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CHAPTER 10

Lager Fermenter Simulator With On/Off Glycol Valves and a Day-Old Diacetyl Result

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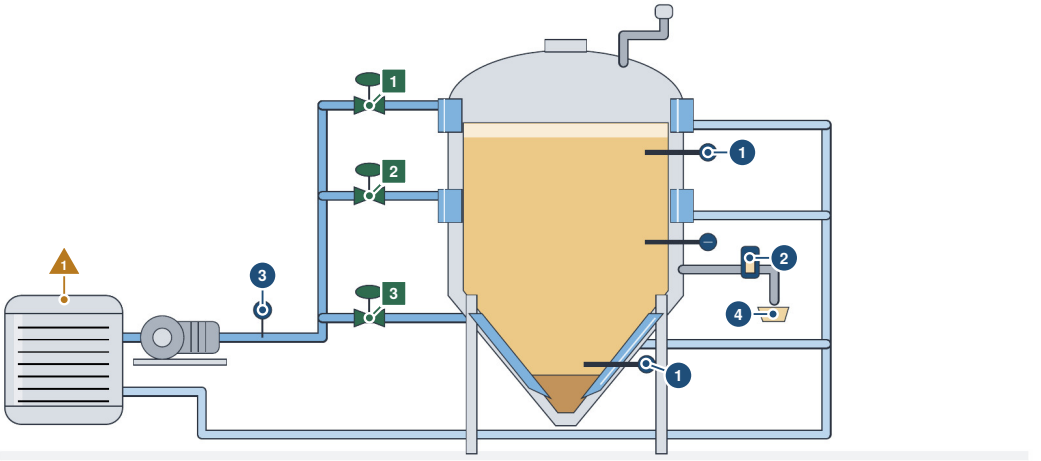
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CHAPTER 10

Lager Fermenter Simulator With On/Off Glycol Valves and a Day-Old Diacetyl Result



The controller moves 1 top jacket valve 2 middle jacket valve 3 cone jacket valve

The controller reads 1 zone temperature probes 2 density meter 3 glycol supply temperature 4 daily laboratory sample

What disturbs it 1 other tanks and lost capacity on the shared glycol plant

A tall lager tank is cooled through three jackets by valves that are only open or shut, from a glycol plant it shares with other tanks, and only its temperature is measured in every zone while gravity and diacetyl are sampled at one valve. Illustration, not to scale.

IN PLAIN TERMS Keeping a Lager Tank on Its Recipe

The main idea. Yeast turn sugar into beer and give off heat as they work. A big lager tank is cooled by cold liquid in jackets on its wall, and the valves on the jackets can only be open or shut.

The challenge. The beer is stirred only while the yeast make gas, so one thermometer stops speaking for the whole tank once the gas stops. The test that says the beer is ready comes back a day late, and the cold supply is shared with other tanks.

Why it matters. The batch is finished on time by what starts and ends each step, more than by fine tuning of the loops.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	the first page, the two history segments (Section 10.2), the two fact segments, both try-it segments (Sections 10.5 and 10.5.2) and the key points
Study	50 min	the whole chapter with its three pause points and the twelve exercises of Section 10.9
Practice	20 min	the first page, the cases and the graded batch (Section 10.5), Technology in Practice (Section 10.6), Limitations (Section 10.7) and the open challenge

The control question A lager tank has only open-or-shut glycol valves, is mixed only while its yeast release gas, ends its diacetyl rest on a result a day old and shares its glycol plant with the cellar. Does the tuning of its temperature loops decide the batch, or do the phase triggers, the endpoint, the probe placement and the shared utility?

Learning objectives

- Explain how a time-proportioned output gives an on/off valve a duty, and why the jacket's heat is a concave function of that duty.
- Compare the limit cycle of hysteresis valves with a time-proportioned PI loop, and relate the swing to the deadband and the probe lag.
- Predict which zone of a quiet tank one probe fails to control during a crash, and in which direction.
- Calculate the correction that a day-old laboratory result gives a model-based estimate, and compare three ways to end a diacetyl rest.
- Choose the valves, probes, triggers and glycol coordination that finish a twelve-day batch on time and in specification.

Prerequisites Sections 1.3 (loop action), 1.4.3 (growth and heat), 1.4.5 (late samples and the bias update) and 1.4.6 (one-way actuators), with Sections 1.6.2 and 1.6.4 on the PID and the scenarios.

The app https://apmonitor.com/apps/brewery-fermentation/

See also Volume 8, Chapter 2 for an exothermic batch under jacket cooling, Volume 8, Chapter 12 for thermostats on a shared refrigeration plant and Volume 8, Chapter 5 for a batch ended on an endpoint. Volume 5, Chapter 10 for a soft sensor corrected by a late laboratory and Volume 5, Chapter 4 for a process steered ahead of its analyzer.

10.1 Introduction

A lager cellar is a set of batch reactors whose heat of reaction arrives on the yeast's schedule rather than the operator's. The tank of this chapter holds 3000 hL of a 12 °P wort that is held at 11 °C through the fermentation, allowed to warm itself to 14 °C for a diacetyl rest, crashed to −1 °C and matured, all inside a twelve-day plan. The temperature program of such a batch has been posed as an optimal control problem with the cooling duty as the single available control, and its solution is bang-bang with a singular arc at the maximum permitted temperature [1]. The rest is often the step the schedule waits for, since lowering the diacetyl of green beer is an expensive and time-consuming part of lager brewing whose rate is usually limited by the spontaneous decarboxylation of a precursor [2].

Four features make the plant hard to control, and none of them appears in a transfer function from valve to thermometer. The heat grows with the yeast and with the temperature, so a tank whose valves stay shut warms only 0.56 °C in its first day and then runs away, to 13.61 °C at 48 h and 21.33 °C on day 5.3. The only actuators are solenoid valves, and a controller that wants a fraction of the cooling has to obtain it in time rather than in position. The tank holds 300 m^3 in three zones, and it is mixed only while the yeast release carbon dioxide (CO_2), with about 330 m^3/h of exchange between zones at the day-two peak against 3 m^3/h of free convection once the gas stops. The measurements that decide each phase are late or partial, an hourly density reading from one sample valve and a diacetyl result a day old, and the glycol comes from a plant that the tank shares with the rest of the cellar.

The misconception this simulator targets is that a batch is kept on its recipe by the tuning of its temperature loops. On the same valves a PI controller with a time-proportioned output holds the primary fermentation between 10.97 and 11.04 °C while a thermostat swings from 10.66 to 11.27 °C, yet the graded batch is decided elsewhere. Shipped with hysteresis valves, one mid-height probe, a free rise timed for day 6, a rest of fixed length and no glycol coordinator, it is crashed on day 12.57 with its unprobed cone 2.73 °C off the recipe. With time-proportioned valves, a probe per zone, a free rise triggered by the density meter, a rest ended on a corrected estimate and the coordinator, it is crashed on day 10.47 with every zone within 0.52 °C. The loop gains are the same in both runs. Hysteresis valves with a probe in every zone hold the zones as closely, but their full openings during

the rest take the shared glycol plant 39.4 kW over its capacity when a neighboring tank starts its crash.

The class of problem is general. It is a batch process with a slow exotherm and a discrete actuator, whose phase changes are decided on measurements that arrive late or see part of the vessel. Jacketed batch reactors with dead time, jacket dynamics and measurable load disturbances share its regulatory part [3], and the exothermic semi-batch reactor of Volume 8, Chapter 2 is one whose heat must likewise be removed when the reaction releases it. A relay in a feedback loop drives a limit cycle whose period and amplitude are set by the process [4], and a phase ended on a result a day old is the problem that soft sensors and inferential control address across the process industries [5], with state estimation already demonstrated on batch beverage fermentation [6]. Wine fermentation shares the failure of a batch that stops before its sugar is gone, described as one of the most challenging problems of wine production and troublesome to diagnose [7], and a refrigeration plant that serves many loads in a brewery is a design and load-management problem of its own [8].

However, process control texts treat on/off control, feedback tuning and inferential measurement as separate topics [9], and the brewing literature treats the temperature profile as an optimization [1] and the kinetics as a model [10]. In neither literature can a thermometer on target, a laboratory a day late and a supply shared with other tanks be set against what the beer actually does. This chapter measures what decides a lager batch, on a browser fermenter that logs every zone's true temperature, gravity, diacetyl and yeast apart from what the probes, the density meter, the laboratory and the estimator report. The kinetics, the time-proportioned output, the bias update and the supervisory rules are established methods, and the chapter works with them through measured comparisons on one plant, among them the concave heat characteristic of the modeled time-proportioned jacket. The eight cases and the graded batch are arranged to separate an actuator command from a heat flow, a probe from a tank, a laboratory from an estimator, and a tank from the plant it shares.

Section 10.2 follows the domain from mechanical refrigeration to kinetic models. Section 10.3 sets out the tank as a 38-state model whose extract, ethanol, CO_2, yeast and energy ledgers close to within 3×10^{-11}, in the detail needed to rebuild it. Section 10.4 describes the zone loops, a time-proportioned output that carries its rounding and minimum-time errors so that the mean opening equals the duty, the glycol coordinator, and a supervisor that declares a stuck fermentation or a late crash from its own measurements. Section 10.5 reports the eight cases and the graded batch, Section 10.6 names the devices and the controller platform of a real cellar, Section 10.7 states the limits of the model, Section 10.8 draws the lessons together, and the exercises of Section 10.9 work through the cases.

10.2 Refrigeration, Fermenting Vessels and Diacetyl

A lager brewery is a refrigeration plant as much as a fermentation plant, and its refrigeration has a record of its own.

> ⧖ HISTORY **Refrigeration Comes to the Brewery (1912 to 1989)**
>
> Mechanical refrigeration as applied to the brewing industry was already the subject of a 39-page paper in the Journal of the Institute of Brewing in 1912 [11]. The design and operation of a brewery's refrigeration plant were later studied by simulating its components against real load variations, and design optimization, a better operating strategy and load management together cut primary fuel use by an ideal 15 % and a practical 10 % [8]. In the tank simulated here the glycol plant carries the whole heat of the batch, and the glycol coordinator is a small instance of that load management.

Practice in the vessel changed as well. A system for fermenting and then maturing lager, the Nathan system, was described to the Institute of Brewing in 1930, when an English brewery was already working on it [12]. The tank modeled here is a closed vessel of the tall cylindroconical kind, with a cone at the bottom where the yeast settles and a jacket zone on each part of its wall. Its interior is not at one temperature. The temperature and velocity fields inside an industrial cylindroconical

fermenting tank of 30 m^3 have been measured with a grid of 43 resistance thermometers and an ultrasound Doppler technique in order to determine the convective flow that carries its heat [13], and a thermowell reports only the liquid around it.

Diacetyl, which the warm rest of the recipe removes, was studied in brewing long before it was modeled.

> ⧖ HISTORY **Diacetyl Becomes a Brewing Problem (1957 to 2013)**
>
> The formation and prevention of diacetyl in beer were under study in 1957 [14]. A review in 1973 found that an excess of diacetyl is a flavor defect in every type of beer, that diacetyl and 2,3-pentanedione form in every brewery fermentation, that much of the trouble comes from the precursor acetolactic acid, which gives rise to diacetyl in the finished beer, and that the yeast strain, the condition of the pitching yeast, the wort and the management of the fermentation all affect what remains [15]. The current account adds that the removal is typically rate-limited by the spontaneous decarboxylation of α-acetolactate to diacetyl, which the yeast then take up with their reductases [2]. A warm rest therefore precedes the crash in the recipe simulated here, and its end is decided on a measurement.

Models followed the practice. Balling's relations among original extract, real and apparent extract and alcohol, on which every gravity reading of this simulator depends, were re-examined against 532 commercial and pilot brews in 2009 [16]. A kinetic model extended with temperature effects turned the temperature program into an optimal control problem in 1988 [1], optimal regulatory control of jacket-cooled fermentation reactors followed in 1991 [3], and in 1996 an extended Kalman filter with recursive parameter identification tracked batch beverage fermentations, simulated and real, well enough despite an imperfect model [6]. The kinetic structure of this simulator follows a model for beer production under industrial operational conditions [10], with constants chosen for teaching. The failure of case 8 has a literature of its own in wine, where the causes of stuck and sluggish fermentations are numerous and difficult to rectify [7]. This simulator gathers the pieces into one tank, with a record that no cellar keeps, the true state of every zone beside what each instrument reported.

10.3 The Tank as Modeled

The simulated tank holds 300 m^3 of wort in a 5.0 m cylinder on a cone, divided into a top and a middle zone of 130 m^3 each and a cone zone of 40 m^3. Each zone has its own jacket, glycol valve and thermowell, the middle zone carries the sample valve of the density meter and the laboratory, and the glycol comes from a plant shared with other tanks, as shown in Figure 10.1.

Table 10.1 classifies the variables by role, as controlled (CV), manipulated (MV) and disturbance (DV) variables, parameters and states. Each zone carries seven states and each jacket one, and with the plant's averaged load, the settled yeast and twelve cumulative ledgers of extract fermented, yeast grown, CO_2, heat released, the heat each jacket removed, the ambient gain, the heat returned to the glycol and each valve's open time, the state vector has 38 entries. Because the ledgers advance with the same integrator as the plant, each balance is checked from the state vector alone. Time is in hours, temperatures in °C, species in kg/m^3, yeast in Mcells/mL (million cells per milliliter), vicinal diketones (VDK) in mg/L, heat in kW and flows in m^3/h and kg/s.

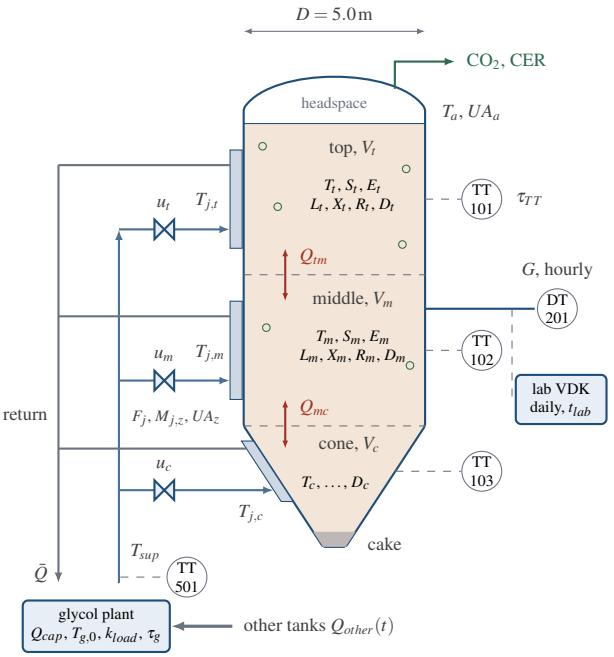


Figure 10.1 Lager fermenter as modeled. The top, middle and cone zones, of volumes V_t, V_m and V_c, each carry a temperature T, fermentable extract S, ethanol E, lag-phase yeast L, active yeast in suspension X, growth reserve R and total vicinal diketones D, and exchange liquid at Q_{tm} and Q_{mc}. Each jacket holds glycol at $T_{j,z}$ behind an on/off valve u_z that passes F_j from a supply at T_{sup} (TT-501), fed by a plant of capacity Q_{cap} whose averaged load $\bar{Q}$ includes the other tanks' $Q_{other}(t)$. Probes TT-101 to TT-103 lag by τ_{TT}, DT-201 reads the gravity G at the middle zone every hour, and the laboratory reports a daily sample from the same valve t_{lab} after it is drawn. Settled yeast collects as the cake and CO_2 leaves at its evolution rate CER. Not to scale.

Table 10.1 Variables of the Tank by Role, With Their Values at Knock-Out

Variable	Role	Knock-out	Range
T_t, T_m, T_c	CVs, TT-101 to TT-103	11.0 °C	−1.5 to 21.3
T_{SP}	setpoint, supervisor	11.0 °C	−1 to 14
G	measured, DT-201	12.0 °P	2.10 to 12.0
D_{lab}, $\hat{D}_c$	laboratory, estimate	0 mg/L	0 to 0.93
u_t, u_m, u_c	MVs, valve duties	0 %	0–100
Q_{other}	DV, metered	300 kW	0–600
ℓ	DV, capacity lost	0 %	0–100
β_G	DV, meter bias, unmeasured	0 °P	±1
T_a	DV, ambient	15 °C	−10 to 35
valve fault	DV, event	none	shut or open
ΔQ_n, τ_n	DV, event, neighbor crash	220 kW, 30 h	—
v	parameter, unmeasured	95 %	5–100
T_z, S_z, E_z	states, per zone	11, 86.8, 0	see text
L_z, X_z, R_z, D_z	states, per zone	14.25, 0, 44, 0	see text
$T_{j,z}$	states, jackets	11.0 °C	−4 to 14
$\bar{Q}$, C_k	states, plant load, cake	300 kW, 0	—
12 ledgers	states	0	—

S_z, E_z in kg/m^3, L_z, X_z, R_z in Mcells/mL, D_z in mg/L.

10.3.1 Kinetics in Each Zone

Lag-phase yeast activates, active yeast grows on a reserve of new growth that the wort's oxygen and the yeast's sterols can support, and active yeast ferments the extract, as shown in Equation (10.1).

$$\begin{aligned} r_a &= k_L\, a(T)\, L, \qquad r_g = \mu_{11}\, a(T)\, X\, \frac{S}{K_x + S}\, \frac{R}{2 + R} \\ r_S &= q_s\, a(T)\, X\, \frac{S}{K_s + S}\, \max\left(0,\, 1 - \frac{E}{E_{max}}\right) \\ r_D &= f_D\, k_D\, r_g - f_R\, k_R\, a_D(T)\, X\, D \end{aligned} \tag{10.1}$$

where r_a and r_g are the activation and growth rates in Mcells/mL/h, r_S is the extract fermented in kg/(m^3 h), r_D is the net VDK rate in mg/(L h), the reserve's half-saturation is fixed at 2 Mcells/mL, every concentration is taken as zero if negative, and f_D and f_R are the strain's factors on the textbook formation and reduction constants. The zone balances are Equation (10.2).

$$\begin{aligned} \frac{\mathrm{d}S_z}{\mathrm{d}t} &= -r_S + \mathscr{M}_z[S], \qquad \frac{\mathrm{d}E_z}{\mathrm{d}t} = Y_E\, r_S + \mathscr{M}_z[E] \\ \frac{\mathrm{d}L_z}{\mathrm{d}t} &= -r_a - k_{s,z} L_z + \frac{V_{z^-}}{V_z} k_{s,z^-} L_{z^-} + \mathscr{M}_z[L] \\ \frac{\mathrm{d}X_z}{\mathrm{d}t} &= r_a + r_g - k_{s,z} X_z + \frac{V_{z^-}}{V_z} k_{s,z^-} X_{z^-} + \mathscr{M}_z[X] \\ \frac{\mathrm{d}R_z}{\mathrm{d}t} &= -r_g + \mathscr{M}_z[R], \qquad \frac{\mathrm{d}D_z}{\mathrm{d}t} = r_D + \mathscr{M}_z[D] \\ \frac{\mathrm{d}C_k}{\mathrm{d}t} &= k_{s,c}\,(X_c + L_c)\,\frac{V_c}{V_T} \end{aligned} \tag{10.2}$$

where the rates are evaluated in zone z, z^- is the zone above it (settling enters the middle zone from the top and the cone from the middle), C_k is the cake expressed over the tank volume $V_T = 300\,\mathrm{m}^3$, and the exchange with the neighbors is

$$\mathscr{M}_z[\psi] = \frac{1}{V_z} \sum_n Q_{zn}\,(\psi_n - \psi_z) \tag{10.3}$$

over the one or two neighbors n of zone z. Ethanol and CO_2 follow the Balling split, in which 2.0665 kg of extract make 1 kg of ethanol, 0.9565 kg of CO_2 and 0.11 kg of yeast and by-products, so $Y_E = 0.484$ and $Y_C = 0.463$, and the tank's CO_2 evolution is $\mathrm{CER} = Y_C \sum_z r_{S,z} V_z$ in kg/h.

10.3.2 Temperature, Settling and Exchange

The yeast's activity is a double Arrhenius law, growth against thermal deactivation, normalized to one at $T_r = 11\,^\circ\mathrm{C}$, and VDK reduction has a single activation energy of its own, as shown in Equation (10.4).

$$\begin{aligned} a(T) &= \max\left(0,\, \frac{\phi_1(T) - \delta\,\phi_2(T)}{1 - \delta}\right), \qquad a_D(T) = \phi_D(T) \\ \phi_i(T) &= \exp\left[-\frac{E_i}{R_g}\left(\frac{1}{T} - \frac{1}{T_r}\right)\right], \quad \delta = \frac{E_1}{E_2}\,\frac{\phi_1(T_{opt})}{\phi_2(T_{opt})} \end{aligned} \tag{10.4}$$

with temperatures in kelvin, R_g the gas constant, $E_1 = 60\,\mathrm{kJ/mol}$, $E_2 = 250\,\mathrm{kJ/mol}$, $E_D = 110\,\mathrm{kJ/mol}$ and $T_{opt} = 30\,^\circ\mathrm{C}$, where δ makes a largest at T_{opt}. The activity is 1.30 at 14 °C, 3.74 at 30 °C and zero at 40 °C, and a_D is 1.63 at the 14 °C rest and 0.128 at −1 °C. Suspended yeast settles faster when cold, when the sugar is gone and when the gas stops stirring, and neighbors exchange liquid at a rate

that rises with the CO_2 and with a density inversion, as shown in Equation (10.5).

$$\begin{aligned} k_s &= \frac{k_{set}\,\mathrm{e}^{-\theta_s(T-11)}\,K_f}{(K_f+S)\,(1+\mathrm{CER}/C_{ref})} \\ Q &= Q_{free}+k_c\,\mathrm{CER}+k_b\left[\rho(T_{up})-\rho(T_{low})\right]^+ \\ \rho(T)-\rho_{max} &= -0.007\,(T-4)^2 \end{aligned} \tag{10.5}$$

where T is in °C, ρ in kg/m^3, $[x]^+ = \max(0,x)$, and T_{up} and T_{low} are the zones above and below a boundary. The density maximum at 4 °C is water's, an illustrative stand-in for beer's, so below 4 °C the colder liquid is the lighter. The settling rate is 0.015 h^{-1} at 11 °C without sugar or gas and 0.30 h^{-1} at −1 °C, and the exchange is 3 m^3/h in a still tank, 333 at 110 kg/h of CO_2 and 150 across a boundary with 1 °C over 0 °C.

10.3.3 Heat, Jackets and the Shared Plant

Each zone gains the heat of fermentation and the ambient gain and loses heat to its jacket, as shown in Equation (10.6).

$$\begin{aligned} \rho c_p V_z \frac{\mathrm{d}T_z}{\mathrm{d}t} = 3600\Big[&q_{f,z}-UA_z\,(T_z-T_{j,z}) \\ &+UA_a\frac{V_z}{V_T}\,(T_a-T_z)\Big]+\rho c_p V_z\,\mathscr{M}_z[T] \end{aligned} \tag{10.6}$$

where $\rho c_p = 4100\,\mathrm{kJ/(m^3\,K)}$, the heat terms are in kW, the factor 3600 converts them to kJ/h, $q_{f,z} = q_f\,r_{S,z}V_z/3600$ is the heat released in the zone, and $q_f = 500\,\mathrm{kJ/kg}$ is the declared heat of fermentation. The tank holds 1.23 GJ/K. Each jacket is a glycol holdup mixed at its outlet temperature, as shown in Equation (10.7).

$$M_{j,z}c_g\frac{\mathrm{d}T_{j,z}}{\mathrm{d}t} = 3600\left[u_z F_j c_g\,(T_{sup}-T_{j,z})+UA_z\,(T_z-T_{j,z})\right] \tag{10.7}$$

where u_z is 0 or 1 for an on/off valve and the position for a modulating one, $c_g = 3.6\,\mathrm{kJ/(kg\,K)}$ for 35 % propylene glycol, $F_j = 2.5\,\mathrm{kg/s}$, and the holdup is $M_j = 600\,\mathrm{kg}$ for each cylinder jacket and $M_j UA_c/UA_t = 369\,\mathrm{kg}$ for the cone. A shut valve keeps cooling until the holdup has warmed to the beer, with a time constant of 5.5 min, and an open one settles in 2.3 min (1.7 min for the cone) at $q = UA_{eff}(T-T_{sup})$, with $UA_{eff} = UA\,F_j c_g/(UA+F_j c_g)$ of 3.77, 3.77 and 2.77 kW/K. With every valve open, beer at 11 °C and glycol at −4 °C, the jackets remove 155 kW. The plant is shared, and its buffer averages the loads it is sent, as shown in Equation (10.8).

$$\begin{aligned} \tau_g\frac{\mathrm{d}\bar{Q}}{\mathrm{d}t} &= Q_{other}(t)+\sum_z u_z F_j c_g\,(T_{j,z}-T_{sup})-\bar{Q} \\ T_{sup} &= T_{g,0}+k_{load}\,\max\left(0,\ \bar{Q}-(1-\ell)Q_{cap}\right) \\ Q_{other}(t) &= Q_{base}+\Delta Q_n\,\mathrm{e}^{-(t-t_n)/\tau_n},\quad t\ge t_n \end{aligned} \tag{10.8}$$

where $\tau_g = 0.5\,\mathrm{h}$, $T_{g,0} = -4\,°\mathrm{C}$, $Q_{cap} = 500\,\mathrm{kW}$, $k_{load} = 0.03\,\mathrm{K/kW}$, ℓ is the share of capacity lost, Q_{base} is the other tanks' base load and a neighbor that starts crashing at t_n adds ΔQ_n decaying over τ_n (220 kW over 30 h for the event in the interface).

10.3.4 Gravity, Alcohol and Freezing

The fermentable extract at knock-out is $S_0 = \varphi\,\varepsilon(\mathrm{OE})$, with $\varepsilon(P) = 10P\,\mathrm{sg}(P)$ in kg/m^3 and $\mathrm{sg}(P) = 1+P/(258.6-227.1P/258.2)$, which for a 12 °P wort and $\varphi = 0.69$ is 86.8 kg/m^3, 26.04 t in the

Table 10.2 Parameters of the Tank. V Marks a Slider of the Show Model Dialog, H a Value Kept From It, and F a Constant of the Code

Symbol	Meaning	Value	Class
OE, φ	original extract, fermentable share	12 °P, 0.69	V
G_f	target apparent extract	2.6 °P	V
R_{O_2}	growth the wort's oxygen supports	44 Mcells/mL	V
X_0, v	pitch rate, viability	15 Mcells/mL, 95 %	V
T_0	pitching temperature	11 °C	V
k_L, μ_{11}	activation and growth at 11 °C	0.05, 0.052 h^{-1}	V
K_x	extract half-saturation of growth	4 kg/m^3	H
n_{gen}	doublings of a viable cell	3	V
q_s	uptake per cell at 11 °C	0.0165[a]	V
K_s	extract half-saturation of uptake	8 kg/m^3	V
E_{max}	ethanol that stops uptake	120 kg/m^3	H
k_D	VDK formed per cell grown	0.021[b]	V
k_R	VDK reduction per cell at 11 °C	0.00026[c]	V
f_D, f_R	strain factors, estimator assumes 1	1.15, 0.8	V
E_1, E_2, E_D	activation energies	60, 250, 110 kJ/mol	F
k_{set}	settling, 11 °C, no sugar or gas	0.015 h^{-1}	V
θ_s	settling increase per kelvin colder	0.25 K^{-1}	V
K_f, C_{ref}	sugar and CO_2 that halve settling	6[d], 15 kg/h	H
Q_{free}	free-convection exchange	3 m^3/h	V
k_c, k_b	exchange per CO_2, per inversion	3, 3000[e]	V
q_f	heat per kg of extract fermented	500 kJ/kg	F
ρc_p, c_g	heat capacities, beer and glycol	4100, 3.6[f]	F
UA_t, UA_m, UA_c	jacket conductances	6.5, 6.5, 4.0 kW/K	V
F_j, M_j	open-valve flow, cylinder holdup	2.5 kg/s, 600 kg	V
$T_{g,0}$, Q_{cap}	supply in capacity, plant capacity	–4 °C, 500 kW	V
k_{load}	supply warming per kW over	0.03 K/kW	V
τ_g, UA_a	plant buffer lag, ambient gain	0.5 h, 0.5 kW/K	H
τ_{TT}, t_{lab}	probe lag, laboratory turnaround	10 min, 24 h	V
t_{plan}	plan from knock-out to finish	12 days	V
V_t, V_m, V_c	zone volumes	130, 130, 40 m^3	F

[a] kg/(m^3 h) per Mcells/mL. [b] mg/L per Mcells/mL. [c] h^{-1} per Mcells/mL. [d] kg/m^3.
[e] m^3/h per kg/h and per kg/m^3. [f] kJ/(m^3 K), kJ/(kg K).

tank. The gauge reads degrees Plato through Balling's relations [16], as shown in Equation (10.9).

$$
\begin{aligned}
f &= \frac{\mathrm{OE}\,(S_0 - \bar{S})}{\varepsilon(\mathrm{OE})}, & w &= 100 - \frac{1.0665\,f}{2.0665} \\
n &= \frac{100\,(\mathrm{OE} - f)}{w}, & A &= \frac{100\,f}{2.0665\,w} \\
G &= \frac{n - 0.1808\,\mathrm{OE}}{0.8192}
\end{aligned}
\tag{10.9}
$$

where $\bar{S}$ is the volume-weighted mean extract, f the extract fermented in °P, n the real extract, A the alcohol by mass and G the apparent extract. Alcohol by volume is $A\,\mathrm{sg}(G)/0.7907$, and the beer's freezing point, used only to flag ice, is an illustrative $-0.42A - 0.04n$ in °C. The target of 2.6 °P is reached when 95.1 % of the fermentable extract is gone, and complete fermentation would leave 2.10 °P with the freezing point at –1.91 °C.

10.3.5 Knock-Out, Mid-Batch Starts and the Integrator

Table 10.2 gives the parameter values. A batch starts at knock-out with every zone and jacket at T_0, $S = S_0$, $E = 0$, the viable pitch $X_0 v/100 = 14.25\,\mathrm{Mcells/mL}$ as lag-phase yeast, $X = 0$, the reserve $R_0 = \min\left(R_{O_2}, X_0 v(2^{n_{gen}} - 1)/100\right) = 44\,\mathrm{Mcells/mL}$, $D = 0$, $\bar{Q}$ equal to the other tanks' load and the ledgers at zero. The wort, the pitch, n_{gen} and t_{lab} are read when a batch starts, so a change takes effect before the run or after a Reset, and the gauge keeps the knock-out OE. Cases 5 to 7 start part-way through a batch. Their history from knock-out is integrated first with every zone held exactly

on the recipe temperature, using a 3 min midpoint step on the kinetics, the free rise at its trigger, the rest ended when the true VDK is below 0.10 mg/L and the true gravity at its target, and a laboratory sample recorded at each whole day. At hand-over each jacket is set to remove its zone's heat of fermentation and ambient gain q_z, with $T_{j,z} = T_{SP} - q_z/UA_z$ and nothing removed during a free rise, and the controller replays the estimator from knock-out on the history's temperatures, passes the results already reported through its bias update and queues those still at the laboratory.

The engine of Section 1.6.1 integrates the plant on a fixed 30 s step, the controllers execute once a minute, the historian records every 5 min, and the default seed is 20261102. The speed selector spans 0.25 to 12 simulated hours per second, one by default, so a twelve-day batch takes 24 s at the top speed, and the trend windows are 12, 48, 168 and 336 h. Halving the step leaves the crash completion of case 3 on the same control step and moves its finishing VDK by 2.1×10^{-5} mg/L and its worst recipe deviation by 0.0011 °C. Over 280 h of each of the nine scenarios the ledgers close to 2.8×10^{-14} relative in case 3 and to 2.9×10^{-11} at worst, and the heat released in case 3, 13.01 GJ from 26.03 t of extract, is the declared 0.5 MJ/kg. The app's own checks require closure below 1×10^{-9}.

10.3.6 Assumptions

The liquid is three well-mixed zones with exchange across two boundaries, while a real tank has continuous temperature and velocity fields set by convection [13]. The zones keep the one fact the lessons need, that the tank is stirred while the yeast are busy and stratifies when they are not, and they fail for the position of a probe within a zone.

The kinetic constants are illustrative, calibrated so that a 12 °P wort held at 11 °C reaches 2.6 °P in about seven days (on day 6.95 in the engine), and are not fitted to a strain. Growth has one oxygen and sterol reserve, and flocculation is an empirical rate. Total VDK is one state formed with growth and reduced by suspended yeast, so the precursor's spontaneous conversion outside the cell, which usually limits the real removal [2], is lumped into one rate with a high activation energy, and the laboratory is assumed to measure that total. The model therefore cannot show diacetyl rising again after a crash from precursor left in the beer.

The heat of fermentation is the declared 0.5 MJ/kg, the heat capacity, density and volume are constant although about 4 % of the mass leaves as CO_2, and the density maximum is water's. Each jacket is one well-mixed holdup behind a valve with no stroke time. The glycol plant is a capacity and a buffer whose supply temperature is an algebraic function of the averaged load above capacity, so the tripped plant of case 4 settles near 6.5 °C instead of warming for as long as the trip lasts, and the other tanks are a load profile that does not respond to the supply temperature. The density meter reads one valve and the laboratory one sample a day, and neither drifts except through the bias disturbance. Ice is flagged below the freezing point and not modeled, and pH, pressure, temperature shock and yeast health beyond viability are outside the model. Every size, capacity and limit was chosen for teaching and is not a design basis.

10.4 Implemented Control System

Three zone loops, TIC-101 to TIC-103, a glycol coordinator, a recipe supervisor and a VDK estimator run every $\Delta t_c = 1$ min, two physics steps, at 1, 2, 3 minutes and so on after a priming execution at $t = 0$, in the order of Figure 1.10. After the integrator advances, the app's own bookkeeping of ice, plant capacity and recipe deviation runs before the outputs and the historian are updated. No part of the controller reads a zone's contents.

10.4.1 Instruments

Each thermowell probe lags its zone's true temperature to first order with $\tau_{TT} = 10$ min, adds first-order colored noise of 0.02 °C standard deviation and 3 min correlation time, and is read to 0.01 °C. With the one-probe option only TT-102 is installed. The density meter DT-201 samples the middle zone every hour through a sample line of 3 min dead time, reports 3 min later with 0.05 °P of noise,

and adds a bubble spike of ±0.6 °P with probability 0.01 per report and any calibration bias. A reading more than 0.4 °P from the last accepted one is rejected unless three in a row fall on the same side, and a reading that repeats exactly or is overdue by three cycles is stale. Over the batch of case 3, to the completion of its crash, the meter reports 250 times, one report carries a spike, and the gate rejects it. The laboratory analyzes a sample from the same valve at every whole day of batch age from day 1 and reports it $t_{lab} = 24\,\text{h}$ later with 0.01 mg/L of noise. The meter and the laboratory are instances of the framework's shared sampled analyzer, and the estimator's correction is the framework's shared bias update, the logarithmic form of Equation (1.8). TT-501 reads the supply through a 3 min lag, and the glycol meters report this tank's return heat through a 10 min filter and the other tanks' through 5 min.

10.4.2 Zone Loops and the Time-Proportioned Output

All three loops run the velocity-form PID law of Section 1.6.2, written for these loops in Equation (10.10), where s_k is the running sum S_k of Equation (1.13) and d_k the limited output u_k.

$$\begin{aligned} e_k &= \gamma(\text{SP}_k - \text{PV}_k), \qquad P_k = K_c\, e_k \\ s_k &= s_{k-1} + (P_k - P_{k-1}), \qquad v_k = s_k + I_{k-1} \\ d_k &= \text{clamp}(v_k,\, 0,\, 100) \\ I_k &= I_{k-1} + \left[\frac{K_c}{\tau_I}\, e_k + \frac{d_k - v_k}{\tau_I}\right]\Delta t_c \end{aligned} \tag{10.10}$$

where $\gamma = -1$ because the valve must open as the zone warms, so that a zone warmer than its setpoint raises its duty d_k in percent. The loops are therefore direct acting in the convention of Section 1.3, since more glycol lowers the temperature. The app's source and its own checks use the same name. The output bias is zero and the loops have no derivative action, so s_k is P_k. The integral is protected by back-calculation with τ_I as the tracking time, the duty has no rate limit, and in MANUAL the integral tracks the operator's duty d_{op}, all as in Section 1.6.2. The shipped tunings are $K_c = 150\,\%$ per °C with $\tau_I = 8\,\text{h}$ for the top and middle loops and $K_c = 60\,\%$ per °C with $\tau_I = 8\,\text{h}$ for the cone, from sliders of 0 to 400 and 0.5 to 48 h.

The duty becomes an on-time. At the start of every cycle of $N = 10$ ticks of 1 min, the latched duty $d \in [0, 1]$ sets the number of open ticks, as shown in Equation (10.11).

$$n_{on} = \text{round}(dN + c), \qquad c \leftarrow dN + c - n_{on} \tag{10.11}$$

where the carry c holds the rounding error and any correction the 2 min minimum on and off times impose. An on-time of one tick becomes zero or two, whichever is nearer to the demand, one of nine ticks becomes eight, and a duty of 0 or 1 shuts or opens the valve for the whole cycle and clears the carry. The three outputs are staggered by 0, 3 and 7 min so that the valves do not open together. Over 200 cycles the mean opening equals duties of 3, 37 and 97 % exactly, where the app's own check asks for 0.002. In the hysteresis mode each valve opens when its probe reads above $\text{SP} + d_b/2$ and shuts below $\text{SP} - d_b/2$, with $d_b = 0.5\,^\circ\text{C}$, and the PI tracks the relay. In the modulating mode the valve is positioned at $u = d/100$. With one mid probe, TIC-102 computes the duty for all three valves and the other two loops track it.

10.4.3 Glycol Coordinator

The coordinator acts only from the start of the crash to the end of the batch. It takes as this tank's allotment the plant's capacity less the other tanks' metered load and a reserve, $A = \max\big(0,\, (1 - \ell)Q_{cap} - \hat{Q}_{other} - Q_{res}\big)$ with $Q_{res} = 20\,\text{kW}$, and integrates a scale factor κ on every duty from this tank's metered draw $\hat{Q}_{tank}$, as shown in Equation (10.12).

$$\kappa \leftarrow \text{clamp}\Big(\kappa + \frac{A - \hat{Q}_{tank}}{\max(20, A)}\,\frac{\Delta t_c}{0.25\,\text{h}},\; 0,\; 1\Big) \tag{10.12}$$

Table 10.3 Recipe Supervisor. Every Transition Is Decided on a Measurement or the Batch Clock

Phase	Setpoint	Ends when
primary	$T_{pri} = 11\,^{\circ}\mathrm{C}$	by the chosen trigger, DT-201 reads $G_{rise} = 6.0\,^{\circ}\mathrm{P}$, or day $d_{rise} = 6$ arrives
free rise	$+r_{rise} = 0.07\,^{\circ}\mathrm{C/h}$	the setpoint reaches $T_{rest} = 14\,^{\circ}\mathrm{C}$
rest	T_{rest}	by the chosen rule, $\hat{D}_c < D_{lim} = 0.10\,\mathrm{mg/L}$, or a laboratory result below D_{lim} for a sample drawn in the rest, each with DT-201 at or below G_f, or $t_{rest} = 48\,\mathrm{h}$ have passed
crash	$-r_{crash} = 0.3\,^{\circ}\mathrm{C/h}$ to $T_{crash} = -1\,^{\circ}\mathrm{C}$, waiting while a probe is 0.5 K behind, the coordinator limits, or TT-501 is above $T_{crash} - 1\,\mathrm{K}$	the setpoint is at T_{crash} and every probe at or below $T_{crash} + 0.5\,\mathrm{K}$
maturation	T_{crash}	$t_{mat} = 24\,\mathrm{h}$ have passed
held	$+r_{rise}$ to $\max(T_{pri}, T_{rest})$	the operator decides

It feeds back on the meter rather than on a jacket model, because a time-proportioned jacket removes more heat than its duty suggests (Section 10.5.2). Hysteresis valves cannot be scaled, so the warmest zones are opened first while $\lfloor 3\kappa \rfloor$ remain. The cooling of the fermentation itself is never cut.

10.4.4 Recipe Supervisor

The supervisor publishes the setpoint of all three loops and moves through the phases of Table 10.3. The free rise has no heater behind it, so a zone keeps pace with the rising setpoint only while the fermentation releases enough heat. From day 3, once DT-201 has twelve accepted hourly readings and reads more than 0.1 °P above the target, the supervisor projects the finish from the measured trend, as shown in Equation (10.13).

$$t_{fin} = t + \frac{G_{DT} - G_f}{-\dot{G}\, a(T_{hi})/a(\bar{T})} + \frac{T_{rest} - T_{crash}}{r_{crash}} \tag{10.13}$$

where $\dot{G}$ is the least-squares slope of the last 24 accepted readings, $\bar{T}$ is the mean of the installed probes and $T_{hi} = \max(T_{pri}, T_{rest})$ is the warmest temperature the recipe permits. A projection beyond the plan declares the fermentation stuck and holds the batch. During the crash the supervisor projects the completion by cooling the tank as one lump from $\bar{T}$ to $T_{crash} + 0.5\,\mathrm{K}$ at $q = \min\left(A,\ \sum_z UA_{eff,z}(T - T_{sup})\right)$ in steps of 0.25 h, capped at 1000 h, and announces a late crash when the projection passes the plan, with 3 h of hysteresis. The ranges of the recipe sliders are 8 to 14 °C, 10 to 18 °C and −2 to 4 °C for the three temperatures, 0.02 to 0.3 °C/h for the rise and 0.05 to 1 °C/h for the crash, with 3 to 9 °P for the trigger gravity, day 2 to 10 for the timed rise, 12 to 120 h for the timed rest, 0 to 96 h for the maturation, 0.05 to 0.20 mg/L for the VDK limit, 2 to 30 min for the cycle, 0.1 to 2 °C for the deadband and 0 to 100 kW for the reserve.

10.4.5 VDK Estimator and Its Laboratory Correction

The estimator integrates Equation (10.1) for one well-mixed zone by explicit Euler at Δt_c, on the volume-weighted mean of the installed probes, from the declared pitch with an assumed viability of 95 % and the textbook factors $f_D = f_R = 1$, and records $\ln \hat{D}$ every hour. A laboratory result is compared with what the model said when its sample was drawn, a day before the result arrived, and the correction is an exponentially weighted average of the log ratio, as shown in Equation (10.14).

$$\begin{aligned} b &\leftarrow b + \lambda\left[\ln D_{lab} - \ln \hat{D}(t_s) - b\right], \qquad |b| \le 1.5 \\ \hat{D}_c(t) &= \hat{D}(t)\,\mathrm{e}^{b} \end{aligned} \tag{10.14}$$

where t_s is the sampling time, D_{lab} is floored at 0.005 mg/L, and $\lambda = 0.5$ by default on a slider from 0 to 1, with $\lambda = 0$ ignoring the laboratory. With a constant model error e the bias approaches it as $e[1 - (1 - \lambda)^k]$ after k results, which the app checks to 1×10^{-12}.

Table 10.4 The Eight Cases and the Graded Batch

#	Scenario and event	Teaching point
1	Manual, valves shut, from knock-out	the exotherm arrives
2	Hysteresis valves, $d_b = 0.5\,°C$	a limit cycle and its lags
3	Time-proportioned PI, 10 min cycle	on/off valves, no cycle
4	16 °P wort, plant trips 42 to 54 h	capacity at the peak
5	One mid probe, crash from day 7.95	a quiet tank stratifies
6	Laboratory-ended rest, from day 4.18	a result a day old
7	Crash, others at 478 kW of 500	a shared utility
8	Viability 15 %	honest infeasibility
9	Twelve days, neighbor crash on day 7	graded challenge

> ✦ DID YOU KNOW? **A Flavor Threshold Near the Limit**
>
> A review of beer aroma compounds puts the odor threshold of diacetyl at 0.1 to 0.2 mg/L in lagers and 0.1 to 0.4 mg/L in ales, and above it the beer smells and tastes spoiled [17]. The rest of this chapter's recipe ends below 0.10 mg/L, at the bottom of the lager range.

10.4.6 Plant, Loop Response and Controller Models

Everything in Section 10.3 belongs to the plant, including this strain's $f_D = 1.15$ and $f_R = 0.8$ and whatever viability the scenario sets. No control model is identified by the application, and open-loop steps in MANUAL measure the plant that a loop sees. From the state of case 3 at 36 h, with the duties held where the loops left them, a step of 10 % on the middle valve's duty cools the top, middle and cone zones by 0.142, 0.150 and 0.150 °C after 6 h, because 234 to 302 m^3/h of exchange mixes the tank over those hours. From the start of case 5, with the CO_2 gone and every duty at 50 %, the same step cools them by 0.027, 0.148 and 0.065 °C. The loop sees close to an integrator of 0.025 °C/h per 10 % of one jacket's duty while the tank is stirred, and a zone of its own once it is not. The controller's internal models are the estimator's kinetics with textbook constants and an assumed viability, the activity ratio and the lumped cooling curve in the supervisor's two projections, and the capacity and reserve in the coordinator's allotment. None of them contains the strain's own diacetyl constants or the mixing.

10.5 Cases and What They Measure

The eight cases and the graded batch appear in Table 10.4. Every case begins from the same reference settings, three probes on time-proportioned valves, the free rise at 6.0 °P on the density meter, the rest ended on the corrected estimate and the coordinator on, and each alters only what its row states. The engine supplied every number below, at the default seed and without the interface, stepped exactly as the page steps it, with each change made after the case is loaded and before it runs (Section 1.6.4), which gives the same run as the change carried through a Reset, and days count batch age from knock-out. The scorecard of each case run to the completion of its crash is collected in Table 10.5. Its worst deviation of 0.51 to 0.53 °C in most rows is set by the crash rules, which let a probed zone trail the ramp by 0.5 K before the ramp waits and complete the crash with every probe within 0.5 K of −1 °C.

> ✦ DID YOU KNOW? **Many More Strokes, the Same Batch**
>
> From the simulator: run to the completion of the crash, hysteresis valves in case 2 and the time-proportioned PI loops in case 3 finish on days 10.28 and 10.39, both at 2.10 °P, with 0.090 and 0.089 mg/L of VDK and the same worst deviation of 0.52 °C, while the valves switch 81 times against 2783 (Table 10.5).

Table 10.5 Scorecard of Each Case Run to the Completion of Its Crash. G and D Are the True Tank Values Then, and the Worst Deviation Is Any Zone From the Published Setpoint

Case and configuration	Day	G (°P)	D (mg/L)	Dev. (°C)	Over (kW, h)	Switches
2 hysteresis	10.28	2.10	0.090	0.52	0	81
3 time-proportioned	10.39	2.10	0.089	0.52	0	2783
3 modulating	10.39	2.10	0.089	0.51	0	—
3 one probe	10.21	2.10	0.090	1.38	0	2485
4 trip[a]	9.63	2.90	0.073	0.52	348.5, 12.0	3379
5 one probe	10.73	2.10	0.071	1.95	0	873
5 three probes	10.93	2.10	0.070	0.52	0	1199
6 laboratory	11.99	2.10	0.044	0.52	0	1417
6 estimate	10.37	2.10	0.089	0.53	0	1399
6 estimate, $\lambda = 0$	9.64	2.12	0.123	0.52	0	1331
6 rest of 48 h	10.95	2.10	0.069	0.52	0	1413
7 coordinator on	12.71	2.10	0.040	0.52	0	2129
7 coordinator off	11.11	2.10	0.067	0.51	70.9, 41.5	1225
8 viability 15 %[b]	held	4.72	—	1.41	0	—
3 at viability 45 %[c]	11.36	2.11	0.108	0.52	0	2789
3 at viability 75 %[c]	10.66	2.11	0.099	0.51	0	2787
9 as shipped	12.57	2.10	0.058	2.73	0	99
9 suggested	10.47	2.10	0.087	0.52	0	2825

[a] Target 3.5 °P, and the plant has no capacity during the trip. [b] G on day 12, deviation to day 12.5. [c] Viability set before the run. Cases 5 to 7 count switches from their start.

10.5.1 The Exotherm With the Valves Shut

Case 1 pitches 15 Mcells/mL of 95 % viable yeast into the 12 °P wort at 11 °C with all three valves shut, in MANUAL. The fermentation releases 5.7 kW at 12 h and 13.7 kW at 24 h, which against 1.23 GJ/K warms the tank only to 11.17 °C and 11.56 °C, and the first degree takes until 31.9 h. Then the heat compounds, because $a(T)$ is 1.30 times larger at 14 °C than at 11 °C. The beer is at 13.61 °C at 48 h and releasing 40.6 kW, against the 32.8 kW peak at 47 h of the same batch held at 11 °C, it is at 16.61 °C at 72 h with 44.8 kW, and it peaks at 21.33 °C at 127.2 h. At 72 h the hot tank is at 7.04 °P and the controlled one at 8.13 °P, and the supervisor, still publishing its recipe, starts the free rise on day 3.38 without being obeyed. Opening all three valves at 24 h cools the tank from 11.56 to 9.29 °C in 6 h and to 7.39 °C in 12 h, and fixed duties of 20, 20 and 10 % from knock-out overcool it to 8.35 °C at 24 h and 6.13 °C at 72 h. The jackets can remove far more than the yeast make, and the task is to open them for the right share of the time.

> **TRY IT IN THE APP** **1 · Manual Valves on Day One**
>
> Load the case and press run. All three valves stay shut. Watch the beer temperature on the Tank view: it barely moves for a day, warming only 0.56 °C, and then runs away, to 13.61 °C at 48 h, because warmer yeast work faster and release more heat.

10.5.2 A Thermostat, a Pulse Train and a Positioned Valve

Case 2 opens each valve above 11.25 °C and shuts it below 10.75 °C. Between days 1 and 3 the zones swing from 10.66 to 11.27 °C and the valves switch 29 times in 48 h, with about 8 h (7.4 to 9.4 h) between successive openings of a valve. The bottom of the swing lies 0.09 °C below the lower switch point, mainly because the probe reports the cooling 10 min late. The glycol left in the jacket after the valve shuts adds little, as the holdup runs below show. The cycle is the relay limit cycle, whose amplitude and period the plant sets [4]. A 0.2 °C deadband gives 10.80 to 11.12 °C with 62 switches and cycles of 3.3 to 4.7 h, and a 1.0 °C deadband gives 10.43 to 11.52 °C with 17 switches and cycles of 13.8 to 14.7 h. The holdup barely matters in a tank this large, since 150 or 1500 kg per jacket puts the bottom of the swing at 10.66 or 10.65 °C, while the probe lag does matter, with 10.70 to 11.25 °C

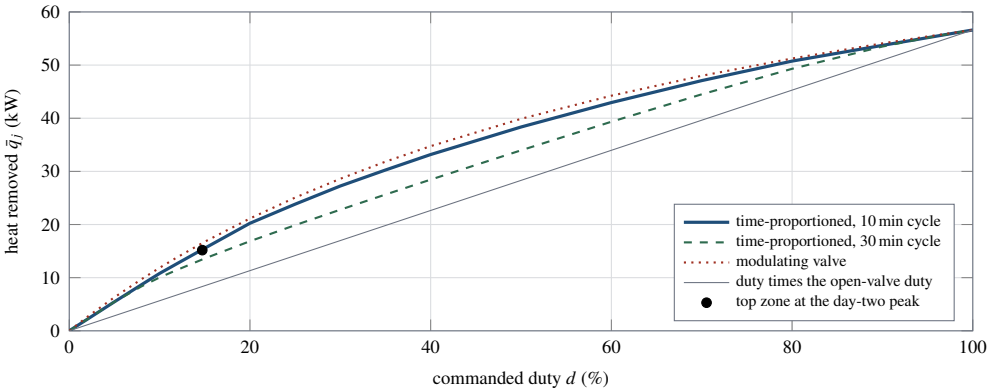


Figure 10.2 Heat removed by one cylinder jacket against its commanded duty, with the beer held at 11 °C and the glycol at −4 °C: the time-proportioned output on a 10 min cycle (thick solid line) and a 30 min cycle (dashed), the modulating valve (dotted) and the duty times the open-valve heat (thin solid). The curves come from the jacket equation and the application's own time-proportioned output averaged over 180 h, and the round marker is the engine's top zone at the day-two peak of case 3.

at 2 min and 10.55 to 11.29 °C at 30 min. These swings are read at the 30 s integration step, and the 5 min log agrees with them within 0.003 °C.

> **TRY IT IN THE APP** **2 · On/Off With Hysteresis**
>
> Run the case to day 3 and watch the zone temperatures on the trend. Each valve opens above 11.25 °C and shuts below 10.75 °C, and the zones swing from 10.66 to 11.27 °C with about 8 h between openings of a valve. Then load case 3, whose time-proportioned PI loops hold the same valves between 10.97 and 11.04 °C.

Case 3 drives the same valves from the PI loops through the ten-minute cycle. Between days 1 and 3 the zones stay between 10.97 and 11.04 °C, nearly nine times tighter, at 802 switches in 48 h against 29. A 30 min cycle gives 10.96 to 11.05 °C with 492 switches, a 5 min cycle 10.97 to 11.04 °C with 810, and a modulating valve 10.99 to 11.03 °C. The pulses are smoothed twice before they reach the beer, by the glycol held in the jacket and by the 1.23 GJ/K of the tank, so the cycle length barely matters to the temperature.

The duty is not a heat meter. At the day-two peak, between 44 and 50 h, the top valve is open 14.7 % of the time and its jacket removes 15.2 kW, 1.8 times the open share times the 56.7 kW that an open valve removes at steady state, because each pulse fills the jacket with glycol at the supply temperature that goes on cooling after the valve shuts. Figure 10.2 gives the whole characteristic for one cylinder jacket. It is concave, like a quick-opening valve, with a slope of about 1.1 kW per percent of duty near zero and 0.3 kW near full opening, and on the ten-minute cycle it follows the modulating valve within 1.6 kW. The loops therefore see an actuator gain that falls by more than three times between the primary fermentation, where they ask for 12 to 15 % at the peak, and the crash, where the top and middle valves stay fully open.

Pause. Try Exercise 10.1 before reading on.

10.5.3 Sizing for the Peak or for the Crash

Case 4 ferments a 16 °P wort pitched at 24 Mcells/mL with the oxygen for 65 Mcells/mL of growth and trips the glycol plant from 42 to 54 h. Without the trip its heat peaks at 49.2 kW at 43.9 h, against 32.8 kW for the 12 °P batch, while every open valve could remove 155 kW, and the loops never ask

for more than 32 % or let a zone past 11.05 °C. With the trip the supply warms to 5.8 °C within half an hour and to 6.46 °C before the restart, the capacity of the open jackets falls to 51 to 56 kW while the fermentation releases 50.0 kW at 44.9 h, the top and middle valves reach 100 % by 48.5 h, loops are saturated for 6.45 h in all, and the beer reaches 11.42 °C at the restart. The margin and the thermal mass carry the batch through twelve hours without a plant.

The jackets are sized for the crash. Cooling 300 m^3 from 14 to −1 °C removes 18.45 GJ, and over the batch of case 3 the jackets remove 31.03 GJ against the 13.01 GJ the fermentation releases. The crash ramp of 0.3 °C/h asks for 102.5 kW, and the open jackets can deliver that only while the beer is above about 5.9 °C. The ramp runs unhindered until day 8.63, then waits 21.3 h in all for the slowest zone, the top and middle valves stay at full duty for about 50 h, the two-hour average of the jackets' heat peaks at 111.7 kW on day 7.77, and the crash that started on day 7.42 is complete on day 10.39.

10.5.4 One Probe in a Quiet Tank

Case 5 starts on day 7.95 as the crash begins, with TT-102 the only probe and TIC-102 driving all three valves. With the CO_2 gone the zones exchange 7.4 m^3/h after 6 h and 3.8 after 24 h. The cone has 0.069 kW/K of open jacket per cubic meter against 0.029 for the cylinder zones, so the duty that suits the middle overcools it. It is 1.95 °C below the recipe on day 8.98, and the zones spread by 2.69 °C on day 9.12. Once the cone is colder than 4 °C and further from 4 °C than the middle, it is the lighter, and the exchange across its boundary rises to 20.3 m^3/h at 36 h and 28.4 at 48 h. The cold cone drops its yeast early, 18.1 Mcells/mL of cake over the tank volume 36 h into the crash against 14.7 Mcells/mL with three probes. The crash is declared complete on day 10.73, when TT-102 reads −0.51 °C, with the zones at −0.39, −0.49 and −0.63 °C. With a probe and a loop per zone the spread stays within 0.47 °C, every zone within 0.52 °C of the recipe, and the crash completes on day 10.93. The same single probe is harmless while the yeast are busy. Over the whole batch of case 3 with one probe the spread stays below 0.10 °C through the primary fermentation and the rest, first passes 0.5 °C on day 7.53, 2.7 h into the crash, when the CO_2 has fallen to 7.2 kg/h, and the cone runs up to 1.38 °C off the recipe.

🕮 **Pause.** Try Exercise 10.2 before reading on.

10.5.5 The Diacetyl Rest and a Result a Day Old

Case 6 starts on day 4.18 at the free-rise trigger, with the rest ended on the laboratory. The beer reaches 14 °C on day 5.97. The daily samples read 0.242 mg/L on day 1, 0.923 on day 2, then 0.681, 0.505, 0.377, 0.253, 0.179 and 0.083 on day 8, each reported a day after it was drawn. The true VDK falls below 0.10 mg/L on day 7.96, the result for day 8 arrives on day 9.00 and the crash starts then, with the true VDK at 0.062 mg/L, and the beer is crashed on day 11.99 at 0.044 mg/L, just inside the plan. The run 120 h after its start, 4.4 h into that crash, is shown in Figure 10.3.

Ending the rest on the corrected estimate starts the crash on day 7.40, with the estimate at the limit, its uncorrected model at 0.066 mg/L and the truth at 0.130 mg/L. By then the truth is 1.96 times the model, because this strain forms 15 % more VDK and reduces it 20 % more slowly than the estimator's textbook yeast, and the correction, built from results a day old, has reached a factor of 1.52. The yeast keep working into the crash, and the beer is crashed on day 10.37 at 0.089 mg/L. Without the correction ($\lambda = 0$) the crash starts on day 6.70 at 0.180 mg/L and the beer finishes at 0.123 mg/L, over the limit. A gain of 0.25 starts the crash on day 7.19 and finishes at 0.098 mg/L, and a gain of 1 on day 7.57 at 0.083. A limit of 0.08 mg/L on the estimate starts it on day 7.78 at 0.109 and finishes at 0.075, and a timed rest of 48 h starts it on day 7.97 and finishes at 0.069. The laboratory's turnaround is read when the batch starts, so it is set before the run. With a 12 h turnaround the day-8 result reports 0.101 mg/L, just above the limit through the analysis noise, and the crash waits for the day-9 result on day 9.50. The laboratory is exact but a day old and the estimator is current but only as good as its constants, so the useful arrangement gives the model the timing and the laboratory the level, as inferential schemes do [5, 6]. The spray dryer of Volume 5, Chapter 10 corrects a soft

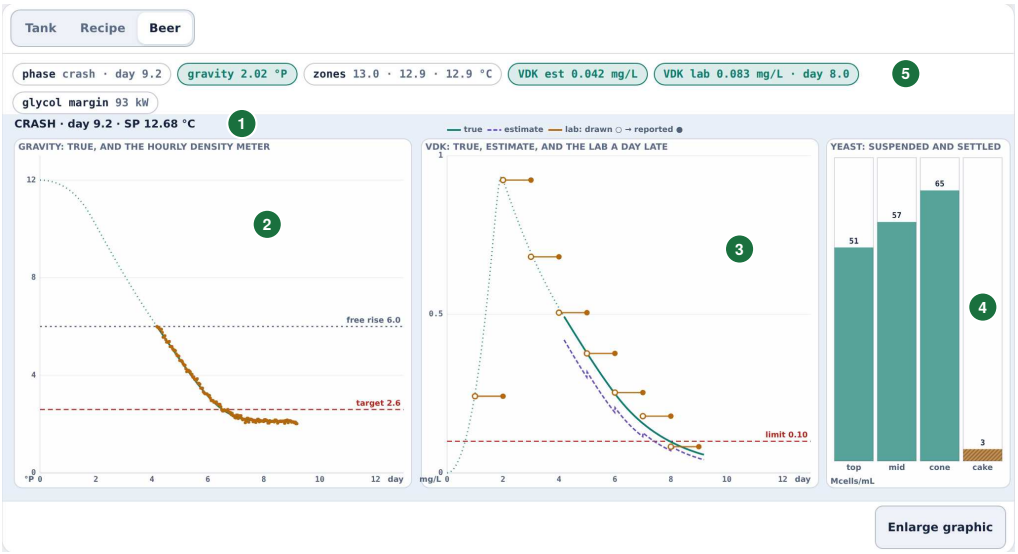


Figure 10.3 The diacetyl rest of case 6 at $t = 120$ h (5d 00:00), on batch day 9.2, in the Beer view with no control changed, cropped to the plant view. Callout 1 is the status line: the supervisor has started the crash on the laboratory's result for the day-8 sample, 0.083 mg/L, and the setpoint has ramped to 12.68 °C, with the probes at 13.0, 12.9 and 12.9 °C in the badge row above. Callout 2 is the gravity panel, with the history as a dotted line and the true gravity and the hourly density readings falling from the 6.0 °P free-rise line to 2.02 °P, below the 2.6 °P target. Callout 3 is the VDK panel, with the true value, the estimate and eight laboratory results, each drawn from its sample day to its report day, from 0.242 mg/L for day 1 and the peak of 0.923 for day 2 down to 0.083, against the 0.10 mg/L limit. Callout 4 is the yeast bars, 51, 57 and 65 Mcells/mL in suspension in the top, middle and cone and 3 in the cake, and callout 5 the badges of the estimate, 0.042 mg/L, and the latest laboratory result.

sensor's bias from a delayed laboratory in the same way, and Chapter 8 corrects its culture model from a daily count.

🕮 **Pause.** Try Exercise 10.3 before reading on.

10.5.6 A Crash on a Short Glycol Plant

Case 7 starts its crash on day 7.95 while the other tanks draw 478 kW of the plant's 500, easing over the next days. With the coordinator on, this tank may draw between 1.8 and 85.3 kW during its crash, the ramp waits, and the supervisor marks the crash late at its first control step. The lumped projection is pessimistic while the neighbors' load is easing, beyond day 19 at the start, day 14.5 after one day and day 12.4 near day 11, and the beer is crashed on day 12.71 with the plant never over capacity and the supply at −4 °C. With the coordinator off the valves take what they pass, the plant runs up to 70.9 kW over capacity for 41.5 h, the supply warms to −1.87 °C for every tank on it, and on day 8.06 the crash itself is held, because glycol less than a degree colder than −1 °C cannot reach it. That beer is crashed on day 11.11. A shared utility turns the tank's schedule into a plant-wide question, and the coordinated answer is a late batch announced from the first hour rather than a warmer supply for every tank. The refrigeration pack of Volume 8, Chapter 12 shows the same coupling through a shared suction pressure, where thermostats that exchange no signal still act on one another. Load management of this kind was one of the three levers by which a brewery's refrigeration plant was found to save fuel [8].

Table 10.6 The Twelve-Day Batch, Shipped, Suggested and With One Lever Returned to Its Shipped Setting

Configuration	Rise (day)	Crash (day)	Done (day)	D (mg/L)	Dev. (°C)	Over (kW)
as shipped	6.00	9.79	12.57	0.058	2.73	0
suggested	4.21	7.42	10.47	0.087	0.52	0
rest of 48 h	4.21	8.00	10.98	0.069	0.52	0
hysteresis valves	4.25	7.41	10.53	0.083	0.52	39.4
one mid probe	4.21	7.42	10.28	0.088	1.45	0
free rise on day 6	6.00	8.51	11.49	0.088	1.59	0
rest on the laboratory	4.21	9.00	11.98	0.044	0.52	0
coordinator off	4.21	7.42	10.39	0.089	0.52	10.2

10.5.7 A Stuck Fermentation

Case 8 pitches yeast of 15 % viability. On day 3.00 the density meter reads 11.16 °P and falls 0.51 °P a day, where the healthy batch of case 3 is at 8.13 °P, and projected at 14 °C the target is out of reach until day 17.9. The supervisor declares the fermentation stuck, warms the beer to 14 °C and holds it there for a re-pitch decision, and the true gravity is still 4.72 °P on day 12, so a crash on schedule would have shipped unfinished beer. The rule knows nothing of the viability. The pitch is read at knock-out, so a viability is set on case 3 before the run. A 30 % viability is declared stuck on day 7.98, on a projected finish of day 12.0 at the edge of the plan, while at 45 % the batch is crashed on day 11.36 at 2.11 °P but at 0.108 mg/L, because the estimator still assumes a healthy pitch and ends the rest too soon, and at 75 % on day 10.66 at 0.099 mg/L. Honest infeasibility is a control function here. In wine, where stuck and sluggish fermentations have been reviewed at length, their causes are many and hard to diagnose [7], and a rule on the measured trend flags the symptom without having to know the cause.

10.5.8 The Twelve-Day Challenge

The challenge runs a whole batch from knock-out, with a neighbor tank starting its crash on day 7 and drawing 150 kW that eases over about a day. The target is a crash to −1 °C completed by day 12 at no more than 2.6 °P and below 0.10 mg/L of true VDK, with every zone within 1 °C of the recipe throughout and the plant never over capacity. As shipped, with one mid-height probe, hysteresis valves, a free rise on day 6, a 48 h rest and no coordinator, the free rise comes too late for the fermentation's own heat, and the beer reaches only 12.77 °C while the recipe asks for 14. The rest starts on day 7.79, the crash on day 9.79, and the unprobed cone runs 2.73 °C off the recipe on day 10.55. The beer is crashed on day 12.57 at 2.10 °P and 0.058 mg/L, too late and outside the band. The suggested configuration of three probes on time-proportioned valves, the free rise at 6.0 °P, the rest ended on the corrected estimate and the coordinator on completes the crash on day 10.47 at 2.10 °P and 0.087 mg/L, every zone within 0.52 °C and the plant never over capacity, which leaves margins of 1.53 days, 0.50 °P, 0.013 mg/L and 0.48 °C on the target. The challenge is scored on the tank as given, so a change to a model parameter or a disturbance voids the attempt, and a change to a valve mode, a probe arrangement, a trigger or the coordinator does not. Table 10.6 returns one lever at a time. A timed rest and a rest ended on the laboratory both pass, the latter on day 11.98 with half a day to spare. Hysteresis valves with three probes hold every zone within 0.52 °C on 103 valve switches against 2825, but during the rest their full openings meet the neighbor's crash and hold the plant 39.4 kW over capacity for 1.2 h. One probe breaks the band at 1.45 °C, a free rise on day 6 at 1.59 °C with the beer reaching only 12.57 °C, and without the coordinator the neighbor's crash and this one hold the plant 10.2 kW over capacity for 3.1 h. Every failing lever is a trigger, a measurement, the valve law or the shared utility, and none is a gain. Figure 10.4 draws the table as bars.

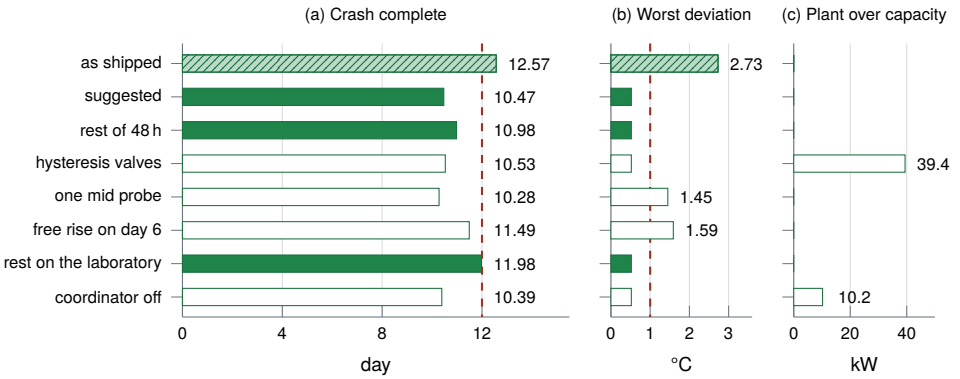


Figure 10.4 The twelve-day batch of Table 10.6 drawn as bars, with the challenge's targets dashed: the crash complete by day 12 and every zone within 1 °C of the recipe. The hatched bar is the batch as shipped, solid bars pass and white bars fail. Notice that each white bar fails on one panel only, on the deviation or on the plant, and that the passing ones differ only in when the rest ends.

10.6 Technology in Practice

The simulated tank carries three temperature loops, a density meter, a daily laboratory sample and a shared glycol supply. Figure 10.5 draws them with the devices a cellar would install.

What Measures It

Each zone has a thermowell with a resistance thermometer, TT-101 to TT-103, and the supply carries a fourth, TT-501. The chapter models each probe as a first-order lag of 10 min with a little colored noise, which is what a well and its element add to the true beer temperature. The gravity comes from DT-201 on the sample line of the middle zone, read once an hour, and the diacetyl only from the laboratory, a day after the sample was drawn. No device in the model measures the cone's gravity or any zone's diacetyl.

> **TECHNOLOGY Sensor: Resistance Thermometer in a Thermowell**
>
> A zone temperature is read by a resistance temperature detector, a fine wire of pure metal, usually platinum, whose resistance rises with temperature. It is less sensitive than a thermistor but far more linear, which is why platinum is the common industrial choice [18]. The element sits in a thermowell, a pressure-tight sheath that lets it be replaced without opening the vessel. The well's mass adds a first-order lag, and an element not seated against the bottom of the well adds a second lag through the air gap, which can push a feedback loop toward oscillation [18]. On a trend that fault shows as a probe that trails its zone and a limit cycle that grows. The chapter's 10 min first-order lag stands for the well.

What Moves It

Three on/off valves admit glycol to the three jackets. A solenoid valve has two positions and a resting position set by its spring, so the controller's only freedom is when to switch it. The time-proportioned output of Section 10.4 turns a duty into an on-time, and its minimum on and off times of 2 min keep it from asking for shorter pulses. The chapter's valves open and shut instantly, which no real valve does.

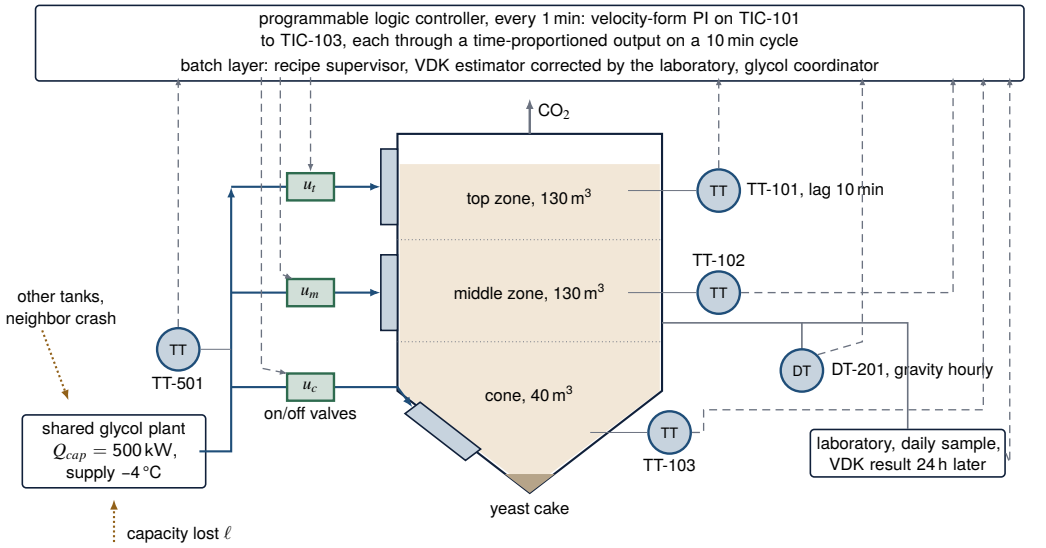


Figure 10.5 The chapter's loops with the devices a cellar would install. Thick blue lines carry glycol, dashed gray lines the signals and dotted amber arrows the disturbances. Notice that the three valves are on/off solenoid valves fed from one shared plant, and that only temperature is measured in every zone: the gravity is read at the middle zone once an hour and the diacetyl only by the laboratory, a day late.

TECHNOLOGY Final Element: On/Off Solenoid Valve

A jacket valve that is only open or shut is commonly a two-way solenoid valve. An energized coil pulls a ferrous armature that lifts a small plug off its seat, and a return spring sets the resting position, normally closed or normally open, which is where the valve goes when the coil is de-energized [18]. Process pressure should act with the spring, or it may keep the valve from returning to rest, and fast action needs a solenoid force well above the spring force [18]. A valve that fails to shut shows on a trend as a zone that keeps cooling below its setpoint while its duty sits at zero, the stuck-valve fault of the chapter's variables table. The simulated valves have no stroke time.

Where the Controller Runs

The zone loops would run on a programmable logic controller or in a distributed control system. A programmable logic controller holds instructions for input and output, logic, timing, counting and three-mode PID control, and in a distributed control system it serves as a local controller within a supervisory scheme [19]. Supervisory and lower loops run continuously with cycle times from milliseconds to minutes [19]. The chapter's loops execute once a minute on a ten-minute valve cycle, slow for a controller and fast for a tank of 1.23 GJ/K. In a function block program the PID block feeds a time-proportioning block that switches a discrete output, the arrangement used where a final element can only be fully on or fully off [18]. The recipe supervisor, the estimator and the glycol coordinator belong one layer above the loops, in the batch logic that moves the tank from phase to phase.

What Is Modernizing It

Two lines of work would move the measurement boundary this chapter draws. The first is wider monitoring. Automated monitoring of fermentation has long meant little more than temperature, and electronic noses, electronic tongues and other sensors are being studied for the variables that decide a batch, so far mostly in laboratories [20]. The second is connected, low-cost instrumentation.

Large breweries adopted sensors and digitization before smaller ones, and connected devices are now spreading to mid-sized and craft breweries, with real-time monitoring feeding data-driven decision support, while data ownership and standardization remain open [21]. Both would feed model-based state estimation, which has already tracked batch beverage fermentations with an imperfect model [6]. Each shortens the day that the simulated estimator must bridge between a sample and its result.

> **IN PRACTICE** **A Differential Gap, and the Wear of Every Stroke**
>
> On/off control with a single setpoint is possible but usually not practical, because the final element then cycles too often. A working on/off loop has two setpoints with a gap between them, a differential gap, and the process variable cycles between the upper and lower setpoints without ever settling at the setpoint [18]. Each cycle is mechanical wear, and frequent cycling of the final element may contribute to its premature failure [18]. The gap therefore trades the swing of the temperature against the number of strokes, which the chapter's scorecard counts as valve switches.

10.7 Limitations

The kinetic constants are illustrative and not fitted to a strain, the VDK is one lumped state that cannot reappear from its precursor after the crash, and the heat of fermentation is a declared constant. The tank is three well-mixed zones, so it shows stratification between zones but not a gradient within one, and the density maximum is water's.

The glycol plant is a capacity with an algebraic supply temperature, the other tanks are a load profile that does not respond to it, and the valves have no stroke time. The density meter fails only through its bias disturbance, noise and bubble spikes, and the laboratory only through its noise. The estimator shares the plant's structure and differs only in its constants and the viability, where a real estimator would also differ in structure. The supervisor's crash projection cools the tank as one lump at the present allotment, so it is pessimistic while the other tanks' load is easing, beyond day 19 at the start of case 7 for a crash completed on day 12.71, and optimistic on an uncontended plant, where it first projects day 9.7 for a crash completed on day 10.39 because it ignores the ramp and the slowest zone. Mid-batch starts replay a history held exactly on the recipe, and every size, capacity and limit is a teaching value.

> **OPEN CHALLENGE** **Seeing More of a Fermentation Than Its Temperature**
>
> Automated monitoring of alcoholic fermentation is often limited to a few parameters, mainly temperature. A review of the sensors proposed for beer, wine and spirits found that the solutions are mostly isolated laboratory studies yet to be tested in industrial plants, that a public database of recorded sensor data is needed but missing, and that the machine learning in these studies generally falls short of the established standards of data science [20]. Progress would look like an in-line measurement of gravity or diacetyl proven in a production cellar against the laboratory, with its data open to others.

10.8 Conclusion

This chapter studied a lager fermenter, a batch reactor whose heat arrives on the yeast's schedule, whose valves are open or shut, whose mixing comes and goes with the CO_2 and whose endpoint is a day-old laboratory result, on a simulator that logs every zone's truth beside every instrument. With the valves shut the beer runs away to 21.33 °C, and on the same valves a thermostat holds 10.66 to 11.27 °C where a time-proportioned PI holds 10.97 to 11.04 °C, although a 14.7 % open share removes 1.8 times its linear share of heat. One mid-height probe lets the quiet crash spread the zones by 2.69 °C. A rest ended on the laboratory starts the crash 1.04 days after the beer was ready, the corrected estimator 1.60 days earlier, and without the correction the beer ships at 0.123 mg/L. On the short plant the coordinated crash is announced late and completes on day 12.71 without the 70.9 kW overload of the uncoordinated crash, and a fermentation at 15 % viability is declared stuck on day 3.00 rather than crashed off target. The graded batch improves from day 12.57, its cone 2.73 °C off

the recipe, to day 10.47 within 0.52 °C on unchanged gains. The model is lumped in its zones and illustrative in its constants. A fuller model would add a diacetyl precursor, a glycol inventory that warms in an outage, responsive neighboring tanks and valve stroke times. The tank makes visible that a lager batch is decided by what triggers each phase, what ends it and what its measurements can see.

KEY POINTS

- A lager batch is decided by what triggers each phase, what ends it and what its measurements can see, not by the tuning of its temperature loops.
- On the same valves a thermostat holds 10.66 to 11.27 °C where a time-proportioned PI holds 10.97 to 11.04 °C.
- One mid-height probe lets the quiet crash spread the zones by 2.69 °C.
- A rest ended on the laboratory starts the crash 1.04 days after the beer was ready, and without the correction the estimator ships the beer at 0.123 mg/L.
- The graded batch improves from day 12.57 to day 10.47 on unchanged gains.

Where else this applies. Volume 8, Chapter 2 removes the heat of an exothermic batch through a jacket, Volume 8, Chapter 12 runs thermostats on a shared refrigeration plant, and Volume 5, Chapter 10 corrects a soft sensor from a late laboratory.

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10.9 Exercises

10.1 Concept check · 2 min

At the day-two peak of case 3 the top valve is open 14.7 % of the time, and its jacket removes 15.2 kW. That is 1.8 times the open share times the 56.7 kW that a valve held open removes at steady state. Which explanation is right?

(a) Each pulse fills the jacket with supply glycol that goes on cooling after the valve shuts

(b) The probe lag makes the loop ask for a larger duty than the zone needs at the peak

(c) The carry of the time-proportioned output keeps the valve open longer than its duty

(d) The glycol supply runs colder at the peak than in the steady test of the open valve

10.2 Concept check · 1 min

Case 5 crashes a quiet tank, with the CO_2 gone, on one mid-height probe, and TIC-102 sends the same duty to all three valves. Which zone ends furthest from the recipe, and in which direction?

(a) The top zone, too warm, because warm beer rises once the gas stops

(b) The cone, too cold, because it has the most open jacket per cubic meter

(c) The middle zone, too warm, because its probe lags the beer by ten minutes

(d) The cone, too warm, because the settled yeast insulate it from its jacket

10.3 Concept check · 2 min

In case 6 the rest is ended on the estimate twice, once with the laboratory bias update gain λ at 0.5 and once at 0. What does the run at $\lambda = 0$ show, and why?

(a) The crash starts later, because the uncorrected model forms more diacetyl than the strain

(b) The crash starts on the same day, because the estimate takes its timing from the model alone

(c) The crash starts earlier and the beer finishes over the limit, because the model's yeast clear diacetyl faster

(d) The crash starts earlier but the beer finishes inside the limit, because the yeast keep working in the crash

10.4 Theory and calculation · 6 min

A cylinder jacket has $UA = 6.5\,\mathrm{kW/K}$ and a glycol holdup $M_j = 600\,\mathrm{kg}$ with $c_g = 3.6\,\mathrm{kJ/(kg\,K)}$, and an open valve passes $F_j = 2.5\,\mathrm{kg/s}$. The cone jacket has $UA = 4.0\,\mathrm{kW/K}$.

(a) From Equation (10.7) at steady state with the valve open, find the effective conductance UA_{eff} between the beer and the supply for a cylinder jacket and for the cone. *Checkpoint:* 3.77 kW/K and 2.77 kW/K.

(b) Find the time constant of the cylinder holdup with the valve open and with it shut. *Checkpoint:* 2.3 min open and 5.5 min shut.

(c) Find the heat the three open jackets remove with the beer at 11 °C and the supply at −4 °C, and compare it with the 32.8 kW peak of the 12 °P batch held at 11 °C. *Checkpoint:* 155 kW, 4.7 times the peak.

10.5 Theory and calculation · 5 min

The crash cools 300 m^3 of beer with $\rho c_p = 4100\,\mathrm{kJ/(m^3\,K)}$ from the rest at 14 °C to −1 °C on a ramp of 0.3 °C/h.

(a) Find the heat capacity of the tank and the heat the crash removes. *Checkpoint:* 1.23 GJ/K and 18.45 GJ.

(b) Find the heat flow that the ramp asks for. *Checkpoint:* 102.5 kW.

(c) The three open jackets give $\sum UA_{eff} = 10.32\,\mathrm{kW/K}$ against a supply at −4 °C. Find the beer temperature below which they cannot keep up with the ramp. *Checkpoint:* About 5.9 °C.

10.6 Theory and calculation · 7 min

The estimator's VDK reduction uses $a_D(T)$ of Equation (10.4) with $E_D = 110\,\mathrm{kJ/mol}$ and $T_r = 11\,^\circ\mathrm{C}$, and its level is corrected by Equation (10.14).

(a) Find a_D at the 14 °C rest and at the −1 °C crash temperature. *Checkpoint:* 1.63 and 0.128.

(b) Suppose the truth stays at a constant 1.96 times the model, so the log error is $e = \ln 1.96$. With $\lambda = 0.5$ and $b = 0$ at the start, find the correction factor e^b after one, two and three results, and the number of results after which it is within 10 % of 1.96. *Checkpoint:* 1.40, 1.66 and 1.80. Three results.

(c) Repeat the factor after three results for $\lambda = 0.25$, and say what a smaller gain buys. *Checkpoint:* 1.48.

10.7 App challenge · 8 min

Load scenario 2, On/off with hysteresis, and change no setting. Run to 72 h at the top speed with the default seed and export the CSV file. Then do the same with scenario 3, Time-proportioned PI.

(a) For each run find the lowest and the highest zone temperature in the columns `T_t_C`, `T_m_C` and `T_c_C` over the rows from 24 h to 72 h, within 0.01 °C. *Checkpoint:* 10.66 to 11.27 °C, and 10.97 to 11.04 °C.

(b) Read `metric_switches` in the rows at 24 and 72 h and find the valve switches between them in each run. *Checkpoint:* 29 and 802.

(c) Find how many times narrower the PI swing is, and say why the hysteresis swing reaches below its lower switch point of 10.75 °C. *Checkpoint:* 8.7 times.

10.8 App challenge · 9 min

Load scenario 6, The diacetyl rest. Use the default seed, run at the top speed, and let each run go on until it stops itself at the end of the batch. For each run read the Crashed (finished) and VDK tiles of the scorecard, and in the exported CSV file find the first row whose `phase` is `crash`, where `batch_age_h` divided by 24 gives the day the crash starts and `metric_vdk_at_crash_mgL` the true VDK then.

(a) Run the case as shipped, with the rest ended on the laboratory. *Checkpoint:* Crash on day 9.00 at 0.062 mg/L. Tiles: day 12.0, 0.044 mg/L.

(b) Press Reset, set Rest ends on to Estimate, and run again. *Checkpoint:* Crash on day 7.40 at 0.130 mg/L. Tiles: day 10.4, 0.089 mg/L.

(c) Press Reset, keep the Estimate, set the Lab bias update gain to 0, and run again. *Checkpoint:* Crash on day 6.70 at 0.180 mg/L. Tiles: day 9.6, 0.123 mg/L.

Accept a day within 0.01 and a VDK within 0.002 mg/L. The true VDK falls below 0.10 mg/L on day 7.96. Say what each ending costs.

10.9 App challenge · 8 min

Load the challenge, A twelve-day lager, at the default seed and run at the top speed. Before Run set Jacket valves to Time-proportioned, Temperature probes to Three zones, Free rise starts to At a gravity, Rest ends on to Estimate and the Glycol coordinator On. Run until the batch stops itself.

(a) Read the Crashed (finished), VDK, Worst recipe deviation and Glycol over capacity tiles and the Challenge target tile. *Checkpoint:* Day 10.5, 0.087 mg/L, 0.52 °C (top), 0.0 kW for 0.0 h, met.

(b) Press Reset, set Jacket valves to Hysteresis and change nothing else. Run again and read the same tiles. *Checkpoint:* Day 10.5, 0.083 mg/L, 0.52 °C (top), 39.4 kW for 1.2 h, not met.

Explain why the hysteresis valves fail although they hold every zone as closely as the time-proportioned valves.

10.10 Application area · 4 min

In case 7 the other tanks draw 478 kW of the glycol plant's 500 kW at the start of this tank's crash, and the coordinator keeps a reserve of 20 kW.

(a) Find this tank's allotment at the start from the coordinator's rule. *Checkpoint:* About 2 kW.

(b) The allotment rises to at most 85.3 kW during the crash. Find the shortest time in which that draw could remove the 18.45 GJ of a crash from 14 to −1 °C. *Checkpoint:* About 60 h.

(c) Give the engineering case for announcing a late crash rather than taking the glycol.

10.11 Application area · 3 min

A brewer reads that ending the rest on the laboratory cost 1.04 days of tank time, and proposes to end the rests of a real cellar on a model-based estimate corrected by the laboratory, as case 6 does. Name two limitations stated in the chapter that bear on this proposal, and say what each could do in a real tank.

10.12 Review the agent · 5 min

An AI assistant is asked why the challenge fails as shipped and replies as follows. "The cone runs 2.73 °C off the recipe, and the cone loop has the weakest tuning, $K_c = 60\,\%$ per °C against 150 for the other two. Raise the cone gain to 150 and shorten all three integral times from 8 to 2 h, and the cone will stay inside the 1 °C band." Find the flaw in the proposal and say how to check it.