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CHAPTER 7

Soft Drink Carbonation Simulator Whose Foam Limit Moves With Temperature

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Edited by John D. Hedengren

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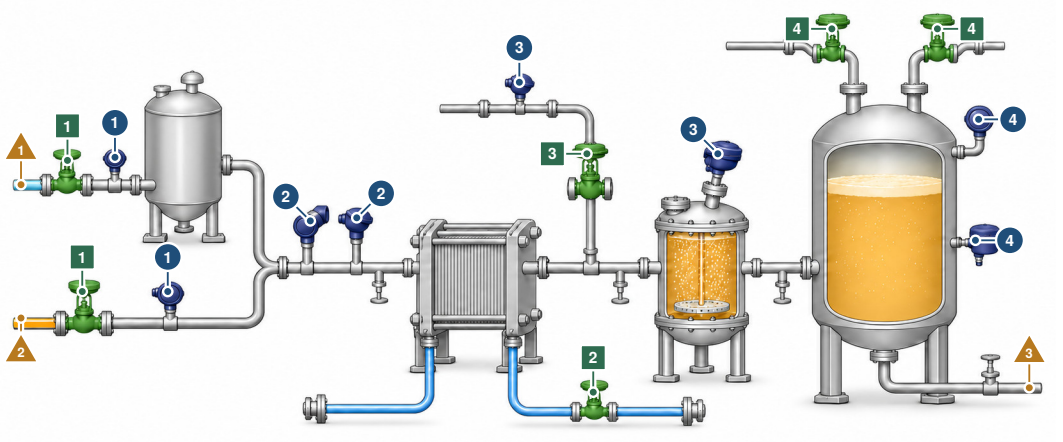
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CHAPTER 7

Soft Drink Carbonation Simulator Whose Foam Limit Moves With Temperature



The controller moves 1 water and syrup valves 2 glycol valve of the chiller 3 carbon dioxide dosing valve 4 gas make-up and vent valves on the tank

The controller reads 1 water and syrup flow meters 2 product temperature and sugar strength 3 gas flow and dissolved gas 4 tank pressure and level

What disturbs it 1 warmer water feed 2 weaker syrup batch 3 filler slowing or stopping

Notice the faint foam on the tank's liquid: the drink can carry the right amount of gas and still foam when it warms, unless the tank's pressure is kept above the gas's own push. Illustration, not to scale.

IN PLAIN TERMS The Right Fizz Is Not Enough

The main idea. A soft drink line mixes syrup and water in a fixed proportion, chills the mix and dissolves carbon dioxide gas in it under pressure. The controllers add syrup and gas in step with the measured flow, the way a cook scales a recipe to the size of the pot.

The challenge. The gas meter reports how much gas is dissolved. Foaming depends on how hard that gas pushes to escape, and a warmer drink pushes harder. So the meter can read right while the bottles foam over.

Why it matters. Only the tank's pressure, more cooling or a slower line keep the drink from foaming at the filling machine.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	the first page, the fact on the first sparkling water (Section 7.1), the history of the first apparatus and of Henry's law (Section 7.2), the try-it segments of cases 2 and 4 and the fact on the fooled analyzer (Section 7.6) and the key points
Study	50 min	the whole chapter with its three pause points and the twelve exercises at its end
Practice	20 min	the first page, the results (Section 7.6), Technology in Practice (Section 7.7), Limitations (Section 7.8) and the two open challenges

The control question The CO_2 analyzer measures a content, but the filler needs a margin between the tank's top pressure and the product's own gas pressure. How can a line whose analyzer reads its setpoint fill foaming product, and which of cooling, top pressure and throughput buys the margin back?

Learning objectives

- Compute the CO_2 pressure, breakout margin and foam index of the product from Henry's law.
- Explain how a trimmed ratio blend and a dose in ratio to the flow hold the recipe.
- Predict what a warm feed, a weak CO_2 supply or a filler stop costs.
- Tell an analyzer fooled by air or by its thermometer from a real CO_2 error.
- Judge when to cut the rate, hold the filler or raise the top pressure.

Prerequisites Sections 1.4.4 (ratio with a trim), 1.4.3 (static feedforward), 1.6.2 (velocity form) and 1.6.4 (scenarios and exported files).

The app https://apmonitor.com/apps/beverage-carbonation/

See also Volume 4, Chapter 4 and Volume 4, Chapter 6 for a line speed bounded by a constraint, Volume 4, Chapter 5 for ratio loops under a throughput supervisor. Volume 6, Chapter 7 and Volume 6, Chapter 8 for where the production rate is set.

7.1 Introduction

A carbonated soft drink is made from a concentrated syrup and treated water, and the two meet on the way to the filler rather than in a batch. A syrup proportioner delivers the prescribed amount of syrup to the water, the blend is mixed in line and carbonated, and the product goes on to the filler, an arrangement that has always been the main one in the carbonated soft drinks industry [1]. Carbonation and filling are engineered together because the carbon dioxide (CO_2) has to be dissolved, held and filled under pressure [2], and the control of food lines is judged by the out-of-specification product it avoids as much as by its operating cost [3]. Three checks are made on what the filler takes, its sweetness in degrees Brix, its CO_2 in volumes, and whether it fills without foaming.

DID YOU KNOW? Sparkling Water in Two Minutes, 1772

Living near a public brewery, Joseph Priestley poured water back and forth between two vessels held close to the yeast of the fermenting liquor, and in two or three minutes had a glass of pleasant sparkling water. Shaking water hard under the gas, he wrote, gave it more than its own bulk of gas in a few minutes [4].

The first two checks are compositions and the third is a pressure margin. CO_2 stays in solution only while the pressure over the liquid exceeds the pressure the dissolved gas would exert, and at a fixed content that equilibrium pressure rises with temperature [5, 6]. In the line of this chapter the product in the buffer tank at 3.05 °C carries 3.79 vol in equilibrium with 2.70 bar of CO_2 under a headspace at 4.01 bar absolute, a margin of 1.12 bar once its dissolved air and water vapor are counted. When the water feed warms from 12 to 26 °C and the chiller runs out of refrigeration, the CO_2 analyzer stays on 3.80 vol while the tank warms to 10.5 °C, the margin falls to 0.48 bar, and 4.37 m^3 of the 6.67 m^3 filled in 20 min would foam. Bottled carbonated waters show the same dependence, since at a given CO_2 content the number of bubbles likely to form in a glass grows with the water temperature [7].

The simulator is built against one belief, that a carbonation line whose analyzer reads its setpoint is making good product. The analyzer measures a content, the filler needs a margin, and the temperature, the dissolved air and the top pressure move the margin without touching the content. The class of problem is general. Every carbonated product shares it, from champagne to bottled water [7, 8], and so does any liquid in which a gas is held by an imposed pressure, because a supersaturated liquid releases its excess as bubbles grown from gas cavities [9]. The line has a second general shape. Where a plant's production rate is set decides how every inventory in it must be controlled [10], as the recycle loop of Volume 6, Chapter 7 shows for a reactor and its column. Here the rate is set at the

outlet by a filler that slows, stops and speeds up, so the buffer tank's level is held by the flow entering it, and a headspace that shares its volume with that level breathes CO_2 through the vent whenever the level swings. A transfer function from dose to analyzer reading carries neither the margin nor the breathing.

The beverage literature treats carbonation and filling as unit operations [2], and the control literature treats ratio control, feedforward and throughput manipulation as structure [10, 11]. This chapter puts the two on one plant, on which the analyzer can be watched on its setpoint while the product foams. It turns the margin against foaming into something a student can measure, on a soft drink blending and carbonation line that runs on the simulator framework of Section 1.6. Dissolved and free CO_2 are separate states everywhere, the tank's level and headspace are one gas inventory, and what the filler receives is logged apart from what the instruments report. Henry's law, ratio control with a quality trim, analyzer feedback, split pressure control and the coordination logic are standard practice. What the model adds is a 185-state line with finite-rate dissolution through 30 fixed-mass cells, water, sugar, CO_2 and air ledgers that close to round-off, a pressure and temperature analyzer that dissolved air or its own thermometer can fool, and a coordinator that holds the filler when the recipe cannot be made. The model is written out fully enough to rebuild it from this text. Eight cases and one graded shift separate a content from a margin, a ratio from its trim, and an instrument from the product.

Section 7.2 traces the domain from fixed air to the modern filler. Section 7.3 gives the model of the line, from Henry's law through the cells, the chiller, the dose and the tank to what the filler receives and what the analyzer reports. Section 7.4 measures the margin against foaming at the design point and names the three levers that act on it. Section 7.5 describes the eight loops and the line coordinator, and Section 7.6 measures the eight cases and the shift. Section 7.7 sets the two ratio structures on real hardware, Section 7.8 states the limitations, Section 7.9 concludes, and the exercises of Section 7.10 close the chapter.

7.2 Fixed Air, Proportioners and Fillers

Water charged with CO_2 is older than the name of the gas, and the first apparatus and the law of solubility came between 1772 and 1803, as the history below tells.

> ⧖ HISTORY **From a Glass Apparatus to Henry's Law, 1775 to 1803**
>
> In 1775 John Mervin Nooth described to the Royal Society a glass apparatus of three vessels for impregnating water with fixed air. He built it because the bladder in Priestley's arrangement tainted the water and the process asked for more skill than most users had [12]. In 1803 William Henry recorded that Nooth's apparatus had in turn been superseded by condensing many times the water's bulk of gas into it, and credited Priestley with first suggesting the influence of pressure. His experiments gave the general law that water under two or three atmospheres takes up twice or three times the gas it takes up at one, and the law now carries his name [5, 13]. The solubility of CO_2 in water has since been correlated from about 100 experimental studies below 1 MPa [6] and compiled with its temperature dependence among the constants of many other gases [13].

Rates came after equilibria. The two-film theory of gas absorption appeared in 1924 [14], and the lumped coefficient $k_L a$ with which the simulator dissolves its gas descends from it. Production moved from the bottle to the line. Syrup proportioners have ranged from a simple pump with a manually adjustable piston stroke to computerized flow rate regulators, while the principle of delivering the prescribed syrup to the treated water stayed the same [1], and the supply and storage of CO_2, carbonation systems and the principles of filling are now treated as one subject [2]. Measurement followed the product. An automatic method for determining the CO_2 in bottled beer was published in 1969 [15], and a sample's equilibrium pressure and temperature give its CO_2 through Henry's law, which is the method the simulated analyzer uses.

Table 7.1 Variables of the Line by Role, With Their Values at the Reset of Case 1

Variable	Role	Design value	Range
B_{103}	CV, AT-103	10.80 °Bx SP	9–13
R	CV, FFC-102	0.2195 SP	0.15–0.30
Q_w	CV, FT-101	17.08 m³/h	—
T_{104}	CV, TT-104	3.0 °C SP	1–12
V_{105}	CV, AT-105	3.80 vol SP	2.5–5
P_t	CV, PT-201	3.0 bar(g) and 3.3 SP	1–5.5
L	CV, LT-201	50 % SP	20–80
B_f, V_f, FI	truth at the filler	10.80, 3.79, 30	see text
x_w, x_s, x_g	MVs, valves	59.3, 52.1, 56.3 %	0–100
$\dot{n}$	MV, CO_2 dose	147 kg/h	0–300
x_{mu}, x_v	MVs, make-up, vent	0.61, 0 %	0–100
Q_{SP}	MV of LIC-201	20 m³/h	0–25
ΔR, ΔV	MVs of the trims	0, −0.054 vol	±0.02, ±0.6
filler	DV, demand	100 %	0–120
T_w, P_w	DVs, water	12 °C, 100 %	4–32, 10–120
B_{batch}	DV, unmeasured	60.0 °Bx	54–66
P_{sup}	DV, CO_2 supply	9.0 bar(g)	0–12
P_{vac}	DV, deaerator	40 mbar	20–600
β	DV, unmeasured	0 °C	±3
w_k, T_k, c_k, g_k, a_k	states, 30 cells	see text	—
A_1, A_2	states, deaerator	0.083, 0.029 mol/m³	—
P_v, B_{syr}	states	40 mbar, 60.0 °Bx	—
T_g, $\dot{n}$, F	states	1.75 °C, 147, 20	—
M_L, S_L	states, tank	2604, 281 kg	—
$H_L = M_L T_L$	state, tank	$T_L = 3.05$ °C	—
N_c, N_a, N_b	states, tank	422.4, 0.11, 0 mol	—
n_c, n_a	states, headspace	435.5, 0.54 mol	—

Foam is the defect the arrangement exists to prevent. Bubble nucleation from gas cavities in supersaturated liquids has been reviewed [9], and in champagne and carbonated beverages bubbles were mostly found to form from tiny gas pockets trapped in cellulose fibers, at a frequency set by the dissolved CO_2, the temperature, the viscosity and the ambient pressure [8]. For bottled carbonated waters holding about 3 to 7 g/L of CO_2, the partial pressure of the gas depends strongly on temperature [7]. The recipe simulated here holds 7.46 g/L. Control of the line grew around these facts. The proportioner holds the recipe as a ratio of two flows, which is ratio control [11] as in Section 1.4.4, a refractometer after the blend corrects the ratio for syrup that is not what the recipe assumes, and the filler sets the rate at which everything upstream must run. The simulator puts these pieces in one line and adds a record that no plant keeps, the true Brix, CO_2 and foam index of every liter the filler takes.

7.3 The Line as Modeled

The simulated line makes 20 m³/h of one soft drink, 10.80 °Bx from a 60.0 °Bx syrup with 3.80 vol of CO_2, chilled to 3.0 °C and held at 3.0 bar(g) for a filler whose demand is imposed. The deaerator, the water and syrup valves, the chiller and its glycol circuit, the CO_2 header, the dissolution section, the buffer tank with its make-up, vent and purge, the filler and all of their instruments appear in Figure 7.1.

Table 7.1 sorts the variables by the part each plays. The state vector has 185 entries, 20 lumped states, 150 cell states and 15 cumulative ledgers of the water, sugar, CO_2, air and cooling that enter and leave. The ledgers are integrated by the same step as the plant, so every balance can be closed from the state itself. Units are SI inside the model, pressures absolute, and the panels show m³/h, kg/h, bar(g), mbar, °Bx and volumes.

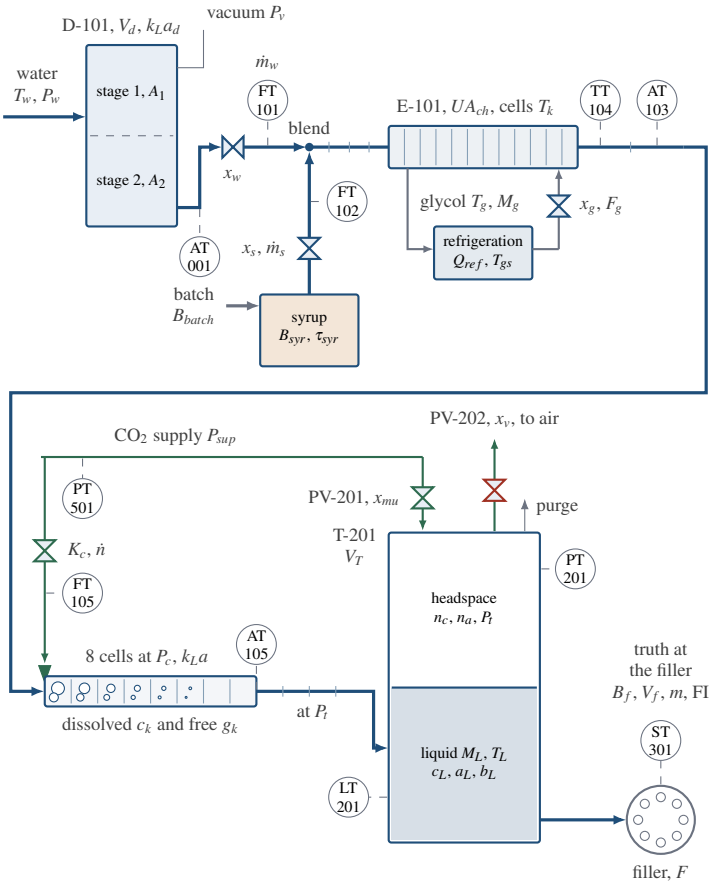


Figure 7.1 Blending and carbonation line as modeled, drawn in two rows. Water at T_w is stripped of air in the two stages of deaerator D-101 (A_1, A_2) at vacuum P_v, passes the water valve x_w and FT-101, and meets syrup of strength B_{syr} from the syrup valve x_s and FT-102 at the blend point. The product crosses the twelve cells of chiller E-101 against glycol at T_g, fed through valve x_g by a refrigeration plant limited to Q_{ref}, passes TT-104 and the refractometer AT-103, and continues in the lower row. There it takes its CO_2 dose $\dot{n}$ from the supply header through the dosing valve and FT-105 at the injector, and dissolves it in eight cells at P_c ahead of the analyzer AT-105. Buffer tank T-201 holds the liquid under a headspace of CO_2 and air at P_t, with make-up PV-201, vent PV-202, a fixed purge, LT-201 and PT-201, and the filler draws F. Dashed lines are measurements, and the open circles in the dissolution section stand for free gas.

7.3.1 Solubility

Every cell, the tank and the analyzer use one solubility law, Henry's law with a van 't Hoff temperature dependence, as shown in Equation (7.1).

$$\begin{aligned} H_i(T) &= H_i^\circ \exp\left[\theta_i\left(\frac{1}{T}-\frac{1}{T_i^\circ}\right)\right], \qquad i \in \{C,A\} \\ p_C &= \frac{\rho\, c}{H_C(T)}, \qquad p_A = \frac{\rho\, a}{H_A(T)}, \qquad V = \frac{\rho\, c}{\nu_1} \end{aligned} \tag{7.1}$$

where c and a are the dissolved CO_2 and air in mol/kg of solution, T is the absolute temperature, $\rho = \rho_B(B)$ is the density of a sucrose solution at Brix B, $H_C^\circ = 3.3 \times 10^{-4}\,\mathrm{mol/(m^3\,Pa)}$ at $T_C^\circ =$

298.15 K with $\theta_C = 2400\,\mathrm{K}$, $H_A^\circ = 9.3 \times 10^{-6}\,\mathrm{mol/(m^3\,Pa)}$ at $T_A^\circ = 288.15\,\mathrm{K}$ with $\theta_A = 1500\,\mathrm{K}$, and $\nu_1 = 44.615\,\mathrm{mol/m^3}$ is one volume, a liter of CO_2 at 0 °C and one atmosphere per liter of beverage, or 1.9635 g/L. The CO_2 constants are the compilation value [13], 1.47 g/L at 25 °C and one atmosphere. The air constants are fitted to water saturated with air, which holds 27.3 mg/L at 15 °C. The density is a cubic fitted to the sucrose table at 20 °C, $\rho_B = 998.282 + B(3.83315 + B(0.0143612 + 2.98508 \times 10^{-5} B))$ in $\mathrm{kg/m^3}$, the heat capacity is $c_p(w) = 4190 - 2350\,w$ in J/(kg K) with $w = B/100$, and the vapor pressure of water p_w follows the Magnus form $610.94 \exp[17.625\,T/(T + 243.04)]$ in Pa with T in °C. At 3 °C the recipe's 3.80 vol are in equilibrium with 2.70 bar of CO_2, and at 10.5 °C with 3.40 bar.

A bubble in contact with the liquid holds water vapor and the dissolved air's own pressure besides CO_2, so the dissolved CO_2 that a bubble can stand at a local pressure P is given by Equation (7.2).

$$c^*(T,P,a,B) = \frac{H_C(T)}{\rho}\,\max\left(0,\; P - p_w(T) - p_A\right) \tag{7.2}$$

7.3.2 Transport, Dissolution and Breakout

The line from the blend point to the tank is a chain of 30 cells of fixed mass $M_c = 5.2\,\mathrm{kg}$, 5 L at $1040\,\mathrm{kg/m^3}$, carried by the blend's mass flow $\dot{m}$ with upwind advection. Four cells lead to the chiller, twelve form the chiller, two lead to the injector, eight form the dissolution section and four lead to the tank. Each cell k holds its sugar mass fraction w_k, its temperature T_k, its dissolved CO_2 c_k, the free CO_2 g_k that moves with the liquid as bubbles, and its dissolved air a_k, all per kilogram of solution, as shown in Equation (7.3).

$$\begin{aligned}
\frac{\mathrm{d}w_k}{\mathrm{d}t} &= q\,(w_{k-1} - w_k), \qquad \frac{\mathrm{d}a_k}{\mathrm{d}t} = q\,(a_{k-1} - a_k)\\
\frac{\mathrm{d}T_k}{\mathrm{d}t} &= q\,(T_{k-1} - T_k) + \chi_k\,\frac{UA_{ch}\,(T_g - T_k)}{12\,M_c\,c_p(w_k)}\\
\frac{\mathrm{d}c_k}{\mathrm{d}t} &= q\,(c_{k-1} - c_k) + r_k\\
\frac{\mathrm{d}g_k}{\mathrm{d}t} &= q\,(g_{k-1} - g_k) - r_k + \delta_{k,18}\,\frac{\dot{n}}{M_c}
\end{aligned} \tag{7.3}$$

where $q = \dot{m}/M_c$, χ_k is one in the twelve chiller cells and zero elsewhere, $\delta_{k,18}$ places the dose in the first cell of the dissolution section (cells are numbered from 0), and the inlet values at $k = -1$ are the blend's composition, temperature and air with no CO_2. Transfer between free and dissolved CO_2 follows Equation (7.4).

$$r_k = k_L a\,\frac{g_k}{g_k + g_s}\,(c_k^* - c_k) - k_b\,\max(0,\; c_k - c_k^*) \tag{7.4}$$

Here c_k^* is Equation (7.2) at the cell's temperature and air and at P_c inside the dissolution section or P_t beyond it. The first term dissolves gas at $k_L a = 0.35\,\mathrm{s^{-1}}$ while it is plentiful, and the factor with $g_s = 0.015\,\mathrm{mol/kg}$ makes the interfacial area vanish with the last bubble. The second term releases gas from a liquid holding more than c_k^* at $k_b = 0.02\,\mathrm{s^{-1}}$, with or without bubbles present. Dissolved and free CO_2 are separate states everywhere, so a bubble exists in the model only where CO_2 was injected and has not dissolved, or where the liquid is supersaturated. The application's own check integrates a still cell with plenty of gas and finds the dissolved CO_2 after $1/k_L a$ within 0.054 % of the first-order 63.2 % of its approach.

7.3.3 Deaerator, Blend and Chiller

The deaerator is two well-mixed stages that strip air-saturated water toward the equilibrium of the vacuum space, as shown in Equation (7.5).

$$\begin{aligned} \frac{\mathrm{d}A_1}{\mathrm{d}t} &= \frac{q_w}{V_d}(A_{in} - A_1) + k_L a_d\,(A^* - A_1) \\ \frac{\mathrm{d}A_2}{\mathrm{d}t} &= \frac{q_w}{V_d}(A_1 - A_2) + k_L a_d\,(A^* - A_2) \\ A_{in} &= H_A(T_w)\,P_{atm} \\ A^* &= H_A(T_w)\,\max\left(0,\; P_v - p_w(T_w)\right) \end{aligned} \tag{7.5}$$

where A_1 and A_2 are the stage air concentrations in mol/m^3, $q_w = \dot{m}_w/\rho_w$ is the water volume flow with $\rho_w = 999.7\,\mathrm{kg/m^3}$, $V_d = 0.5\,\mathrm{m^3}$ per stage, $k_L a_d = 0.15\,\mathrm{s^{-1}}$, and the vacuum follows its disturbance through $\tau_{vac}\,\mathrm{d}P_v/\mathrm{d}t = P_{vac} - P_v$ with $\tau_{vac} = 20\,\mathrm{s}$. At 40 mbar the water leaves with 0.31 mg/L of oxygen, taken as 37 % of the dissolved air by mass. The valves and the blend follow Equation (7.6).

$$\begin{aligned} \dot{m}_w &= x_w\,\dot{m}_{w,max}\sqrt{P_w/100}, \qquad \dot{m}_s = x_s\,\dot{m}_{s,max} \\ w_{-1} &= \frac{\dot{m}_s\,w_s}{\dot{m}}, \qquad \tau_{syr}\frac{\mathrm{d}B_{syr}}{\mathrm{d}t} = B_{batch} - B_{syr} \\ T_{-1} &= \frac{\dot{m}_w c_p(0)\,T_w + \dot{m}_s c_p(w_s)\,T_{syr}}{\dot{m}_w c_p(0) + \dot{m}_s c_p(w_s)} \end{aligned} \tag{7.6}$$

where $\dot{m} = \dot{m}_w + \dot{m}_s$, $w_s = B_{syr}/100$, P_w is the water header in percent of design, and the blend's air is $a_{-1} = (\dot{m}_w A_2/\rho_w + \dot{m}_s a_{syr})/\dot{m}$, with a_{syr} the 4 mg/L of air the syrup carries. Each valve responds to its command as a first-order lag, 1 s for water and syrup, 5 s for glycol and 0.5 s for make-up and vent. The glycol side of the chiller is one well-mixed temperature fed by a refrigeration plant of limited duty, as shown in Equation (7.7).

$$\begin{aligned} M_g c_g \frac{\mathrm{d}T_g}{\mathrm{d}t} &= F_g c_g\,(T_{gs}^e - T_g) + \sum_k \chi_k \frac{UA_{ch}}{12}\,(T_k - T_g) \\ T_{gs}^e &= \max\left(T_{gs},\; T_g - \frac{Q_{ref}}{F_g c_g}\right), \qquad F_g = x_g F_{g,max} \end{aligned} \tag{7.7}$$

The plant cools the returning glycol by at most $Q_{ref} = 320\,\mathrm{kW}$, so beyond that load the glycol supply itself warms and more glycol flow no longer helps. At the design flow the chiller takes the 13.02 °C blend to 3.00 °C with 228 kW and the glycol valve at 56.3 %. A 26 °C water feed raises the blend to 25.24 °C, which needs 506 kW at 20 m^3/h, and 320 kW would leave it at 11.19 °C at that rate or hold 3.0 °C up to 12.6 m^3/h.

7.3.4 Carbonator Pressure and the Dose

The dissolution section is held above the tank by a back-pressure that falls with the square of the flow, and the CO_2 dosing valve passes gas in proportion to the root of the difference of the squared pressures on its two sides, as shown in Equation (7.8).

$$\begin{aligned} P_c &= P_t + \Delta P_c\left(\frac{\dot{m}}{\dot{m}_0}\right)^2, \qquad \dot{n}_{max} = K_c\sqrt{P_{sup}^2 - P_c^2} \\ \tau_n\frac{\mathrm{d}\dot{n}}{\mathrm{d}t} &= \min(\dot{n}_{cmd},\,\dot{n}_{max}) - \dot{n} \end{aligned} \tag{7.8}$$

where $\dot{m}_0 = \rho_B(B_{rec})\,Q_0$ is the design mass flow, $\Delta P_c = 1.2\,\mathrm{bar}$, $K_c = 0.178\,\mathrm{mol/(s\,bar)}$ with the pressures in bar under the root, $\tau_n = 1\,\mathrm{s}$ and the command $\dot{n}_{cmd}$ is clamped to 0 to 300 kg/h. At the design flow the section runs at 4.20 bar(g), where pure CO_2 could hold 7.3 vol at 3 °C, and the valve can pass 241 kg/h against the 147 kg/h dosed. At a 5.0 bar(g) supply it can pass 84.5 kg/h, 57 % of the 149 kg/h that the recipe needs at the full rate.

7.3.5 Buffer Tank and Headspace

The tank is one well-mixed liquid, with its own holdup of rising bubbles, under a headspace of CO_2 and air, as shown in Equation (7.9).

$$\begin{aligned}
\frac{dM_L}{dt} &= \dot{m} - \dot{m}_f, \qquad \frac{dS_L}{dt} = \dot{m}\,w_{29} - \dot{m}_f\,w_L \\
\frac{dN_c}{dt} &= \dot{m}\,c_{29} - \dot{m}_f\,c_L + M_L\,(r_s + r_b) \\
\frac{dN_a}{dt} &= \dot{m}\,a_{29} - \dot{m}_f\,a_L + M_L\,r_{sa} \\
\frac{dN_b}{dt} &= \dot{m}\,g_{29} - M_L\,r_b - N_b/\tau_{rise} \\
\frac{dH_L}{dt} &= \dot{m}\,T_{29} - \dot{m}_f\,T_L + UA_t\,(T_{amb} - T_L)/c_p(w_L)
\end{aligned} \tag{7.9}$$

where M_L is the liquid mass, S_L its sugar, N_c and N_a its dissolved CO_2 and air, N_b the CO_2 in its bubbles and $H_L = M_L T_L$ its heat content, with $c_L = N_c/M_L$, $a_L = N_a/M_L$, $b_L = N_b/M_L$ and $w_L = S_L/M_L$. The filler draws $\dot{m}_f = \rho_L F$. The liquid exchanges CO_2 with the headspace across its surface at $r_s = k_L a_s (c_s - c_L)$, with $c_s = H_C(T_L)\,y_c\,(P_t - p_w)/\rho_L$, and air likewise at r_{sa}, and it exchanges CO_2 with its own bubbles at $r_b = k_L a_t\,b_L/(b_L + g_s)\,(c_t^* - c_L) - k_b \max(0, c_L - c_t^*)$, where c_t^* is Equation (7.2) at the tank. Bubbles rise into the headspace with $\tau_{rise} = 15\,\text{s}$. The headspace is an ideal gas at the liquid's temperature, as shown in Equation (7.10).

$$\begin{aligned}
\frac{dn_c}{dt} &= \dot{n}_{mu} - y_c(\dot{n}_v + \dot{n}_p) + N_b/\tau_{rise} - M_L\,r_s \\
\frac{dn_a}{dt} &= -(1 - y_c)(\dot{n}_v + \dot{n}_p) - M_L\,r_{sa} \\
P_t &= \frac{(n_c + n_a)\,R\,T_L}{V_T - V_L} + p_w(T_L)
\end{aligned} \tag{7.10}$$

Here $y_c = n_c/(n_c + n_a)$, $V_L = M_L/\rho_B(B_L)$, the headspace is kept to at least 2 % of V_T, and the make-up, vent and purge flows are $\dot{n}_{mu} = x_{mu} K_{mu} \sqrt{P_{sup}^2 - P_t^2}$, $\dot{n}_v = x_v K_v \sqrt{P_t^2 - P_{atm}^2}$ and $\dot{n}_p = K_p \sqrt{P_t^2 - P_{atm}^2}$, with bar under the roots. A rising level compresses the headspace. At the 50 % design level the headspace is 2.5 m^3, so 0.32 m^3 of product pushed in with no gas removed would raise it from 4.01 to 4.60 bar absolute. The make-up and the vent have their own setpoints, 3.0 bar(g) and 3.3 bar(g), so the pressure floats between them without spending CO_2, and the purge bleeds 0.61 kg/h of CO_2 at 3.0 bar(g) so that the air the product gives up does not collect. Liquid above 95 % of the tank leaves through the vent line and is booked as overflow, the filler stops itself below 8 % and restarts above 15 %, and standing product in the chiller colder than its freezing point, 0.061 °C lower per °Bx, is flagged as a freeze risk.

7.3.6 What the Filler Receives and What AT-105 Reports

The filler's product is judged on the true tank state. Its breakout margin and foam index follow Equation (7.11).

$$\begin{aligned}
m &= P_t - \left[p_C(c_L, T_L) + k_N\,p_A(a_L, T_L) + p_w(T_L)\right] \\
FI &= 100\,\text{clamp}\big(1 - m/M_{ok},\ 0,\ 1\big)
\end{aligned} \tag{7.11}$$

where $k_N = 5$ counts dissolved air five times over, on the model's reasoning that air bubbles do not redissolve and each one seeds CO_2 breakout, and $M_{ok} = 1.6\,\text{bar}$. The index is 0 with a margin of 1.6 bar or more, 50 at the limit of 0.8 bar and 100 at breakout. The foam index and its limit are an illustrative indicator of fill stability built from that margin, and they have not been validated against a filler. A liter the filler draws is in specification while $|B_f - 10.80| \le 0.10\,°\text{Bx}$, $|V_f - 3.80| \le 0.15\,\text{vol}$

Table 7.2 Parameters of the Line. Visible Entries Are Sliders in the Show Model Panel, and Hidden Entries Never Reach It

Symbol	Meaning	Value	Class
B_{rec}, V_{rec}	recipe	10.80 °Bx, 3.80 vol	visible
—	tolerances at the filler	±0.10 °Bx, ±0.15 vol	visible
—	foam index limit	50	visible
M_{ok}, k_N	foam index scale, air weight	1.6 bar, 5	hidden
V_d	deaerator stage volume	0.5 m^3	hidden
$k_L a_d$	deaerator stripping	0.15 s^{-1}	visible
τ_{vac}	vacuum settling	20 s	hidden
T_{syr}, a_{syr}	syrup temperature, air	20 °C, 4 mg/L	hidden
τ_{syr}	syrup tank mixing	150 s	visible
$\dot{m}_{w,max}$, $\dot{m}_{s,max}$	valve capacities	8.0, 2.0 kg/s	hidden
—	water, syrup valve lags	1, 1 s	visible
UA_{ch}, $F_{g,max}$	chiller, glycol valve	55 kW/K, 30 kg/s	visible
T_{gs}, Q_{ref}	glycol supply, refrigeration	−2 °C, 320 kW	visible
M_g, c_g	glycol holdup	150 kg, 3600 J/(kg K)	hidden
—	glycol valve lag	5 s	hidden
$k_L a$, k_b	dissolution, breakout	0.35, 0.02 s^{-1}	visible
g_s	free gas halving the area	0.015 mol/kg	hidden
ΔP_c	carbonator back-pressure	1.2 bar	visible
K_c	dosing valve	0.178 mol/(s bar)	visible
—	dose range, lag	300 kg/h, 1 s	hidden
V_T, $k_L a_s$	tank, surface transfer	5.0 m^3, 5×10^{-5} s^{-1}	visible
$k_L a_t$, τ_{rise}	bubbles in the tank	0.02 s^{-1}, 15 s	hidden
UA_t, T_{amb}	tank heat gain	60 W/K, 22 °C	hidden
K_{mu}, K_v, K_p	make-up, vent, purge	0.25, 0.60, 0.001	hidden
—	overflow, low-level stop	95, 8 %	hidden
Q_0	filler design demand	20 m^3/h	visible
—	filler ramp lag	3 s	hidden
—	AT-103, AT-105 lags	4, 10 s	visible
—	flow, TT-104, PT, LT, AT-001	0.5, 3, 0.5, 2, 30 s	hidden
M_c, v_1	cell mass, one volume	5.2 kg, 44.615 mol/m^3	fixed

K_{mu}, K_v and K_p in mol/(s bar).

and $FI \leq 50$, with $B_f = 100\, w_L$ and $V_f = \rho_L c_L / v_1$, and the scorecard books each liter as in or out of specification, with the reason.

The analyzer AT-105 at the last cell of the dissolution section measures its sample's equilibrium pressure and temperature and converts them with Henry's law at the temperature its own thermometer reports, as shown in Equation (7.12).

$$V_{AT} = \frac{H_C(T+\beta)}{v_1}\Big[p_C + p_A + p_w(T) - p_w(T+\beta) - \mu\, p_A\Big] \tag{7.12}$$

where β is the bias of that thermometer, and $\mu = 1$ for a multiple-expansion method that separates the air and 0 for the single-expansion default, which reads the dissolved air's pressure as CO_2. At the 1.3 mg/L of air in case 1 that error is 0.054 vol, and a 2 °C bias lowers H_C by 6.1 %, about 0.23 vol at the recipe.

🕮 **Pause.** Try Exercise 7.2 before reading on.

7.3.7 Numbers, Initialization and Numerics

The parameters are listed in Table 7.2. Each scenario opens at the steady state of its own configuration, solved at reset, and a setting changed before the run starts solves it again, as Reset does, so a tank pressure setpoint chosen then starts the tank at that pressure. The flows are those the filler demand asks for at the recipe ratio, the glycol temperature puts TT-104 on its setpoint through the chiller's cell recursion, the dose is found by bisection so that the analyzer reads its setpoint, the dissolved and free CO_2 of every cell are found by bisection, and the tank's dissolved CO_2, bubbles and headspace

composition by nested bisection and a fixed-point iteration. At reset no state derivative outside the ledgers exceeds 2.7×10^{-15} in any of the nine scenarios. The engine of Section 1.6.1 advances the plant by a fixed 0.1 s step of the fourth-order Runge-Kutta method, the controllers act every 0.2 s, the historian keeps one row a second, and the default seed is 20261021. The speed selector spans 1 to 60 times real time, 10 by default. Halving the step, with the controllers still acting every 0.2 s, moves the CO_2 vented in 600 s of case 5 by 3×10^{-6} % and the worst foam index in 900 s of case 2 by 1.3×10^{-7}. Doubling the cells to 60 of 2.5 L moves the filler's CO_2 in case 1 by 0.0004 vol and the lowest filler Brix of case 3 by 0.000 03 °Bx. Over the 2400 s challenge the water, sugar, CO_2 and air ledgers close to 8.2×10^{-15} relative, and closure below 1×10^{-9} is one of the 39 checks the application passes.

7.3.8 Assumptions

The line is plug flow through 5 L cells with the numerical mixing of upwind advection, and bubbles move with the liquid without displacing it, although at the injector the gas volume is comparable to the liquid's. The last traces of free gas depend on the grid, 0.012 % of the dose at AT-105 with 30 cells and 0.0008 % with 60, which matters to no reported result.

Henry's law uses the pure-water constants with a constant van 't Hoff slope. Against the correlation of about 100 low-pressure studies [6] the model's solubility is 3.5 % low at 25 °C, 6.7 % low at 3 °C and 7.8 % low at 0 °C, so it overstates the CO_2 pressure of a product at a given content. The salting-out by sugar, a few percent at 11 °Bx, would act the other way and is not modeled, and neither is the non-ideality of CO_2 at a few bar.

Air is one pseudo-species with a fixed oxygen share, and the deaerator is two well-mixed stages with one stripping coefficient. The dissolution coefficient, the bubble-area function, the breakout rate and the tank's surface coefficient are illustrative constants rather than correlations for a particular mixer or tank, and the dissolution coefficient does not rise with the turbulence of the flow.

The filler is a volumetric demand that can be slowed, held or starved, and its own mechanics, counter-pressure, snift and fill height, are outside the model. The tank is well mixed, its headspace an ideal gas at the liquid's temperature. The glycol side is one temperature, the refrigeration plant a duty limit, and freezing is flagged rather than modeled. Densities are those at 20 °C, valves are linear with first-order actuators and no stiction, and the pumps are represented only by the valve capacities. All sizes, capacities and limits are teaching values for one recipe, not a design basis.

7.4 The Margin Against Foaming

Three measurements fix the design point of case 1. The dissolution section's $1/k_La$ is 2.9 s against a residence of 7.2 s, so 59 % of the dose is still gas in the first cell, 11 % in the third, 0.84 % in the fifth and 0.012 % at AT-105, and the product reaches the tank 27.0 s after the blend point. In the tank the product is undersaturated by more than a bar, in equilibrium with 2.70 bar under a 4.01 bar headspace, so it gains 0.037 vol through its surface in its 7.5 min residence and reaches the filler at 3.79 vol. Counting its air five times over and its water vapor, the product's gas pressure is 2.90 bar, a margin of 1.12 bar and a foam index of 30.

The margin is set by the temperature, the dissolved air and the top pressure, and by the CO_2 only through the recipe, as shown in Figure 7.2. With 1.28 mg/L of air the product reaches the foam limit at 6.3 °C under 3.0 bar(g) and at 11.2 °C under 3.5 bar(g), and it breaks out at 13.9 °C and 18.1 °C. Half a bar of top pressure therefore moves the foam limit by 4.9 °C, and near the design point the margin falls by 0.09 bar for every degree. That shift comes mostly from the slope of the product's CO_2 pressure, about 0.1 bar per degree, so it moves little with the illustrative constants, from 4.5 to 5.4 °C for a limit drawn anywhere between 0.4 and 1.2 bar of margin and 4.85 °C with the air counted once. Raising the temperature setpoint of case 1 in steps on the running line finds the same limits within a few tenths of a degree, near 6.5 °C under 3.0 bar(g) and near 11.4 °C under 3.5 bar(g). They lie slightly above the curves because the tank's product holds 3.78 vol rather than 3.80.

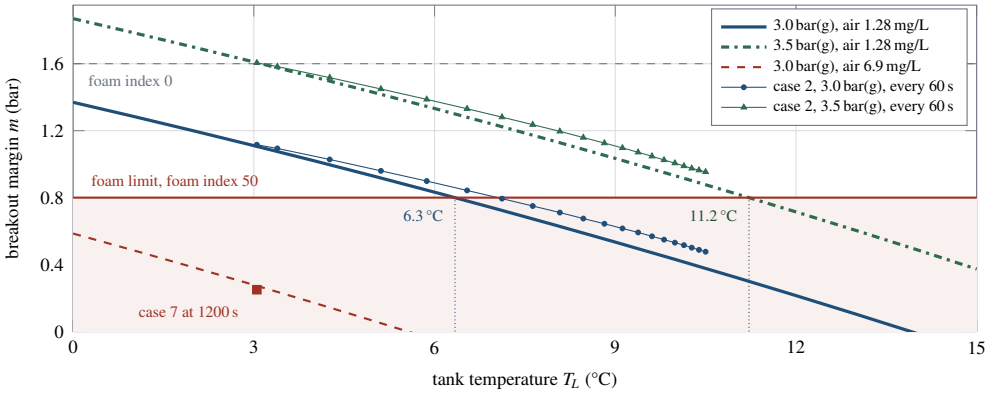


Figure 7.2 Breakout margin of the recipe product against the tank temperature. The three curves are Equation (7.11) for 3.80 vol at 10.80 °Bx with the tank at its setpoint and a fixed dissolved air: solid at 3.0 bar(g), dash-dotted at 3.5 bar(g), and dashed at 3.0 bar(g) with the higher air of case 7. The shaded band lies below the foam limit. The thin paths of markers are the engine's own tank states in case 2 every 60 s to 1200 s, circles as shipped and triangles with the tank at 3.5 bar(g) from the start, and as the tank warms they run slightly above the curves because water at 26 °C brings less air and the tank pressure floats inside the make-up and vent gap.

Air enters the margin five times over. At the 6.9 mg/L that the weak deaeration of case 7 reaches, the air's term is 1.02 bar against 0.19 bar at 1.28 mg/L, and the product passes the limit at any temperature on the chart. The analyzer sees none of this, because the CO_2 content that it measures does not change.

Three levers act on the margin. Cooling lowers the product's CO_2 pressure but is bounded by the 320 kW refrigeration plant. The top pressure raises the tank's side of the margin and costs a headspace of CO_2 and a higher make-up and vent. A throughput cut lowers the cooling load until 320 kW suffices and costs volume. A controller that holds the CO_2 content perfectly uses none of them, which is why the shipped case 2 foams while the CO_2 and pressure loops hold their setpoints.

7.5 Implemented Controller

Eight loops and a line coordinator, FY-100, run every $\Delta t_c = 0.2$ s, two physics steps, with the integrals advancing by that period. They follow the order of work of Figure 1.10, with the overflow, freeze and filler logic after the integration, so a setting changed between two executions reaches the plant at the next one.

7.5.1 Instruments

No loop reads a cell or the tank contents. Each transmitter takes the true value at its own location, lags it exactly to first order and adds first-order colored noise. The lags are 0.5 s for FT-101 and FT-102, 4 s for the refractometer AT-103, 3 s for TT-104, 10 s for AT-105, 0.5 s for PT-201 and FT-105, 2 s for LT-201 and 30 s for the dissolved oxygen meter AT-001. Noise standard deviations are 0.1 % of reading on FT-101 and FT-102, 0.2 % on FT-105, 0.005 °Bx on AT-103, 0.02 °C on TT-104, 0.008 vol on AT-105, 0.003 bar on PT-201 and 0.05 % on LT-201. FT-101, FT-102 and FT-105 read zero below 0.1 m^3/h, 0.02 t/h and 0.5 kg/h. The product flow the loops use is inferred, $Q_m = (\dot{m}_{w,m} + \dot{m}_{s,m})/\rho_B(B_{103,m})$, from the two mass meters and the refractometer. The dosing controller reports when its valve is at capacity, the one plant status any loop reads.

Table 7.3 Loop Pairings, Directions and Shipped Tunings

Tag	CV	MV	γ	K_c	τ_I, output
FIC-101	Q_w	x_w	$+1$	2.5	1 s, 0–100
FFC-102	$\dot{m}_s$	x_s	$+1$	14	1.5 s, 0–100
AIC-103	B_{103}	ΔR	$+1$	0.003	6 s, ±0.02
TIC-104	T_{104}	x_g	-1	8	40 s, 0–100
AIC-105	V_{AT}	ΔV	$+1$	0.6	15 s, ±0.6
PIC-201	P_t	x_{mu}	$+1$	150	120 s, 0–100
PIC-202	P_t	x_v	-1	150	120 s, 0–100
LIC-201	L	Q_{SP}	$+1$	0.5	300 s, 0–25

Gains in % per m³/h, % per t/h, kg/kg per °Bx, % per °C, vol per vol, % per bar, % per bar and m³/h per %, in the order of the rows.

7.5.2 The PI Algorithm

All eight loops use the shared PI law in its velocity form, as shown in Equation (7.13).

$$\begin{aligned} e_k &= \gamma(\mathrm{SP}_k - \mathrm{PV}_k), \qquad P_k = K_c\, e_k \\ S_k &= S_{k-1} + (P_k - P_{k-1}), \qquad v_k = b_k + S_k + I_{k-1} \\ u_k &= \mathrm{slew}\big(\mathrm{clamp}(v_k, u_{min}, u_{max}),\, u_{k-1},\, \rho_u\big) \\ I_k &= I_{k-1} + \Big[\frac{K_c}{\tau_I}\, e_k + \frac{u_k - v_k}{\tau_I}\Big]\Delta t_c \end{aligned} \tag{7.13}$$

where $\gamma = -1$ for the two loops whose valve must open as the measurement rises and $+1$ for the other six, b_k is an output bias, and ρ_u is a rate limit that only the level loop uses. This is the framework's law of Section 1.6.2, Equations (1.9) to (1.12), with $\gamma = a$, $b_k = u_b$ and the slew inside the saturation. No loop here uses derivative action, so S_k equals P_k, and the loops that integrate use back-calculation with a tracking time of τ_I. In MANUAL each loop tracks by setting $I_k = u_{op} - b_k - S_k$, so both transfers are bumpless. The pairings and shipped tunings are listed in Table 7.3.

7.5.3 Ratio and Brix Trim

LIC-201 sets the throughput Q_{SP}, and the coordinator splits it into the two flow setpoints at the ratio in force, as shown in Equation (7.14).

$$\begin{aligned} \dot{m}_t &= Q_{SP}\, \rho_B(B_{SP}), \qquad R = R_{SP} + \Delta R \\ Q_{w,SP} &= \frac{\dot{m}_t}{(1+R)\,\rho_w}, \qquad \dot{m}_{s,SP} = R\,\rho_w\,\hat{Q}_w \end{aligned} \tag{7.14}$$

where $R_{SP} = 10.8/49.2 = 0.2195\,\mathrm{kg/kg}$ makes 10.80 °Bx from 60.0 °Bx syrup, and $\hat{Q}_w$ is the measured water flow $Q_{w,m}$ on the default basis or the water setpoint $Q_{w,SP}$ on the setpoint basis. On the first the syrup follows the water it sees, and on the second both flows are asked for at once, the two bases of Section 1.4.4. AIC-103 trims ΔR on the refractometer, and ΔR adds to the ratio that multiplies the water flow, as in Equation (1.6). Both trims integrate only while the product flow exceeds 20 % of design, while the throughput setpoint, lagged by 15 s and its rate by 10 s, moves slower than 1 m³/h per minute, and once 0.25 m³ has passed since the flow last fell below 5 %. Outside those conditions they track, because a Brix or CO_2 error during a ramp or a flush says nothing about the syrup or the dose. A flow setpoint below its meter's cutoff shuts the valve.

7.5.4 The CO_2 Dose and the Dosing Balance

AIC-105 does not set the dose. The dose is the measured product flow times the setpoint volumes plus a trim, as shown in Equation (7.15).

$$\dot{n}_{cmd} = Q_m \rho_1 \left(V_{SP} + \Delta V\right), \qquad V_{bal} = \frac{\dot{n}_m}{\rho_1 Q_m} \tag{7.15}$$

where $\rho_1 = 1.9635\,\mathrm{kg/m^3}$ per volume, ΔV is the PI output on AT-105, and $\dot{n}_m$ is FT-105, the dosing controller's own mass-flow reading. The ratio part moves the dose with the flow at once, and the trim corrects the volumes. While the dosing valve is at capacity and the error is positive, AIC-105 runs with $\tau_I = \infty$, conditional integration against a limit the trim cannot move [11]. The dosing balance V_{bal} is an independent measurement of the same content, the CO_2 actually dosed per liter, in the manner of redundant flow and inventory data reconciled against a balance [16]. With the check on, a disagreement with AT-105 of more than 0.15 vol that lasts 60 s raises an alarm and returns the dose to the ratio alone, ΔV decaying with a 30 s time constant until the two agree within 0.075 vol.

7.5.5 Tank Pressure and Level

PIC-201 holds 3.0 bar(g) with the make-up valve and PIC-202 opens the vent only above 3.3 bar(g), each on its own setpoint, so the pressure floats in the gap between them. At reset the vent, resting shut below its setpoint, starts with no integral, so that measurement noise cannot crack it open. LIC-201 sets the throughput with the filler's speed as its output bias, so the throughput follows the filler and the level loop only trims. A change of the feedforward setting is offset in the integral, so the throughput does not jump, and the throughput setpoint is rate limited to 10 $\mathrm{m^3/h}$ per minute, with its upper limit lowered to the coordinator's rate cap. One $\mathrm{m^3/h}$ of imbalance moves the level 0.33 % per minute, an integrating plant.

7.5.6 The Coordinator

FY-100 stops, cuts and holds. A filler demand below 5 % of design is a stop, and with stop handling on the coordinator closes both flow valves, the dose and the glycol valve at the same instant, holding TIC-104's output for the restart. The feasibility test uses the dosing valve's own capacity curve with the measured supply and tank pressures, as shown in Equation (7.16).

$$\begin{aligned} Q_{feas} &= \max\left\{ Q \le 25 : \dot{n}_{max}(Q) \ge 1.05\, Q V_{SP}\, \nu_1 \right\} \\ \dot{n}_{max}(Q) &= K_c \sqrt{P_{sup,m}^2 - P_c(Q)^2} \\ P_c(Q) &= P_{t,m} + \Delta P_c \left(Q/Q_0\right)^2 \end{aligned} \tag{7.16}$$

where Q is in $\mathrm{m^3/h}$, converted to $\mathrm{m^3/s}$ in the inequality. With the cut on, the rate cap is Q_{feas}, no lower than 6 $\mathrm{m^3/h}$, while the chiller cap falls at 2 $\mathrm{m^3/h}$ per minute whenever the glycol valve is saturated and TT-104 is more than 0.2 °C above its setpoint, and rises at 1 $\mathrm{m^3/h}$ per minute while TT-104 is less than 0.1 °C above its setpoint and the glycol valve is below 95 %. The filler draws the smaller of its demand and the cap. When the supply is less than 0.3 bar above the tank setpoint, or Q_{feas} is below 6 $\mathrm{m^3/h}$, no rate can make the recipe, and after 10 s of that the hold stops the filler and records why, releasing it after 30 s of feasibility. In MANUAL the operator sets the five valves and the dose, the filler draws its demand, and the coordinator neither cuts nor holds.

7.5.7 Simulation, Control and Internal Models

The model of Section 7.3 is the simulation model. The application identifies no control model of its own, and open-loop steps in MANUAL from the case 1 line-up measure the plants that the loops see, each step made at 60 s and timed from that instant. A 10 % step of the glycol valve moves the true product temperature at TT-104 by −0.039 °C per percent, 63 % of the way in 16.2 s. A 10 kg/h step of the dose adds 0.254 vol at the analyzer's location, 63 % in 8.9 s, and 18.7 s after the analyzer's

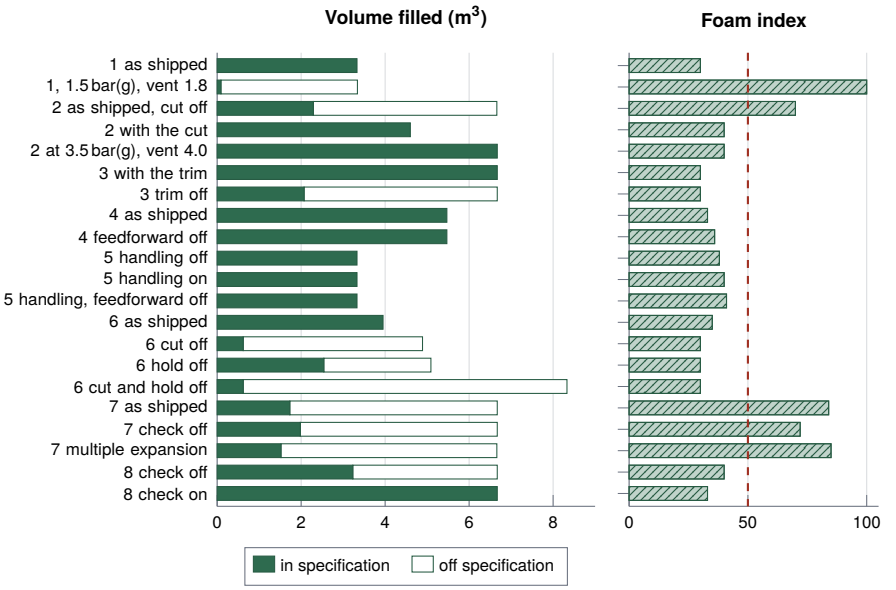


Figure 7.3 Table 7.5 redrawn: for every case and variant, the volume the filler took in and off specification, and the worst foam index, whose limit of 50 is the dashed line. Runs last 1200 s except where the table's caption says otherwise. Notice that the off-specification bars of case 1 at low top pressure and of cases 2 and 7 come with a foam index past its limit, while those of cases 3, 6 and 8 come with a foam index inside it: there the product failed on its Brix or its CO_2 content.

lag. A 2 % step of the syrup valve adds 0.338 °Bx at the refractometer, 63 % in 18.2 s. The filler sees the CO_2 through the tank, 63 % of the change it shows an hour after the step in 454 s, close to the tank's 7.5 min residence. The controllers' internal models are the recipe split of Equation (7.14), the ideal-gas volume ρ_1 in the dose, the valve curve of Equation (7.16), the density fit in Q_m and Henry's law inside the analyzer, and none of them contains the margin.

7.6 Scenarios and Measured Results

Table 7.4 lists the eight cases and the shift. Each case opens on the reference configuration, which has the filler feedforward, stop handling, the cut, the hold, both trims and the dosing-balance check on, the syrup on the measured-water basis and the single-expansion analyzer, and it changes only what its row names. The numbers below are the engine's own, read at the default seed from runs without the interface, and every time is in simulated seconds. A configuration that differs from the case's is set at $t = 0$ before the run starts, as a learner does after choosing the case, and a change meant as a step is made after the run has started. The scorecard's counts for each case are collected in Table 7.5, and Figure 7.3 draws them as bars. The exported file holds the filler's true Brix, CO_2, margin and foam index beside the refractometer and analyzer readings, with the running totals of product, CO_2 vented and cooling (Section 1.6.4).

7.6.1 Nominal Production and the Top Pressure

Case 1 blends 17.08 m^3/h of water deaerated to 0.31 mg/L of oxygen with 3.75 t/h of syrup into 20 m^3/h of product, doses 147 kg/h of CO_2 and uses 7.47 kg of CO_2 per m^3 filled. AT-105 reads 3.80 vol while the product carries 3.75 vol, because the single-expansion analyzer counts the 1.3 mg/L of dissolved air as CO_2 and the trim, at –0.054 vol after reset, holds that reading. Lowering the top pressure to 1.5 bar(g), with the vent at 1.8, a minute into the run shows what the margin is for. The vent releases 4.86 kg of CO_2 in the next minute, the margin turns negative 71 s after the change, the

Table 7.4 The Eight Cases and the Shift

#	Scenario and event	Teaching point
1	Nominal production	where the gas dissolves
2	Water 12 to 26 °C at 60 s, cut off	cooling is solubility
3	Syrup batch 58.0 °Bx at 60 s	the trim, the tank filters
4	Filler to 60, then 100 %	which flow is the master
5	Filler stop, 60 s to 360 s, handling off	a stop breathes CO_2
6	Supply to 5.0, then 2.6 bar(g)	cut, then hold
7	Vacuum 40 to 300 mbar	air foams, fools AT-105
8	AT-105 thermometer +2 °C, check off	a biased analyzer
9	2400 s shift	graded challenge

Table 7.5 Truth-Log Scorecard for Each Case and Variant. Runs Last 1200 s, Except 600 s for Case 1 (From the Change at 60 s in Its Second Row), 900 s for Case 5 and 1500 s for Case 6

Case and configuration	In spec (m^3)	Off spec (m^3)	Vented (kg)	Foam index
1 as shipped	3.33	0	0.10	30
1, 1.5 bar(g), vent 1.8 at 60 s	0.09	3.25	6.81	100
2 as shipped, cut off	2.29	4.37	0.21	70
2 with the cut	4.60	0	0.20	40
2 at 3.5 bar(g), vent 4.0	6.67	0	0.23	40
3 with the trim	6.67	0	0.20	30
3 trim off	2.07	4.60	0.20	30
4 as shipped	5.47	0	0.21	33
4 feedforward off	5.47	0	2.00	36
5 handling off	3.33	0	1.36	38
5 handling on	3.33	0	0.16	40
5 handling and feedforward off	3.33	0	6.78	41
6 as shipped	3.95	0	0.26	35
6 cut off	0.62	4.27	0.26	30
6 hold off	2.54	2.55	0.26	30
6 cut and hold off	0.62	7.71	0.26	30
7 as shipped	1.73	4.94	0.20	84
7 check off	1.98	4.69	0.20	72
7 multiple expansion	1.52	5.14	0.20	85
8 check off	3.23	3.44	0.20	40
8 check on	6.67	0	0.20	33

foam index reaches 100, and 3.25 m^3 of the 3.33 m^3 filled in the ten minutes after the change would foam while 6.81 kg of CO_2 leaves through the vent.

7.6.2 A Cooling Shortage Is a Solubility Shortage

In case 2 the water warms at 60 s, the glycol valve is wide open from 90 s, and the refrigeration plant delivers its full 320 kW, so its glycol supply warms from −2.0 °C to 6.5 °C by 600 s, when TT-104 reads 11.2 °C and the tank has reached 8.5 °C. The CO_2 loop holds the content at 3.80 vol, but the margin falls from 1.12 to 0.68 bar by 600 s, the foam index passes 50 at 413 s and reaches 70 by 1200 s, when the tank is at 10.5 °C and 3.8 vol are in equilibrium with 3.40 bar. The plant view at 900 s, with the foam index at 66, is shown in Figure 7.4, while the filler's CO_2 is still on its band. By 1200 s, 4.37 m^3 of the 6.67 m^3 filled would foam.



Figure 7.4 The carbonation line in case 2, warmer feed, at $t = 15.00$ min (900 s, a clock outside the crop), 840 s after the water feed warmed from 12 to 26 °C, with the throughput cut off as shipped, cropped to the Carbonation view. (1) The status chips and the FY-100 line, with the foam index at 66 and the line running at the filler's 20 m³/h. (2) The solubility chart: the tank's point, marked off specification, sits inside the hatched foam region beside the carbonator outlet's point (the run has them at 9.8 °C and 3.80 vol, and at 11.2 °C and 3.76 vol), and the highlighted 3 bar(g) curve carries the tank's own dashed saturation line. (3) The dissolution profile: free gas shrinks cell by cell under a section that holds 5.7 vol at 4.2 bar(g), with 0.4 % of the CO_2 still free at AT-105. (4) The tank panel: a headspace of 4.04 bar absolute at 99.9 % CO_2 against a product gas pressure of 3.49 bar, a margin of 0.55 bar, the foam gauge at 66 past its limit of 50, both valves shut and 0.2 kg vented. (5) The status line: off-spec product reaching the filler, foam. Outside the crop, over a 20 min window, the trends show the filler's true CO_2 at 3.804 vol and AT-105 at 3.806 vol on the recipe band, the true CO_2 at the analyzer at 3.763 vol, the dose at 148.5 kg/h against its 149.4 kg/h feedforward, the foam index climbing through its limit at 413 s to 66, the tank pressure floating at 3.03 bar(g) inside its gap and the level at 49.9 %, and the loop scorecard gives the glycol valve saturated for 83.7 % of the run.

TRY IT IN THE APP **2 · Warmer Feed**

Load the scenario, press Run and run to 1200 s. Watch the analyzer AT-105: it stays on 3.80 vol throughout. Then switch to the Carbonation view and watch the foam index. It passes its limit of 50 at 413 s and reaches 70, and 4.37 m³ of the 6.67 m³ filled would foam.

The three levers of Section 7.4 give three answers. With the cut on, the coordinator starts slowing the line and the filler at 90 s, as soon as the glycol valve saturates. Every liter stays in specification and the tank peaks at 4.9 °C, but only 4.60 m³ are filled, and the rate does not settle. Between 1200 and 2400 s of a longer run the filler's draw cycles between 11.69 and 13.41 m³/h with a period of about 227 s, around a mean of 12.72 m³/h against the 12.6 m³/h that 320 kW can hold. The cap falls while the glycol valve is saturated and TT-104 is hot, rises once TT-104 has recovered, and the glycol holdup delays both, so the cut overshoots in each direction. Volume 4, Chapter 4 meets the same difficulty in a feed rate held against constraints that are measured late. With the cut off and the tank at 3.5 bar(g), vent 4.0, from the start, the tank still warms to 10.5 °C, but the foam index peaks at 40 and all 6.67 m³ are in specification. The pressure's CO_2 lies in the headspace, which holds 2.4 kg more at 3.5 bar(g) than at 3.0 bar(g) and starts the case full, so the run itself uses 7.43 kg per m³ against 7.44,

while the cut spends 22.7 kWh of cooling per m^3 filled against 15.7.

🕮 **Pause.** Try Exercise 7.1 before reading on.

7.6.3 The Brix Trim and the Tank as a Filter

In case 3 a 58.0 °Bx batch enters the syrup tank at 60 s and mixes in with its 150 s time constant. At the recipe ratio the blend would settle at 10.44 °Bx. The true Brix at the refractometer, which sees each liter 16.2 s after the blend point, reaches its lowest value, 10.715 °Bx, at 161 s, and AIC-103 raises the ratio by 0.0094 kg/kg, 4.3 % more syrup, by 1200 s. The tank, holding 7.5 min of production, averages the dip, and the filler's worst is 10.777 °Bx at 412 s. With the trim off the filler leaves the band at 372 s and reaches 10.48 °Bx by 1200 s, and 4.60 m^3 of the 6.67 m^3 filled are off specification.

7.6.4 Following the Filler

In case 4 the filler slows to 60 % at 60 s and returns at 600 s. The feedforward brings the throughput from 20 to 12 m^3/h in 49 s at the ramp limit, the level stays between 49.2 and 51.0 % and the tank between 2.96 and 3.07 bar(g), so nothing is vented but the purge. On the measured-water basis the syrup lags the water through the ramps, and the true Brix at the refractometer peaks at 10.943 °Bx at 125 s and dips to 10.648 °Bx at 634 s, which the tank averages to within 0.010 °Bx at the filler. On the setpoint basis it stays between 10.772 and 10.823 °Bx. The measured-water basis earns its place when the water valve cannot follow its setpoint. With the advanced water header dip to 30 % fired at 700 s, the measured-water basis keeps the filler at 10.80 °Bx, while the setpoint basis drives it to 11.33 °Bx and fills 1.69 m^3 off specification by 1200 s. Without the feedforward the level loop alone lets the level swing from 42.9 to 58.4 %, the pressure reaches 3.35 bar(g), and 1.8 kg of CO_2 is vented beyond the purge.

> **TRY IT IN THE APP** **4 · Filler Slowdown**
>
> Run the scenario and watch the tank level while the filler slows to 60 % and returns: it stays between 49.2 and 51.0 %. Reload the scenario with its reload button, set Filler-speed feedforward Off on the FY-100 card before 60 s and run again. The level loop alone lets the level swing from 42.9 to 58.4 %, and 1.8 kg of CO_2 is vented beyond the purge.

7.6.5 A Stop That Breathes

In case 5 the filler stops at 60 s for 300 s, with stop handling off, and the feedforward ramps the blend down at 10 m^3/h per minute. The 0.32 m^3 made meanwhile lifts the level to 56.4 % at 204 s, squeezes the headspace by an eighth and raises the pressure to 3.39 bar(g) at 134 s, over the vent setpoint, so the vent and the purge release 1.36 kg of CO_2 in 900 s, against 0.16 kg from the purge alone when the stop is handled. The restart sends a standing slug past the refractometer, whose true Brix swings from 11.15 to 10.48 °Bx. With stop handling the feeds, the dose and the glycol close together at 60 s, the level does not rise, only the purge is vented, and the product standing in the chiller cools no lower than –0.16 °C, above its freezing point of –0.66 °C at 10.8 °Bx. The restart has its own cost, since the filler draws 20 m^3/h at once while the blend ramps back, and the level dips to 43.5 % at 481 s. Without the feedforward and without stop handling the level climbs to 69.7 %, the pressure to 3.47 bar(g), and 6.8 kg of CO_2 is vented. With stop handling but no feedforward the restart is left to the level loop, which brings back only 1.6 m^3/h by 395 s, so the product trickling through the chiller cools to –0.68 °C and is flagged as a freeze risk, and the level sinks to 29.0 % at 766 s.

🕮 **Pause.** Try Exercise 7.3 before reading on.

7.6.6 An Infeasible Recipe

In case 6 the CO_2 supply sags from 9.0 to 5.0 bar(g) at 60 s. The coordinator reads the valve curve with PT-501 and PT-201, finds that about 13.95 m^3/h can be carbonated (13.87 to 14.01 m^3/h with the noise on PT-201), and slows the line and the filler to that rate from 61 s, so the product stays in

specification. At 600 s the supply drops to 2.6 bar(g), below what the tank needs, no rate is feasible, and the filler is held at 611 s. The tank keeps its product while it waits, its pressure sagging to 2.94 bar(g) by 1200 s with a 1.04 bar margin left, and the hold is released at 1230 s, 30 s after the supply returns. The line fills 3.95 m^3 of the 8.33 m^3 the filler asked for, none of it off specification. Without the cut the dose saturates and off-specification product is filled from 112 s, 4.27 m^3 of it. Without the hold the uncarbonated blend reaches the filler from 660 s, 2.55 m^3 falling to 2.61 vol by 1229 s, and with neither 7.71 m^3 are off specification, some of it at 0.78 vol. The hold loses volume, and the off-specification product it prevents could not have been recovered. The steady balance decides which recipes are reachable at all, as it decides which compositions are reachable in Volume 2, Chapter 3.

7.6.7 Instruments That Can Be Fooled

In case 7 the deaerator's vacuum rises to 300 mbar at 60 s, the oxygen after the deaerator rises from 0.31 to 3.04 mg/L, and the dissolved air at the filler climbs from 1.3 to 6.9 mg/L by 1200 s. Its saturation pressure, 0.04 bar at the start, 0.10 bar at 300 s and 0.20 bar at 1200 s, counts five times in the foam index, which passes its limit at 311 s, and 4.94 m^3 of the 6.67 m^3 filled would foam. The single-expansion analyzer counts the same air as CO_2 and reads 0.32 vol high. The dosing balance sees it disagree with the CO_2 dosed per liter, alarms at 165 s and returns the dose to the ratio, so the CO_2 at the filler stays in specification. With the check off the trim cuts the dose until the filler's CO_2 has fallen to 3.55 vol by 1200 s, and 4.01 m^3 are off for CO_2 as well as foam. The multiple-expansion analyzer never makes the error, but 5.14 m^3 still foam, because only the vacuum can remove the air.

In case 8 AT-105's own thermometer reads 2 °C high from 60 s, with the check off. Believing its sample warmer, the analyzer credits its pressure with 6.1 % less CO_2 and reads low, and the trim raises the dose until the reading is back at 3.80 vol. The true CO_2 reaches 3.99 vol at the analyzer and 4.01 vol at the filler by 1200 s, over the 3.95 vol limit from 581 s, and 3.44 m^3 of the 6.67 m^3 filled are off specification while every instrument reads normally. With the check on, the analyzer and the dose per liter differ by more than 0.15 vol for a minute, the alarm comes at 127 s, and the filler stays in specification, at worst 3.84 vol. An independent balance that the plant already has catches both faults, as redundant flow and inventory data can [16]. In Volume 11, Chapter 13 a drifting analyzer likewise takes a plant outside its permit while the loop it feeds reads on target.

> **DID YOU KNOW? Every Instrument Reads Normally**
>
> From the simulator: with its thermometer 2 °C high and the dosing balance off, the analyzer of case 8 fills 3.44 m^3 off specification and 3.23 m^3 in it. With the balance on, all 6.67 m^3 are in specification (Table 7.5).

7.6.8 The Shift Challenge

The challenge runs 2400 s. The filler slows to 70 % at 300 s and returns at 600 s, the water warms to 26 °C from 700 to 1800 s, the filler jams from 1200 to 1440 s and speeds up to 110 % at 1860 s, and a 58.8 °Bx batch arrives at 1600 s. It starts without the filler feedforward, stop handling or the cut, with a loose level loop ($K_c = 0.3$, $\tau_I = 900$ s) and the vent at 3.05 bar(g). The target asks for at least 11.5 m^3 in specification, at most 0.05 m^3 off, at most 3 kg of CO_2 vented, a foam index never above 50 while filling, a level never above 80 % with no overflow, and at most 16 kWh of cooling per m^3 filled, with the model parameters and disturbances as given. A changed model parameter or disturbance voids the attempt. Table 7.6 compares the measured configurations.

As shipped the line fills 10.98 m^3 in specification and 0.82 m^3 that would foam, vents 10.6 kg of CO_2, lets the level reach 70.7 % and the foam index 58, and uses 15.2 kWh of cooling per m^3. The suggested configuration fills all 11.80 m^3 in specification, with the foam index peaking at 39 while the tank warms to 9.6 °C, the level between 43.3 and 50.6 %, 0.77 kg vented and 14.1 kWh per m^3. Each element pays for itself. With the feedforward and stop handling but the tank left at 3.0 bar(g), 3.16 m^3 still foam, and with the cut on at 3.0 bar(g) every liter is in specification but only 9.52 m^3 are

Table 7.6 Challenge Configurations Over 2400 s of a Filler Demand of 11.80 m^3

Configuration	In spec (m^3)	Off (m^3)	Vented (kg)	Foam index	Level (%)
as shipped	10.98	0.82	10.62	58	40.7–70.7
suggested[a]	11.80	0	0.77	39	43.3–50.6
suggested, 3.0 bar(g), vent 3.3	8.64	3.16	1.47	68	43.3–50.6
the same, cut on	9.52	0	0.41	45	44.3–50.5

[a] feedforward and stop handling on, cut off, 3.5 bar(g), vent 4.0, level loop $K_c = 0.5$ and $\tau_I = 300$ s

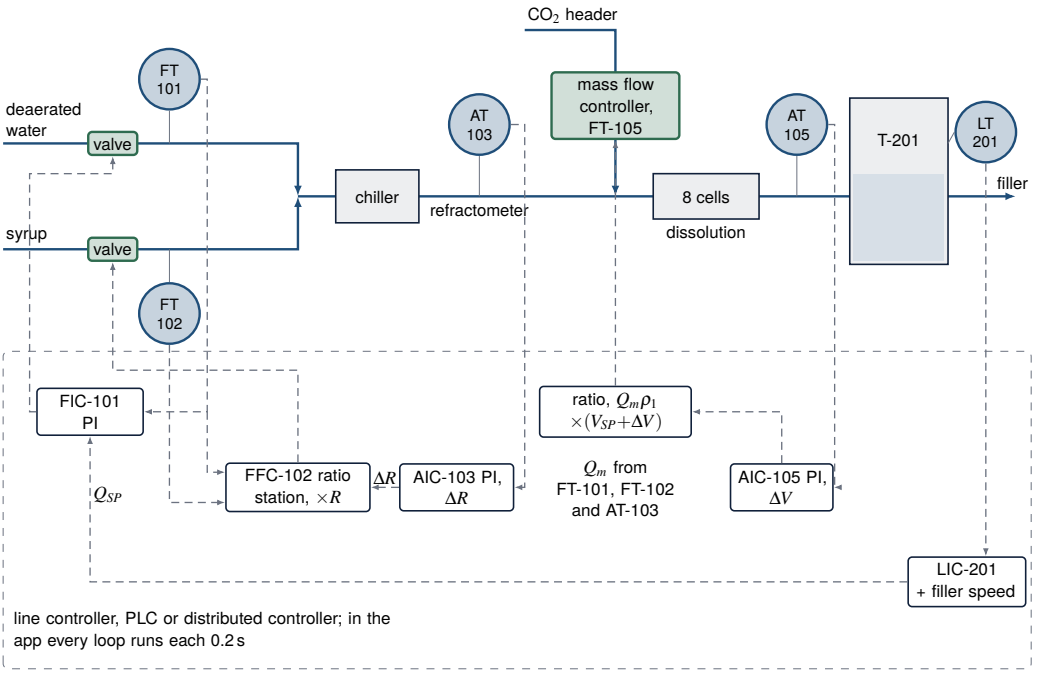


Figure 7.5 The two ratio structures of the line on real hardware. The water mass meter FT-101 is the wild flow: FIC-101 holds it at its share of the throughput Q_{SP} that LIC-201 sets with the filler speed as its feedforward, and the ratio station FFC-102 multiplies it by the ratio, trimmed by AIC-103 on the refractometer, to give the syrup setpoint. The dose block multiplies the measured product flow by the setpoint volumes plus the trim of AIC-105 on the pressure-and-temperature analyzer, and sends the result to the gas mass flow controller at the injector. Solid arrows are process streams and dashed gray arrows are signals. Notice that the analyzer only trims a dose that already follows the flow, so a wrong analyzer moves the product off specification without upsetting any loop.

filled. The coordination keeps the level and the CO_2, and the top pressure keeps the rate. Against the target, the shipped configuration fails four of the bounds, the in-specification volume by 0.52 m^3 and the off-specification volume more than 16 times over. The suggested one passes with 0.30 m^3, 2.2 kg, 11 points of foam index and 1.9 kWh per m^3 to spare.

7.7 Technology in Practice

Figure 7.5 draws the two ratio structures of Section 7.5, the trimmed syrup ratio and the CO_2 dose in ratio to the measured flow, with their hardware.

What Measures It

Four measurements carry the ratios. The water and syrup mass meters give the wild and the captive flow, the refractometer AT-103 trims the syrup ratio, and the CO_2 analyzer AT-105 trims the dose. The analyzer is the one that can be fooled. It infers a content from a pressure and a temperature, and the international method for sparkling products shows how strongly that conversion leans on temperature: a pressure read at 3 °C is multiplied by 1.68 to give its value at 20 °C [17]. In the model AT-105 is Equation (7.12) behind a 10 s lag, with its thermometer bias β and the single-expansion reading of air as its two ways to be wrong.

> **TECHNOLOGY Sensor: Equilibrium Pressure and Temperature**
>
> A CO_2 meter of this kind does not see the gas directly. It brings its sample to equilibrium, reads that pressure and the sample temperature, and converts them with Henry's law, whose constant depends on temperature [13]. The international wine method reads the same equilibrium pressure in a sealed bottle with a needle gauge, either a Bourdon tube or a piezoelectric cell. A class 1 gauge of 1000 kPa full scale reads within 10 kPa. A reading taken away from 20 °C is multiplied by a correction factor, 1.68 at 3 °C, which shows how much the temperature weighs [17]. An error in that temperature, or air counted as CO_2, shifts the reading with nothing on its trend to show it, as cases 7 and 8 of this chapter show.

What Moves It

The dose leaves the CO_2 header through a gas mass flow controller, whose own sensor is FT-105 and whose valve curve, Equation (7.8), sets the most it can pass against the carbonator pressure. Its calibration assumes one gas, which suits a header of pure CO_2 [18]. The water, syrup and glycol valves are modeled as linear with first-order lags of 1 s, 1 s and 5 s, and the make-up and vent valves at 0.5 s.

> **TECHNOLOGY Final Element: A Gas Mass Flow Controller**
>
> A thermal mass flow controller combines a flow sensor, a throttling valve and its own control electronics in one small body. The sensor holds a heated element in the gas beside an unheated one, and the heat the flow carries away measures the mass flow. The calibration holds for one gas only, because it rests on that gas's specific heat, and a change from turbulent to laminar flow shifts it. Such meters are less accurate than Coriolis meters but far cheaper, and suit purified gases of stable composition [18]. The chapter's dose controller is of this kind: FT-105 is its own reading, and its valve reports when it is at capacity.

Where the Controller Runs

Programmable logic controllers act as local controllers under a supervisory control scheme, or as the primary controller of a smaller system, and their programs hold logic, timing, counting, PID control and arithmetic [19]. Control cycles range from milliseconds to minutes [19]. In the app every loop and the coordinator run each 0.2 s, against a dose that reaches 63 % of its effect at the analyzer's location in 8.9 s. The structures map onto standard blocks. A signal multiplying relay, or ratio station, multiplies the wild flow by a factor and sends the product to the captive flow controller as its setpoint [18]. FFC-102 is that block with the factor $R_{SP} + \Delta R$ from AIC-103, and the dose command of Equation (7.15) is a second one whose factor is $V_{SP} + \Delta V$.

> **IN PRACTICE Check the Gauge Before the Product**
>
> The international method for sparkling wine, resolution OENO 21/2003, reads a bottle only after its temperature has been stable for at least 24 h, and only once shaking has brought the pressure to a constant value. The gauges are verified at least once a year on a test bed against a reference gauge of a higher class traced to national standards, comparing the two at rising and at falling pressures and adjusting the tested gauge when they differ [17]. Here the dosing balance is the analyzer's second opinion.

What Is Modernizing It

Three developments bear on this line. The first is a direct optical reading of dissolved CO_2. Infrared sensors usually need a gas sample or an equilibrated headspace, while attenuated total reflectance reads the liquid itself through an evanescent wave at a crystal face. For dissolved CO_2 it has so far been used mainly with laboratory instruments, and compact devices are now being shown [20]. The second is rapid, standardized assessment of bubbles and foam by near-infrared spectroscopy and computer vision in place of slow manual tests [21]. The third is the industrial internet of things, with networked instruments and computing at the edge that acts on data where it is collected [19]. The same connectivity raises the need for resilience, safety and security [19].

7.8 Limitations

The foam index is an illustrative indicator built from the breakout margin with dissolved air weighted five times, and it has not been validated against a filler. The filler itself is a demand, without counter-pressure, snift or fill-height mechanics.

The solubility is the pure-water compilation value with a constant van 't Hoff slope, 3.5 to 7.8 % below a critically evaluated correlation between 25 and 0 °C [6], without the salting-out by sugar or the non-ideality of CO_2. The dissolution, breakout and surface rates are constants chosen for the teaching point rather than correlations for a mixer or tank.

> ⚠ **OPEN CHALLENGE** **How Much Gas a Sweet Drink Holds**
>
> Sugars lower the solubility of CO_2 in water, and the more sugar, the lower it is. Models of the gas in sugar, water and alcohol are hard to calibrate because measured data are limited, and for the mixture with alcohol one main gap is the lack of data at low pressures [22]. An analyzer that converts pressure to content with a pure-water law inherits that gap. Progress would be measured solubility for real recipes at filling pressures, built into the analyzer's conversion and into the margin a coordinator protects.

The instruments fail only through the thermometer bias and the air the analyzer misreads, with no laboratory sampling schedule, valves are linear and free of stiction, and every size and limit is a teaching value for one recipe. The warm spell of case 2 and the thermometer error of case 8 arrive as steps, which a plant would not deliver, but steps separate one cause from the others.

> ⚠ **OPEN CHALLENGE** **Judging Foam Without Trial and Error**
>
> The traditional ways of judging the bubbles and foam of carbonated drinks are slow and costly for small and medium producers, and partly subjective. A review calls for rapid, standardized methods such as near-infrared spectroscopy and computer vision, and notes that trial and error still dominates the industry [21]. The foam index of this chapter has not been validated against a filler. Progress would be an online measure of fill stability that a controller can close a loop on, in place of a margin computed from a model.

7.9 Conclusion

A soft drink carbonation line is a plant in which the analyzer measures a content and the filler needs a margin, and the simulator of this chapter logs the true tank state beside every instrument so that the two can be compared. At the design point the product in the tank at 3.05 °C is 1.12 bar from breakout, and the foam limit lies at 6.3 °C under 3.0 bar(g) and at 11.2 °C under 3.5 bar(g). A 26 °C water feed that outruns the 320 kW chiller takes the tank to 10.5 °C while the analyzer stays on 3.80 vol, and 4.37 m^3 of 6.67 m^3 would foam. A throughput cut saves the product by filling 4.60 m^3 at a rate that cycles every 227 s, while half a bar of top pressure fills all 6.67 m^3. A supply below the tank's own pressure is held rather than filled, avoiding 2.55 m^3 of off-specification product, and a dosing balance catches both an analyzer that reads dissolved air as CO_2 and one whose thermometer, 2 °C high, would otherwise fill 3.44 m^3 over the CO_2 limit. The shift improves from 0.82 m^3 off specification to

all 11.80 m^3 in specification. The model is plug flow with an illustrative foam index and constant transfer coefficients. A fuller model would add a filling model with counter-pressure, the salting-out by sugar, a dissolution coefficient that follows the turbulence, and a laboratory sampling schedule. Within those limits the line shows that a gas held in solution by pressure defines a margin, not a setpoint.

KEY POINTS

- The analyzer measures how much gas is in the drink, but the filler needs a margin of pressure, and a warmer drink loses that margin while the analyzer reads its setpoint.
- A trimmed ratio blend and a dose in ratio to the measured flow hold the recipe, while the filler-speed feedforward keeps the level and the vent quiet.
- Cooling, top pressure and throughput are the three levers on the margin: half a bar of top pressure fills all 6.67 m^3 where the throughput cut fills 4.60 m^3.
- A dosing balance catches both an analyzer that counts air as CO_2 and one whose thermometer reads high.

Where else this applies. Chapter 6 also computes a dose from measured flows and trims it on a slow analyzer, and Chapter 4 trims a ratio on a measured quality.

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7.10 Exercises

7.1 Concept check · 2 min

In case 2 the CO_2 loop holds AT-105 on 3.80 vol while 4.37 m^3 of the 6.67 m^3 filled would foam. What does the analyzer fail to see?

(a) The free CO_2 that has not yet dissolved when the product reaches AT-105
(b) A rise of the CO_2 content that the 10 s lag of AT-105 hides
(c) The dissolved air, which the single-expansion method reads as CO_2
(d) The warmer tank, which raises the gas pressure of an unchanged content

7.2 Concept check · 1 min

At the design point of case 1, AT-105 reads 3.80 vol while the product at its location carries 3.75 vol. Why does it read high?

(a) It counts the pressure of the dissolved air as CO_2
(b) It samples free CO_2 that has not yet dissolved
(c) Its thermometer reads high, so it credits more CO_2
(d) Its 10 s lag leaves it behind a rising content

7.3 Concept check · 2 min

In case 5 the filler stops for five minutes with stop handling off, and 1.36 kg of CO_2 leaves through the vent and the purge in 900 s, against 0.16 kg with stop handling on. Where does the extra CO_2 come from?

(a) The dose carries on after the stop and overcarbonates the tank
(b) Product made during the ramp-down squeezes the headspace over the vent setpoint
(c) The idle tank warms and its product breaks out into the headspace
(d) The make-up valve opens to hold the setpoint while the level falls

7.4 Theory and calculation · 6 min

Use Equation (7.1) with $H_C^\circ = 3.3 \times 10^{-4}\,\mathrm{mol/(m^3\,Pa)}$, $T_C^\circ = 298.15\,\mathrm{K}$, $\theta_C = 2400\,\mathrm{K}$ and $\nu_1 = 44.615\,\mathrm{mol/m^3}$. Since $V = \rho c/\nu_1$, the CO_2 pressure of a product is $p_C = V\nu_1/H_C(T)$.

(a) Find H_C and the CO_2 pressure of 3.80 vol at 3.0 °C and at 10.5 °C. *Checkpoint:* $H_C = 6.27 \times 10^{-4}$ and 4.98×10^{-4} in mol/(m^3 Pa), $p_C = 2.70$ bar and 3.40 bar.

(b) The product at the filler in case 1 holds 3.79 vol at 3.05 °C, its air exerts $p_A = 0.038$ bar and water vapor $p_w = 0.0076$ bar, and the headspace is at 3.0 bar(g), or 4.013 bar absolute. Find the effective gas pressure of Equation (7.11), the margin and the foam index. *Checkpoint:* 2.90 bar, 1.11 bar and 30.

(c) At 6.3 °C the same air gives $5p_A = 0.202$ bar and $p_w = 0.0095$ bar. Find the margin and foam index of 3.80 vol under 3.0 bar(g) and under 3.5 bar(g). *Checkpoint:* 0.80 bar and 50, and 1.30 bar and 19.

7.5 Theory and calculation · 5 min

The recipe makes 10.80 °Bx from 60.0 °Bx syrup by the mass ratio R_{SP} of Equation (7.14).

(a) Show that $R_{SP} = 10.8/49.2$, and find the Brix of the blend if a 58.0 °Bx batch arrives and the ratio is not changed. *Checkpoint:* 0.2195 and 10.44 °Bx.

(b) Find the ratio that makes 10.80 °Bx from 58.0 °Bx syrup, the trim ΔR it needs and the percentage of extra syrup. *Checkpoint:* 0.2288, $\Delta R = +0.0093$ and 4.2 %.

(c) Find the dose command of Equation (7.15) at 20 m^3/h for $V_{SP} = 3.80$ vol, first with $\Delta V = 0$ and then with the trim of case 1, $\Delta V = -0.054$ vol. *Checkpoint:* 149.2 kg/h and 147.1 kg/h.

7.6 Theory and calculation · 6 min

The dosing valve of Equation (7.8) passes $\dot{n}_{max} = K_c\sqrt{P_{sup}^2 - P_c^2}$ with $K_c = 0.178$ mol/(s bar), the pressures absolute in bar, $P_{atm} = 1.013$ bar and $M_{CO_2} = 44.01$ g/mol. The tank is at 3.0 bar(g), and $P_c = P_t + 1.2\,(Q/20)^2$ in bar with Q in m^3/h.

(a) At the design flow $P_c = 4.20$ bar(g). Find the valve capacity in kg/h with the supply at 9.0 bar(g) and at 5.0 bar(g), and the second as a share of the 149 kg/h the recipe needs. *Checkpoint:* 241 kg/h, 84.5 kg/h and 57 %.

(b) With the supply at 5.0 bar(g), test the feasibility condition of Equation (7.16) at 13 and at 14 m^3/h, and bracket Q_{feas}. *Checkpoint:* Feasible at 13 (111.8 against 101.8 kg/h), not at 14 (109.2 against 109.7 kg/h), so Q_{feas} just under 14.

(c) The supply then falls to 2.6 bar(g). What rate is feasible, and what does FY-100 do? *Checkpoint:* None. The filler is held.

7.7 App challenge · 9 min

Load scenario 2, Warmer feed, and use the default seed. Change nothing, run to 1200 s and export the CSV file. Then press the reload button, set Tank pressure setpoint to 3.5 bar(g) and Vent setpoint to 4.0 bar(g) before Run, run to 1200 s and export again.

(a) From the first run report the Filled in spec, Filled off spec and Worst foam index tiles, the first row where `foam_index` exceeds 50, and `T_tank_C` and `margin_bar` at 1200 s. *Checkpoint:* 2.29 and 4.37 m^3, 70, 413 s (within 1 s), 10.5 °C and 0.48 bar.

(b) Report the same tiles, `T_tank_C` and `margin_bar` for the second run. *Checkpoint:* 6.67 and 0.00 m^3, 40, 10.5 °C and 0.95 bar.

(c) The top pressure setpoint rose by 0.5 bar, but the margins at 1200 s differ by 0.48 bar. Read `P_true_barg` at 1200 s in both files and explain. *Checkpoint:* 3.02 bar(g) and 3.50 bar(g).

7.8 App challenge · 8 min

Load scenario 8, Analyzer bias, in which the dosing-balance check ships Off, and use the default seed. Run to 1200 s and export the CSV file. Then press Reset, set Dosing-balance check On on the AIC-105 card before Run, run to 1200 s and export again.

(a) From the first file read `V_meas_vol`, `V_true_an_vol`, `V_filler_vol` and `V_balance_vol` at 1200 s, the first row where `V_filler_vol` exceeds 3.95, and the Filled off spec tile. *Checkpoint:* About 3.80 (within 0.03, it is noisy), 3.99, 4.01 and 4.00 vol, 581 s and 3.44 m^3.

(b) From the second file find the first row with `balance_alarm_flag` equal to 1, the highest `V_filler_vol` and the Filled off spec tile. *Checkpoint:* 128 s, 3.84 vol and 0.00 m^3.

Explain why the first run fills product over the limit while every instrument reads normally, and what the check compares.

7.9 App challenge · 9 min

Load the challenge, a shift of filler demand, and use the default seed.

(a) Change nothing and run the full 2400 s. Report the Filled in spec, Filled off spec, CO_2 vented, Worst foam index and Highest level tiles, and name the bounds of the target that fail. *Checkpoint:* 10.98 and 0.82 m^3, 10.6 kg, 58 and 70.7 %. Four bounds fail.

(b) Press Reset and before Run set Filler-speed feedforward On, Stop handling On, Level loop gain 0.5 m^3/h per %, Level loop integral time 300 s, Tank pressure setpoint 3.5 bar(g) and Vent setpoint 4.0 bar(g). Run 2400 s and report the same tiles, the Cooling tile and the cooling per m^3 filled. *Checkpoint:* 11.80 and 0.00 m^3, 0.8 kg, 39, 50.6 %, 166 kWh and 14.1 kWh per m^3. Target met.

(c) Press Reset, set Tank pressure setpoint to 3.0 bar(g) and Vent setpoint to 3.3 bar(g), keep the other changes, and run again. *Checkpoint:* 8.64 and 3.16 m^3, 1.5 kg and 68.

Say what each change of (b) protects.

7.10 Application area · 3 min

Section 7.3 states that the model's CO_2 solubility is 6.7 % below a correlation of about 100 studies at 3 °C, and that the salting-out by sugar is not modeled.

(a) Does the model place the foam limit at a lower or a higher temperature than a product that follows the correlation would have? Estimate the difference for 3.80 vol under 3.0 bar(g), given that the correlation's solubility moves the limit from 6.3 to about 8.5 °C. *Checkpoint:* Lower, by about 2 °C.

(b) Which way does the missing salting-out act, and what should a plant engineer do before trusting the model's limit on a real line? *Checkpoint:* It lowers the solubility and partly cancels (a). Calibrate on the plant.

7.11 Application area · 4 min

Case 2 offers two ways to keep the product in specification through a warm water feed: the throughput cut, which fills 4.60 m^3 in 1200 s, and a top pressure of 3.5 bar(g), which fills all 6.67 m^3. The higher pressure costs about 2.4 kg of CO_2 once, held in the headspace.

(a) Over the 1200 s of the case, how much product does the cut give up, and what is the CO_2 cost of the pressure per m^3 of that product? *Checkpoint:* 2.07 m^3, about 1.2 kg per m^3.

(b) Figure 7.2 gives a margin of 0.71 bar at 12 °C under 3.5 bar(g). If a hotter feed took the tank to 12 °C, would the pressure alone keep the product in specification, and what would the engineer add? *Checkpoint:* No. Foam index 55. Add the cut, or more pressure within the tank's rating.

7.12 Review the agent · 5 min

An engineer asks an AI assistant how to stop the foaming of case 2. It replies: “The foam index passes 50 at 413 s because the margin is too small. Raise the PIC-201 setpoint from 3.0 to 3.5 bar(g). The margin rises by 0.5 bar, so the foam index falls by about 31 points and the whole run stays in specification. No other change is needed.” Find the flaw, and say how you would check the claim in the app.