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CHAPTER 6

A Flash Steam Vessel Whose Level Rises While It Loses Water

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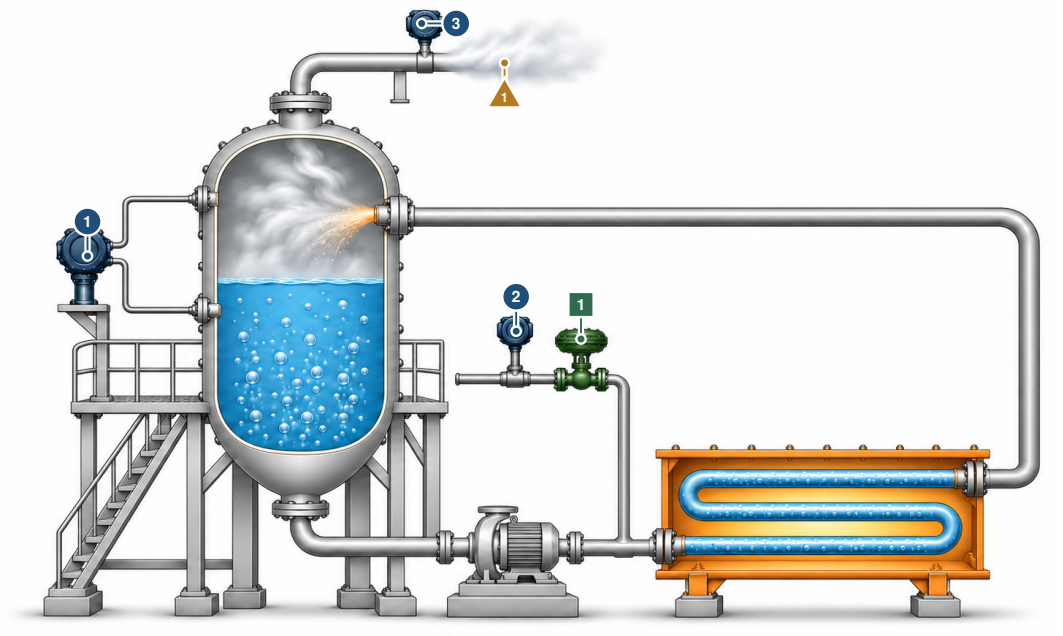
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CHAPTER 6

A Flash Steam Vessel Whose Level Rises While It Loses Water



The controller moves 1 feedwater valve

The controller reads 1 level of the surface 2 feedwater flow 3 steam flow

What disturbs it 1 more steam taken by the users

Notice the bubbles below the surface, which lift the level the transmitter reads, although in the model the coil water stays liquid and the steam goes to a plant header rather than to the air. Illustration, not to scale.

IN PLAIN TERMS A Steam Vessel Whose Level Can Mislead

The main idea. Hot water under pressure is let down into a tall tank at a lower pressure, and part of it boils into steam at once. The rest stays as water, and a pump sends it back through a coil of pipes in hot exhaust gas to pick up more heat.

The challenge. When the users take more steam, the pressure in the tank falls and water boils all through it. The bubbles lift the surface, so the level reads higher just as the tank is losing water.

Why it matters. A controller that trusts the level alone cuts the water supply at the worst moment.

THREE WAYS TO READ THIS CHAPTER

Explore	11 min	the first page, the history of the steam tables (Section 6.2), the fact on fast property calculation (Section 6.3), the try-it segments of cases 2 and 3 (Section 6.4.2), the fact on the swell peak (Section 6.6) and the key points
Study	50 min	the whole chapter with its three pause points and the twelve exercises at its end
Practice	15 min	the first page, the results (Section 6.6), Technology in Practice (Section 6.7), Limitations (Section 6.8) and the open challenge

The control question A rise in steam demand makes the level of a flash vessel rise while the vessel loses water. Which disturbances move the indicated level against the inventory in a heat-recovery unit, and what can single-element, three-element and predictive feedwater control do about it?

Learning objectives

- Write the water and energy balances of the vessel and its loop, and explain why the circulation cancels from the water balance.
- Compute the integrating gain of the inventory, the flash quality and the pressure settling time at the design point.
- Explain swell and shrink as an inverse response through pressure, and say why colder feedwater does not shrink this vessel.
- Compare single-element, three-element and predictive control on a demand step by error, inventory dip and valve travel.
- Judge which plant changes an inventory estimator can follow and which ones, such as foaming or a transmitter bias, it cannot.

Prerequisites Sections 1.4.2 (balances), 1.4.4 (integrating response), 1.4.7 (inverse response) and 1.6.2 (velocity form), and Chapter 2 for a tank level loop. Section 1.6.3 is needed only for the estimator and the predictive controller.

The app https://apmonitor.com/apps/flash-steam/

See also Volume 3, Chapter 2 for flow feedforward and a level-to-flow cascade, Volume 3, Chapter 9 for an inverse response met with an inner loop. Volume 5, Chapter 12 for an observer of an inventory no instrument measures, and Volume 5, Chapter 11 for a soft sensor of a state no instrument reaches.

6.1 Introduction

A flash vessel makes steam without a burner. Water pumped through a heat-recovery coil at 18 bar comes back at 190.3 °C, well above the 170.4 °C at which water boils in a vessel held at 8 bar absolute, and about 4.3 % of it flashes to vapor as an orifice drops it to that pressure. In the generic unit simulated here, 39 kg/s of circulating water recovers 4.08 MW from 18 kg/s of flue gas at 450 °C and delivers 1.75 kg/s of saturated steam to a plant header, while feedwater from a deaerator replaces what leaves. Opening the steam user's valve by a quarter raises the indicated level from 55.0 to 58.0 % of the vessel height in ten seconds, while the water in the vessel falls from 51.90 to 51.78 % of the height as a mass-equivalent level.

Steam recovered from waste heat is one of the larger levers on industrial energy use, and the equipment that recovers it takes many forms, among them recuperators, waste heat boilers and heat-recovery steam generators [1]. Flash separation of a pressurized hot-water stream is the working principle of the single-flash geothermal power plant [2], and the flash evaporation of a liquid pool after a pressure drop depends on how fast the pressure falls and how deep the pool is [3]. The level of any vessel in which vapor forms inside the liquid swells during a depressurization, a transient that nuclear safety analysis treats with drift-flux models [4], and the drum of a natural-circulation boiler shows the same inverse response that the drum-boiler model of Åström and Bell carries as an explicit state of steam below the surface [5]. Level control of such vessels is a long-standing problem of boiler and heat-recovery practice [6–8], and an integrating process with inverse response needs identification and tuning rules of its own [9].

The simulator is built to correct a specific belief, that a level transmitter measures how much water a vessel holds. In this model the transmitter reports the surface above the liquid and submerged vapor. Pressure-driven changes in that vapor can move the indicated level opposite to the liquid inventory. A single-element controller that trusts the level reads a swell as too much water. On the 20 % demand step of case 5 it closes the feedwater valve from 43.7 % to 34.0 % within fourteen seconds, at the moment the vessel is losing water. The same plant also contradicts a belief carried over from drum boilers. The tested cold-feedwater step produces no initial shrink in this model: feedwater mixes with

circulating water upstream of the coil, rather than entering the vessel directly. This result depends on the loop holdup, heat supply and bubble closure.

The usual sources treat the parts of this problem apart. Drum-boiler models are written for natural circulation and a firing rate that the plant controls [5], heat-recovery level control is reported for large multi-pressure units [7, 8], and flash evaporation is studied as heat and mass transfer without a level loop [3]. This chapter works with a browser simulator of a forced-circulation flash unit in which the indicated level, the water inventory and the vapor below the surface are logged side by side. It measures how single-element, three-element and predictive control, with and without an inventory estimate, deal with the gap between them. The balances, the IAPWS-IF97 properties [10], the velocity-form PID, the Kalman filter [11] and the offset-free MPC [12] are established methods. The results are measurements on one plant and seed, and the central one is that in a heat-recovery unit both the swell and the shrink come from the steam side through pressure.

Section 6.2 follows the domain from flash tanks and geothermal separators to drum-level control. Section 6.3 sets out the unit as a ten-state model whose mass and energy ledgers close to the integrator's precision, with properties from an IAPWS-IF97 module checked against the release's verification values and two independent implementations, and it states every equation, constant and default needed to build the simulator again. Section 6.4 reads the dynamics from the model: an integrating inventory, and in Section 6.4.2 the swell and shrink that make this plant the volume's example of an inverse response. Section 6.5 describes the controllers and the measurement boundary that keeps every one of them away from the simulator's truth. Section 6.6 measures the fifteen cases, from a hand-closed water balance to a graded challenge, Section 6.7 names the instruments, valves and platform of a real unit, and Sections 6.8 and 6.9 state the limits of the model and what the cases show.

6.2 Flash Steam, Recovered Heat and the Level Problem

When a pressurized liquid at its boiling point is let down, part of it flashes, and recovering that vapor is the basis of flash tanks on boiler blowdown and condensate returns and of the separators of geothermal plants. In a single-flash geothermal plant a separator divides the two-phase flow from the wells into steam for the turbine and liquid that is returned to the reservoir, and the separator pressure is chosen to balance the steam fraction against the energy each kilogram of steam carries [2]. The same trade appears in the unit simulated here, where the loop pressure keeps the hot return liquid and the vessel pressure decides how much of it flashes.

Industrial waste heat became a design target in its own right as energy prices and emission limits rose. A review of recovery technologies surveys them by the temperature of the source, from recuperators and regenerators to waste heat boilers that raise steam from exhaust and flue gas [1]. A forced-circulation loop with a separate flash vessel suits a source that is variable or dirty, because the coil can remain liquid-filled at elevated pressure while vapor separates in the downstream vessel. The simulation assumes this operating regime and does not model isolation, drainage or bypass equipment.

The level problem came to these units from boilers. Feedwater regulation on boiler drums began with a single measurement of level and moved to two-element control with a steam-flow feedforward and then to three-element control with an inner feedwater-flow loop, which became the standard arrangement on industrial and utility boilers because the drum level swells and shrinks with load [6]. Model-based designs followed. A cascade generalized predictive controller for drum level was reported in 2005 [13], and heat-recovery steam generators, whose load follows a gas turbine or a process rather than a burner, have since been given robust drum level controllers for wide-range operation [7] and three-element schemes with fractional-order PID and fuzzy elements [8]. The physical understanding underneath these designs rests on models in which the steam held below the surface is a state of its own [5], and on two-phase level swell during depressurization [4]. The flash unit simulated here adds two features of the modeled arrangement: its tested feed-temperature

Table 6.1 Variables by Role, With Their Values at the Design Point of Case 1

Variable	Role	Design	Range
L_m	CV, measured surface	55.0 %	SP 40–65 %
v	MV, feedwater valve	43.75 %	0–100 %
$\dot{m}_{f,SP}$	MV of the outer loops	1.75 kg/s	0–4.0 kg/s
d	DV, steam demand	100 % of design	20–150 %
$\dot{m}_g$	DV, flue-gas flow	18 kg/s	0–130% design
T_g	DV, gas temperature	450 °C	300–550 °C
T_{fw}	DV, feedwater	105 °C	20–140 °C
Δp_f, a_{line}	DV, feed delivery	100, 100 %	20–130, 10–100
ϕ	DV, water-side fouling	1	0.4–1
$\dot{m}_b$	DV, blowdown	0	0–0.2 kg/s
σ_L, b_L	DV, transmitter noise, bias	0.2 %, 0	0–1.5, ±6
M, U	states, vessel	1269.0 kg, 1.0943 GJ	—
p	algebraic, pressure	8.00 bar	p_{hdr}−12.5
h_h, T_{hot}	state, loop	809.1 kJ/kg, 190.3 °C	subcooled ≥ 3 K
T_m	state, coil metal	200.5 °C	—
β	state, submerged share	0.0646	0–0.35
$\dot{m}_r$	state, circulation	39 kg/s	≥ 45 %
$\dot{m}_s$	output, steam	1.75 kg/s	—

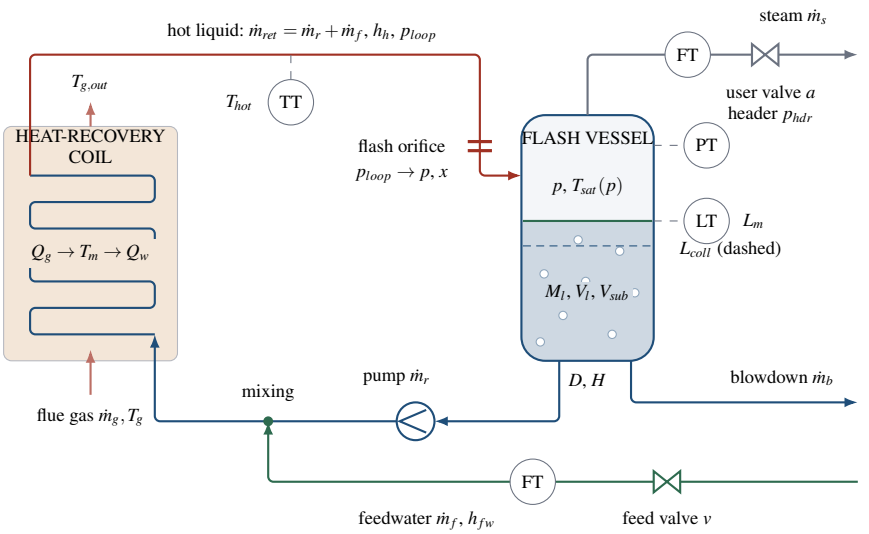
disturbance does not cause an initial shrink, and its available upstream heat constrains sustained steam production.

> ⧖ HISTORY **Steam Tables Become Equations, 1929 to 2003**
>
> International agreement on the properties of water and steam began with steam-table conferences in 1929, 1930 and 1934, and the 1934 meeting agreed on skeleton tables of pressure, enthalpy and volume on a coarse grid. After the Second World War new power plants were designed for higher temperatures and pressures, and new skeleton tables approved in 1963 reached 100 MPa and 800 °C. As computers spread through industry, equations took the place of tables. An industrial formulation adopted in 1966 and revised in 1967 served for three decades, until IAPWS-IF97 replaced it in 1997 [14]. A familiar book of steam tables was first printed from the 1967 equations [15]. The last skeleton tables were withdrawn in 2003, and the recommendations have been equations ever since [14].

6.3 The Unit as Modeled

The simulated unit is a generic industrial design with no proprietary source, as shown in Figure 6.1. Flue gas passes a finned-tube coil whose metal is one node at T_m. A circulation pump draws saturated water from the bottom of a vertical flash vessel 1.2 m across and 2.4 m tall (2.71 m^3), raises it to the loop pressure p_{loop}, and sends it through the coil, where it is lumped as one well-mixed holdup M_h at enthalpy h_h. Feedwater enters the loop at the pump discharge. An orifice drops the hot return to the vessel pressure p, steam leaves through the steam user's valve of opening a to a header at p_{hdr}, and a continuous blowdown $\dot{m}_b$ can take liquid out. The level transmitter LT reads the surface, the feedwater flow FT and a steam flow meter supply the three-element and predictive controllers, the thermowell TT reads the hot return, and PT reads the vessel pressure.

Each variable in Table 6.1 carries its role in the loop, controlled (CV), manipulated (MV), disturbance (DV) or state. Ten states are integrated. Eight are physical, the vessel's water mass M and internal energy U, the loop enthalpy h_h, the coil metal temperature T_m, the share β of the vessel's vapor mass held below the surface, the feedwater valve position v, the circulation flow $\dot{m}_r$ and the steam user's valve opening a. Two are ledgers that integrate the flows and energy crossing the plant boundary, so that conservation can be checked exactly. Units are seconds, kilograms, kg/s, cubic meters, bar absolute, °C, kJ/kg and kW.



What the level means

Surface (solid line)
$L_{surf} = L_{coll} + L_{sub}$

Collapsed liquid volume (dashed line)
$L_{coll} = 100 M_l v_l(p)/V$

Submerged vapor contribution
$L_{sub} = 100 V_{sub}/V$

Liquid inventory at fixed density
$L_{mass} = 100 M_l/(\rho_{ref} V)$

Density changes separate L_{coll} from L_{mass}.

$M = M_l + M_v$ includes *all* vessel water. Submerged vapor is part of M_v.

Dashed links: instrument taps.
FT: flow, TT: temperature,
PT: pressure, LT: level.

Figure 6.1 Forced-circulation flash steam unit as modeled. The coil at T_m receives Q_g from the gas and gives Q_w to the loop, which holds M_h at h_h and returns $\dot{m}_{ret}$ through the orifice with flash quality x. The vessel of diameter D and effective height H holds total water mass M and water-plus-shell energy U at pressure p, liquid M_l of volume V_l and submerged vapor V_{sub}, so the surface L_{surf} stands above the collapsed level L_{coll}. Feedwater $\dot{m}_f$ at h_{fw} passes the valve v and mixes at the pump discharge. The steam and feedwater FT measurements support three-element control. The panel below the drawing distinguishes volume-based levels from mass-equivalent inventory. Process model only, not a construction or safety piping diagram. Not to scale.

6.3.1 The Vessel and Its Saturation Closure

The vessel holds saturated liquid and vapor at one pressure in a fixed volume V, and its shell, of heat capacity C_d, stays at the saturation temperature, as shown in Equation (6.1).

$$\begin{aligned} M &= M_l + M_v, \qquad V = M_l\, v_l(p) + M_v\, v_v(p) \\ U &= M_l\, u_l(p) + M_v\, u_v(p) + C_d\, T_{sat}(p) \end{aligned} \tag{6.1}$$

where v_l, v_v, u_l and u_v are the specific volumes and internal energies of saturated liquid and vapor. Given M and U, the three equations fix p, M_l and M_v. Eliminating the masses leaves one equation in p, which is solved by Newton's method at every stage of the integrator with the exact slopes of the property interpolant. The iteration always starts at the design pressure, so that the pressure is a function of (M, U) alone and two runs that reach the same state agree to the last bit. It stops when the step falls below 10^{-12} of the pressure. The same solution supplies the two partial derivatives that turn

the balances into a pressure rate, $(\partial U/\partial p)_M$ and $(\partial U/\partial M)_p = (v_v u_l - v_l u_v)/(v_v - v_l)$. At design $(\partial U/\partial p)_M = 34.9\,\text{MJ/bar}$, 1263.6 kg of the water is liquid and 5.43 kg is vapor.

6.3.2 Water and Steam Properties

All properties come from the IAPWS Industrial Formulation 1997 [10], Region 1 for the liquid, Region 2 for the vapor, Region 4 for the saturation line in both directions, and the Region 1 backward equation $T(p,h)$ refined by one Newton step on the forward equation. The implementation reproduces the release's computer-program verification values to better than 2×10^{-9} relative. Between 1 and 20 bar its saturation temperature, specific volumes and enthalpies agree with the IAPWS-IF97 implementations of the *iapws* package and of CoolProp [16] to 4×10^{-15}, and with the scientific formulation IAPWS-95 [17] to 7×10^{-5}, which is the consistency IAPWS-IF97 is designed to have. Because the closure is solved several hundred thousand times per simulated hour, the saturation properties are read from a cubic Hermite interpolant built from the equations at load, with nodes every 0.025 bar from 0.5 to 25 bar. Its largest relative error against the equations is 2.0×10^{-8} for the values and 2.7×10^{-6} for the slopes.

> **+ DID YOU KNOW? A Steam Table Called Millions of Times**
>
> Steam properties are often called millions of times within design calculations, so the steam power industry needs a formulation built for speed [15]. IAPWS-IF97 computes the industrially most important properties on average more than five times faster than the 1967 formulation it replaced [18].

6.3.3 Mass and Energy Balances

The water in the vessel changes by feedwater minus steam minus blowdown, and its energy by the hot return minus the liquid drawn to the pump, the steam, the blowdown and a small loss, as shown in Equation (6.2). Each line is the accumulation balance of Equation (1.1) written for one inventory, as Section 1.4.2 does for a tank.

$$\begin{aligned} \frac{\mathrm{d}M}{\mathrm{d}t} &= \dot{m}_f - \dot{m}_s - \dot{m}_b \\ \frac{\mathrm{d}U}{\mathrm{d}t} &= \dot{m}_{ret} h_h - \dot{m}_r h_l - \dot{m}_s h_v - \dot{m}_b h_l - Q_{loss} \\ M_h \frac{\mathrm{d}h_h}{\mathrm{d}t} &= \dot{m}_r h_l + \dot{m}_f h_{fw} - \dot{m}_{ret} h_h + Q_w \\ C_m \frac{\mathrm{d}T_m}{\mathrm{d}t} &= Q_g - Q_w \end{aligned} \tag{6.2}$$

where $\dot{m}_{ret} = \dot{m}_r + \dot{m}_f$ because the loop holdup is constant, h_l and h_v are the saturated enthalpies at p, h_{fw} is the feedwater enthalpy at its temperature and the feed pump's discharge pressure, and $Q_{loss} = UA_{loss}(T_{sat} - 25\,^\circ\text{C})$, 7.3 kW at design. The circulation leaves and returns, so it cancels from the mass balance, and adding the three energy balances leaves feedwater enthalpy plus gas heat minus steam, blowdown and losses. Flashing is not written as a separate loss. The closure of Equation (6.1) decides how much of the returning energy becomes vapor. Over a 360 s run with blowdown and a demand step, the vessel mass differs from its ledger by less than 10^{-10} of the throughput and the stored energy from its ledger by less than 10^{-9}.

6.3.4 Heat Transfer on Both Sides of the Coil

The coil metal is heated by the gas through an effectiveness and gives heat to the loop water through a conductance that scales with the circulation, as shown in Equation (6.3).

$$\begin{aligned} Q_g &= \varepsilon\, \dot{m}_g c_{p,g} (T_g - T_m) \\ \varepsilon &= 1 - \exp\!\Big(-\frac{UA_g}{\dot{m}_g c_{p,g}}\Big) \\ UA_g &= UA_{g,0} \Big(\frac{\dot{m}_g}{\dot{m}_{g,0}}\Big)^{0.6} \\ Q_w &= UA_{w,0} \Big(\frac{\dot{m}_r}{\dot{m}_{r,0}}\Big)^{0.8} \phi\, (T_m - T_{hot}) \end{aligned} \tag{6.3}$$

where $T_{hot} = T(p_{loop}, h_h)$ and ϕ is the water-side fouling factor. The gas-side conductance is not a parameter but is sized so that the design steam flow comes out at the design pressure. At design the vessel balance fixes $h_{h,0} = 809.1\,\mathrm{kJ/kg}$, the loop balance gives $Q_{w,0} = 4078\,\mathrm{kW}$, the metal sits at $T_{m,0} = T_{hot,0} + Q_{w,0}/UA_{w,0} = 200.5\,^\circ\mathrm{C}$, the required effectiveness is 0.826, and therefore $UA_{g,0} = 34.6\,\mathrm{kW/K}$ with the gas leaving at 244.0 °C. The exponents 0.6 and 0.8 are the usual dependences of gas-side and water-side film coefficients on velocity.

6.3.5 Flashing at the Inlet and Boiling in the Bulk

The hot return carries more enthalpy than saturated liquid at the vessel pressure, and the excess over the latent heat is the equilibrium flash quality. A falling pressure also boils the liquid already in the vessel, because the liquid and the shell must give up the sensible heat that their lower saturation temperature no longer allows, as shown in Equation (6.4).

$$\begin{aligned} x &= \frac{h_h - h_l(p)}{h_v - h_l}, \qquad \dot{m}_{flash} = \dot{m}_{ret} \max(0, x) \\ \dot{m}_{bulk} &= -\frac{\big(M_l\, h_l'(p) + C_d\, T_{sat}'(p)\big)\, \dot{p}}{h_v - h_l} \\ \dot{p} &= \frac{\dot{U} - (\partial U/\partial M)_p \dot{M}}{(\partial U/\partial p)_M} \end{aligned} \tag{6.4}$$

where the primes denote derivatives along the saturation line. At design $x = 4.30\,\%$ and $\dot{m}_{flash} = 1.754\,\mathrm{kg/s}$. Neither rate enters the balances. Both are diagnostics that drive the bubble closure below, and $\dot{m}_{bulk}$ turns negative when the pressure rises, which is how the closure condenses bubbles.

6.3.6 Vapor Held Below the Surface

A share of the vapor generated stays in the liquid for a residence time, and the held share relaxes toward that, as shown in Equation (6.5).

$$\begin{aligned} \dot{m}_{sub} &= \max\big(0,\ \eta\, \dot{m}_{flash} + \eta_b\, \dot{m}_{bulk}\big) \\ \beta^* &= \min\big(\beta_{max},\ \tau_{res}\, \dot{m}_{sub}/M_v\big) \\ \tau_\beta \frac{\mathrm{d}\beta}{\mathrm{d}t} &= \beta^* - \beta, \qquad V_{sub} = \beta\,(V - V_l) \end{aligned} \tag{6.5}$$

where $V_l = M_l v_l$ and βM_v is the vapor mass below the surface. The submerged vapor is part of M_v, so it is counted once, and because $M_v v_v = V - V_l$ it never exceeds the vapor volume and the freeboard never becomes negative. Most of the inlet flash separates at a tangential inlet ($\eta = 0.1$), while vapor formed in the bulk must rise through the liquid ($\eta_b = 0.8$). The two shares are a synthetic teaching closure. With the inlet flash alone, at $\eta = 0.2$, a 25 % demand step swelled the level by only 0.8 points, and the bulk term raises the swell to 3.1 points while keeping the bubble contribution at design at 3.1 points.

6.3.7 Three Levels

Three levels are computed from the state, as shown in Equation (6.6).

$$\begin{aligned} L_{surf} &= 100\,\frac{V_l + V_{sub}}{V}, \qquad L_{coll} = 100\,\frac{V_l}{V} \\ L_{mass} &= 100\,\frac{M_l}{\rho_{ref} V}, \qquad L_{sub} = 100\,\frac{V_{sub}}{V} \end{aligned} \tag{6.6}$$

where $\rho_{ref} = 897.03\,\mathrm{kg/m^3}$ is the saturated liquid density at the design pressure. The simulated transmitter idealizes a surface-level instrument. Actual radar, float and differential-pressure readings depend on foam, phase density and instrument configuration. The collapsed level removes the bubbles but still moves with liquid density. The mass-equivalent level expresses liquid inventory at a fixed reference density. It changes with both boundary flows and internal evaporation or condensation, since $\dot{M}_l = \dot{M} - \dot{M}_v$. Total water mass M, rather than liquid mass M_l, exactly integrates feedwater minus steam and blowdown. Thus $L_{surf} = L_{coll} + L_{sub}$, while $L_{mass} + L_{sub}$ generally differs from the surface away from the design pressure. At design $L_{surf} = 55.00\,\%$, $L_{mass} = 51.89\,\%$ and the bubble contribution $L_{sub} = 100 V_{sub}/V$ is 3.11 points. One percentage point of mass-equivalent level is 24.3 kg of liquid water.

6.3.8 Valves, Pump and Steam User

The feedwater valve follows its target with a first-order lag and a stroking-rate limit, and its flow depends on the feed pump's pressure drop and the line's capacity, as shown in Equation (6.7).

$$\begin{aligned} \frac{\mathrm{d}v}{\mathrm{d}t} &= \mathrm{clip}\Big(\frac{v^* - v}{\tau_v},\ \pm r_v\Big) \\ \dot{m}_f &= \dot{m}_{f,max}\, a_{line}\, f(v)\sqrt{\Delta p_f} \\ \dot{m}_s &= K_s\, a\,\sqrt{\max(0, p^2 - \max(p_{hdr}, 0.55p)^2)} \\ \tau_r \frac{\mathrm{d}\dot{m}_r}{\mathrm{d}t} &= \dot{m}_{r,0}\, u_{pump} - \dot{m}_r, \qquad \tau_a \frac{\mathrm{d}a}{\mathrm{d}t} = a_0 d - a \end{aligned} \tag{6.7}$$

where $f(v) = v$ for the linear trim and $(R_v^v - 1)/(R_v - 1)$ for the equal-percentage option, Δp_f and a_{line} are fractions of design, d is the steam demand as a fraction of the design opening $a_0 = 0.6$, and the valve is blocked at its stops. The target v^* is the controller's command passed through a stiction band S, which holds the stem until the command has moved more than S from the last target and then lets it slip all the way. The compressible steam law chokes when the header falls below 0.55 of the vessel pressure, and $K_s = 0.625\,\mathrm{kg/(s\,bar)}$ is sized so that the design opening passes the design flow at the design pressure. Steam demand is a valve opening rather than a flow, so the pressure decides how much steam leaves.

6.3.9 Instruments

The level transmitter reads the surface through a chain, as shown in Equation (6.8).

$$\begin{aligned} y &= L_{surf} + k_{cal}(p - p_0) + b_L \\ \tau_{LT} \frac{\mathrm{d}y_f}{\mathrm{d}t} &= y - y_f \\ L_m(t) &= q\,\mathrm{round}\Big(\frac{y_f(t - \theta_L) + \sigma_L n(t - \theta_L)}{q}\Big) \end{aligned} \tag{6.8}$$

where $n(t)$ is a unit normal deviate drawn every 0.25 s, $q = 0.05\,\%$ is the quantization, θ_L is a communication delay, and the noise follows the lag so that σ_L is the noise a trend shows. A lost signal is reported as missing with a separate stale value, never as zero. The pressure, feedwater flow, steam

Table 6.2 Model Parameters. All Are Adjustable in the Parameters Panel Unless Marked Derived

Symbol	Meaning	Value	Unit
D, H	vessel diameter, effective height	1.2, 2.4	m
C_d	vessel shell heat capacity	1000	kJ/K
UA_{loss}	vessel loss conductance	0.05	kW/K
$\dot{m}_{s,0}$	design steam flow	1.75	kg/s
p_0	design vessel pressure	8	bar
a_0	steam valve opening at design	60	%
$T_{fw,0}$	design feedwater temperature	105	°C
p_{hdr}	header pressure	6.5	bar
p_{loop}	loop pressure	18	bar
$\dot{m}_{r,0}$, M_h	circulation, loop holdup	39, 2000	kg/s, kg
C_m	coil metal heat capacity	5000	kJ/K
$UA_{w,0}$	water-side conductance	400	kW/K
$\dot{m}_{g,0}$, $T_{g,0}$	design gas flow, temperature	18, 450	kg/s, °C
$c_{p,g}$	flue-gas heat capacity	1.10	kJ/(kg K)
$UA_{g,0}$	gas-side conductance (derived)	34.6	kW/K
K_s	steam valve coefficient (derived)	0.625	kg/(s bar)
η, η_b	submerged shares, inlet and bulk	0.1, 0.8	—
τ_{res}, τ_β	residence, redistribution time	2, 6	s
β_{max}	largest submerged share	0.35	—
$\dot{m}_{f,max}$	feedwater valve capacity	4.0	kg/s
Δp_{ref}	reference valve pressure drop	6	bar
R_v	equal-percentage rangeability (option)	30	—
τ_v, r_v	valve lag, stroking limit	2.5, 6	s, %/s
S	valve stiction band	0	%
τ_r, τ_a	circulation, steam valve response	3, 2	s
τ_{LT}, θ_L	level lag, delay	1.5, 0	s
q	level quantization	0.05	%
k_{cal}	level calibration error	0	%/bar
τ_{FT}, τ_{TT}	flow, thermowell lags	0.5, 5	s

flow and hot-return measurements have default lags of 1, 0.5, 1 and 5 s. The flow lags are τ_{FT} and $2\tau_{FT}$. Pressure noise has standard deviation 0.004 bar, and each flow meter has 0.004 kg/s noise. The hot-return signal has no added noise. Every execution draws the same four deviates whatever the noise settings, so runs that differ in one setting stay comparable sample by sample.

6.3.10 Parameters, Initialization and Numerics

Table 6.2 gives every parameter with its default. Every value is a generic teaching value for a typical industrial unit, chosen so that the design point is consistent rather than measured on a plant. Each case starts in the steady state of its own disturbances. A bisection on the vessel pressure finds where the heat the gas gives up equals the heat the water needs to make the steam the valve passes at that pressure, every other quantity follows from the balances, and the liquid is then placed so that the surface, bubbles included, sits on the setpoint. At 65 % load this gives 8.25 bar and 1.24 kg/s. The derivatives at the initial state are below 10^{-9} of each state's scale. The integrator is the classical fourth-order Runge-Kutta method with a step of 0.05 s, inside the engine of Section 1.6.1. Halving the step changes the peak level of case 5 by less than 10^{-4} points and its integrated error by 0.003 %. A simulated hour costs about 3 s of computing in a browser engine.

6.3.11 Assumptions

The vessel is in saturated equilibrium, so stratification, subcooled pockets and delayed nucleation are absent, and the model is least reliable for a very fast depressurization. The loop is one well-mixed holdup at a fixed pressure and the coil one metal node. The water residence time is $M_h/(\dot{m}_r + \dot{m}_f) = 49$ s at design, while the coil metal introduces an additional thermal state. These coupled dynamics are not a single 49 s lag or a distributed exchanger with transport delay. Pump work, pump curves and pipe hydraulics are omitted. The constant-pressure loop uses $M_h h_h$ as its lumped energy store

and neglects changes in $p_{loop}V_{loop}$. The bubble closure of Equation (6.5) is a synthetic teaching closure, not a prediction for a particular inlet device or water chemistry. The vessel has the constant cross-section of a vertical cylinder, so a horizontal vessel's changing area is not represented. The run stops rather than continue outside the model: when the vessel pressure leaves the range from the header pressure to 12.5 bar, the hot return comes within 3 K of boiling at the loop pressure, or the circulation falls below 45 % of design. These are conservative model-domain checks, not predictions of boiling onset or equipment damage.

6.4 Dynamic Character

6.4.1 An Integrator in the Water

Neglecting the small change in vapor mass, liquid inventory integrates the flow imbalance, as the pumped tank of Equation (1.9) does, with a gain of $100/(\rho_{ref}AH) = 0.041\,\%/\mathrm{s}$ per kg/s. One percent of valve passes 0.04 kg/s at the design pressure drop, so the single-element process gain is 0.001 64 %/s per percent of valve. In case 1 a four-point valve step adds 0.16 kg/s and the level climbs from 55.0 to 56.0 % in 150 s. The circulation of 39 kg/s, 22 times the steam flow, appears nowhere in that figure. The level of Chapter 9 is an integrator for the same reason.

6.4.2 Swell and Shrink From the Steam Side

A step in steam demand changes the outflow at once and the heat supply not at all. In case 2 the steam flow jumps from 1.75 to 2.09 kg/s, the pressure falls at about 0.018 bar/s, and bulk boiling reaches 0.31 kg/s four seconds after the step. With the vapor that holds below the surface, the surface reaches 58.0 % ten seconds after the step while the inventory has fallen to 51.78 %, as shown in Figure 6.2a. As the pressure settles toward 7.52 bar the bulk boiling stops and the bubbles clear, and by 600 s the surface is at 53.8 % and the inventory at 50.65 %, still falling because the coil's steam exceeds the fixed feedwater. The decay follows the pressure settling time, the vessel's energy capacity divided by the latent heat times the steam valve's slope, $(\partial U/\partial p)_M/\left(h_{fg}\,\partial \dot{m}_s/\partial p\right) \approx 26.5\,\mathrm{s}$ at design.

> **TRY IT IN THE APP** **2 · More Steam Demand and a Rising Level (Manual)**
>
> Load the case, set the Teaching overlay to show the simulator truth, and press Run. At 90 s the steam user's valve opens a quarter further while the feedwater valve stays put. Watch the level and the water inventory: ten seconds after the step the level stands at 58.0 % while the inventory has fallen from 51.90 to 51.78 %.

This is the inverse response of Section 1.4.7. The steam valve acts on the indicated level through two paths of opposite sign. The inventory path integrates the water lost, while the bubble path answers within seconds through the pressure and decays with it, so the level first moves the wrong way. Chapter 7 has the other classical case, in which the fast path is the water column of a penstock.

Pause. Try Exercise 6.1 before reading on.

A step down does the reverse. In case 3 a 25 % demand cut raises the pressure, the negative bulk rate condenses the bubbles, and the surface drops from 55.0 to 52.4 % in 18 s while the inventory rises from 51.90 to 52.13 %, as shown in Figure 6.2b. The feedwater step that follows at 330 s makes no shrink at all. Thirty degrees colder feedwater, mixed into 39 kg/s of loop water, lowers the coil inlet by about 1.3 °C. It reduces the steam the coil can make, the pressure eases, and the bubble contribution grows slightly, from 2.57 to 2.81 points, while the level keeps rising with the inventory.

Pause. Try Exercise 6.2 before reading on.

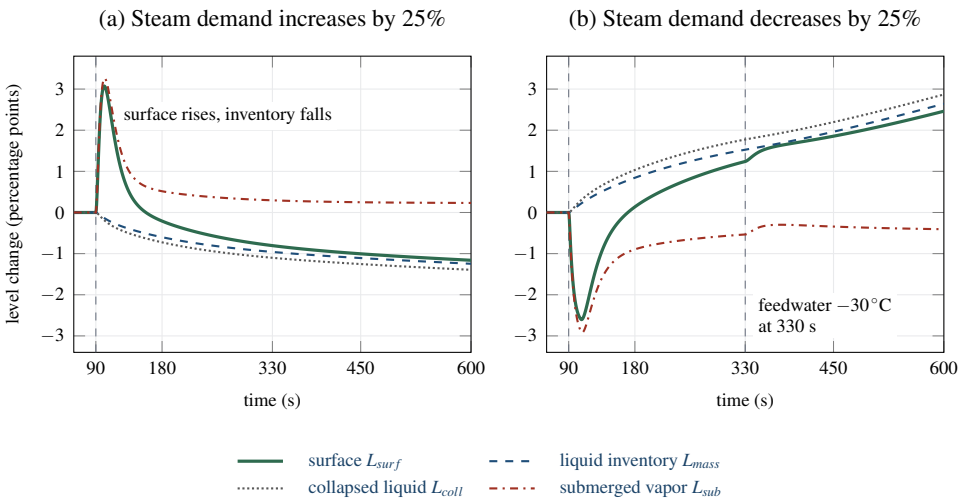


Figure 6.2 Open-loop swell and shrink, from the simulator in Manual. Deviations from the values at 60 s of the surface (thick solid), the mass-equivalent inventory (dashed), the collapsed liquid level (dotted) and the bubble contribution (dash-dotted). Both panels use the same axes, and dashed vertical lines mark the input changes. At every instant $\Delta L_{surf} = \Delta L_{coll} + \Delta L_{sub}$, while density changes separate collapsed level from mass-equivalent inventory. In (a) the surface rises 3 points while the inventory falls, and in (b) it falls 2.6 points while the inventory rises, and the colder feedwater at 330 s produces no shrink.

> **TRY IT IN THE APP** **3 · A Demand Cut Shrinks; Cold Feedwater Does Not (Manual)**
>
> Load the case and run it past 330 s. The demand cut at 90 s drops the level from 55.0 to 52.4 % in 18 s while the inventory rises to 52.13 %. Then watch the bubble trend through the feedwater step at 330 s: no shrink appears, and the bubble contribution creeps up from 2.57 to 2.81 points.

6.4.3 A Steam Production the Heat Decides

In a fired boiler the firing rate follows the load. In a heat-recovery unit the heat is set upstream, so a larger valve opening draws on stored energy only until the pressure has fallen far enough for the opening to pass what the heat supports. After the 25 % step of case 2 the steam flow returns to 1.77 kg/s within ten minutes, against a design of 1.75. A loss of heat is the disturbance that changes production for good. With the flue gas at 75 % in case 6, the heat to the water falls from 4.08 to 3.29 MW, the pressure from 8.00 to 7.52 bar and the steam from 1.75 to 1.42 kg/s, less than in proportion to the gas because the coil's effectiveness rises as the gas slows. These two facts decide the control problem. The inverse response comes from the pressure, so the steam flow is the measurement worth feeding forward, and the level controller can only match the feedwater to the steam that the heat makes.

6.5 Implemented Control System

The controllers execute every $\Delta t_c = 0.25$ s, the scan of the inner flow loop and of the instruments. The level loops run on their own period T_o of 1, 3 or 6 s and the MPC every 2 s, within the engine step of Section 1.6.1, whose plant-side bookkeeping here covers ramps, stiction and protection. The only interface between the simulator and the controllers is a measurement packet holding the transmitter readings of Equation (6.8), their quality flags and their time, and a test of the application fails if the packet ever carries anything else.

6.5.1 Single-Element PID

The single-element loop is the velocity-form PID of Section 1.6.2 with the derivative on the measurement, run every T_o on the measured level filtered by a first-order lag of $\tau_f = 2\,\mathrm{s}$, as shown in Equation (6.9).

$$\begin{aligned} e_k &= L_{SP} - L_{f,k}, \qquad P_k = K_c e_k \\ D_k &= -K_c \tau_D \dot{L}_{f,k} \\ s_k &= s_{k-1} + (P_k - P_{k-1}) + (D_k - D_{k-1}) \\ \hat{u}_k &= s_k + I_{k-1}, \qquad u_k = \min\big(100,\ \max(0,\ \hat{u}_k)\big) \\ I_k &= I_{k-1} + \Big[\frac{K_c}{\tau_I} e_k + \frac{u_k - \hat{u}_k}{\tau_I}\Big] T_o \end{aligned} \tag{6.9}$$

where u is the valve command in percent. The symbols map onto Equations (1.24) to (1.27) with $s_k = S_k$, $\hat{u}_k = v_k$, the bias folded into I, and the tracking time T_t equal to τ_I. A low level opens the valve, so the loop is reverse acting in the instrument sense. Setting the integral time to its maximum of 3000 s removes integral action. The defaults are $K_c = 4\,\%$ per percent, $\tau_I = 600\,\mathrm{s}$ and $\tau_D = 0$. For an integrating process of gain K a PI loop is critically damped at $\tau_I = 4/(KK_c)$, which is 609 s at the default gain.

6.5.2 Three-Element Cascade

The three-element loop sets a feedwater-flow setpoint from the filtered steam flow, the metered blowdown and a level trim, and an inner PI makes the valve deliver it, as shown in Equation (6.10).

$$\begin{aligned} \dot{m}_{f,SP} &= \underbrace{\bar{\dot{m}}_s + \dot{m}_b}_{\text{feedforward}} + \underbrace{\mathrm{PI}_3(L_{SP} - L_f)}_{\text{trim}} \\ v^{cmd} &= \mathrm{PI}_F(\dot{m}_{f,SP} - \dot{m}_{f,m}) \end{aligned} \tag{6.10}$$

where $\bar{\dot{m}}_s$ is the measured steam flow through a 2 s lag. The outer loop is the same velocity-form PID with the feedforward as its bias, an output range of 0 to $\dot{m}^{SP}_{f,max}$ and a rate limit, both shared with the MPC so that comparisons between them are fair, at defaults of 3.5 kg/s and 0.2 kg/s per second. When the inner loop pins the valve, the outer range collapses onto the measured flow, so the outer integral cannot wind up against a flow that is not coming. The gains keep their own units: 0.15 kg/s per percent of level with $\tau_I = 600\,\mathrm{s}$ for the trim, and 20 % of valve per kg/s with $\tau_I = 2.5\,\mathrm{s}$ for the flow loop, which reaches 63 % of a flow step in 2.8 s with 0.8 % overshoot. With the level signal lost the trim is frozen and the setpoint keeps following the steam flow. Volume 3, Chapter 2 compares flow feedforward and a level-to-flow cascade on a tank whose two disturbances enter by different routes.

Every controller that is not driving the valve tracks the one that is, by solving its integral for the present command, so Manual to Auto, a change of architecture and an MPC fallback are all bumpless. In case 14 each of three transfers moves the valve by less than 0.4 %.

6.5.3 Inventory Estimator

A four-state Kalman filter [11] reconstructs the inventory from the measurements alone. Volume 5, Chapter 12 estimates another inventory that no instrument measures, the ammonia stored on a catalyst. Its state is $\hat{x} = [\hat{M},\ \hat{b},\ \hat{d},\ \hat{y}]$, the water mass, the bubble contribution in level points, an unexplained imbalance such as a meter bias, and the transmitter's lagged view of the surface, predicted every

0.25 s as shown in Equation (6.11).

$$\begin{aligned}
\hat{M}^{+} &= \hat{M} + \Delta t_c(\dot{m}_{f,m} - \dot{m}_{s,m} - \dot{m}_b + \hat{d}) \\
\hat{d}^{+} &= \hat{d} \\
\hat{b}^{+} &= \hat{b} + (1 - \mathrm{e}^{-\Delta t_c/\tau_\beta})(b^{*} - \hat{b}) \\
\hat{y}^{+} &= \hat{y} + (1 - \mathrm{e}^{-\Delta t_c/\tau_{LT}}) \\
&\qquad \times \left(L_{coll}(\hat{M}, p_m) + \hat{b} - \hat{y}\right)
\end{aligned} \tag{6.11}$$

where b^{*} is the bubble contribution that the controller's own copy of Equation (6.5) expects from the measured pressure, its filtered rate, the hot-return temperature and the flows. The covariance is propagated with a local linearization that holds the calculated b^{*} fixed, with process noise of $(0.02\,\Delta t_c)^2\,\mathrm{kg}^2$ on the mass, $0.25^2\Delta t_c$ on the bubbles and $0.0006^2\Delta t_c$ on the imbalance, plus 10^{-6} on the transmitter-state variance per scan. Each good level sample corrects the state against $\hat{y}$ as it was one declared delay earlier, with $R = \max(0.05, \sigma_L)^2 + q^2/12$. Delayed samples use a buffered predicted reading with the current covariance, an approximation rather than a full out-of-sequence Kalman update. The quality flag reads lost after 5 s without a level, inconsistent for 120 s after an innovation larger than five standard deviations, degraded when the inventory is uncertain by more than 1.5 points or the filtered normalized innovation exceeds 6, and good otherwise. The estimator's parameters are a copy of the plant's taken when the case starts, and they change only when the reader updates the controller model.

6.5.4 Model Predictive Control

The MPC sets the feedwater-flow setpoint every 2 s through the same inner flow loop. It is the option of Section 1.6.3 with a model of its own. That model is a local linear one, rebuilt at every execution from the measurements, the estimate and the controller's copy of the parameters, as shown in Equation (6.12).

$$\begin{aligned}
\dot{x}_1 &= x_3 - (\dot{m}_{s,m} + \dot{m}_b - \hat{d}), \qquad \dot{x}_3 = (u - x_3)/\tau_{fl} \\
\dot{x}_2 &= \left(k_b\dot{m}_{s,m} + K_{bf}(x_4 - \dot{m}_{s,m} - \dot{m}_b) - x_2\right)/\tau_b \\
\dot{x}_4 &= (x_3 - x_4)/\tau_{th} \\
y_1 &= L_{coll}(\hat{M}) + c_{coll}x_1 + x_2 \\
y_2 &= L_{mass}(\hat{M}) + c_{mass}x_1
\end{aligned} \tag{6.12}$$

where x_1 is the water mass relative to the estimate, x_2 the bubble contribution starting at $\hat{b}$, x_3 the delivered feedwater with $\tau_{fl} = 4\,\mathrm{s}$, and x_4 the feedwater as the loop's thermal holdup has seen it, with $\tau_{th} = M_h/(\dot{m}_r + \dot{m}_f)$, 49 s at design. The steady bubble contribution at the measured steam flow is $k_b\dot{m}_s$ with $k_b = 100\tau_{res}\eta v_v/V = 1.77\,\%$ per kg/s, extra feedwater lowers it by $K_{bf} = -k_b(h_l - h_{fw})/h_{fg} = -0.24\,\%$ per kg/s, and an estimated swell decays in τ_b, the pressure settling time plus τ_β. Its steam-flow slope is $\partial\dot{m}_s/\partial p = \dot{m}_s p/(p^2 - p_{hdr}^2)$ before choking and $\dot{m}_s/p$ when $p_{hdr} \le 0.55p$. That decay is the piece of physics the PID loops do not have. The model is discretized exactly for a zero-order hold, with the affine term mapped step by step so that a forecast of the steam flow can enter. The quadratic program over a 120 s horizon of 60 steps, in twelve blocks of 10 s, is Equation (6.13).

$$\begin{aligned}
\min\ & \textstyle\sum_{k=1}^{60} w_L(y_{1,k} - L_{SP})^2 + \sum_j \frac{w_{\Delta u}}{0.1^2}(u_j - u_{j-1})^2 \\
& \quad + 10^3 s_L^2 + 10^2 w_M s_M^2 \\
\text{s.t. } & 0 \le u_j \le \dot{m}_{f,max}^{SP}, \qquad |u_j - u_{j-1}| \le r_f\,2\,\mathrm{s} \\
& L_{LA} - s_L \le y_{1,k} \le L_{HA} + s_L \\
& \bar{L}_m - \Delta_M - s_M \le y_{2,k} \le \bar{L}_m + \Delta_M + s_M, \quad s \ge 0
\end{aligned} \tag{6.13}$$

Table 6.3 The Fifteen Cases

#	Case and events	Teaching point
1	Manual, valve +4 points at 90 s	the water balance
2	Manual, demand +25 % at 90 s	swell
3	Manual, demand −25 % at 90, feed −30 °C at 330 s	shrink, and none from feed
4	Single, P-only; SP 55 to 59 and back; blowdown at 540 s	P, PI and PID
5	Demand +20 % at 120, back at 480 s	three-element control
6	Flue gas to 75 % over 120–240 s, back at 600 s	heat sets the steam
7	Single; feed pressure drop to 65 % at 120, back at 420 s	flow loop, stiction
8	Single, noise 1 %; demand +20 % at 180 s	filter, sampling, delay
9	MPC; fouling, circulation 70 %, foaming at 1100 s	model mismatch
10	Level bias +4 at 120, signal lost 480–510 s	lying transmitter
11	Demand +25 % at 120, back at 660 s, shared limits	MPC against PI
12	MPC; published gas schedule +25 % at 240 s	forecast value, error
13	Feed line capped at 1.0 kg/s at 120 s	an infeasible balance
14	Start at 65 % load, ramp to design; pump trip	transfers, protection
15	Challenge: four upsets in 1800 s, P-only as shipped	the whole problem

where $w_L = 1$, $w_{\Delta u} = 2$, $w_M = 1$, the level band is the warning band from 30 to 75 %, and the inventory zone is $\pm\Delta_M = \pm 5$ points around $\bar{L}_m$, the estimator's inventory when the case started. The program is solved by the dual active-set method of Goldfarb and Idnani [19] in the solver module the apps share, with 14 variables and 290 constraint rows, and the first move is applied, as in industrial MPC [20]. The estimated imbalance $\hat{d}$ in the model removes offset [12]. A solution that is not optimal, finite and inside its bounds is rejected, and the tracked three-element trim takes the flow setpoint without a bump. If the level has been missing for more than 60 s the MPC is not run and the setpoint follows the steam flow. Over the 599 executions of case 11 no constraint was active, the program never failed, and a whole solve took a median of 0.07 ms.

6.5.5 Protection and the Three Models

A protection layer outside every controller reads the simulator's truth and stops the run at a surface of 18 or 88 %, an inventory of 20 %, the model-domain limits of the assumptions, or an operator's controlled stop. The app names this an exercise stop. A stop latches its reason, marks the trends, freezes the state and pauses the run, and only Reset continues. The application keeps three models apart. The plant is everything in Section 6.3. The identified model is the integrating gain a reader fits from case 1. The controller's model is the estimator's and MPC's copy of the parameters and the reduced structure of Equations (6.11) and (6.12), which knows neither the transmitter bias nor a plant change made after the case started.

6.6 Fifteen Cases, Measured

The fifteen cases appear in Table 6.3. All share one reference configuration (the default tunings above, three-element control, transmitter noise of 0.2 % and the design disturbances) and depart from it only as their rows say. Every number in this section was measured with the engine running headless on the default seed (Section 1.6.1), stepped exactly as the browser steps it, and any setting a row names is entered before the run starts. The exported file carries each measurement beside the truth it measures, in columns whose names begin with `truth_`. Integrated absolute error (IAE) is taken on the true surface against the setpoint from $t = 0$ to the end of the run named, peak deviations on the true surface, and valve travel as the total movement of the stem in percent. Every case also loads identically whether it is selected first, chosen from the list after another case, or rerun with Reset.

6.6.1 Tuning an Integrating Level

Case 4 ships a proportional-only single-element loop at 2 % per percent. The setpoint ramps come out without offset, because the vessel integrates, but once the blowdown takes 0.15 kg/s away the level settles 1.48 % below setpoint over the last 180 s of the 1200 s run. A proportional controller holds

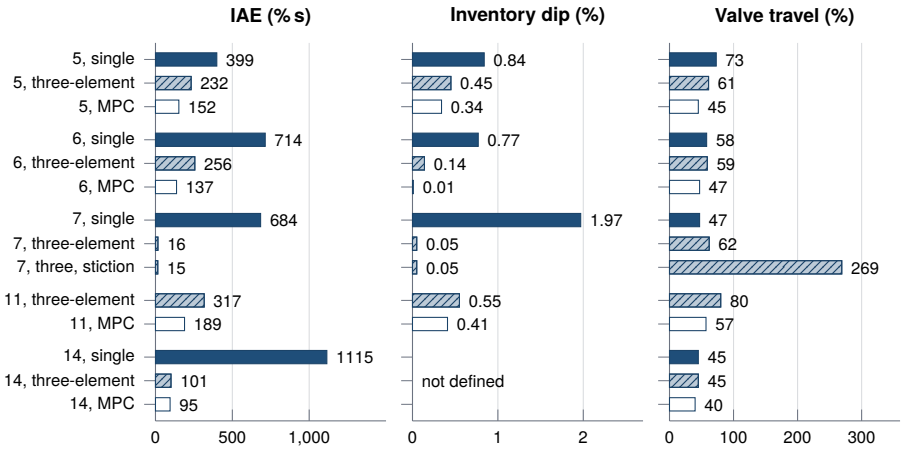


Figure 6.3 The measured comparisons of Table 6.4: single-element control (solid bars), three-element control (hatched) and the MPC (open), with the case number before each controller. Case 14 moves to a new inventory, so it has no dip. Notice that in cases 5, 6 and 11 the MPC has the smallest IAE and dip, and that the stiction band of case 7 more than quadruples the valve travel while the IAE and the dip stay where they were.

the valve away from its starting point only while there is an error. With $K_c = 8$ and $\tau_I = 300\,\text{s}$, near critical damping, the worst error in the same window is 0.19 %, and $K_c = 15$ with $\tau_I = 100\,\text{s}$ reaches 0.04 % at the cost of 39 s saturated and 363 % of valve travel. Adding $\tau_D = 20\,\text{s}$ to $K_c = 6$, $\tau_I = 400\,\text{s}$ raises the travel from 149 to 1947 % with no gain in level, because the derivative differentiates the transmitter noise.

6.6.2 Single Element, Three Element and MPC

The architectures are compared case by case in Table 6.4, and Figure 6.3 draws the same numbers as bars. On the demand steps of case 5 the swell peaks at 57.5 % under every controller, because no feedwater move can stop the pressure from falling within seconds. What changes is the recovery. Single-element control reads the swell as too much water and closes the valve as the vessel empties, with an inventory dip of 0.84 points, while three-element control raises the feedwater with the steam and dips 0.45 points with less valve travel. The MPC, whose model expects the swell to clear, dips 0.331 to 0.349 points depending on the baseline definition, with the least travel. In case 7 the flow loop catches a weaker feed pump within seconds, and the level moves 0.08 points under three-element control against 1.96 points under single-element control. A stiction band of 3 % makes the flow loop hunt, raising the travel from 62 to 269 % while the level still holds within 0.08 points.

> ✦ **DID YOU KNOW? A Swell No Controller Can Stop**
>
> From the simulator: on the demand steps of case 5 the true surface peaks 2.49 points above its setpoint under single-element control, three-element control and the MPC alike. The controllers differ only afterward, with inventory dips of 0.84, 0.45 and 0.34 points (Table 6.4).

The limits of case 11, a flow setpoint of 2.9 kg/s and a rate of 0.06 kg/s per second shared by both controllers, never bind, because a demand step raises the steam only until the pressure has settled. The MPC's advantage there, an IAE of 189 against 317 % s with 57 against 80 % of valve travel, therefore comes from prediction and not from constraint handling. Its inventory-zone slack appears in case 13, where the feed line is capped at 1.0 kg/s against 1.75 kg/s of steam. There the MPC reports a slack from 300 s that grows to 25 points while it keeps asking for 3.5 kg/s it cannot

Table 6.4 Measured Comparisons. IAE on the True Surface Over the Whole Run, Peak Deviation, Inventory Dip and Valve Travel

Case	Controller	IAE (% s)	Peak (%)	Dip (%)	Travel (%)
5, 900 s	single	399	2.49	0.84	73
	three-element	232	2.49	0.45	61
	MPC	152	2.49	0.34	45
6, 1200 s	single	714	1.34	0.77	58
	three-element	256	0.37	0.14	59
	MPC	137	0.41	0.01	47
7, 900 s	single	684	1.96	1.97	47
	three-element	16	0.08	0.05	62
	three, stiction 3 %	15	0.08	0.05	269
11, 1200 s	three-element	317	3.09	0.55	80
	MPC	189	3.09	0.41	57
14, 900 s	single	1115	2.21	—[a]	45
	three-element	101	0.41	—[a]	45
	MPC	95	0.40	—[a]	40

[a]Case 14 moves from the part-load to the design inventory, so no dip is defined.

get, and the low-inventory stop comes at 1060 s, against 1059 s under three-element control and 964 s under single-element control, which opens the valve late. With an imbalance of 0.75 kg/s and 24.3 kg per point the inventory falls about 1.85 % a minute. The stop comes a little sooner than that predicts because the steam rises from 1.75 to 1.83 kg/s as less cold feedwater leaves more of the coil's heat for steam. Closing the steam valve does not help, since the heat still has to leave as steam, and the actions that end the deficit are a gas bypass or a controlled stop.

🕮 **Pause.** Try Exercise 6.3 before reading on.

6.6.3 Noise, Delay, Mismatch and a Lying Transmitter

With 1 % of transmitter noise in case 8, the shipped loop moves its valve 1059 % over 900 s with no level filter, 216 % with the default 2 s filter and 81 % at 8 s, with IAE of 260, 222 and 225 % s. On that slow loop the filter is nearly free. On an aggressive loop ($K_c = 20$, $\tau_I = 60$ s) a 12 s filter with 6 s sampling and a 4 s delay raises the IAE after the step from 156 to 279 % s and deepens the dip after the step from 1.6 to 2.6 points.

In case 9 the MPC runs through water-side fouling to 75 %, a circulation cut to 70 % and, at 1100 s, foaming water that doubles the submerged shares. The estimate follows the first two within 0.02 points of the true inventory, because their effects reach it through measured temperatures and flows. The foam changes a parameter no measurement shows. The estimator explains the higher surface as water, the MPC holds the surface on setpoint, and the true inventory falls to 48.5 % while the estimate stays near 52.0 %, with the residual small and the quality good. Updating the controller model at 1200 s brings the estimate within 0.5 points of the truth by 1450 s. In case 10 a four-point transmitter bias appears at 120 s. It is twenty standard deviations of the noise in one sample, so the estimator flags the level inconsistent for 120 s, and then it absorbs the bias as water. The controller drives the true surface to 50.4 % and the inventory to 47.3 % while the estimate reads up to 53.0 %. During the 30 s loss of signal the estimator carries on with the flows and its $\pm 2\sigma$ band grows only from 0.27 to 0.30 points.

6.6.4 Forecasts and the Load Change

Case 12 publishes the upstream process's production plan, 25 % more flue gas over 30 s from 240 s and back from 780 s. The forecast scales the measured steam by the 0.6 power of the scheduled gas flow, the dependence of Equation (6.3). The MPC's IAE over 1200 s is 119 without preview, 112 with it, and 124 % s when the schedule runs 45 s late, worse than no preview because the MPC feeds water for steam not yet made. The three-element loop given the same forecast as a feedforward 30 s

Table 6.5 The Challenge Over 1800 s

Configuration	IAE (% s)	Travel (%)	Final (%)	Verdict
single, P-only, $K_c = 1.5$ (shipped)	2123	43	3.65	fails
single, $K_c = 8$, $\tau_I = 300$ s	476	233	0.07	fails
three-element, defaults	316	104	0.15	fails
three-element, 0.20, 600 s, $\tau_f = 4$ s	297	104	0.11	passes
MPC, defaults (suggested)	175	72	0.01	passes

ahead scores 228 against 217 % s without it. In case 14, starting at 65 % load and ramping to design over five minutes, three-element control and the MPC hold the surface within 0.41 and 0.40 points, while single-element control strays 2.21 points and ends the run 1.8 points low. A circulation pump trip ends that case on loss of circulation within about 2 s.

6.6.5 The Challenge

The challenge holds 55 % through a 20 % demand rise at 150 s, feedwater 15 °C colder at 510 s, 15 % less flue gas from 870 s and the demand's return at 1230 s. Its target is no exercise stop, an IAE of at most 300 % s after 150 s, valve travel of at most 150 % over the run, and the true surface within ±0.5 % of setpoint over the last 180 s, judged every physics step. Five configurations are listed in Table 6.5. The proportional-only loop it ships with ends 3.65 % off setpoint. Tuning trades IAE against travel, so the three-element loop passes only in a narrow window, while the MPC at its defaults passes with the widest margin on both budgets. The swell of case 2 near its peak is shown in Figure 6.4.

6.7 Technology in Practice

The unit of Section 6.3 reads its level through the chain of Equation (6.8) and moves one feedwater valve. Figure 6.5 draws the three-element loop with plant devices.

What Measures It

A level instrument on a boiling vessel turns a pressure difference or an echo time into a height, and each conversion needs a property of water or steam. A differential-pressure transmitter weighs the column between its taps. In a vessel of constant area that weight follows the mass of liquid whatever its density [21], so the reading sits closer to the chapter's mass-equivalent level than to the surface. A radar transmitter times an echo through the vapor, and its accuracy shifts with the pressure and temperature of that vapor, the gas phase effect [21]. The term $k_{cal}(p - p_0)$ of Equation (6.8) stands for such a pressure-dependent calibration. An orifice meter reads flow as the square root of its pressure drop divided by the density, and a steam table gives that density for steam [21]. No range, accuracy or response time is given here, because none was found in an open source that names no maker.



Figure 6.4 The swell of case 2 near its peak, captured at $t = 104$ s (the clock is in the cut header), on the Level and inventory view with the teaching overlay on. The figure is a composite of the view on top, the controller's readout line in the middle and the trends below, with the other panels cut. The vessel (1) stands beside a zoomed comparison in which the transmitter reads 58.0 % (2) and the estimator splits its 58.1 % surface estimate into collapsed liquid volume and submerged vapor (3). Black ticks show mass-equivalent inventory separately, including the estimate of 51.8 % (±0.3, two standard deviations) and true liquid inventory of 51.7 %, against a surface setpoint of 55 %. The readout line (4) shows Manual with the feedwater valve fixed at 43.8 %. Over a two-minute window the trends show the level rising after the 90 s step (5), the steam flow at 2.03 kg/s against 1.75 kg/s of feedwater, the inventory estimate on top of the truth, and the bubble contribution climbing to 6.3 points from the design value of 3.1 points given after Equation (6.6), which the trend axis does not print.

> **TECHNOLOGY** **Sensor: A Differential-Pressure Level Transmitter on a Steam Vessel**
>
> A differential-pressure transmitter compares the pressure at a tap low on the vessel with the pressure in the vapor space, so the vessel pressure cancels and the output is the head of the liquid alone. On a steam vessel the upper impulse line fills with condensate and becomes a wet leg, whose constant head a zero shift removes. Seal pots are standard on boiler drums, because a wet leg that loses water gives readings in error until steam condenses to refill it. Turning the head into a height needs the density, and hot water at power-boiler temperatures can weigh little more than half as much as cold water [21].

What Moves It

The feedwater valve of Equation (6.7) follows its target with a lag of 2.5 s, a stroking limit and an optional stiction band. A plant valve has a pneumatic actuator, and a positioner corrects the difference

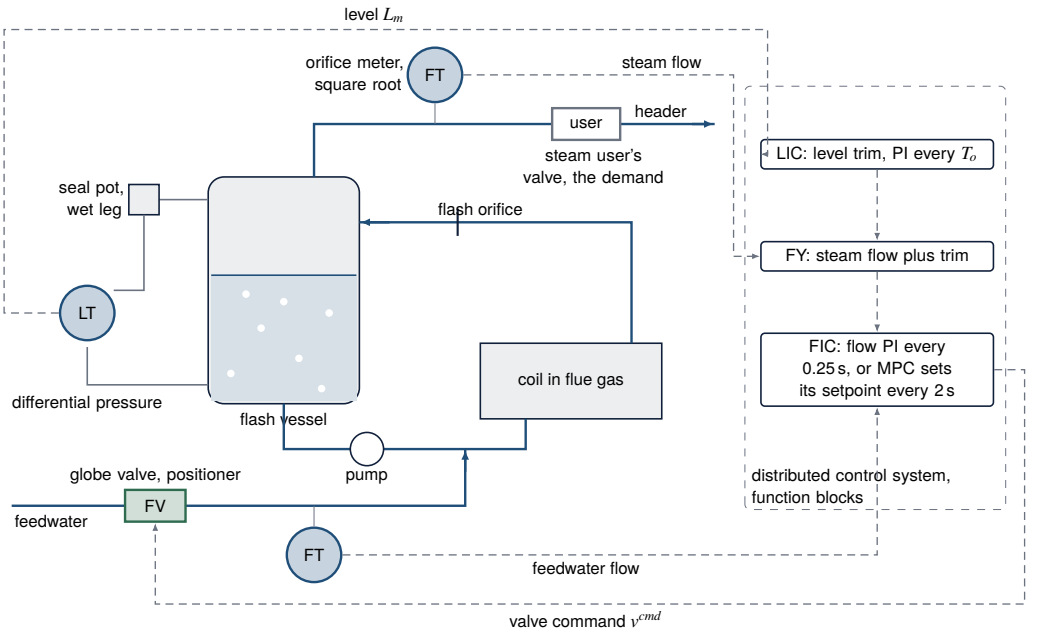


Figure 6.5 The three-element loop of the chapter with plant devices in place of the schematic's symbols. LT reads the level as a differential pressure through a wet leg kept full by a seal pot, an orifice meter reads the steam flow, and on the control platform the steam flow plus the level trim becomes the setpoint of the feedwater flow controller, which moves the globe valve. Notice that the flow loop sits between the level controller and the valve, so a change in feed pressure is corrected before the level sees it.

between the commanded and the actual stem position [21].

> **TECHNOLOGY** **Final Element: Feedwater Valves in Split Range**
>
> A large boiler may feed its drum through two valves in sequence. The small valve opens over the first half of the controller's signal and the large one over the second half. At full power the small valve stands wide open and the large one throttles, while at low power the small one throttles alone. The pair controls the drum level better over the whole range than any single valve. Inside a flow loop, a change in feed pressure is countered before the level is upset [21].

Where the Controller Runs

A distributed control system controls production in industries such as electric power generation and chemical manufacturing. Its loops may be nested or cascaded, with the setpoint of one loop taken from the measurement of another, and they run with cycle times from milliseconds to minutes [22]. The chapter's inner loop and instruments run every 0.25 s, the level loops every 1 to 6 s and the MPC every 2 s, all inside that range. Three-element control is built from standard blocks: a flow controller whose remote setpoint comes from a summing block that adds the steam flow to the level controller's trim [21], the arrangement of Equation (6.10).

> **IN PRACTICE** **Which Water Formulation a Contract Names**
>
> In the steam power industry IAPWS-IF97 is the standard for contracts and tests, while scientific work prefers the more accurate IAPWS-95. The industrial formulation divides its range into five regions, with small discontinuities at their boundaries, and it is weakest near the critical point [15]. Before a property routine is trusted, the release asks that each programmed equation be checked against its tables of test values in eight-byte arithmetic [18]. Because so much rests on it, the industry wants to change its formulation only about every 30 years [15].

What Is Modernizing It

Two developments touch this unit. The first is fast property calculation. An IAPWS guideline describes spline tables that reproduce IAPWS-IF97 at high speed for the simulation of transients and for real-time optimization. It finds the pressure of a two-phase state from its specific volume and internal energy by a one-dimensional Newton iteration [23], the same problem as the closure of Equation (6.1). In flow simulations the spline tables cut the computing time by factors of 6 to 10 [23]. The second is model-based level control. Unplanned reactor trips caused by steam generator level control have been significant contributors to the unavailability of nuclear plants, and there the only true sign of an inventory change is the mismatch between steam and feedwater flows [24]. A predictive controller pairs an estimator of the plant state with an optimizer of future moves [24], the structure of Section 6.5.

6.8 Limitations

The sizes and settings are generic teaching values that make a consistent design point, a 4 MW coil and 6.3 t/h of steam at 8 bar, without being fitted to any unit. The vessel is in saturated equilibrium and the loop and coil are lumped, so the model cannot say where in the vessel the vapor sits or how a temperature front travels through the coil. The bubble closure is synthetic, so the size and timing of the swell are plausible for a teaching unit rather than predicted for a particular vessel, inlet device or water chemistry, and case 9 changes the closure on purpose to show what that means for an estimator. Pump curves, pipe hydraulics, carryover and the chemistry behind foaming are outside the model.

The estimator and the MPC carry a reduced structure with the plant's own declared parameters, so they meet model error only where a case introduces it. The MPC's model omits the gas side and sees heat changes only through the measured steam flow, and its linear prediction is rebuilt every 2 s without any guarantee beyond the horizon. The protection layer reads the truth and is an educational guardrail, not certified trip logic, and a stop freezes the simulation rather than model a shutdown. The disturbances arrive as scheduled steps and ramps rather than as the habits of a real process.

> **OPEN CHALLENGE** **Better Data for the Next Water Formulation**
>
> IAPWS-IF97 was fitted to IAPWS-95 [15], and IAPWS plans to replace IAPWS-95 because new data exist and its functional form has shortcomings. The replacement needs saturation vapor pressures above 373 K measured to 0.02 % or better and liquid densities near saturation above about 400 K to 0.01 %. The metastable fluid inside the two-phase envelope is difficult or impossible to measure, so molecular simulation is asked to fill the gap, and uncertainty estimates for calculated properties are still somewhat ad hoc [25]. Progress would be those measurements, a prescription for the uncertainty of any calculated property, and a formulation built on both.

6.9 Conclusion

This chapter studied a flash vessel on a heat-recovery loop, a plant whose level reads water plus the vapor below the surface. Its simulator logs the indicated level, the inventory and the bubbles side by side from balances closed by IAPWS-IF97. A 25 % rise in steam demand swells the surface 3.0 points in ten seconds while the vessel loses water, a 25 % fall shrinks it 2.6 points while it fills, and the tested 30 °C feedwater cooling causes no initial shrink, because the loop heats it first. Steam production

follows the heat, so a demand step changes the outflow only until the pressure settles. On the demand steps of case 5 three-element control cuts the IAE from 399 to 232 % s against single-element control, and the MPC reaches 152 % s with the least valve travel because its model expects the swell to clear. The inventory estimate follows fouling and lost circulation within 0.02 points but is misled by foaming water and by a persistent transmitter bias, which it flags only in the first 120 s. The model is lumped and its closure synthetic. A fuller model would add a distributed coil with transport delay, a horizontal vessel, a pressure loop with its own actuator, and a bubble closure fitted to a measured transient. The simulator shows that a level controller has to know what its transmitter is measuring before it can act on it.

KEY POINTS

- The level of a boiling vessel reads water plus the vapor below its surface, so more steam demand lifts the level while the vessel loses water.
- IAPWS-IF97 supplies the properties, and the saturation closure turns the vessel's water mass and energy into its pressure.
- Both swell and shrink come from the steam side through pressure, and colder feedwater, heated in the loop first, causes no initial shrink.
- On the demand steps of case 5 three-element control cuts the IAE from 399 to 232 % s against single-element control, and the MPC reaches 152 % s with the least valve travel.

Where else this applies. Chapter 7 has an inverse response whose fast path is a water column, and Volume 5, Chapter 12 estimates an inventory that no instrument measures.

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6.10 Exercises

6.1 ○ Concept check · 2 min

In case 2 the steam user's valve opens 25 % further at 90 s while the feedwater valve stays where it is. Ten seconds later the surface stands at 58.0 % against 55.0 % before the step. What holds the surface up?

(a) The falling pressure lets the feedwater valve pass more water, so the vessel gains mass for a few seconds

(b) The falling pressure boils liquid in the bulk, and vapor held below the surface lifts it while the water mass falls

(c) Saturated liquid expands as the pressure falls, so the collapsed level rises with the same water mass

(d) The circulation pump returns its 39 kg/s faster, so the vessel holds more of the loop's water for a while

6.2 ○ Concept check · 2 min

In case 3 the feedwater from the deaerator arrives 30 °C colder at 330 s, with the feedwater valve fixed in Manual. In a drum boiler such a step shrinks the level. What does the indicated level of this flash vessel do over the following minutes?

(a) It shrinks at once, because the cold water condenses the vapor held below the surface

(b) It falls slowly, because the colder feed lowers the flash quality and the vessel loses water

(c) It keeps rising with the inventory, because the feed is heated in the loop before it reaches the vessel

(d) It ends the run, because the coil inlet cools below the subcooling limit that protects the loop

6.3 Concept check · 1 min

In case 11 the MPC and the three-element loop share the inner flow loop, the measurements and the limits on the flow setpoint. The MPC scores an IAE of 189 against 317 % s. Where does its advantage come from?

(a) The 2.9 kg/s limit on the flow setpoint binds under the PI loop and not under the MPC

(b) The MPC measures the steam flow, which the three-element loop leaves out of its calculation

(c) The MPC drives a faster inner flow loop than the one under the three-element trim

(d) Its model expects the bubble contribution to decay as the pressure settles, so it does not chase the swell

6.4 Theory and calculation · 6 min

The vessel is a vertical cylinder of diameter $D = 1.2\,\mathrm{m}$ and effective height $H = 2.4\,\mathrm{m}$, and one point of mass-equivalent level is measured at the reference density $\rho_{ref} = 897.03\,\mathrm{kg/m^3}$. One percent of feedwater valve passes 0.04 kg/s.

(a) Find the liquid mass in one point of level and the integrating gain of the inventory in percent per second for each kg/s of imbalance. *Checkpoint:* 24.3 kg and 0.0411 %/s per kg/s.

(b) Find the single-element process gain K in percent per second for each percent of valve, and the time the four-point valve step of case 1 takes to raise the inventory by one point. *Checkpoint:* 0.001 64 %/s per percent, and 152 s.

(c) A PI loop on an integrating process of gain K is critically damped at $\tau_I = 4/(KK_c)$. Find that integral time at $K_c = 4$ and at $K_c = 8$ percent per percent. *Checkpoint:* 609 s and 304 s.

6.5 Theory and calculation · 8 min

At the design point the vessel is at $p = 8\,\mathrm{bar}$, where saturated liquid and vapor have $h_l = 721.0\,\mathrm{kJ/kg}$ and $h_v = 2768.3\,\mathrm{kJ/kg}$. The hot return carries $h_h = 809.1\,\mathrm{kJ/kg}$ in $\dot{m}_r + \dot{m}_f = 39 + 1.75\,\mathrm{kg/s}$. The steam valve has $K_s = 0.625\,\mathrm{kg/(s\,bar)}$, opening $a_0 = 0.6$ and a header at $p_{hdr} = 6.5\,\mathrm{bar}$, and $(\partial U/\partial p)_M = 34.9\,\mathrm{MJ/bar}$.

(a) Find the flash quality and the flash rate at the orifice. *Checkpoint:* 4.30 % and 1.75 kg/s.

(b) Find the steam flow from Equation (6.7) and its slope with respect to the vessel pressure. *Checkpoint:* 1.75 kg/s and 0.643 kg/(s bar).

(c) Find the pressure settling time of Section 6.4.2. *Checkpoint:* 26.5 s.

(d) In case 2 the opening becomes $a = 0.75$, while the heat, and with it the steam the coil can make, stays near design. Find the pressure at which the larger opening passes 1.75 kg/s. *Checkpoint:* 7.50 bar.

6.6 Theory and calculation · 6 min

In case 13 a clogged strainer caps the feed line at 1.0 kg/s at 120 s, while the coil goes on making 1.75 kg/s of steam. The inventory starts at 51.90 %, the low-inventory stop is at 20 %, and one point is 24.3 kg.

(a) Find the rate at which the inventory falls with three-element control, which opens the valve fully within seconds, and the time of the stop. *Checkpoint:* 1.85 % a minute, a stop near 1155 s.

(b) The steam rises to 1.83 kg/s as less cold feed reaches the loop. Repeat part (a), and compare with the measured stop at 1059 s. *Checkpoint:* 2.05 % a minute, a stop near 1056 s.

(c) The restriction acts as $a_{line} = 0.25$ in Equation (6.7), with a linear trim and $\dot{m}_{f,max} = 4.0\,\mathrm{kg/s}$. Find the feedwater that passes at the design opening of 43.75 %, and the inventory loss per minute while a single-element loop leaves the valve there. *Checkpoint:* 0.44 kg/s, and 3.2 % a minute.

6.7 App challenge · 8 min

Load scenario 2, More steam demand and a rising level (Manual). Set the Teaching overlay to Show simulator truth and change nothing else. Run at speed 5 to 600 s with the default seed, then export the CSV file.

(a) Read `truth_level_surface_pct`, `truth_inventory_pct` and `truth_bubble_pct` in the rows at 90 and 100 s. *Checkpoint:* 55.00, 51.89 and 3.11 at 90 s. 58.03, 51.78 and 6.30 at 100 s, each within 0.02.

(b) From `truth_mass_kg` in the same two rows, find the water the vessel lost in those ten seconds. Then find the mass that the rise of the surface would mean if every point of it were 24.3 kg of water. *Checkpoint:* 2.9 kg lost, against 74 kg implied.

(c) Read the surface, the inventory, the pressure `truth_pressure_bara` and the steam flow `truth_steam_kgps` at 600 s, and say why the inventory is still falling. *Checkpoint:* 53.84 and 50.65 %, 7.52 bar and 1.77 kg/s, each within 0.01.

6.8 App challenge · 9 min

Load scenario 5, Add three-element control, which ships on Single. Run it to 900 s at speed 20 with the default seed, read the IAE of the scorecard and the Valve travel tile, and export the CSV file. Press Reset, select Three-element on the level card with Steam-flow feedforward On, as shipped, and run to 900 s again.

(a) In the single-element file, read the valve command `fw_valve_cmd_pct` at 120 s and its lowest value between 120 and 170 s. *Checkpoint:* 43.7 %, falling to 34.0 % at about 134 s.

(b) For each run, give the scorecard IAE, the valve travel, the lowest `truth_inventory_pct` and the highest `truth_level_surface_pct`. *Checkpoint:* Single: 429.9, 73 %, 51.06, 57.49. Three-element: 296.2, 61 %, 51.45, 57.49. IAE within 3, travel within 1, levels within 0.01.

(c) Explain why the peak is the same in both runs, and why the scorecard IAE is larger than the 399 and 232 % s of Table 6.4.

6.9 App challenge · 8 min

Load scenario 4, Tune P, PI and PID on the level, which ships as a proportional-only loop with Level gain (valve) 2 % per percent and Level integral time (valve) 3000 s. Run it to 1200 s at speed 20 with the default seed and export the CSV file. Press Reset, set Level gain (valve) to 8 and Level integral time (valve) to 300 s, run to 1200 s again and export.

(a) In the first file, find the mean and the largest deviation of `truth_level_surface_pct` from the 55 % setpoint over the last 180 s. *Checkpoint:* Mean −1.37 %, largest 1.48 %, each within 0.02.

(b) In the second file, find the largest deviation over the same window, and read the Valve travel tile of each run. *Checkpoint:* 0.19 % within 0.02. Travel 46 and 205 %, within 1.

(c) Explain why the proportional loop leaves no offset after the setpoint ramps but does after the blowdown opens at 540 s.

6.10 Application area · 4 min

A site asks whether the unit could export steam at 10 bar instead of 8 bar by raising the vessel pressure, with the coil, the circulation and the 18 bar loop pressure unchanged. At 10 bar saturated liquid and vapor have $h_l = 762.7\,\mathrm{kJ/kg}$ and $h_v = 2777.1\,\mathrm{kJ/kg}$. Saturation at 18 bar is 207.1 °C, and liquid at 849 kJ/kg and 18 bar is at 199.3 °C.

(a) Find the flash quality of the design return, 809.1 kJ/kg, at the higher vessel pressure, and the flash rate from 40.75 kg/s. *Checkpoint:* 2.30 % and 0.94 kg/s.

(b) Find the return enthalpy that flashes the design 4.30 % at 10 bar. Name two limits of the chapter's model that a loop running that hot approaches. *Checkpoint:* 849 kJ/kg, about 199 °C.

6.11 Application area · 3 min

A three-element loop on this vessel holds the level within 0.08 points through the feed-pressure dip of case 7, both with a healthy feedwater valve and with a 3 % stiction band. The level trend gives no sign of the second fault. Which signals show it, and what does it cost?

6.12 Review the agent · 5 min

An AI assistant reviewing the trend of case 2 writes: "After the 25 % demand step the level rose from 55.0 to 58.0 % in ten seconds. At 24.3 kg per point, about 73 kg of water entered the vessel, so the feedwater was too high. In automatic, the level controller should cut the feedwater as soon as the level rises after a demand increase." Find the flaw and say how to check it in the app.