and plays those speeds at about 40 min/s.

10.5.7 Manual Mode and the Shutdown

In manual the operator sets the feed and both heaters, every loop tracks, and switching to manual copies the current outputs to the manual stations. After a CO shutdown the feed and heaters are held at zero and the loops track zero. A manual helper sets the design point, 1001 kg/h of feed with the heaters at 74.9 and 27.4 %.

Table 10.6 Scenario Events and Teaching Points

#	Scenario and event	Teaching point
1	Manual, feed 1000 to 1100 kg/h at 5 min	fast air, slow powder
2	Outlet 80 to 83 °C at 10 min	the price of a kelvin
3	Feed solids 48 to 44 % at 10 min	a proxy holds the wrong thing
4	Case 3, AIC-400 on the soft sensor	the laboratory corrects
5	Intake 8 toward 18 g/kg at 10 min	feedforward meets the weather
6	Inlet 190 to 225 °C at 10 min	throughput, stickiness
7	3.5 mm deposit, inlet 200 to 225 °C	a fire no loop stops
8	AIC-400, bed 70 °C, inlet 205 °C	a second handle
9	Case 4, FY-500, UIC-205, MPC	one plan, two handles
10	480 min, humid hours, solids dip	graded campaign

10.5.8 The Three Models

Section 10.3 is the simulation model, the plant itself. The shipped loops use no identified dynamic control model. Their response can be characterized by step tests at the design point. At a fixed heater, 100 kg/h more feed lowers the outlet by 5.9 K within 2 min and by 7.3 K at steady state, −0.073 K per kg/h, the slower part coming from the walls, and raises the steady powder moisture by 0.65 points, reaching half of its 30 min change 4.3 min after the step. A point of gas heater raises the inlet by 2.20 K. The shipped controllers carry four internal models. The soft sensor is the plant's own drying model with the design atomizer, the feedforward gains are the slopes of Figure 10.2, the deposit estimate is the plant's deposit law driven by the estimated margin, and the optimizer's headrooms are fixed scalings. None of them knows the feed solids unless AT-102 is read. The optional MPC carries a fifth, the steady model evaluated with the declared parameters of Table 10.2 and joined to lags identified offline by step tests on the application, Section 10.5.6. A learner's edit of a plant parameter therefore reaches the soft sensor but not the MPC, for which it is model mismatch.

10.6 Measured Behavior of the Nine Cases

Table 10.6 lists the cases and the campaign. Each starts from the steady state of the reference configuration, the outlet loop in automatic at 80 °C, the inlet at 190 °C, the bed at 55 °C, the soft sensor assuming 48 % solids with the laboratory correction on, and the moisture controller, both feedforwards, the optimizer and both overrides off, and differs from it only where its row says. All numbers below were computed by the engine outside the browser, stepped exactly as the browser steps it (Section 1.6.4), with the default seed and in minutes of simulated time. Every run exports a comma-separated file of 151 columns with the true moisture, margin and deposit beside every instrument and estimate. A setting that a configuration changes is changed after the case is loaded and before the run starts, as a learner does after a Reset. Carrying the same setting through the Reset instead gives identical runs in cases 1 to 8 and moves the campaign by at most 0.007 t and 8 kJ/kg. Where the noise of the transmitters and the laboratory decides a comparison, the range over eight further noise seeds is given. Table 10.7 collects the outcomes of the three cases that turn on the proxy and of case 9, and Figure 10.4 draws them as bars.

10.6.1 Fast Air, Slow Powder

Case 1 runs in manual with the feed at 1000 kg/h, the gas heater at 74.9 % and the bed heater at 27.4 %, and raises the feed to 1100 kg/h at 5 min. The outlet falls from 80.1 °C to 76.9 °C within 30 s, to 75.0 °C within a minute and 74.3 °C within two, and then creeps to 73.5 °C by 30 min and 73.0 °C by 90 min as the walls cool. The particles leaving the chamber go from 4.15 % to 4.81 % within a minute, but the powder has to cross the bed, and its moisture passes 3.8 % at 9.0 min, reaches half of its 30 min change at 9.3 min, and stands at 4.16 % at 30 min, with the margin down to 1.83 K, and at

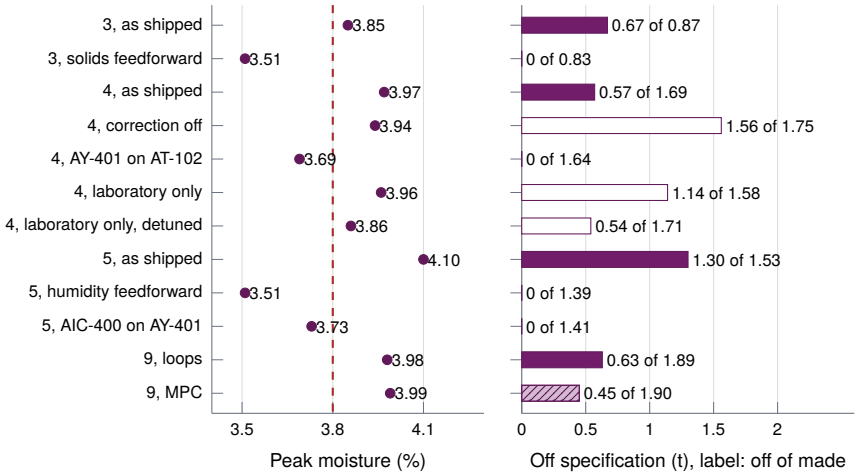


Figure 10.4 The proxy cases and case 9 from Table 10.7: the peak true moisture after the event (left, dashed line at the 3.8 % limit) and the tonnage off specification, labeled with the tonnage made (right). Rows name the case and its configuration, and the detuned row is the table's footnote. Dark bars are the case as shipped, hatched bars add a measurement, a feedforward, the moisture loop or the MPC, and white bars remove the laboratory correction or use the laboratory alone. Notice that in case 4 the rows without the correction and on the laboratory alone at the shipped tuning ship more off-specification powder than the shipped soft sensor, and that every row that reads the true solids or the humidity ships none.

Table 10.7 Truth-Log Outcomes of Cases 3 to 5 and 9. Peak Moisture After the Event, Tonnage Off Specification Out of the Tonnage Made, Worst True Margin and Specific Energy Over the Run

Case and configuration	Peak (%)	Off/made (t)	Worst m (K)	Energy (kJ/kg)
3 as shipped, 120 min	3.85	0.67/0.87	2.38	4820
3 solids feedforward	3.51	0/0.83	2.63	5079
4 as shipped, 240 min	3.97	0.57/1.69	2.27	4990
4 correction off	3.94	1.56/1.75	2.30	4817
4 AY-401 on AT-102	3.69	0/1.64	2.61	5118
4 laboratory only	3.96	1.14/1.58	1.48	5322
4 laboratory only[a]	3.86	0.54/1.71	2.38	4937
5 as shipped, 180 min	4.10	1.30/1.53	−0.26	4177
5 humidity feedforward	3.51	0/1.39	0.47	4589
5 AIC-400 on AY-401	3.73	0/1.41	0.47	4503
9 loops, 240 min	3.98	0.63/1.89	0.61	4817
9 MPC	3.99	0.45/1.90	0.57	4831

[a] detuned, $K_c = 2$ K per % and $\tau_I = 60$ min

4.21 % at 90 min. The laboratory reports 4.11 % at 70 min, from the first sample drawn after the step. The heater works the other way. The feed step is scripted and recurs on every run, so the heater is tested by returning the feed to 1000 kg/h at the scan after the step and raising the heater from 74.9 to 79.9 %. That lifts the inlet to 201.1 °C, the outlet to 84.5 °C within 2 min and 87.0 °C by 30 min, and dries the powder from 3.49 to 2.95 %.

10.6.2 The Price of a Kelvin

Case 2 steps the outlet setpoint from 80 to 83 °C at 10 min. The true outlet is within 0.3 K of its new setpoint 30 s later, stays there after 1.5 min and peaks at 83.17 °C, and the integral of its absolute error from 10 to 60 min is 3.18 K min. The scorecard, which integrates the error of TT-202 and its noise from the start, reads 6.41 K min. A sluggish tuning of 10 kg/h per kelvin and 3 min takes 12.2 min to come within 0.3 K and 13.7 K min. By 60 min the powder is drier, 3.25 % against 3.50 %, and the margin wider, 3.30 against 2.93 K, but the feed has fallen from 1001 to 960 kg/h and the powder from 498 to 476 kg/h, 4.4 % less, while the heaters spend 4402 kJ per kilogram instead of 4219. Dryers are run at the lowest outlet that keeps the powder in specification because every kelvin of it is about 1.4 % of throughput.

10.6.3 Two Ways to Break the Proxy

Case 3 changes the evaporator's product from 48 to 44 % solids at 10 min. Each droplet now carries 1.27 kg of water per kilogram of solids instead of 1.08 kg, and the outlet loop trims the feed to a mean of 931 kg/h over 100 to 120 min while holding the true outlet within 0.39 K of 80 °C, and TT-202 within 0.66 K with its noise. The particles leave the chamber at 4.70 % instead of 4.17 %, the powder passes 3.8 % at 26 min and reaches 3.85 %, and 0.67 of the 0.87 t made in 120 min is off specification. The soft sensor, still told 48 %, gives a raw estimate of 3.40 %, drier than before, because it starts every droplet with the water of a 48 % concentrate, while the laboratory reports 3.78 % at 70 min and 3.87 % at 100 min. With the solids feedforward on AT-102 the outlet setpoint rises to 84.5 °C and the powder stays between 3.48 and 3.51 %, at 5079 kJ/kg over the run against 4820 kJ/kg.

> **TRY IT IN THE APP** **3 · A Weaker Concentrate**
>
> Load the case and press Run. Watch the outlet temperature stay close to 80 °C after the step at 10 min, then the true moisture in the powder moisture trend. It passes 3.8 % at 26 min and reaches 3.85 % while the loop holds its setpoint.

Case 5 turns the weather at 10 min, and the intake humidity follows it through its 20 min lag, 15.8 g/kg at 40 min and 17.5 g/kg at 70 min. At a held 80 °C the exhaust climbs from 49.6 to 60.5 g/kg, 18.9 % relative humidity, and its wet bulb from 45.1 to 47.7 °C. The powder passes 3.8 % at 28 min and reaches 4.10 %, the particles leaving the chamber cross the sticky line at 61 min and reach −0.26 K, 0.40 mm of deposit builds by 180 min and 1.30 t is off specification. The humidity feedforward raises the outlet setpoint to 88.0 °C with the weather and holds the powder between 3.49 and 3.51 % and the margin at 0.47 K or more, at the cost of feed, 922 kg/h at 180 min instead of 1028, and energy, 4660 kJ/kg against 4219 before the weather turned. AIC-400 on the soft sensor also holds the powder, because the soft sensor reads the exhaust humidity, but only after the moisture has reached 3.73 % at 34 min. The feedforward acts on the cause, and the feedback waits for the effect.

10.6.4 A Model Corrected by a Late Laboratory

Case 4 repeats the weak concentrate with AIC-400 on the corrected estimate. At first the loop makes things worse. The soft sensor, told 48 %, reads the weaker concentrate as drier powder, so AIC-400 lowers the outlet setpoint to 78.5 °C while the truth rises, and the powder peaks at 3.97 % at 68 min. The first two results, from powder made before the change, come out 0.06 and 0.05 points low at the default seed and start the bias at −0.03 and −0.04 points, which deepens the dip. The results from 70 to 220 min move the bias to 0.17, 0.32, 0.36, 0.42, 0.47 and 0.46 points, the jump at 70 min coming from the first sample of weak concentrate, and AIC-400 raises the outlet setpoint step by step to 84.4 °C. The powder is back under 3.8 % at 102 min and under 3.6 % at 163 min, and at 240 min it is at 3.49 % while the raw estimate reads 3.05 %, as shown in Figure 10.5. Over three further noise seeds (1, 42 and 20261008), the powder is back under 3.8 % between 80 and 98 min and 0.37 to 0.54 t is off specification, against 0.57 t here, so the default seed lies at the slow end. Without the correction

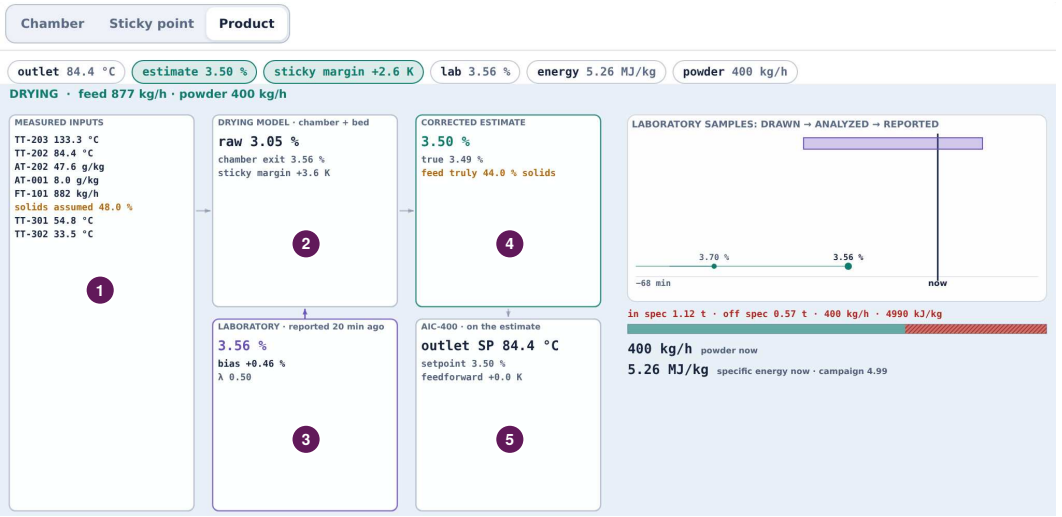


Figure 10.5 The spray dryer application in case 4, soft sensor and lab correction, at $t = 4.00$ h (240 min) in the Product view, 230 min after the concentrate fell from 48 to 44 % solids, run with no control changed, cropped to the view. The signal path shows (1) the measured inputs, among them TT-203 at 133.3 °C, TT-202 at 84.4 °C, AT-202 at 47.6 g/kg, FT-101 at 882 kg/h and the feed solids assumed at 48.0 %, (2) the drying model's raw estimate of 3.05 % with the chamber exit at 3.56 % and an estimated margin of 3.6 K, (3) the laboratory's 3.56 %, reported 20 min earlier, with a bias of 0.46 % at $\lambda = 0.50$, and (4) the corrected estimate of 3.50 % against a true 3.49 % while the feed is truly 44.0 % solids, with (5) AIC-400 holding the outlet setpoint at 84.4 °C. The sample line shows one sample in analysis and the last two results, 3.70 and 3.56 %, above 1.12 t of powder in specification and 0.57 t off, a powder rate of 400 kg/h and 4990 kJ/kg over the run, and the badges give a true margin of 2.6 K.

the controller holds its estimate on 3.50 % while the powder runs at 3.94 %, and 1.56 t of 1.75 t is off specification. Told the true solids by AT-102, the soft sensor needs no correction. The powder peaks at 3.69 % at 24 min, nothing is off specification, and the bias stays within ±0.043 points. Keeping the laboratory correction off when switching to AT-102, as in the three runs that case 4 asks for, gives a peak of 3.68 % at 24 min, no off-specification powder and 5130 kJ/kg.

> **TRY IT IN THE APP** **4 · Soft Sensor and Lab Correction**
>
> Open the Product view, press Run and run to 240 min. Watch the bias in the laboratory box step at each result, 0.17 points at 70 min and 0.46 by 220 min. The true moisture peaks at 3.97 % at 68 min and is back under 3.8 % at 102 min.

The same run also shows what the correction does not reach. The bias is added to the moisture only, so the chamber exit is still estimated at 3.56 % against a true 4.23 %, and the margin at 3.56 K against a true 2.64 K. With the solids assumed, the constraint estimate that the override and the optimizer read is 0.9 K optimistic, and the laboratory never sees it (Section 1.4.6).

On the laboratory alone, AIC-400 moves once per result, and with the shipped tuning it oscillates with a growing amplitude, as a correction that acts on results older than its previous move does (Equation (1.9)). Within the four hours it swings the outlet setpoint between 78.6 and 98.5 °C and the powder between 2.57 and 3.96 %, and 1.14 t is off specification (0.55 to 1.19 t over the three further seeds), and the setpoint reaches its 65 °C limit at 250 min. Slowed to 2 K per point and 60 min it stops

oscillating but is slow, with the powder at 3.86 % at its worst, still at 3.69 % at 240 min and 0.54 t off. The weight trades speed against noise, as Table 1.2 sets out. With $\lambda = 1$ the bias moves to 0.37, 0.46, 0.40, 0.48, 0.52 and 0.45 points at the results from 70 to 220 min, because each update takes the full laboratory noise and the mismatch of powder sampled 40 min earlier, yet the powder is back under 3.8 % at 77 min and 0.40 t is off specification. With $\lambda = 0.2$ the powder is not back under 3.8 % until 136 min and 0.81 t is off. The ordering holds at every seed tried, with 0.24 to 0.40 t off at $\lambda = 1$ and 0.75 to 0.82 t at $\lambda = 0.2$.

> **+ DID YOU KNOW? The Late Truth Loses to a Corrected Guess**
>
> From the simulator: in case 4 the moisture controller fed by the laboratory alone ships 1.14 t off specification of 1.58 t made, while on the soft sensor under laboratory correction it ships 0.57 t of 1.69 t (Table 10.7). Every result is true but late, and a correction that acts on results older than its previous move oscillates.

10.6.5 Throughput Against the Sticky Line

Case 6 raises the inlet setpoint from 190 to 225 °C at 10 min. The outlet loop sends more feed, 1341 against 1001 kg/h at 120 min, the powder rises from 498 to 669 kg/h, 34 % more, the gas heater settles at 90.7 % after touching 100 % in the transient, and the energy per kilogram falls from 4219 to 3778 kJ/kg. The exhaust carries 63.7 g/kg, and at the steady state of a 225 °C inlet the particles leave the chamber at 66.2 °C and 4.42 %, where the glass transition is 45.2 °C, which is 0.98 K past the sticky line. They cross it at 13.7 min. The deposit grows to 0.29, 1.31, 2.46 and 3.64 mm at 30, 60, 90 and 120 min, the roof passes 158 °C at 20.9 min and reaches 167.2 °C, and the layer reaches the 3 mm that can smolder at 104 min. The sticky-margin override settles the inlet at 211.2 °C, with 1207 kg/h of feed and 601 kg/h of powder over the last 20 min, a lowest true margin of 0.40 K and no deposit, although the roof still passes 158 °C at 32.1 min. The exhaust-humidity override at 58 g/kg does nearly the same at 210.8 °C.

10.6.6 A Fire No Loop Can Stop

Case 7 starts with 3.5 mm of powder baked onto the roof and the inlet at 200 °C, where the roof sits at 153.2 °C, and pushes the inlet to 225 °C at 10 min. The particles are sticky from 12.1 min, the roof passes 158 °C at 16.0 min, and after 20 min of both conditions the layer, now 4.0 mm, ignites at 36.0 min with the roof at 165.0 °C. AT-205 reaches the 15 ppm alarm at 41.8 min and the 40 ppm shutdown at 43.7 min, and the run stops at 44.75 min with 0.46 t made. Lowering the inlet to 200 °C at 15 min keeps the roof at 157.4 °C or less, and there is no fire, although 2.95 mm is still on the roof at 120 min. The sticky-margin override holds the inlet at 212.1 °C, where no new deposit forms, but that inlet puts the roof at 159.4 °C, so the old layer ignites at 45.8 min and the dryer shuts down at 53.5 min. This follows from Section 10.4, where the roof reaches 158 °C at a lower inlet than the one at which the powder turns sticky. The case would not arise as a single push in a plant, but it serves to show a constraint that cannot be recovered once crossed, and a deposit that a controller can only keep from growing.

10.6.7 The Bed as a Second Handle

Case 8 holds the moisture with AIC-400 and raises the bed setpoint from 55 to 70 °C at 10 min, then the inlet from 190 to 205 °C at 60 min. The bed air rises from 56 to 81 °C, the powder dips to 3.25 % at 17.3 min, and AIC-400 answers by lowering the outlet setpoint to 75.5 °C by 59 min, so that, averaged over 50 to 59 min, the feed rises from 1001 to 1066 kg/h and the powder from 498 to 530 kg/h, while the energy falls from 4219 to 4087 kJ/kg. The hotter inlet then brings 1204 kg/h of feed, 597 kg/h of powder and 3935 kJ/kg at 180 min, with the outlet setpoint at 76.2 °C. The price is the margin. It falls from 2.93 to 2.21 K with the lower outlet and to 0.60 K with the hotter inlet, because the chamber now leaves the powder wetter, 4.74 % against 4.17 %, and at 180 min the bed powder at 70 °C and 3.51 % is itself only 4.4 K inside its own sticky line. A second handle on the

Table 10.8 Case 9 Over 240 min, Means of Five Seeds. Over: Minutes of True Moisture Above 3.8 %. Lab: Laboratory Results Above 3.8 %, of 40. Travel: Summed Feed Moves

Structure	In (t)	Off (t)	Made (t)	Over (min)	Lab	Energy (kJ/kg)	Travel (kg/h)
Loops (shipped)	1.322	0.570	1.893	72.9	15	4821	16779
MPC (shipped)	1.452	0.444	1.896	56.4	11	4834	1216
AIC-400 15 K/%, 3 min	1.477	0.413	1.890	52.9	11	4839	16991
Loops in hindsight[a]	1.498	0.427	1.925	53.0	11	4808	16999

[a] best of 560 fixed settings at the 1.5 K floor: AIC-400 at 15 K/% and 3 min, FY-500 at 2 K/min, override off

same product lets the cheaper one do more of the work, and the constraint moves to wherever that handle pushes.

10.6.8 Feed and Inlet in One Plan

Case 9, Feed and inlet in one plan (MPC), repeats the weaker concentrate of case 4 with the soft sensor still told 48 % and with AIC-400, FY-500 at its 1.5 K floor and the sticky-margin override on, while the MPC of Section 10.5.6 sets the feed and the inlet. Each row of Table 10.8 changes only the structure or its tuning, over 240 min using five seeds (the scenario default and integers 1 through 4). The instruments, event schedule and noise realization are matched between structures, and neither receives preview information. In these comparisons off-specification powder is produced only from 10 to 130 min.

Like for like, at the loops' own moisture setpoint, floor, heater headroom and climb rate, the MPC makes the same powder as the shipped loops, 1.896 against 1.893 t, at 0.3 % more energy per kilogram, so it offers no throughput gain. It ships 1.452 t in specification against 1.322 t and 0.444 t off against 0.570 t, better at every seed, and moves the feed far less because TIC-202 answers the noise of TT-202. The whole specification gain is the answer to the laboratory result at 70 min, the first from powder made after the change, as shown in Figure 10.6. Before that result both structures hold the same biased estimate on 3.50 % and ship the same wet powder. On the case's seed the true moisture passes 3.8 % at 17.6 min under the MPC and 21.8 min under the loops, and peaks at 3.99 and 3.98 %. After it, the MPC cuts the feed, and its estimate is back at 3.52 % by 74.7 min and the powder under 3.8 % by 74.5 min. AIC-400 at its shipped 5 K per point and 8 min brings the powder under 3.8 % only at 102.7 min and leaves its estimate above 3.52 % until 220 min.

The loops can buy the same speed by tuning. AIC-400 alone at 15 K per point and 3 min brings the powder under 3.8 % at 74.1 min and ships 1.477 t in specification and 0.413 t off, better than the MPC on both at every seed, and so does the best of 560 fixed settings of the shipped structure chosen in hindsight at the same floor, with 1.498 and 0.427 t. The shipped row keeps AIC-400's shipped tuning, which is slow for this case.

Counterfactual copies of the plan show what drives it, as five-seed means. The feed reward drives the throughput and the inlet delivers it (1.409 t of powder without the reward, 1.368 t with the inlet held), the margin floor bounds it (1.990 t without the floor, sticky for 125 min), and the moisture ceiling alone keeps the powder in specification (2.106 t off without it). The outlet band never binds, and leaving it out changes no digit. On the case's seed the true margin reaches 0.57 K against the loops' 0.61 K. Both margin estimates retain the error from the unmeasured weaker concentrate.

In the feed-solids case, case 3's step with the stack on and the soft sensor reading AT-102, the loops with the solids feedforward and the MPC both ship 1.774 t in specification and none off over 240 min, a tie. Case 8 as loaded is a loss, 4.471 against 4.678 t in specification over 480 min at 4027 against 3975 kJ/kg. The plan sets the inlet itself, so the case's scripted step to 205 °C never happens, and it has no handle on the bed. The same is true wherever a case's lesson is a loop or a scripted setpoint step, in cases 2 to 8, which therefore teach their lessons only on the loops, as the application's guide states.

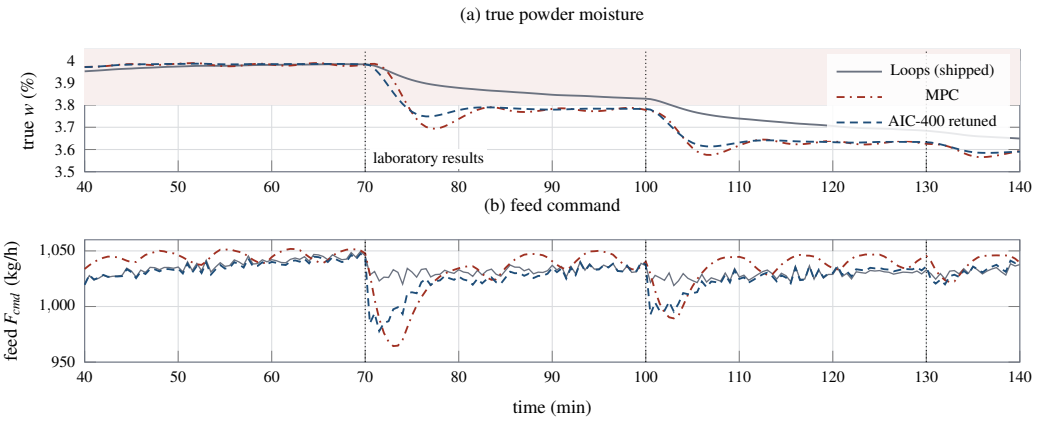


Figure 10.6 Case 9 on its own seed from 40 to 140 min, sampled every 30 s, under the shipped loops (solid), the MPC (dash-dotted) and the loops with AIC-400 retuned to 15 K per point and 3 min (dashed). Dotted vertical lines mark the laboratory results. (a) The true powder moisture, with the region above the 3.8 % limit shaded. After the laboratory result at 70 min the MPC and the retuned loop bring the powder under 3.8 % at 74.5 and 74.1 min, the shipped loop at 102.7 min. (b) The feed command. The MPC cuts the feed by about 70 kg/h within two minutes of the result, while TIC-202's feed carries the noise of TT-202.

Table 10.9 Campaign Configurations Over 480 min, Scored on the Truth Log

Configuration	In (t)	Off (t)	Worst m (K)	Energy (kJ/kg)	Result
as shipped	1.98	2.02	−0.40	4237	fail
AIC-400 on the soft sensor	3.76	0	0.04	4498	fail
and AT-102, both feedforwards	3.76	0	0.06	4500	fail
and the sticky override	3.74	0	0.44	4507	fail
suggested[a]	3.88	0	0.63	4380	pass
suggested, bed at 55 °C	3.78	0	0.61	4496	fail
suggested, optimizer off	3.98	0	0.01	4339	pass[c]
suggested, floor 0.8 K	4.10	0	−0.05	4299	fail
bed 65 °C, sticky override[b]	3.92	0	0.44	4360	pass
as shipped, MPC	3.79	0	0.88	4498	fail
suggested, MPC	3.87	0	0.90	4384	pass

[a] AIC-400, AT-102, both feedforwards, the optimizer at $m_{min} = 1.5$ K, bed 65 °C

[b] as [a] with the sticky-margin override in place of the optimizer

[c] worst margin −0.023 to 0.007 K over three further seeds, one of which passes

10.6.9 The Campaign

The challenge runs 480 min. The intake humidity climbs toward 18 g/kg from 120 min and falls back toward 8 g/kg from 360 min, and from 200 min the concentrate replays an evaporator dip to 45.2 % that recovers to 48 % by 285 min. The target is at least 3.70 t in specification, at most 0.05 t off, no sticky excursion while producing, at most 4450 kJ/kg over the campaign and no CO shutdown. Both the scorecard verdict and challenge credit wait until the full 480 min have elapsed, and the campaign is judged on the case as given, so changing a model parameter or a disturbance voids the attempt. The measured configurations are compared in Table 10.9.

As shipped, on the outlet loop alone at fixed setpoints, the dryer makes 4.00 t, of which 1.98 t is in specification. The powder reaches 4.31 %, the particles are sticky for 191 min from 171 min

with a worst margin of −0.40 K, and 0.90 mm of deposit builds, at 4237 kJ/kg, so the run fails on tonnage, on off-specification powder and on stickiness. The moisture controller alone ships 3.76 t in specification, but the humid hours need a hot outlet and the campaign spends 4498 kJ/kg, over the budget at every seed tried (4486 to 4509 kJ/kg), with the margin down to 0.04 K. The suggested configuration ships 3.88 t, 0.18 t above the target and all of it between 3.44 and 3.56 %, at 4380 kJ/kg, 70 kJ/kg inside the budget, and a worst margin of 0.63 K. Its settings applied before Run and then carried through a Reset give the same trajectory and result. Its optimizer, bound by the estimated margin for more than 479 of the 480 minutes, runs the inlet up to 199.4 °C in the dry hours and down to 175.3 °C in the humid ones. The bed at 65 °C is worth 117 kJ/kg, since the same controls with the bed at 55 °C spend 4496 kJ/kg.

The optimizer's floor is what keeps the true margin positive, and it pays for the optimizer's own speed rather than for the estimator's error. Reading AT-102, the soft sensor's margin stays within 0.15 K of the truth all campaign, yet the worst margin of the suggested run comes at 144 min, with the estimate at 0.62 K, 0.88 K under the floor. The optimizer retreats in proportion to the shortfall, and between 120 and 144 min it lowers the inlet by only 6.9 K while the intake climbs from 8.0 to 15.0 g/kg and takes the true margin from 1.53 to 0.63 K. A floor of 0.8 K ships 4.10 t at 4299 kJ/kg but leaves the true margin at −0.05 K, sticky for 8 min from 138 min. Without the optimizer the same controls ship 3.98 t at 4339 kJ/kg with a worst margin of only 0.007 K at 256 min. That run passes at the default seed, but its worst margin ranges from −0.023 to 0.007 K over three further seeds and two of them fail, so a fixed inlet of 190 °C rides on the sticky line through the humid hours. The suggested run keeps 0.63 to 0.68 K at every seed. The sticky-margin override, a PI loop that retreats as fast as the margin falls, is not the only alternative. With the bed at 65 °C and the override in place of the optimizer, the campaign passes with 3.92 t at 4360 kJ/kg and a worst margin of 0.44 K (0.44 to 0.45 K over the three further seeds), more powder at less energy than the suggested configuration, because the inlet stays near 190 °C in the dry hours and falls only as far as 184.6 °C when the weather turns.

The MPC rows of Table 10.9 are given for information, under the same target and rules. Switched on with nothing else changed, the MPC ships 3.73 to 3.79 t in specification with the margin at 0.88 K or more but spends 4498 kJ/kg, over the budget at every seed (4487 to 4499 kJ/kg), and at seed 2 it also ships 0.058 t off specification. With the suggested settings it passes at all five seeds, with 3.87 to 3.88 t, a worst margin of 0.90 to 0.98 K and 4374 to 4384 kJ/kg, against 0.63 to 0.68 K and 4371 to 4380 kJ/kg for the suggested settings alone.

10.7 Technology in Practice

What Measures It

The loop that steers the dryer reads the exhaust temperature, and the quality that judges it is read by a laboratory. A resistance thermometer in a thermowell is one way to read the exhaust, and it carries two faults that matter here, a lag from its sheath and an offset from its wiring [23].

> **TECHNOLOGY** **Sensor: A Resistance Thermometer in the Exhaust**
>
> A resistance temperature detector is a winding of fine metal wire, usually platinum, whose resistance rises with temperature almost linearly. A 100 Ω element at 0 °C is very common in industry. It is more fragile than a thermocouple but needs no reference compensation. In a duct it sits in a thermowell, a sheath that lets it be replaced without opening the process but adds to the lag of the reading, and an air gap at the bottom of the sheath adds a second lag. The resistance of two connecting wires adds to the element's and reads as a falsely high temperature [23]. TIC-202 would answer such an offset with more feed and wetter powder while its trend sat on the setpoint.

The chapter gives TT-202 one lag of 5 s and filtered noise of 0.1 K, which stand for the element, its sheath and its transmitter. United States rules for dairy plants ask for as many samples from each

dryer production lot as are needed to assure its composition and quality, tested by official methods of laboratory analysis [3]. The chapter's laboratory samples every 30 min and reports 40 min later.

What Moves It

TIC-202 moves the feed pump, TIC-201 the gas heater of the drying air and TIC-301 the bed heater. The model's heaters follow their commands through lags of 30 and 20 s, and the gas heater loses the fouled share of its output.

> **TECHNOLOGY Final Element: The Feed Pump on a Variable-Frequency Drive**
>
> One way to carry out TIC-202's feed command is to set the speed of the concentrate pump. A variable-frequency drive sets the speed of an induction motor by the frequency of the power it applies, and it can limit speed, current, torque, acceleration and deceleration and shut down on overcurrent or overvoltage. Variable-speed machines often cannot change a flow as fast as a control valve, and a stopped pump does not necessarily stop the flow through it [23]. Matching motor speed to the load saved typically 7 to 60 percent of the energy in a range of applications [24]. The model's pump follows its command through one lag of 3 s.

Where the Controller Runs

Loops like these run in a distributed control system. It places a supervisory level over field controllers that hold their process conditions around set points, nests or cascades loops so that one loop sets another's set point, and runs with cycle times from milliseconds to minutes [25]. A 2003 survey of predictive control draws the usual hierarchy. Basic PID loops execute about every second, and above them, about every minute, sits dynamic constraint control, done in the conventional structure by PID algorithms, lead-lag blocks and high and low select logic and in the newer one by a single predictive controller [20]. Here the loops, the soft sensor and FY-500 run every 2 s and the optional MPC every 10 s. The velocity-form PI of Equation (10.7) is the function block of each loop, and the minimum selector ahead of TIC-201, with external reset on the loops it does not select, is the select logic of the conventional structure. Figure 10.7 draws the loops on field devices.

What Is Modernizing It

Three developments bear on this dryer. The first is the soft sensor. A 2013 review of industrial soft sensors prefers a first-principles model wherever one is available with enough accuracy at reasonable modeling effort and computing load, and it reports updating strategies that join a recursive model with an update of the model's output offset [26], the part the laboratory bias plays for AY-401. The second is control for energy. A 2011 guide for dairy plants puts the savings of process control systems at around 5 % or more for many industrial plants without updated systems, and notes that up to 30 % of the heat in a dryer's exhaust can be recovered once the powder it carries is filtered out [24]. The third is predictive control. The 2003 survey found that most industrial predictive controllers carry no process state and feed back through a bias, which it judged probably the best assumption for stable plants without information on the disturbances [20]. The MPC of case 9 carries such an output bias.

> **IN PRACTICE Run at the Lowest Outlet the Powder Allows**
>
> A 2011 energy guide for dairy plants states the rule. For the most efficient operation a spray dryer's inlet air should be as hot as possible and its outlet air as cool as possible, within limits set by the product: too hot an inlet damages the product, and too cool an outlet leaves it sticky and too wet. Because the temperature and humidity of the intake air vary while the settings stay fixed, it also recommends measuring them so that operators can adjust the dryer [24]. The humidity feedforward of FF-400 makes that adjustment automatic.

10.8 Limitations

The drying curve, the isotherm, the sticky criterion and the deposit and fire rules are illustrative teaching values rather than correlations fitted to a milk powder, and the thresholds of the fire rule

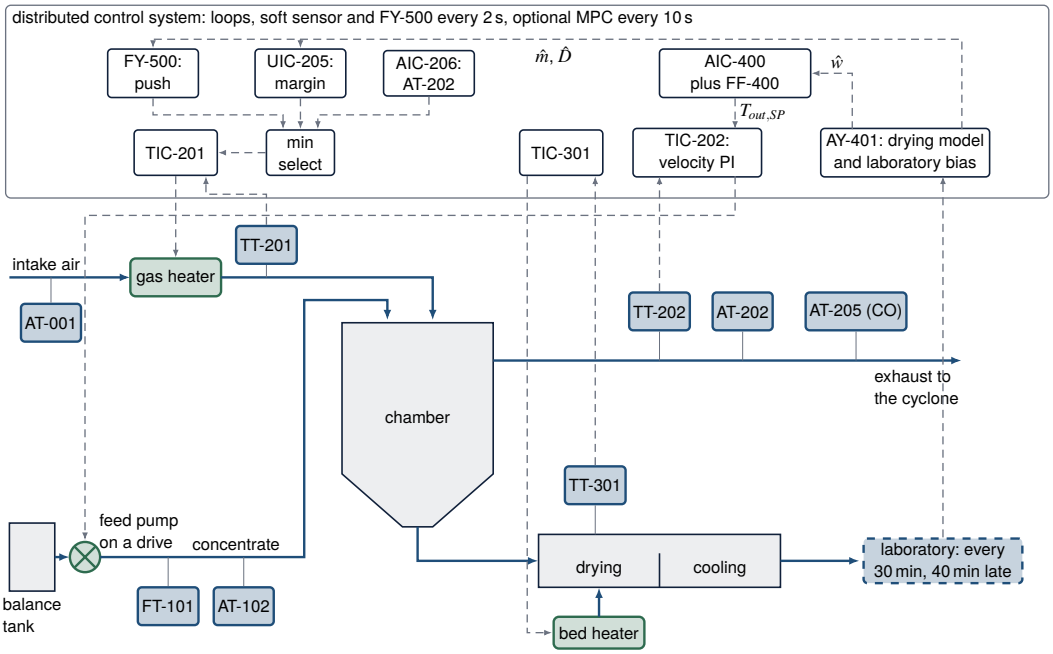


Figure 10.7 The loops of the dryer on plant hardware. TIC-202 holds the exhaust temperature TT-202 by the speed of the feed pump, and AIC-400 with the feedforward FF-400 writes its setpoint from the soft sensor AY-401, which solves the drying model at the measured air and feed (TT-203, AT-202, AT-001, FT-101 and AT-102 are read by it but their lines are not drawn) and takes its bias from the laboratory. The minimum of the push FY-500 and the overrides UIC-205 and AIC-206 sets the inlet that TIC-201 holds with the gas heater, and TIC-301 holds the drying section of the bed. Notice that the laboratory is the only instrument that reads the powder itself.

are not a design basis. The chamber carries one mean particle per cell, with no size distribution, no particle history and no surface stickiness, and the model has no explosion, venting or suppression.

The soft sensor solves the plant's own model, so its only errors come from its inputs, their lags and noise, while a real soft sensor also has structural error for the laboratory bias to absorb. The bias corrects the moisture but not the margin estimate that the overrides and the optimizer read. The optimizer is a constraint pusher with fixed headroom scalings, not a model predictive controller, and the evaporator is a replayed boundary condition rather than a coupled model.

On the laboratory alone, AIC-400 executes once per result, every 30 min. An explicit back-calculation over a step longer than twice its tracking time overcorrects, and with a tracking time of τ_I the integral of a saturated loop grew without bound, to 5.0×10^{12} by 480 min with $\tau_I = 3$ min when the application is rerun with that tracking time. The application now tracks with the longer of τ_I and the time since the last result, which keeps the integral of the same run at or below 425.1 and leaves every shipped case unchanged.

The MPC's model is linear at each decision and identified at one design point, so the sticky margin falls 31 % further after a 5 K inlet step than the plan predicts. The plan reads the same biased estimates as AIC-400 and FY-500, so it cannot ship drier powder before the laboratory reports, it has no handle on the bed and no deposit model beyond a hold on the inlet, and it overrides the scripted inlet steps of cases 6 to 8.

The deposit estimate starts at the scenario's declared initial layer, 3.5 mm in case 7 and zero elsewhere. Two other behaviors limit the shipped structure. UIC-205, which tracks the setpoint applied one scan earlier, is reported as the selected input for 92.9 min of the 240 min of case 9 under

the loops while the estimated margin is 1.44 to 2.99 K against its 0.5 K setpoint, and switching it off adds 0.008 t in specification. The moisture loop's slow response is quantified by the retuned row of Table 10.8.

OPEN CHALLENGE **Measuring What Sticks**

Spray drying still loses product to particles deposited on the walls of the drying chamber [9], and the stickiness behind the deposit reaches no instrument. A 2011 guide for dairy plants names sensors that are inexpensive to install, reliable and able to analyze in real time as an important area for process control, with new sensors still to be developed and demonstrated at commercial scale [24]. In this chapter the laboratory corrects the moisture estimate but never the margin, which stays 0.9 K optimistic in case 4. An online reading of the particles' stickiness, or of the deposit itself, would be progress.

10.9 Conclusion

A milk powder spray dryer is controlled through its exhaust temperature and judged on a moisture its laboratory reports most of an hour later, and this simulator keeps the true powder beside everything its controllers believe. At the design point 12 000 kg/h of air at 190 °C makes 498 kg/h of powder at 3.50 % with the exhaust at 80.0 °C, 4219 kJ per kilogram and the chamber particles 2.93 K inside the sticky line. The same outlet gives 3.85 % when the concentrate weakens to 44 % and 4.10 % with sticky particles when the intake reaches 18 g/kg, and the steady map turns the difference into feedforward gains of 1.1 and 0.8 K. A soft sensor told the wrong solids reads 3.40 % for powder at 3.85 %, and its laboratory bias, learned from results 40 min late, brings the powder back under 3.6 % by 163 min, although the margin it reports stays 0.9 K optimistic. A 225 °C inlet makes 34 % more powder and 2.46 mm of roof deposit in 80 min, and an old deposit ignites even under the override, because the roof reaches 158 °C before the powder turns sticky. The campaign improves from 1.98 t in specification to 3.88 t at 4380 kJ/kg, and a simpler override configuration reaches 3.92 t. An optional MPC of the feed and the inlet makes the same powder as the loops in case 9, 1.896 against 1.893 t, and ships less off specification only by answering the laboratory sooner, 0.444 against 0.570 t, which AIC-400 retuned alone betters at 0.413 t. The model carries mean particles, illustrative drying and stickiness constants and declared fire thresholds. A fuller model would add a particle size distribution, a surface-based sticky criterion, a bias on the margin estimate and a coupled evaporator. The simulator shows that an inferred constraint needs the same care as an inferred quality.

KEY POINTS

- A spray dryer is steered by an exhaust temperature that answers in seconds and judged on a powder moisture that its laboratory reports most of an hour later.
- The same outlet gives 3.85 % when the concentrate weakens to 44 % and 4.10 % with sticky particles when the intake reaches 18 g/kg.
- A soft sensor told the wrong solids reads 3.40 % for powder at 3.85 %, and its laboratory bias, learned from results 40 min late, brings the powder back under 3.6 % by 163 min.
- An inferred constraint needs the same care as an inferred quality.

Where else this applies. Chapter 11 infers an unmeasured core temperature from a model in the same way, and Volume 4, Chapter 6 pushes the line speed of another dryer toward its first binding limit.

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10.10 Exercises

10.1 Concept check · 2 min

In case 3 the evaporator's product falls from 48 to 44 % solids at 10 min. The outlet loop keeps the true outlet within 0.39 K of 80 °C, yet the powder passes 3.8 % at 26 min. Why does a well-held outlet temperature not hold the moisture?

(a) TIC-202 is tuned too slowly for the change, and the outlet error it leaves behind wets the powder

(b) The weaker concentrate cools the inlet air, and TIC-201 cannot restore the heat the air brings

(c) Each droplet brings more water per kilogram of solids, so the same outlet now means a wetter powder

(d) The laboratory reports 40 min late, so the outlet loop works from a moisture that is out of date

10.2 Concept check · 1 min

AY-401 compares each laboratory result with the raw estimate it stored at the instant the sample was drawn, not with its estimate at the moment the result arrives. Why?

(a) The stored value is less noisy, because it is averaged over the 40 min turnaround

(b) The stored values are needed to apply the clamp of ± 2 points to the bias

(c) The result describes the powder at its arrival, and the stored value removes the time spent in the bed

(d) The estimate at arrival already contains the plant's response to earlier corrections, so comparing with it would chase that response

10.3 Concept check · 2 min

UIC-205 protects the sticky margin and AIC-206 the exhaust humidity, and both act by lowering the inlet setpoint rather than by cutting the feed. Why does the inlet carry the overrides?

(a) At a fixed inlet a feed cut heats the particles faster than it dries them, so the margin need not improve

(b) The feed pump saturates at 1500 kg/h, so a feed cut cannot be applied above the design point

(c) The inlet answers within seconds, while the feed pump follows its command with a lag of minutes

(d) A feed cut raises the exhaust humidity, which AIC-206 would then have to undo

10.4 Theory and calculation · 7 min

Use the Gordon–Taylor rule and the margin of Equation (10.5), with $T_{g,s} = 101\,^{\circ}\mathrm{C}$, $T_{g,w} = -135\,^{\circ}\mathrm{C}$, $k_{GT} = 6.7$ and $\Delta T_{st} = 20\,\mathrm{K}$. Moistures are on a wet basis.

(a) Compute the glass transition of the powder at the 3.5 % specification. *Checkpoint:* About 54.9 °C.

(b) At the design point the particles leave the chamber at 4.17 % and 64.8 °C. Compute their glass transition and their sticky margin m. *Checkpoint:* About 47.7 °C and 2.9 K.

(c) At a steady inlet of 225 °C they leave at 4.42 % and 66.2 °C. Compute the margin, and split its change from (b) into the part due to the wetter particle and the part due to the hotter one. *Checkpoint:* About −1.0 K: about −2.5 K from the moisture and −1.4 K from the temperature.

10.5 Theory and calculation · 7 min

The laboratory draws a sample every $T_s = 30\,\mathrm{min}$ and reports it $t_d = 40\,\mathrm{min}$ later, and at reset a sample drawn 30 min earlier reports at 10 min. In case 4 the concentrate weakens at 10 min.

(a) At what time does the first result from a sample drawn after the change arrive, and how long after the change is that? *Checkpoint:* At 70 min, 60 min after the change.

(b) Use Equation (1.8) to find the mean age of a held result, and compare it with the 25 s a particle spends in the chamber and the about 5 min the powder spends in the bed. *Checkpoint:* 55 min, about eleven times the time in the bed.

(c) A constant model error ε is learned as $\varepsilon[1-(1-\lambda)^n]$ after n results. Find the number of results needed to learn 90 % of it at $\lambda = 0.5$ and at $\lambda = 0.2$, and the clock time of that result if the first one to carry the error arrives at 70 min. Use Equation (1.12) to give the standard deviation of the bias in each case for a laboratory noise of 0.05 points. *Checkpoint:* 4 results, 160 min, 0.029 points, and 11 results, 370 min, 0.017 points.

10.6 Theory and calculation · 6 min

FF-400 adds $T_{ff} = K_Y(Y_{001} - 8) + K_S(48 - s_{102})$ to the outlet setpoint, Equation (10.9), with $K_Y = 0.8$ K per g/kg and $K_S = 1.1$ K per point. Take AIC-400 off, so that $T_{base} = 80\,^{\circ}$C, and both feedforwards on.

(a) The concentrate is at 44 % and the intake at 18 g/kg together. Compute the outlet setpoint, and compare the sum of the two terms with the separate shifts of the steady map, Figure 10.2. *Checkpoint:* 92.4 °C, a shift of 12.4 against $4.3 + 8.0 = 12.3$ K.

(b) Near the design point each kelvin of outlet costs 1.42 % of throughput. Estimate the throughput given up in (a). *Checkpoint:* About 18 %.

(c) With the concentrate at 48 % and the intake at the slider's top of 22 g/kg, compute the setpoint FF-400 asks for, compare it with the 90.3 °C that holds 3.5 %, and estimate the moisture with the design slope of 0.085 % per kelvin. What else must change to keep the particles off the sticky line? *Checkpoint:* 91.2 °C, 0.9 K too hot, about 3.42 %. The inlet must come down.

10.7 App challenge · 8 min

Load scenario 1, Manual feed and inlet, with the default seed. Run at 1 min/s to 30 min without touching any control, and export the CSV.

(a) From the columns `Tout_true_C` and `M_true_pct`, read the true outlet temperature at 5, 7 and 30 min, and the time at which the true powder moisture first passes 3.8 %. *Checkpoint:* 80.1, 74.3 and 73.5 °C within 0.1 K. About 9.0 min, 4.0 min after the step.

(b) Read the true powder moisture and `sticky_margin_K` at 30 min, and explain from the holdups of Section 10.3 why the air answers in seconds and the powder in minutes. *Checkpoint:* 4.16 % and 1.83 K, each within one unit of the last digit.

(c) Press Reset and Run. Pause within a minute after the step at 5 min, set Feed rate back to 1000 kg/h and Gas heater to 79.9 %, and run to 30 min. Read the true inlet, the true outlet and the true powder moisture at 30 min. *Checkpoint:* 201.1 °C, about 87.0 °C and 2.95 %, within 0.1 K and 0.01 points.

10.8 App challenge · 9 min

Load scenario 4, Soft sensor and lab correction, with the default seed. Run each part at 60 min/s to 240 min and read the Powder in spec, Powder off spec and Specific energy tiles. Make each change after Reset and before pressing Run.

(a) Run as loaded. From the CSV, also read the peak of `M_true_pct` and its time, and `M_bias_pct` just after the result at 70 min. *Checkpoint:* 1.12 t and 0.57 t, 4990 kJ/kg. Peak 3.97 % at about 68 min. Bias 0.17 points.

(b) Press Reset, set Lab correction to Off on the AY-401 card, and run again. Read the tiles, and the true and estimated moisture at 240 min. *Checkpoint:* 0.19 t and 1.56 t, 4817 kJ/kg. True 3.94 % against an estimate of 3.50 %.

(c) Press Reset, leave Lab correction off, set Feed solids for the soft sensor to AT-102 under Advanced, and run again. Read the tiles and the peak true moisture, and explain why this run needs no laboratory correction. *Checkpoint:* 1.64 t and 0.00 t, 5130 kJ/kg. Peak 3.68 % at about 24 min.

10.9 App challenge · 9 min

Load the challenge, the eight-hour campaign, with the default seed. Run each part at 60 min/s to 480 min and read the Powder in spec, Powder off spec, Worst sticky margin, Specific energy and Campaign target tiles. Reload the scenario before each new configuration and make the change before pressing Run.

(a) Run as loaded. *Checkpoint:* 1.98 t, 2.02 t, −0.4 K, 4237 kJ/kg, not met.

(b) Set the Moisture controller On and change nothing else. *Checkpoint:* 3.76 t, 0.00 t, 0.0 K, 4498 kJ/kg, not met.

(c) Press Reveal suggested tuning, which sets the moisture controller on, the soft sensor on AT-102, both feedforwards and the throughput optimizer on, and the bed at 65 °C. Say which target each of (a) and (b) missed, and where (c) recovers the energy. *Checkpoint:* 3.88 t, 0.00 t, 0.6 K, 4380 kJ/kg, met.

10.10 Application area · 3 min

At the design point the gas heater delivers 561.5 kW and the bed heater 22.0 kW, and the dryer evaporates 503.1 kg/h of water to make 497.9 kg/h of powder.

(a) Compute the heat per kilogram of water evaporated, in GJ/t, and per kilogram of powder, and compare the first with the 4.87 GJ/t average of the energy survey of Section 10.2. *Checkpoint:* 4.18 GJ/t, about 14 % below the average, 4219 kJ/kg of powder.

(b) Case 2 raises the outlet setpoint by 3 K. The powder falls to 476 kg/h and the heat per kilogram rises to 4402 kJ/kg. Explain why plants run at the lowest outlet that keeps the powder in specification, and what one kelvin is worth. *Checkpoint:* About 1.4 % of throughput, some 7 kg/h of powder, per kelvin.

10.11 Application area · 4 min

In case 7 a 3.5 mm layer sits on the roof. Lowering the inlet to 200 °C prevents ignition, while the sticky-margin override, which holds the inlet at 212.1 °C, does not.

(a) Explain from the steady results of Section 10.4 why the override cannot prevent the fire. *Checkpoint:* The roof reaches 158 °C at an inlet of 208.5 °C, below the 215.7 °C at which the particles turn sticky.

(b) With no new deposit, the air hammers remove the layer at $r_{clean} D/(D+0.05)$, Equation (10.5). Estimate the time to take 3.5 mm below the 3 mm of the fire rule, and say what an engineer should do with the dryer meanwhile. *Checkpoint:* About 1.7 h. Keep the inlet below 208.5 °C until the layer is gone or cleaned out.

10.12 Review the agent · 5 min

An AI assistant summarizes case 9 for a plant manager: “On the default seed the MPC ships 0.45 t off specification against 0.63 t for the shipped loops. Its model predicts the moisture ahead of the laboratory, so it cuts the feed before the powder goes wet. Replacing AIC-400 and FY-500 with the MPC is therefore the way to reduce off-specification powder on this dryer.” Find the flaw, and say how you would check it in the app.