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CHAPTER 6

Offshore Three-Phase Separator Simulator for Slug Absorption and Delayed Quality Measurement

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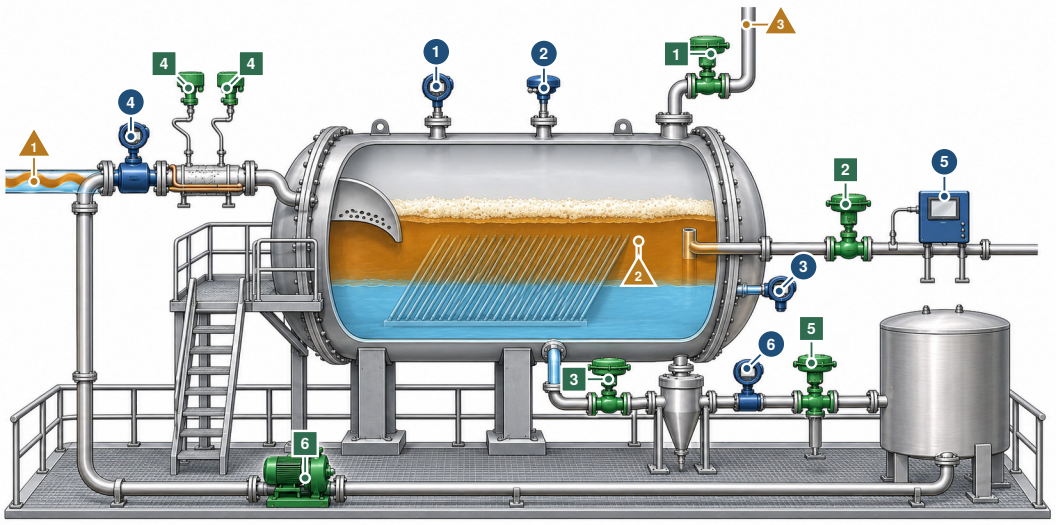
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CHAPTER 6

Offshore Three-Phase Separator Simulator for Slug Absorption and Delayed Quality Measurement



The controller moves 1 gas valve to the compressors 2 oil valve to the second stage 3 water valve to the hydrocyclone 4 demulsifier and antifoam dosing 5 routing valve, sea or hold tank 6 hold-tank recycle pump

The controller reads 1 separator pressure 2 total liquid level 3 oil–water interface 4 inlet multiphase meter 5 water in the export oil 6 oil in the overboard water, four minutes late

What disturbs it 1 a slug from the riser 2 a tighter emulsion 3 gas header pressure

Notice that the slug arrives at the left far faster than the three outlet valves on the right can pass it, and that the oil-in-water reading beside the routing valve describes water sampled minutes earlier. Illustration, not to scale.

IN PLAIN TERMS **A Tank That Takes the Surge**

The main idea. Oil, gas and water arrive mixed from the seabed and flow into a large tank on the platform. After a few quiet minutes the water sinks below the oil, and three valves draw off gas, oil and water.

The challenge. Now and then a huge gulp of liquid arrives far faster than the valves can pass, so the tank must hold it. The meter that checks the cleaned water reports minutes late, after dirty water has gone to sea.

Why it matters. How fast the stored liquid is let out decides whether the next equipment copes and the sea stays clean.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	This page, the two History boxes in Section 6.2, the first Did you know? box in the Introduction, the Try it boxes and the second Did you know? box in Section 6.6, and Key points at the end of the Conclusion. No equations.
Study	60 min	The whole chapter in order, stopping at the three pause points, then Exercises 1 to 12.
Practice	25 min	This page, Section 6.6 with Figure 6.5, Section 6.7 and Section 6.8 with its Open challenge boxes.

The control question A riser slug arrives far faster than any outlet valve can pass it, and the analyzers on the oil and water outlets report minutes late. If the separator must store the slug whatever the tuning, what does the level tuning decide, and what keeps the export oil and the overboard water in spec when the measurement arrives after the water has gone?

Learning objectives

- Derive the level gains of a horizontal separator from its geometry and valve capacities, and explain why the gain matrix is triangular.
- Compute the closed-loop time constant and damping of tight and averaging level tuning on an integrating level.
- Explain why no tuning keeps a slug out of the vessel, and measure how the tuning shares it between the vessel, the second stage and the hydrocyclone.
- Estimate what a diversion on a delayed analyzer lets overboard, and compare a faster analyzer, a second hydrocyclone bank and an averaged interface loop.
- Decide which element of a configuration (averaging, feedforward, supervisor or MPC) each clause of a campaign target needs.

Prerequisites Sections 1.4.3 (slugging), 1.4.4 (the level as an integrator, averaging level control), 1.6.2 (the framework's PID), 1.6.3 (for case 9) and 1.6.4 (the apps).

The app https://apmonitor.com/apps/offshore-separation/

See also Volume 6, Chapter 2 for a triangular gain matrix whose relative gain array shows no interaction, and Volume 6, Chapter 7 for inventory control structures. Volume 5, Chapter 7 for diversion on a late analyzer, and Volume 5, Chapter 3 for control through a slow analyzer. Volume 9, Chapter 4 for an offset-free MPC whose estimator carries an unmeasured disturbance, and Volume 9, Chapter 7 for storage that absorbs an inflow under a downstream limit.



6.1 Introduction

An offshore platform sells oil and gas and discharges water, and its first-stage separator decides the quality of all three. The riser delivers the phases together, and the vessel sends oil to a second stage, gas to the compressors and produced water through a hydrocyclone to the sea. The export oil is judged by its water content, the water by its dispersed oil and the gas by the liquid it carries, and each of those depends on droplets that need time and a quiet layer to leave the other liquid [1]. The vessel and the loops that hold its levels set that time, and separator design is organized around retention times, droplet settling and the gas capacity of the vessel [2, 3].

Three properties separate the separator from a set of independent level loops. Every height and the gas pressure follow from volumes in one horizontal cylinder, so the water valve moves the interface and the total level together, the oil valve moves only the total level, and a rising level compresses the gas cap. The separation is a residence-time process, so a disturbance at the inlet reaches the outlet qualities over minutes rather than seconds. The analyzers that report those qualities are late as well, and the one on the overboard line reads through a four-minute sample delay. The class is broad, since any inventory whose level loop exists to smooth or condition an outflow has this shape, from surge drums and flash drums to decanters and settlers, and averaging level control was posed for exactly that class [4].

The wellstream supplies the disturbances. Deepwater risers slug, as liquid collects at the riser base until the gas behind it pushes the column out in one piece [5, 6], water cuts rise as a field ages, and the stability of the emulsion changes with the crude that the wells deliver [7]. Feedback on the topside choke can suppress severe slugging [8, 9], and whatever it leaves reaches the separator. Section 1.4.3 explains how a riser slugs and Section 1.4.4 why a separator level is an integrator.

✦ DID YOU KNOW? More Water Than Oil

A 2021 review reports that produced water rose from less than 30 million barrels a day in 1990 to about 100 million barrels a day in 2015 [10], and a 2022 review estimates about three barrels of it for every barrel of oil [11]. The design wellstream of this chapter is 30 % water.

The simulator addresses the belief that tight level control keeps a slug out of the vessel and out of the equipment downstream at the same time. A slug arrives far faster than any outlet valve can pass it, so the vessel stores most of it under any tuning, and the tuning decides only how fast the stored liquid is handed to the second stage and the hydrocyclone. A second belief is that a diversion triggered by the oil-in-water analyzer protects the sea, when the analyzer reports on water that has already gone overboard. Control-oriented separator models have been published for loop design and estimation [12, 13]. However, a transfer function from valve opening to level carries neither the capacity downstream of the valve nor the delay of the analyzer, and those two quantities decide what a slug costs.

This chapter follows a slug, a water cut or a fault from the riser to each outlet of a simulated offshore three-phase separator, and on to what its analyzers report later, with the geometry, the droplet populations, the water treatment and the instruments modeled together. Gravity separation, averaging level control, feedforward and rule-based supervision are all in routine industrial use, and the optional model predictive controller [14] is measured against the loops on the same slug and inflow step. Every height of the simulated vessel comes from one volume function, its four cells carry three droplet classes per phase with balances that close to round-off, and its record of what left each outlet is kept apart from the instruments. The application offers nine cases and a campaign in which the cost of a tuning choice, an instrument delay or an equipment limit is measured in the units of the plant. Section 6.2 reviews how separators came to be sized and controlled, Section 6.3 gives the model, Section 6.4 measures how its loops are coupled, Section 6.5 states the controller as implemented and Section 6.6 reports the cases. Section 6.7 sets the hardware of a platform separator beside the model, Section 6.8 lists what the model leaves out, and the exercises in Section 6.10 put the cases to work.

6.2 Separator Sizing, Riser Slugs and Surge Control

Separator design began as a sizing problem. The allowable gas velocity through a vessel or a mesh pad is still stated through the capacity factor that Souders and Brown introduced in 1934 for the entrainment limit of fractionating columns [15], and the simulator states the gas load on its mist extractor in that form. Liquid sections were sized by two competing arguments, one requiring a droplet of a design size to settle before its liquid leaves and one requiring the liquid to be held for a design time, and the two theories were compared for oil and water separators in 1990 [2]. Handbook practice for three-phase vessels sizes the oil and water sections with both kinds of argument [3].

Beneath those rules lie droplet settling, coalescence and emulsion stability. The sedimentation of water and oil dispersions, from the coalescence of single droplets to the internals that promote it in gravity separators, has been reviewed [1], as have the stability of crude-oil emulsions and their treatment [7]. Foam received a measure of its own in 1938, when Bikerman defined a unit of foaminess as the ratio of the steady foam volume to the gas flow that sustains it [16], which makes the foam height proportional to the gas velocity through the liquid surface, the form the simulator uses. The produced water then passes treatment whose technologies have been reviewed [17], and the separation achieved by a deoiling hydrocyclone has been measured as its flow varies [18].

Riser slugging became a control problem of its own, as the first History box below tells, and a stability criterion for severe slugging was published in 1986 [6].

> ⧖ HISTORY **1980 to 2002: Slugs From the Riser**
>
> In 1980 an experimental pipeline and riser, built to simulate an offshore line, showed two kinds of slug flow. Severe slugging appeared at low gas and liquid rates where the pipeline sloped down toward the riser, and it produced slugs from one to several riser heights long. A mathematical model agreed well with the measurements, and choking the flow was found to remove the severe slugging [5]. By 2002 field tests and dynamic simulations had shown feedback control holding such lines stable, instead of leaving the receiving facilities to cope with the slugs. In many cases the control also let the pipeline inlet run at a lower pressure, which means a higher production rate [8]. The separator of this chapter is such a receiving facility, and its wells deliver their slugs with no control upstream.

The separator's own loops were treated as a surge problem. A level controller on a surge vessel is detuned on purpose so that the vessel absorbs flow variations [4], and the second History box below follows averaging level control from its optimal form into model predictive control. Three-phase separators with their pressure and level loops have been modeled for control design [12], and a first-principles gravity separator model has been built for control and estimation [13]. The simulator belongs to that line and puts the instruments, the water treatment and a record of what each outlet actually carried into the same model.

> ⧖ HISTORY **1986 and 1989: A Level Allowed to Move**
>
> In 1986 an optimal averaging level control problem was defined and solved for a surge tank, and two controllers were built on its solution, a ramp controller and an optimal predictive controller. Against averaging level controllers reported before, for step and sinusoidal changes in the inlet flow, the optimal predictive controller filtered most of the disturbances better and was very simple to implement [4]. In 1989 Campo and Morari posed the problem with the rate of change of the outlet flow as its objective and then as model predictive control. Their controller minimized the largest rate of change of the outlet flow, kept integral action and respected limits on the tank level and the outlet flow, and a single adjustable parameter traded flow filtering against fast settling [19]. The move price of case 9 makes the same trade.

6.3 Separator Model

The simulated vessel is a horizontal cylinder of diameter $D = 3.0\,\mathrm{m}$ and effective length $L = 10.0\,\mathrm{m}$ between the inlet diverter and the outlets, held at 10.0 barg with the total level at 1200 mm and the interface at 500 mm. At design it receives 149.8 $\mathrm{m^3/h}$ of oil, 64.2 $\mathrm{m^3/h}$ of water and 22 080 $\mathrm{Sm^3/h}$ of gas, a water cut of 30 % and a gas-oil ratio of 150 $\mathrm{Sm^3/Sm^3}$. The riser, the inlet heater, the four cells, the plate pack, the mist extractor, the three outlet valves, the hydrocyclone, the routing valve, the hold tank and every instrument appear in Figure 6.1.

Table 6.1 sorts the quantities into controlled, manipulated and disturbance variables, outputs and states. Thirteen lumped states and 24 dispersed inventories are integrated together with 15 ledgers that accumulate every flow across the vessel boundary, and the slug schedule, the trip latch, the stuck valves and the routing valve are discrete plant state updated after each step.

6.3.1 Heights and the Gas Cap

The liquid volume below a height h follows from the circular segment, as shown in Equation (6.1).

$$\begin{aligned} V(h) &= L\left[R^2\cos^{-1}\frac{R-h}{R} - (R-h)\sqrt{2Rh-h^2}\right] \\ h_{int} &= V^{-1}(V_w + Y) \\ h_{tot} &= V^{-1}(V_w + Y + V_o + X) \end{aligned} \tag{6.1}$$

Here $R = D/2$, the continuous water and oil volumes are V_w and V_o, and X and Y are the total dispersed water in the pad and dispersed oil in the water layer. The inverse is found by table interpolation and Newton steps, exact to 10^{-9} m over the whole diameter, and the scene draws its layers at the same

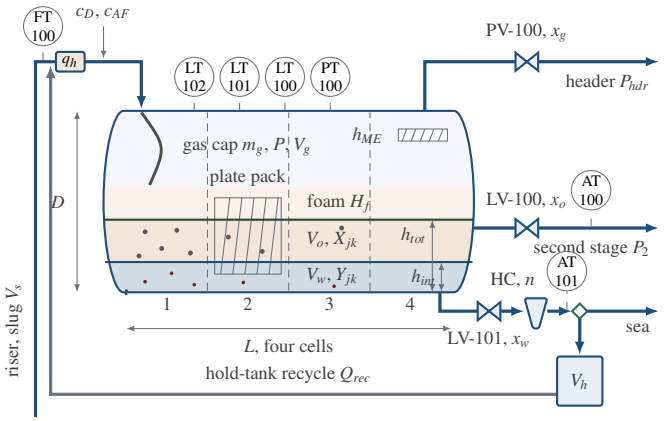


Figure 6.1 Offshore three-phase separator as modeled. The wellstream and its slugs pass FT-100, take in the hold-tank recycle and pass the heater q_h and the chemical injection onto the inlet diverter. The oil pad (V_o, X_{jk}) and the water layer (V_w, Y_{jk}) cross four cells under the foam H_f and the gas cap m_g. Gas leaves through PV-100, oil through LV-100 and AT-100, and water through LV-101, the hydrocyclone HC, AT-101 and the routing valve to the sea or to the hold tank V_h, which recycles to the inlet.

Table 6.1 Classification of the Separator Variables, Design Point and Ranges

Variable	Role	Design value	Range
P	CV, PIC-100 on PT-100	10.00 barg SP	8–11.5
h_{tot}	CV, LIC-100 on LT-100	1200 mm SP	900–1800
h_{int}	CV, LIC-101 on LT-101	500 mm SP	300–850
u_g, u_o, u_w	MV, valve commands	35.3, 50.2, 47.7 %	0–100
c_D, c_{AF}	MV, treating chemicals	8, 2 ppm	0–40, 0–15
q_h, n	MV, heater, banks	1.5 MW, 1	0–3, 1–2
Q_{rec}, r	MV, recycle, throughput	0, 100 %	0–20, 50–110
Q_l, wc	DV, liquid, water cut	214 m^3/h, 30 %	100–300, 0–70
GOR, E	DV, gas-oil ratio, emulsion	150, 1.0	50–450, 0.5–3
P_{hdr}, T_{arr}	DV, header, arrival	8.0 barg, 40 °C	6–12, 15–70
b_l, V_s	DV, LT-101 bias, slug	0 mm, 15 or 40 m^3	±300, events
BS&W, OiW	outputs, AT-100, AT-101	0.104 %, 12.4 mg/L	limits 0.5, 30
m_g, V_o, V_w	states	375 kg, 18.6, 7.7 m^3	—
H_f, T, q_h	states	543 mm, 49.5 °C, 1.5 MW	—
x_g, x_o, x_w	states, valve positions	0.353, 0.502, 0.477	0–1
x_{in}, r	states, inlet valve, wells	1, 1	0–1, 0–1.2
V_h, O_h	states, hold tank	10, 0.02 m^3	0–100
X_{jk}, Y_{jk}	states, 24 dispersions	4 cells, 3 classes	—

heights. A volume change moves a level by $\mathrm{d}V/[L\,w(h)]$ with the surface width $w(h) = 2\sqrt{2Rh - h^2}$, so the vessel holds 29.4 m^3 per meter of level at 1200 mm and 22.4 m^3 per meter at the 500 mm interface. The gas fills whatever the liquid leaves, as shown in Equation (6.2).

$$
\begin{aligned}
P &= \frac{m_g Z \bar{R} T}{M V_g} \\
V_g &= \max\left(\pi R^2 L - V_{liq},\, 0.02\,\pi R^2 L\right) \\
\frac{\mathrm{d}m_g}{\mathrm{d}t} &= w_{g,in} - K_g\, x_g \sqrt{\rho_g\, \Delta P_g} \\
\Delta P_g &= \mathrm{clamp}\left(P - P_{hdr},\, 0,\, P/2\right)
\end{aligned}
\tag{6.2}
$$

Here m_g is the gas mass, $Z = 0.97$, $M = 20.0\,\mathrm{kg/kmol}$, T the liquid temperature in kelvin, $\rho_g = PM/(Z\bar{R}T)$, K_g the effective flow area of the open gas valve and P_{hdr} the pressure of the compressor header, and the cap at $P/2$ stands in for choked flow. At design the cap holds 374.8 kg of gas in 44.3 m^3, 34.0 kg per bar, and the arriving gas replaces it every 72 s. A rising level compresses the gas, by 0.25 bar per cubic meter of liquid at a fixed gas mass.

6.3.2 Outlet Valves, Wells and the Inlet

The two liquid valves are linear, with rated capacities K_v in cubic meters per hour at a differential of 1 bar, as shown in Equation (6.3).

$$\begin{aligned} Q_o &= \phi\, K_{v,o}\, x_o \sqrt{\frac{P - P_2}{SG_o}} \\ Q_w &= \phi\, K_{v,w}\, x_w \sqrt{\frac{P + g(\rho_o h_{pad} + \rho_w h_{int}) - P_{hc}}{SG_w}} \end{aligned} \tag{6.3}$$

where the differentials are expressed in bar, $\phi = \mathrm{clamp}(h_{tot}/0.1\,\mathrm{m}, 0, 1)$ stops both flows as the vessel empties, $h_{pad} = h_{tot} - h_{int}$, $P_2 = 3.0$ barg is the second stage, $P_{hc} = 4.0$ barg the hydrocyclone inlet and SG the specific gravities 0.85 and 1.025. Fully open at design the oil valve passes 298.4 m^3/h and the water valve 134.3 m^3/h. Each position follows its command u in percent through $\tau_v\,\mathrm{d}x/\mathrm{d}t = u/100 - x$, with 3 s for the liquid valves and 2 s for the gas valve, and a stuck stem sets $\mathrm{d}x/\mathrm{d}t = 0$.

The wells deliver an imposed stream that the separator pressure does not affect. At full throughput the oil is the liquid rate Q_l times $1 - wc$, the water the rest, and the gas $w_g = \mathrm{GOR}\, Q_o(\rho_o/\rho_{os})\rho_{gs}$ in kilograms per second, with the standard densities $\rho_{os} = 865\,\mathrm{kg/Sm}^3$ and $\rho_{gs} = 0.846\,\mathrm{kg/Sm}^3$. What arrives is each of these times the throughput r and the inlet valve position x_{in}, plus any slug, and the recycle from the hold tank joins it at the inlet. The wells follow a throughput request through $\tau_w\,\mathrm{d}r/\mathrm{d}t = r_{req} - r$ with $\tau_w = 180$ s, and an inlet shutdown valve closes with a 4 s time constant on a trip. A slug of volume V_s launched at the riser base climbs for 60 s and arrives as a half-sine at the stream's water cut over $t_a = 60$ s, while the gas behind it is held back, as shown in Equation (6.4).

$$q_s = \frac{\pi V_s}{2t_a} \sin\frac{\pi t'}{t_a}, \qquad w_g = w_{g,0}\left[1 - 0.8 \sin\frac{\pi t'}{t_a}\right] \tag{6.4}$$

Here t' is the time since arrival began. The gas then blows down over 120 s as a half-sine whose peak adds $1.2\,w_{g,0}$. A 15 m^3 slug peaks at 1414 m^3/h on top of the normal 214 m^3/h, and the 40 m^3 slug of the event button arrives over 90 s. The inlet heater duty follows its command through a 60 s lag up to 3 MW, the stream enters at $T_{in} = T_{arr} + q_h/\sum \dot{m} c_p$, 49.5 °C at the design 40 °C arrival and 1.5 MW, and the liquid follows $C_{liq}\,\mathrm{d}T/\mathrm{d}t = \sum \dot{m} c_p\,(T_{in} - T)$ with C_{liq} its heat capacity in the vessel.

6.3.3 Droplets, Cells and Coalescence

The inlet diverter disperses $e_w = 4\,\%$ of the incoming water into the oil pad and $e_o = 0.07\,\%$ of the oil into the water layer. Each dispersion is split into three size classes, 60, 180 and 540 µm for water drops and 15, 45 and 135 µm for oil drops, by a log-normal distribution of spread 0.8 whose median follows Equation (6.5).

$$d_{50} = d_{50,ref}\left(\frac{\rho v^2}{2.5\,\mathrm{kPa}}\right)^{-0.3} \frac{1 + 0.8\,c_D/(c_D + 20)}{E^n} \tag{6.5}$$

Here ρv^2 is the momentum of the whole stream at the 0.40 m nozzle, with its ratio to 2.5 kPa floored at 0.05, c_D the demulsifier dose in ppm, E the emulsion tightness, $n = 1$ for water drops and 0.3 for oil drops, $d_{50,ref}$ is 275 µm and 55 µm, and the class boundaries are the geometric means of neighboring sizes. At design, with 8 ppm of demulsifier and 2.51 kPa of momentum, the water median is 338 µm.

Each class settles or rises at its Stokes velocity, corrected once for the particle Reynolds number in Equation (6.6).

$$v_k = \frac{g\,\Delta\rho\,d_k^2}{18\,\mu_c}\,\frac{1}{1+0.15\,Re_k^{0.687}} \qquad \mu_o = \mu_{o,40}\,\exp\!\left[B_o\left(1/T - 1/313.15\,\mathrm{K}\right)\right] \tag{6.6}$$

where $\Delta\rho = 175\,\mathrm{kg/m^3}$, μ_c is the viscosity of the continuous phase, $\mu_{o,40} = 9.0\,\mathrm{cP}$ and $B_o = 3000\,\mathrm{K}$, and the water follows the same law with 0.65 cP and 1800 K. At the design 49.5 °C the oil is at 6.8 cP, the water classes sink through it at 0.05, 0.45 and 3.86 mm/s against an overflow rate, oil flow over interface area, of 1.86 mm/s, and the oil classes rise through the water at 0.04, 0.35 and 2.81 mm/s.

Along the vessel the pad and the water layer are each four well-mixed cells, the inlet zone, the plate pack and two settling cells, under a level taken to be the same in all four. The dispersed volume X_{jk} of water class k in pad cell j obeys Equation (6.7).

$$\frac{\mathrm{d}X_{jk}}{\mathrm{d}t} = B_j c_{j-1,k} - B_{j+1} c_{jk} - s_k c_{jk} - \kappa_j X_{jk} + \kappa_j X_{j,k-1} \qquad c_{jk} = \frac{N X_{jk}}{V_{pad}}, \qquad s_k = \min\!\left(\frac{v_k\, w(h_{int})\, L}{N}, \frac{V_{pad}}{N\,2\,\mathrm{s}}\right) \tag{6.7}$$

Here $N = 4$, B_j is the pad flow into cell j, taken upwind when it reverses, the first cell receives $e_w Q_{w,in}$ times the class fraction, the last cell's outflow is the pad draw, and the cap on s_k keeps a vanishing layer from stiffening the step. Coalescence moves each class into the next larger one at the rate $\kappa = [1 + 3c_D/(c_D + 20)]\sqrt{\mu_{o,40}/\mu_o}/(\tau_{c,o} E)$ with $\tau_{c,o} = 320\,\mathrm{s}$, four times faster in the plate pack, and the largest class coalesces into drops that fall straight onto the interface, so its coalescence joins the settling flux. The oil drops Y_{jk} follow the same equations with their rise velocities, $\tau_{c,w} = 900\,\mathrm{s}$, $E^{0.3}$ in place of E, no viscosity factor and a plate pack factor of 2.

The cell flows follow from continuity under the common level. The pad inflow is $B_0 = Q_{o,in}(1 - e_o) + e_w Q_{w,in}$, each $B_{j+1} = B_j + \rho_j - \sigma_j - \dot{V}_{pad}/N$ with σ_j and ρ_j the volumes settling out of and rising into pad cell j, and the water layer mirrors it. The continuous phases gain what leaves the dispersions, which Equation (6.8) states.

$$\frac{\mathrm{d}V_o}{\mathrm{d}t} = Q_{o,in}(1 - e_o) + \textstyle\sum_j \rho_j - D_p(1 - C_p) \qquad \frac{\mathrm{d}V_w}{\mathrm{d}t} = Q_{w,in}(1 - e_w) + \textstyle\sum_j \sigma_j - D_w(1 - C_w) \tag{6.8}$$

where D_p and D_w are the draws from the last pad and water cells and C_p and C_w the dispersed fractions there. A layer thinner than its outlet's draw zone, $\delta_o = 250\,\mathrm{mm}$ for the pad and $\delta_w = 200\,\mathrm{mm}$ for the water, makes that outlet take the share $f = [(\delta - h)/\delta]^2$ of its flow from the other phase. The pad draw is then $D_p = (1 - f_{dw})Q_o + f_{do} Q_w + q_{co}$, with q_{co} the liquid carried into the gas, the export oil carries BS&W $= (1 - f_{dw})C_p + f_{dw}(1 - C_w)$, and the separator's water outlet carries $[(1 - f_{do})C_w + f_{do}(1 - C_p)]\rho_o$ of oil, expressed in milligrams per liter. At design 93.9 % of the dispersed water and 74.6 % of the dispersed oil are removed, leaving 0.104 % BS&W and 353 mg/L of oil in the water.

6.3.4 Foam, Mist Extractor and Carryover

Foam grows toward a height proportional to the superficial velocity j_g of the arriving gas through the liquid surface $w(h_{tot})L$, and the gas load on the mist extractor is its capacity factor, as shown in Equation (6.9).

$$\tau_F \frac{\mathrm{d}H_f}{\mathrm{d}t} = \Sigma\, j_g - H_f, \qquad \Sigma = \frac{\Sigma_0\sqrt{\mu_o/\mu_{o,40}}}{1 + c_{AF}/K_{AF}} \qquad K = \frac{Q_g}{A_{ME}}\sqrt{\frac{\rho_g}{\rho_o - \rho_g}} \tag{6.9}$$

Here $\Sigma_0 = 50\,\mathrm{s}$, the antifoam dose c_{AF} halves Σ at $K_{AF} = 3\,\mathrm{ppm}$, $\tau_F = 60\,\mathrm{s}$, Q_g is the actual gas flow through the valve and $A_{ME} = 1.2\,\mathrm{m}^2$. Liquid leaves with the gas at $5\,\mathrm{L/MSm^3}$ through a working mesh, multiplied by $1 + 50\varphi_K + 400\varphi_F + 5000\varphi_L$. The factor φ_K rises smoothly from 0 to 1 as K goes from 0.8 to 1.3 times $K_{max} = 0.10\,\mathrm{m/s}$, $\varphi_F = [1 - g_F/0.3\,\mathrm{m}]^2$ clamped to $[0,1]$ with g_F the clearance between the foam top and the mesh at $h_{ME} = 2.50\,\mathrm{m}$, and φ_L is the same for the liquid surface within 0.1 m. At design the foam is 543 mm, K is 0.051 m/s and the carryover is $5.0\,\mathrm{L/MSm^3}$.

6.3.5 Hydrocyclone, Routing and Hold Tank

Each hydrocyclone bank takes $Q_{hc} = 80\,\mathrm{m^3/h}$, and its grade efficiency depends on its load $\ell = Q_w/(nQ_{hc})$ as shown in Equation (6.10).

$$\begin{aligned} \eta(d) &= 1 - \mathrm{e}^{-(d/d_c)^2} \\ d_c &= d_{c0}\left[1 + 3\max(0, \ell - 1) + 5\max(0, 0.4 - \ell)\right] \end{aligned} \tag{6.10}$$

with $d_{c0} = 12\,\mu\mathrm{m}$, and above 130 % load the share $(\ell - 1.3)/\ell$ bypasses untreated. The reject, 2 % of the treated water with the oil separated from it, goes to a $100\,\mathrm{m^3}$ hold tank, and so does the polished water while the routing valve points to hold, otherwise the water goes overboard. A pump returns the tank contents to the inlet at a commanded rate of up to $20\,\mathrm{m^3/h}$, tapering linearly to zero as the tank falls below $0.5\,\mathrm{m^3}$, and an overflow spills untreated water and is recorded. At design one bank runs at 80 % load, removes 79 % of the 15 µm class and all of the larger ones, and passes 12.4 mg/L.

6.3.6 Trips and the Truth Record

Separate safety transmitters read the total level, the interface and the pressure as the truth plus white noise of 3 mm on each level and 0.005 bar on the pressure, through a 1 s filter sampled on the control scan. A reading beyond its setting for 2 s trips the separator on high-high level at 2100 mm, low-low level at 750 mm, high-high interface at 950 mm, low-low interface at 200 mm or high-high pressure at 12.0 barg, closes the inlet valve and latches. Fifteen ledgers integrate every boundary flow with the same step as the inventories. The scorecard counts the oil exported while its true BS&W was within 0.5 %, the water discharged while its true oil in water exceeded 30 mg/L and the worst carryover against $13\,\mathrm{L/MSm^3}$, all from these records, which no loop and no rule of the supervisor can see.

6.3.7 Numbers, Initialization and Integration

The parameters are listed in Table 6.2, and constants fixed in the code are given where they enter the equations above. Every scenario starts from the steady state at its setpoints, found by fixed-point iteration on the cell equations, which are linear in the concentrations once the cell flows are known, with the hold tank at 10 %. At that state every separator derivative is below 10^{-15}. All 52 states advance together under fourth-order Runge-Kutta integration at a fixed 0.25 s step, in the engine of Section 1.6.1. After the 1200 s slug case the ledgers close the oil and water balances to $1.6 \times 10^{-12}\,\mathrm{m^3}$ and $1.7 \times 10^{-12}\,\mathrm{m^3}$ and the gas balance to $3.5 \times 10^{-10}\,\mathrm{kg}$ of the 6544 kg that arrived. Halving the step moves the peak level of that case by 9×10^{-8} mm and its peak oil outflow by $2 \times 10^{-10}\,\mathrm{m^3/h}$, because the loops keep their fixed 0.5 s scan and only the integration error changes. Both checks are among the application's 50 passing tests.

6.3.8 Assumptions

The wells deliver an imposed stream, so the separator pressure does not feed back on the riser or the reservoir. A real riser responds to the pressure it discharges against, which is how topside choke control acts on slugging [8].

The level is flat along the vessel and the heads are not counted. Waves appear only as noise on the level transmitter, and a real vessel's heads add volume that the $26.4\,\mathrm{m^3}$ surge figure omits.

Liquids are incompressible at constant density, the gas is ideal at a fixed compressibility, and all the gas arrives free, so flashing, solution gas, the shrinkage of the oil and the inversion of an emulsion at high water cut are absent.

Table 6.2 Parameters of the Separator, Marked Visible (v) Where Show Model Offers a Slider and Hidden (h) Where It Does Not

Symbol	Meaning	Value	
D, L	vessel diameter, length	3.0, 10.0 m	v
h_{ME}, A_{ME}	mist extractor	2.50 m, 1.2 m^2	v
D_{noz}	inlet nozzle	0.40 m	h
δ_o, δ_w	outlet draw zones	250, 200 mm	v
—	level trips, high, low	2100, 750 mm	v
—	interface trips	950, 200 mm	v
—	pressure trip	12.0 barg	v
$K_{v,o}$, $K_{v,w}$	liquid valves	104, 55 m^3/h	v
K_g	gas valve area	113 cm^2	v
τ_v, τ_{vg}	actuator lags	3, 2 s	v, h
P_2, P_{hc}	outlet pressures	3.0, 4.0 barg	v
Q_{exp}	second stage capacity	250 m^3/h	v
ρ_o, ρ_w	liquid densities	850, 1025 kg/m^3	v
ρ_{os}, ρ_{gs}	standard densities	865, 0.846 kg/Sm^3	h
M, Z	gas	20.0 kg/kmol, 0.97	v
$\mu_{o,40}$, B_o	oil viscosity	9.0 cP, 3000 K	v, h
$\mu_{w,40}$, B_w	water viscosity	0.65 cP, 1800 K	h
$c_{p,o}$, $c_{p,w}$, $c_{p,g}$	heat capacities	2.0, 4.1, 2.3 kJ/(kg K)	h
τ_w, τ_{ESD}	wells, inlet valve	180, 4 s	v, h
$q_{h,max}$, τ_H	heater	3 MW, 60 s	v, h
N	cells along the vessel	4	fixed
$d_{50,w}$, $d_{50,o}$	inlet medians	275, 55 µm	v
—	log-normal spread	0.8	h
d_k	water drop classes	60, 180, 540 µm	fixed
d_k	oil drop classes	15, 45, 135 µm	fixed
e_w, e_o	inlet dispersion	4, 0.07 %	v
$\tau_{c,o}$, $\tau_{c,w}$	coalescence times	320, 900 s	v
—	plate pack factor	4	v
—	momentum exponent, reference	0.3, 2.5 kPa	h
K_D	demulsifier half dose	20 ppm	h
—	demulsifier on size, rate	0.8, 3.0	h
—	tightness exponent, oil	0.3	h
Σ_0, τ_F	foaminess, foam lag	50, 60 s	v
K_{AF}, c_0	antifoam, base carryover	3 ppm, 5 L/MSm^3	h
K_{max}	mist extractor capacity	0.10 m/s	v
Q_{hc}, d_{c0}	hydrocyclone bank	80 m^3/h, 12 µm	v
—	reject share	2 %	h
V_{hold}, $Q_{rec,max}$	hold tank, pump	100 m^3, 20 m^3/h	v, h
τ_{PT}, τ_{LT}, τ_{IT}	transmitter lags	1, 2, 3 s	h
τ_{MP}, σ_{MP}	inlet meter	5 s, 4 %	v
τ_{BSW}, θ_{OiW}, τ_{OiW}	analyzers	20, 240, 30 s	v, v, h
—	limits, BS&W, OiW, carryover	0.5 %, 30, 13	v

Settling is computed in four vertically well-mixed cells. A mixed cell removes large droplets less completely than a quiescent layer would, so the model errs toward carrying water forward, and the four cells are a residence-time model of the vessel rather than a grid to refine. Every quality correlation, from the droplet median to the coalescence times, the foam, the mist extractor and the hydrocyclone, is illustrative and fitted to no named crude or device.

The limits of 0.5 % BS&W, 30 mg/L of oil in water and 13 L/MSm^3 of carryover are typical figures rather than a regulation for a named site. The oil in water is scored instant by instant, while many discharge limits are monthly averages. Each transmitter is a lag with correlated noise, only LT-101 can carry a bias, and the valves are linear with no stiction band.

6.4 One Inventory, Three Outlets

The three loops share the vessel through volumes, and manual mode measures the sharing directly. With both level loops in manual at their balance positions, 50.24 % for oil and 47.72 % for water, a

Table 6.3 The Two Level Presets on the Identified Integrators, With $\tau_c = 1/(K_c k)$ and $\zeta = \frac{1}{2}\sqrt{\tau_I/\tau_c}$

Loop and preset	K_c	τ_I	τ_c	ζ
total level, tight	5.0 %/cm	240 s	71 s	0.92
total level, averaging	0.4 %/cm	1500 s	890 s	0.65
interface, tight	4.0 %/cm	400 s	150 s	0.82
interface, averaging	1.5 %/cm	600 s	399 s	0.61

5 % step of either valve changes the level rates by the amounts of Equation (6.11), measured against an unstepped run once the valve has settled, at the end of the minute after the step.

$$\begin{bmatrix} \dot{h}_{tot} \\ \dot{h}_{int} \end{bmatrix} = \begin{bmatrix} -0.0281 & -0.0126 \\ 0.0001 & -0.0167 \end{bmatrix} \begin{bmatrix} \Delta u_o \\ \Delta u_w \end{bmatrix} \quad \frac{\text{mm/s}}{\%} \tag{6.11}$$

The entries follow from the geometry. One percent of the oil valve passes 2.98 m^3/h over the 29.4 m^2 surface at 1200 mm, 0.0282 mm/s, and one percent of the water valve passes 1.34 m^3/h, which lowers the 22.4 m^2 interface by 0.0167 mm/s and the whole liquid by 0.0127 mm/s. The matrix is triangular. The oil valve reaches the interface only through the gas pressure, so the pairing of oil with total level and water with interface is forced, the relative gain array is the identity to within 0.3 %, and the interaction runs one way, from the water valve into the total level. The reverse osmosis train of Volume 6, Chapter 2 has the same shape, a triangular gain matrix whose relative gain array says there is no interaction while one loop still disturbs the other. When the water valve cannot act, the level loop can hold the total level only by taking out oil, which thins the pad from below. Both levels are integrating, because the outlet flows depend on the gas pressure and hardly at all on the liquid heights.

The pressure is not integrating. A 1 % step of the gas valve in manual lowers the pressure by 0.091 bar, with 63 % of the change in 23 s, because the gas flow grows with both the gas density and the differential and so regulates the 34.0 kg per bar cap by itself. The pressure is coupled to both levels through the gas volume, 0.25 bar per cubic meter of liquid at a fixed gas mass, and it drives both liquid valves through their differentials, 10.7 m^3/h of oil and 5.2 m^3/h of water per bar.

The surge volume is set by the trips. Between the 1200 mm normal level and the 2100 mm high-high trip the vessel holds 26.4 m^3, and 12.6 m^3 lie between the normal level and the 750 mm low-low trip, while the water layer can gain 11.5 m^3 before the high-high interface trip and lose 5.7 m^3 before the low-low one.

A proportional-integral loop on an integrator k/s has the characteristic polynomial $\tau_c \tau_I s^2 + \tau_I s + 1$ (Section 1.4.4), and with the identified gains k of Equation (6.11) the two level presets give the time constants and damping ratios of Table 6.3. The averaging preset lengthens the response of the total level twelvefold, from 71 s to 890 s, which is fifteen times the 60 s a slug takes to arrive, and all four settings are underdamped, with ζ from 0.61 to 0.92. The pressure loop, 15 % per bar and 30 s on the 0.091 bar per percent first-order response, has a loop gain of 1.4.

6.5 Implemented Controller

The loops execute every 0.5 s, once per two 0.25 s physics steps, the supervisor every 10 s, and one sample is logged every second. Each step executes the control scan when it is due, integrates the plant, and only then evaluates the trips and adds to the truth record. The page offers speeds of 1, 2, 5, 10, 30 and 60 times real time, with 10 as the default.

6.5.1 Instruments

No loop reads the plant's truth. Each transmitter in Table 6.4 passes the true value through its own first-order lag, solved exactly over the scan, and adds Gaussian noise filtered to the stated correlation time and scaled to the stated standard deviation. The radar level adds waves with a standard deviation

Table 6.4 Instruments. Noise Is One Standard Deviation With Its Correlation Time

Tag	Measures	Lag	Noise
PT-100	separator pressure	1 s	0.01 bar, 1 s
LT-100	total level, radar	2 s	2 mm, 2 s, waves
LT-101	interface, displacer	3 s	3 mm, 2 s, bias b_I
LT-102	interface, profiler	10 s	6 mm, 5 s
LT-102	foam top, profiler	10 s	20 mm, 5 s
TT-100	liquid temperature	10 s	0.05 °C, 10 s
PT-150	gas header	1 s	none
FT-100	inlet oil, water, gas	5 s	4 % each, 8 s
FT-101	produced water flow	2 s	1 %, 2 s
AT-100	BS&W, oil outlet	20 s	0.01 %, 10 s
AT-101	oil in water, overboard	240 s + 30 s	1 mg/L, 20 s
LT-200	hold tank level	2 s	none
ZT	valve positions	1 s	0.03 % on gas

of 4 mm for each unit by which the momentum ratio $\rho v^2/2.5\,\mathrm{kPa}$ exceeds 0.8, which is 0.8 mm at design and 21 mm at the peak of a 15 m^3 slug. The oil-in-water analyzer reads the polished water through a pure sample delay of 240 s and then a 30 s lag.

6.5.2 The PI Algorithm

All three loops use the velocity-form PID routine that every framework app shares, described in Section 1.6.2 and written for this separator as Equation (6.12).

$$\begin{aligned} e_k &= a(\mathrm{SP}_k - \mathrm{PV}_k), \quad P_k = K_c e_k, \quad D_k = -K_c \tau_D a \dot{\mathrm{PV}}^f_k \\ S_k &= S_{k-1} + (P_k - P_{k-1}) + (D_k - D_{k-1}) \\ c_k &= b_k + S_k + I_{k-1}, \qquad u_k = \mathrm{clamp}(c_k, 0, 100) \\ I_k &= I_{k-1} + \left[\frac{K_c}{\tau_I} e_k + \frac{u_k - c_k}{T_t}\right]\Delta t_c \end{aligned} \tag{6.12}$$

Here $a = -1$, b_k is the feedforward bias, $\Delta t_c = 0.5\,\mathrm{s}$ and the tracking time T_t equals τ_I. The derivative is switched off by $\tau_D = 0$ in all three loops, and no output has a rate limit. In manual the loop sets $I_k = u_{op} - b_k - S_k$, so its output equals the operator's valve and the return to automatic is bumpless. Every process gain here is negative, since opening a valve lowers its variable, so $a = -1$ and each loop is direct acting under the ISA convention, opening its valve as its variable rises. The same algorithm shows why a pinned valve does not wind the integral without bound. With u_k at a limit u_{lim} and $T_t = \tau_I$, the last line of Equation (6.12) reduces to $\tau_I\,\mathrm{d}I/\mathrm{d}t = u_{lim} - b - I$, so the integral term settles at $u_{lim} - b$ whatever the error [20].

6.5.3 Loops, Tunings and Feedforward

PIC-100 moves the gas valve on PT-100 with $K_c = 15\,\%$ per bar and $\tau_I = 30\,\mathrm{s}$ against a 10.00 barg setpoint. LIC-100 moves the oil valve on LT-100 and LIC-101 the water valve on LT-101, or on the LT-102 profiler when the operator selects it, with the presets of Table 6.3 written to both loops by one selector and a custom setting once either gain is edited. Any loop can be put in manual on its own, and the mode switch in the header moves all three together. A loop that starts a run in manual holds the balance opening the start-up computed.

With feedforward on, each bias is the opening that would pass the metered inflow of the loop's own phase at the measured differential, from the valve's rated capacity, as shown in Equation (6.13).

$$b = 100\,\frac{\tilde{Q}_{in}}{Q_{max}(P_m)}, \qquad \tau_{FF}\,\frac{\mathrm{d}\tilde{Q}_{in}}{\mathrm{d}t} = Q_{in,m} - \tilde{Q}_{in} \tag{6.13}$$

Here Q_{max} is the flow of the fully open valve by Equation (6.3) or (6.2) at the measured pressures and, for water, the measured head, $\tau_{FF} = 900\,\text{s}$ for the two liquids, so that a slug is not passed straight through, and 2 s for the gas. The recycle flow, which the meter does not see, is added to the metered liquids as 1 % oil and 99 % water. Switching the feedforward moves each integral by the old bias minus the new one, so no valve jumps.

6.5.4 Supervisor, Routing and Diagnostics

A rule-based supervisor, off by default, scans every 10 s. It trims the demulsifier on AT-100 at 0.6 ppm/s per point of BS&W above a 0.20 % target, up to 40 ppm, and then the heater at 30 kW/s per point up to 3 MW, giving back heat first and chemical second at a tenth of those rates once the reading is 0.05 % below the target. It adds 0.5 ppm of antifoam per scan, up to 15 ppm, while the profiler's foam top is within 0.45 m of the mist extractor, and removes 0.1 ppm per scan down to the operator's setting once the gap exceeds 0.8 m. It brings in the second hydrocyclone bank after the measured water flow has stayed above 85 % of one bank for 20 s and withdraws it after 120 s below 70 %. It runs the hold-tank recycle at 12 m^3/h while the tank is above 15 % and the separator has room. Finally it cuts the throughput request in 10 % steps down to 50 % for a reason it cannot otherwise remove, a hold tank above 70 % while diverting, BS&W above its limit for 300 s with both trims at their limits, a level or interface heading for its trip with its valve at its limit or stuck, a pressure within 0.3 bar of its trip with the gas valve open, or an estimated mist extractor load above 85 % of K_{max}. A reason must persist for 30 s and the cuts are 120 s apart, or 180 s and 360 s for the gas load so that the wells can answer, and the request is restored by 5 % after 300 s without a reason.

Independently of the supervisor, the routing valve sends the polished water to the hold tank while AT-101 reads above 30 mg/L and back overboard after 60 s below 25.5 mg/L. Two diagnostics watch the instruments. A valve whose position feedback differs from its command by more than 10 % for 20 s raises a not-following alarm, and LT-101 and LT-102 differing by more than 60 mm for 60 s raise a disagreement alarm.

6.5.5 The Model Predictive Controller

A control structure selector offers one model predictive controller (MPC) in place of the three loops, which stay the default of every case but case 9. Section 1.6.3 describes how the apps set up such an option, and the paragraphs below give this controller's model and objective. It moves all three outlet valves every $T_s = 2\,\text{s}$ over $N_p = 150$ steps (5 min) in 12 move blocks, from 1 step at the start to 105 at the end, and the supervisor and the routing valve act as under the loops. Its model is the balance of Section 6.3 at the declared parameter values, never those of the run, reduced to three inventories, three valve lags and three unmeasured inflows, as in Equation (6.14).

$$\begin{aligned} \frac{\mathrm{d}V_w}{\mathrm{d}t} &= \bar{Q}_{w,in} - Q_w + d_w, \qquad \frac{\mathrm{d}d}{\mathrm{d}t} = 0 \\ \frac{\mathrm{d}V_l}{\mathrm{d}t} &= \bar{Q}_{o,in} + \bar{Q}_{w,in} - Q_o - Q_w + d_l \\ \frac{\mathrm{d}m_g}{\mathrm{d}t} &= \bar{w}_{g,in} - w_g + d_g \end{aligned} \tag{6.14}$$

Here V_l is the liquid volume, the heights, pressure and flows follow Equations (6.1), (6.2) and (6.3) without dispersed volumes and with $\phi = 1$, and d collects what the model cannot explain. The inflows $\bar{Q}_{in}$ are the design wellstream, or with the optional preview the feedforward's filtered meter signals plus the recycle, held over the horizon. At each decision the model is linearized by central differences about the estimate and the applied openings and discretized with an exact hold, so an edited plant parameter is model mismatch, as on a real vessel. Against ±5-point valve steps in manual from the design point, 120 s open loop, it reproduces the plant's −16.2 mm of level, −9.7 mm of interface and −398.4 mbar of pressure within 0.4 mbar and 0.1 mm, because it is the simulator's own balance.

Each plan minimizes Equation (6.15) over the changes of the three openings, taken as offsets from the openings applied now.

$$\begin{aligned} \mathscr{J} = & \sum_{k=1}^{N_p} \left[q_h (e_{int,k}^2 + e_{tot,k}^2) + q_P e_{P,k}^2 \right] + \sum_j \left(a_j \varepsilon_j^2 + b_j \varepsilon_j \right) \\ & + \sum_k \left[\lambda \left(s_o^2 \Delta u_{o,k}^2 + s_w^2 \Delta u_{w,k}^2 \right) + \lambda_G s_g^2 \Delta u_{g,k}^2 \right] \\ & + 10\lambda \left[(Q_{w,N_p} - \hat{Q}_w)^2 + (Q_{l,N_p} - \hat{Q}_l)^2 \right] \end{aligned} \tag{6.15}$$

The errors e are the predicted heights in millimeters and pressure in millibar less their setpoints, with $q_h = 10^{-3}$ and $q_P = 0.01$. Each move is priced by the outflow it changes, s_o, s_w and s_g being the flow one percent of opening passes at the present state (2.98 m³/h of oil and 1.34 m³/h of water at design), with $\lambda = 10$ per (m³/h)² and $\lambda_G = 100$ per (kSm³/h)². The terminal term asks the water and total liquid outflows Q_w and Q_l to pass the expected inflow $\hat{Q} = \bar{Q}_{in} + \hat{d}$ at the horizon's end, so that no plan parks an outflow for the next one to undo. The openings are bounded hard by the PI loops' 0 to 100 %, and a loop in manual pins its valve. Every other limit is soft, with one slack ε_j per output priced at a_j and b_j, the level within 500 mm and the interface within 200 mm of their setpoints at 100λ per mm² and 1000λ per mm, the pressure within 300 mbar at 100 and 1000, and the oil and water outflows under the second stage's Q_{exp} and the nQ_{hc} of the banks in service at 10λ and 100λ per m³/h, judged every third step. The level and interface bands are funnels, the upper bound at step k being $y_{max} + \max(0, y_0 - y_{max})\, \mathrm{e}^{-kT_s/\tau_f}$ with $\tau_f = 120$ s and the lower bound its mirror. As a design note, a slack that covers the whole horizon would charge a violation already present, which no move can change, and leave later violations up to that size free, while the funnel asks for the return at the rate of τ_f. Each decision is one receding-horizon quadratic program [21] of 36 moves and five slacks, solved with Goldfarb and Idnani's dual active-set method [22].

A steady-state Kalman filter for the model at the declared design point corrects its nonlinear prediction every 0.5 s scan, under either structure, with the interface transmitter in use (3 mm for LT-101, 6 mm for LT-102), LT-100 at 3 mm and PT-100 at 10 mbar. The unmeasured inflows follow a random walk of variance $\gamma(2 \times 10^{-4}\ \mathrm{m^3/s})^2$ per scan with $\gamma = 0.01$, which removes offset at steady state [23], as the offset-free controller of Volume 9, Chapter 4 does with a fuel bias. The values of λ and γ and the preview off came from one pass on case 9 that ranked by oil outflow standard deviation the settings holding both bands with no more liquid valve travel than averaging PI.

The PI loops track the applied openings every scan with no preload. A plan the solver did not take to its optimum, or one with an opening outside the valve's travel or not finite, is discarded. The loops then take the valves, the historian is marked MPC FALLBACK, and the next valid plan takes them back. With the noise off, two forced rejections in case 9 at 600 s move a valve at most 0.195 % per scan, against 0.019 % before. Switching the other way, from averaging PI at 600 s with 86.1 m³/h of water against one bank's 80 m³/h, the first plan closes the water valve 9.4 points at once, from 63.9 to 54.6 %, as the soft ceiling acts. In Chrome a plan takes a mean of 1.92 to 1.95 ms in case 9, 0.1 % of one core at real time.

6.5.6 Simulation, Control and Internal Models

Three models should be kept apart. Section 6.3 is the simulation model. The identified control model is that of Section 6.4, two integrators of Equation (6.11) and a first-order pressure response of −0.091 bar per percent with a time constant near 22 s, measured in manual. Under the PI loops the controller's internal model is only the valve equation inside the feedforward, with data-sheet capacities and measured pressures, and the supervisor's estimate of the mist extractor load from the metered gas, the measured pressure and the measured temperature. Neither contains droplets, cells or the hydrocyclone. Under the MPC the model of Equation (6.14) replaces the feedforward and contains none either.

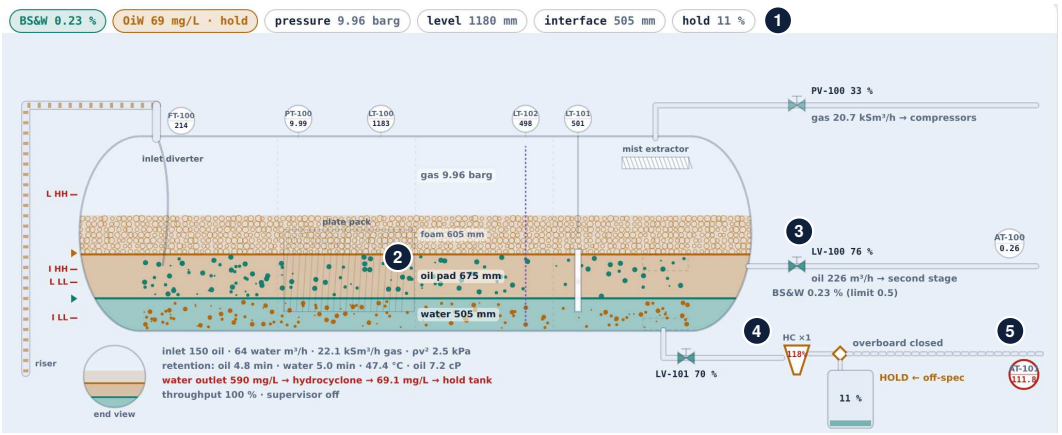


Figure 6.2 Separator application in case 2, liquid slug, at $t = 7.00$ min (420 s) with the shipped tight level tuning, 240 s after the 15 m^3 slug finished arriving, cropped to the plant view. The riser is empty. (1) The badges: the level has fallen back to 1180 mm, the interface is at 505 mm and the hold tank is 11 % full. (2) The vessel, with a foam band 605 mm deep. (3) The oil valve LV-100 at 76 % passes 226 m^3/h of oil at 0.23 % BS&W to the second stage. (4) The water valve LV-101 is at 70 %, and the single hydrocyclone bank runs at 118 %. (5) The routing valve has closed the overboard line and sends the water to the hold tank, while AT-101 reads 111.8 mg/L in alarm on water sampled four minutes earlier and the polished water now leaving the hydrocyclone carries 69.1 mg/L.

Table 6.5 Principal Measured Outcomes, Default Seed

Case	Measured outcome
1, design	retention 7.5 and 7.3 min, 0.104 %, 12.4 mg/L
1, interface 700, 350 mm	0.151 and 0.085 %, 7.5 and 18.0 mg/L
2, tight	317 m^3/h, 268 s over 250 m^3/h, 8.4 m^3 off spec
2, averaging	219 m^3/h, 6.9 m^3 off spec, 1772 L/MSm^3
2, 40 m^3 slug	level trip at 181.0 and 179.0 s
3, one and two banks	134 %, 7.7 m^3 off spec, or worst 14.4 mg/L
4	K 0.113 m/s, 1150 L/MSm^3, antifoam 185 L/MSm^3
4, supervisor	cuts to 90, 80, 70 %, clear from 1225 s
5, alone, supervisor	53.6 m^3 of 75.0 m^3 off spec, or none
6	interface trip at 1404 s
6, supervisor	cuts from 420.5 s to 50 %, 15.7 m^3 deferred
7	11.52 barg with the valve open, undershoot 8.58 barg
8	6.8 m^3 off spec, 6.1 m^3 in spec diverted

6.6 Measured Cases

Table 6.6 sets out the sequence of nine cases and the campaign. Each case starts from the steady state of Section 6.3 with tight level tuning, no feedforward and the supervisor off, as a cautious operator would commission the plant, and differs only as stated, with each changed setting in force from $t = 0$. Every reported number was measured on the engine without its user interface, at the default seed, with plant events resolved to the 0.25 s step and controller actions to the 0.5 s scan, and Table 6.5 gathers the principal outcomes.

6.6.1 The Design Point and the Interface

In case 1 the oil spends 7.5 min in its pad and the water 7.3 min in its layer, and the dispersed water falls from 1.00 % of the pad in the inlet cell to 0.32, 0.18 and 0.104 % along the vessel, because only the 540 µm class outruns the 1.86 mm/s overflow rate without coalescing first. The interface setpoint

Table 6.6 The Nine Cases and the Campaign

#	Scenario and events	Teaching point
1	Balanced feed	retention and the interface
2	15 m^3 slug launched at 60 s	the vessel stores it
3	Water cut 30 to 50 %, 60–300 s	polishing runs out
4	Gas-oil ratio 150 to 330, 60–180 s	foam and the mesh
5	Emulsion ×2.5 at 60 s	a retention time of delay
6	Water valve sticks, water cut 45 %	a trip or a cut
7	Gas header 8.0 to 11.3 barg, 60–240 s	no valve authority
8	LT-101 reads 150 mm high at 60 s	the wrong interface
9	Case 2's slug, wells to 250 m^3/h at 1200 s	an MPC prices outflow
10	2400 s wellstream campaign	graded challenge

trades one outlet against the other at an unchanged throughput. At steady state, 700 mm gives the water 11.8 min and the oil 5.5 min, which lowers the oil overboard to 7.5 mg/L and raises the BS&W to 0.151 %, while 350 mm gives 0.085 % and 18.0 mg/L. Both qualities stay within their limits over that range, so the choice spends margin on one outlet or the other.

6.6.2 A Riser Slug, Stored Either Way

Case 2 launches 15 m^3 at the riser base at 60 s, and it arrives between 120 and 180 s at up to 1414 m^3/h, with its gas held back. The nozzle momentum rises from 2.5 to 15.0 kPa and the water droplet median at the inlet falls from 338 to 198 µm. Neither tuning keeps the slug out of the vessel, since both valves fully open pass only 433 m^3/h at design pressure. When the level peaks, at 177 and 179 s, 14.9 and 15.0 m^3 of the slug have arrived, and the vessel holds 12.8 m^3 of it under the shipped tight tuning and 14.4 m^3 under averaging, at peaks of 1629.6 and 1682.1 mm. The tight loop has its oil valve command at the limit from 138.5 s and its water valve command from 162.0 s, so the 2.1 m^3 it passes on during the arrival is set by the valves rather than by the gain. Across a fifty-fold range of level gain at a 1500 s integral time, from 0.1 to 5 %/cm, the peak level moves only from 1692 to 1640 mm, while the peak oil outflow moves from 175 to 318 m^3/h. The plant at 420 s under tight tuning, with the slug stored and on its way out, is shown in Figure 6.2.

> **TRY IT IN THE APP** **2 · Liquid slug**
>
> Load the case, press Run and watch the level in the vessel. The slug pours in faster than both open valves can pass, so the level climbs to 1629.6 mm at 177 s and the vessel holds 12.8 m^3 of the 15 m^3 slug before the valves draw it back down.

The tuning decides what happens after the arrival, as shown in Figure 6.3. The tight loop returns the stored liquid as fast as the valves pass it. With the gas blowdown lifting the pressure to 10.92 barg at 224 s, the wide-open oil valve delivers 317 m^3/h, more than its 298 m^3/h at design pressure, and the oil outflow exceeds the 250 m^3/h second stage for 268 s. The level first returns within 50 mm of its setpoint at 372 s, undershoots to 1142 mm and stays within the band from 586 s. Averaging spreads the return over a quarter of an hour, with the oil outflow never above 219 m^3/h and the level back within 50 mm at 947 s. The largest rate of change of the oil outflow over 5 s is 15.1 m^3/h per second with tight tuning and 2.09 with averaging, the quantity that optimal averaging control minimizes [4]. At a 1500 s integral time the second stage is respected up to 0.6 %/cm, which peaks at 246 m^3/h, while 0.8 %/cm reaches 272 m^3/h. The pressure transient comes from the gas rather than the levels, with a dip to 9.69 barg at 154 s while the gas is held back, the rise during the blowdown and an undershoot to 9.26 barg at 309 s, and it agrees under both tunings to within 0.09 bar.

Pause. Try Exercise 6.1 before reading on.

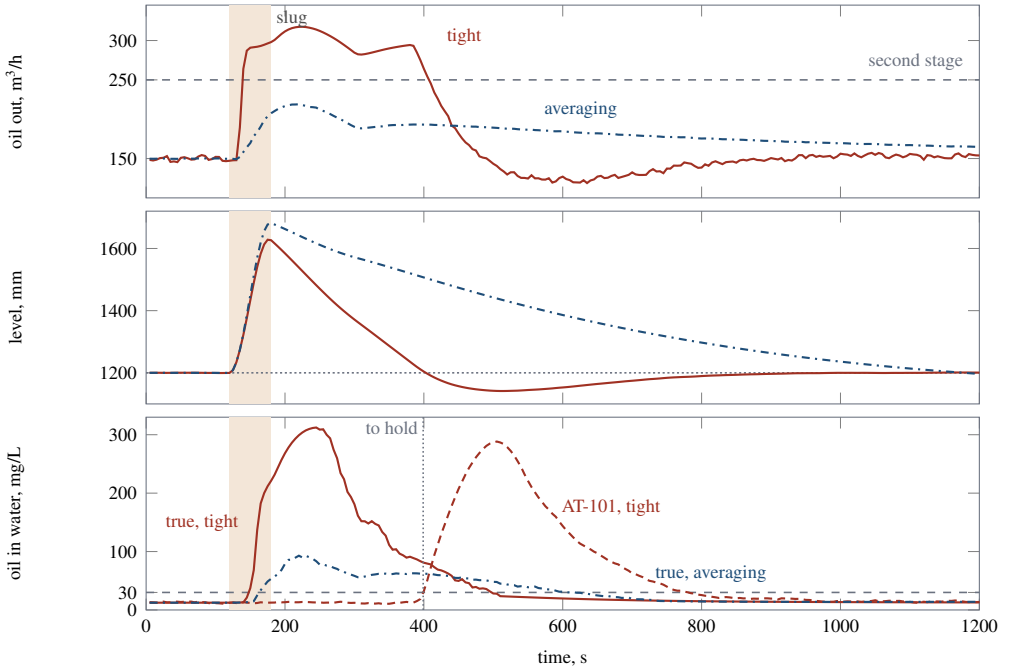


Figure 6.3 The 15 m^3 slug of case 2 under tight (solid) and averaging (dash-dotted) level tuning, from headless runs at the default seed. The shaded band is the arrival of the slug. The oil outflow is shown against the 250 m^3/h second stage (thin dashed), the total level against its 1200 mm setpoint, and the oil in the polished water against the 30 mg/L limit (thin dashed), with the AT-101 reading for the tight case (densely dashed). The vertical dotted line marks the diversion to the hold tank at 399 s.

The price of averaging is freeboard. With the level higher during the blowdown the foam top comes within 21 mm of the mist extractor instead of 193 mm, and the carryover peaks at 1772 L/MSm^3 against 335 L/MSm^3.

6.6.3 Where the Slug's Water Goes

The produced water fares badly under either tuning. The tight interface loop drives the water outflow to 144 m^3/h and the single hydrocyclone bank to 180 % of its capacity, and the polished water peaks at 312 mg/L at 246 s. Averaging lowers the peak load to 134 % but keeps the bank overloaded for 585 s instead of 366 s, so the off-spec water discharged falls only from 8.4 to 6.9 m^3, as listed in Table 6.7. The analyzer sees the excursion late. The true value passes 30 mg/L at 148 s, AT-101 diverts the water to the hold tank at 399 s, and by then the whole 8.4 m^3 has gone overboard. Shortening the analyzer's delay from 240 to 30 s cuts that volume to 1.39 m^3 without removing it. A diversion on a late analyzer always lets through what passed during the delay, the same problem that the continuous drug line of Volume 5, Chapter 7 meets when it routes product on a result that describes material already downstream. The second hydrocyclone bank removes the loss under both tunings, with the tight case peaking at 29.97 mg/L, just under the limit. The supervisor brings that bank in on the measured water flow, at 151 s under tight tuning and 161 s under averaging, and leaves 0.07 m^3 and none off spec. The interface loop can protect the water itself. Averaged to 0.5 %/cm and 1500 s, it holds the water outflow to 82 m^3/h and the single bank to 103 %, the polished water peaks at 25.0 mg/L and nothing goes off spec, while the interface rises only to 680 mm against 673 mm with the preset. Under tight level tuning the same interface loop still protects the water, but the level loop then passes the held-back volume as oil, and the second stage stays overloaded for 351 s instead of 268 s. Feedforward undoes

Table 6.7 Case 2 Variants Over 1200 s. Off-Spec Is Water Discharged Above 30 mg/L. Interface Rows Use $\tau_I = 1500$ s

Configuration	Oil peak m^3/h	Over 250 s	Off spec m^3	Carryover L/MSm^3
tight (shipped)	317.5	268	8.40	335
averaging	219.1	0	6.92	1772
tight, two banks	317.5	268	0	335
averaging, two banks	219.1	0	0	1772
averaging, feedforward 900 s	246.8	0	7.51	2089
averaging, feedforward 300 s	304.6	178	8.23	1203
averaging, supervisor	219.1	0	0	273
averaging, interface 0.5 %/cm	220.8	0	0	2078
tight, interface 0.5 %/cm	317.6	351	0	742
tight, AT-101 delay 30 s	317.5	268	1.39	335
tight, AT-101 delay 120 s	317.5	268	4.84	335
tight, AT-101 delay 480 s	317.5	268	10.77	335

part of the averaging, up to 305 m^3/h with a 300 s filter (Table 6.7).

Pause. Try Exercise 6.3 before reading on.

The slug also shows where tuning stops mattering. Launched from the design state in model runs with slug sizes the application does not offer, the largest slug that arrives over 60 s without a high-high trip is 29.0 m^3 under tight tuning and 27.7 m^3 under averaging, against the 26.4 m^3 surge volume, and the 40 m^3 slug of the event button, fired at 60 s in case 1, trips the level at 181.0 and 179.0 s. Tight tuning buys 1.35 m^3 of slug tolerance and pays for it at the second stage and the hydrocyclone.

DID YOU KNOW? A Faster Analyzer Only Shrinks the Loss

From the simulator (Table 6.7). Under tight tuning in case 2 the off-spec water discharged before AT-101 diverts is 1.39 m^3 with a 30 s delay, 4.84 with 120 s, 8.40 with the shipped 240 s and 10.77 m^3 with 480 s. No delay short of zero keeps it all on board.

6.6.4 A Rising Water Cut and the Hydrocyclone

Case 3 raises the water cut from 30 to 50 % in five steps between 60 and 300 s at an unchanged 214 m^3/h of liquid. The interface loop holds the interface within 52 mm while the water outflow rises from 64 to 107 m^3/h and the water valve settles near 80 %. The separator copes, and its water outlet improves from 353 to 222 mg/L because less oil enters to be dispersed, even though the water retention falls from 7.3 to 4.3 min. The single hydrocyclone bank does not. It runs at 126 % of its capacity by 400 s and 134 % at 1800 s, the polished water passes 30 mg/L at 377 s and peaks at 55.8 mg/L, and AT-101 diverts only at 637 s, after 7.7 m^3 of off-spec water has gone overboard. The hold tank then fills from 10 to 46 % by 1800 s. With both banks in service the worst is 14.4 mg/L, and the supervisor brings the second bank in at 171 s, once the measured water flow has stayed above 85 % of one bank for 20 s, holding the worst at 12.6 mg/L.

6.6.5 More Gas, Foam and the Mist Extractor

Case 4 raises the gas-oil ratio from 150 to 330 in three steps between 60 and 180 s, 2.20 times the design gas. The pressure loop copes, opening the gas valve from 35.3 to 77.6 % after a peak of 10.55 barg and returning within 0.05 bar of setpoint by 345 s. The mist extractor does not. Its capacity factor reaches 0.113 m/s against 0.10 m/s, the foam grows to 1206 mm with its top 92 mm below the mesh, and the carryover passes 13 L/MSm^3 at 129 s and peaks at 1150 L/MSm^3. Antifoam at 8 ppm collapses the foam to 548 mm but leaves 185 L/MSm^3, the overloaded mesh alone. A throughput

request of 75 % with the antifoam lowers the capacity factor to 0.085 m/s and the carryover to 11.6 L/MSm^3 by 1800 s. The supervisor reaches the same answer by itself, raising the antifoam to 6.0 ppm, which it relaxes to 4.7 ppm once the foam has fallen, and cutting the throughput to 90, 80 and 70 % at 350, 710 and 1090 s, and the carryover stays under its limit from 1225 s.

6.6.6 A Tighter Emulsion and a Retention Time of Delay

Case 5 makes the emulsion 2.5 times tighter at 60 s, and the water median at the inlet falls from 338 to 135 µm at once. The outlet does not follow at once. Ten seconds later the BS&W has moved from 0.104 to 0.1065 %, and it takes 340 s to cover 63 % of its rise against a 448 s oil retention time, crosses 0.5 % at 513 s and settles at 0.59 %, so that 53.6 m^3 of the 75.0 m^3 exported by 1800 s is off spec. With 40 ppm of demulsifier from the start the BS&W never passes 0.328 %. The supervisor's trim reaches 40 ppm at 571 s and then raises the heater to 3 MW by 1031 s, warming the liquid to 58.3 °C, so the BS&W peaks at 0.445 % at 516 s and falls back to 0.27 % with nothing off spec. The trim starts only at 240.5 s, after AT-100 has passed its 0.2 % target at 236.5 s, so the rise already held in the pad reaches the outlet before the extra demulsifier and heat can act on it.

6.6.7 Limits No Tuning Moves

In case 6 the water valve stem seizes at 47.6 % at 60 s, and at 120 s the water cut rises to 45 %, so 96 m^3/h of water arrive and 64 m^3/h leave. The not-following alarm is raised at 206 s, and the interface loop's command reaches 100 % at 377 s without effect. The level loop holds the total level by the only route the triangular structure leaves it, taking out 150 m^3/h of oil while 118 m^3/h arrives, so by 1200 s the interface is at 884 mm, the pad has thinned from 700 to 316 mm and the BS&W has risen to 0.314 %. At 1404 s the interface reaches its 950 mm trip and the wells are shut in. The stem freezes wherever valve noise has left it, and over eight noise seeds the trip falls between 1350 and 1448 s. With the supervisor on, the not-following alarm and the rising interface cut the throughput from 420.5 s in 10 % steps to 50 %, the interface peaks at 720 mm at 941 s, nothing trips under any of the eight seeds, and 15.7 m^3 of oil is deferred by 1800 s.

🕮 **Pause.** Try Exercise 6.2 before reading on.

In case 7 the gas header rises from 8.0 to 11.3 barg in four steps between 60 and 240 s. The separator pressure passes 11.0 barg at 187 s, the gas valve command reaches its limit at 231 s, and the pressure settles at 11.52 barg, 0.22 bar above the header and 0.48 bar below the trip. Back-calculation then holds the integral term at 100.0 %, as the algorithm predicts, while the proportional term adds 23.0 %, so the unclamped demand of 123.0 % is the proportional term and nothing more. The higher pressure pushes more liquid out, and the level loops close the oil valve from a mean of 50.0 % over the first minute to 45.3 % over 400 to 600 s and the water valve from 48.0 to 42.1 %, while the denser gas lowers the foam from 543 to 478 mm. A throughput cut would not help, since 80 and 50 % still give 11.44 and 11.36 barg, so the supervisor does not cut. When the header falls back to 8.0 barg at 600 s, the gas valve is still wide open with its integral at the limit, the cap drains and the pressure undershoots to 8.58 barg at 622 s, returning within 0.05 bar only at 807 s. Raised to 11.8 barg at 1200 s instead, the header trips the separator on high pressure 15.5 s later. No tuning creates a differential that the header has removed.

6.6.8 A Biased Interface Transmitter

In case 8 LT-101 starts reading 150 mm high at 60 s, and the interface loop obeys it. The loop drains the water layer at up to 134 m^3/h, the hydrocyclone runs at 168 %, and the polished water peaks at 170.5 mg/L at 111 s. The true value is back under 30 mg/L at 280 s, but AT-101 diverts only at 308.5 s, after 6.8 m^3 of off-spec water has gone overboard, and the diversion then sends 6.1 m^3 of water already in spec to the hold tank. The disagreement between LT-101 and the LT-102 profiler raises its alarm at 119.5 s. By 1800 s the true interface sits at 350 mm, the water keeps 4.3 min instead of 7.3 min, and the separator outlet carries 470 mg/L instead of 353 mg/L, still 18.0 mg/L after the

Table 6.8 Loops and MPC on the Slug and the Inflow Step, Default Seed. IAE and Travel Are the Scorecard's. Interface Averaged Sets the Interface Loop to 0.5 %/cm and 1500 s

Structure	Oil out, m^3/h peak	SD	Water peak m^3/h	Off spec m^3	Level max mm	Level IAE mm·s	Pressure IAE bar·s	Carry-over L/MSm^3	Travel, % oil+ water	gas
Case 9, 2400 s										
tight PI (shipped)	317.5	45.73	144.3	8.40	1630	76 951	138	335	1256	186
averaging PI	219.1	12.25	107.4	6.92	1682	252 904	135	1772	310	184
averaging, interface averaged	220.8	13.24	82.2	0.00	1687	268 133	135	2078	152	184
MPC (as loaded)	202.8	9.38	83.0	0.00	1697	414 246	280	2098	57	151
MPC with preview	238.1	20.04	84.3	0.00	1688	193 206	133	2149	105	459
Case 2, 1200 s										
tight PI (shipped)	317.5	64.35	144.3	8.40	1630	73 102	124	335	604	123
averaging PI	219.1	16.52	107.4	6.92	1682	192 038	120	1772	174	120
averaging, interface averaged	220.8	17.02	82.2	0.00	1687	233 574	120	2078	87	120
MPC	202.8	13.03	83.0	0.00	1697	283 112	124	2098	48	125
Inlet step, 2400 s										
tight PI (shipped)	187.4	6.05	79.4	0.00	1216	5288	17	5	1275	123
averaging PI	179.9	8.45	78.5	0.00	1327	240 338	17	5	269	123
MPC	175.5	7.06	77.9	0.00	1360	305 920	268	5	26	50

MPC runs: 1200 plans in 2400 s and 600 in 1200 s, none rejected.

hydrocyclone, while the thicker pad lowers the BS&W to 0.085 %. With LT-102 as the measurement the loop does not move and nothing goes off spec.

> **TRY IT IN THE APP 8 · Biased interface sensor**
>
> Press Run with Interface measurement on LT-101 displacer. The disagreement alarm comes at 119.5 s, and AT-101 diverts at 308.5 s, after 6.8 m^3 of off-spec water has gone overboard. Set Interface measurement to LT-102 profiler, press Reset and run again: the loop does not move and nothing goes off spec.

6.6.9 Averaging by a Predictive Controller

Case 9 repeats the 15 m^3 slug of case 2 at 60 s, and at 1200 s the wells' liquid rate steps from 214 to 250 m^3/h and stays there. It loads under the MPC, and its comparison is the PI loops with the averaging preset. Table 6.8 measures case 9, case 2 and an inlet step, case 1 with the same rise at 60 s, with the same seed, instruments and noise and the MPC always at the settings case 9 ships, and Figure 6.4 shows case 9. No run in the table trips, and none of its 4200 plans was rejected.

The MPC spends the band on the oil. In case 9 it lets the level climb to 1697 mm, against 1682 mm under averaging, and raises the oil only to 202.8 m^3/h, against 219.1 m^3/h, with a standard deviation of 9.38 against 12.25 m^3/h and 57 % of liquid valve travel against 310 %. The soft ceiling of the one bank holds the water to 83.0 m^3/h, so none goes off spec, against 6.92 m^3 under the preset. That is not the MPC's alone. With the interface loop averaged as well, at 0.5 %/cm and 1500 s as in Table 6.7, the PI loops hold the water to 82.2 m^3/h with 0 m^3 off spec, and the MPC's lead narrows to the oil, a peak of 202.8 against 220.8 m^3/h and a standard deviation of 9.38 against 13.24 m^3/h, and to liquid valve travel, 57 against 152 %.

The MPC loses on the level and the pressure. Its level IAE is 414 246 against 252 904 mm·s under the preset and 268 133 with the interface averaged, and at 1200 s the level is at 1288 mm, where averaging has been within 50 mm since 947 s. The higher level raises the worst carryover to 2098 L/MSm^3 against 1772 L/MSm^3, and the pressure IAE is 280 against 135 bar·s, although its range, 9.75 to 10.80 barg, is narrower than the loops' 9.26 to 10.92 barg. After the step the level peaks at 1316 mm at 2121 s, against 1263 mm under averaging at 2400 s, and run on to 21 600 s it is back within 50 mm from 6289 s and within 10 mm from 13 334 s, with no offset. The estimate of the unseen inflow is slow on purpose, so that a slug does not look like a lasting flood. It still credited

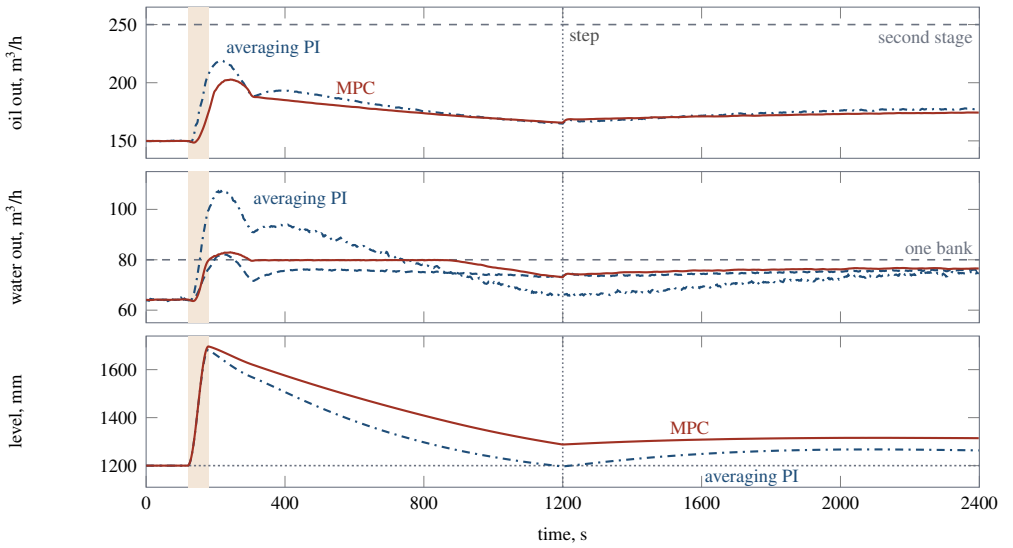


Figure 6.4 Case 9 over the 40 min window as at $t = 2400$ s, default seed, under the MPC as loaded (solid) and averaging PI (dash-dotted), with the slug shaded and the step of the wells dotted. Oil peaks at 202.8 m³/h at 243 s and 219.1 m³/h at 219 s, water at 83.0 and 107.4 m³/h (82.2 m³/h with the interface loop averaged, densely dashed), and the level ends at 1314 and 1263 mm. Thin dashed lines mark the second stage and one hydrocyclone bank.

17.8 m³/h to the slug at 1200 s, when the true excess was zero, and only 27.5 of the step's 36 m³/h at 2400 s, so every plan expected less liquid than arrived. Told the true step, a diagnosis the application does not offer, the MPC returns within 50 mm by 1762 s. The return is a trade of the tuning, not a defect of the estimator.

The move price λ sets how the slug is shared between the vessel and the second stage. At $\lambda = 3$ the oil peaks at 242.8 m³/h and the level is back within 50 mm by 910 s. At the shipped 10 the peak is 202.8 m³/h, and at 30 it is 190.2 m³/h with the level still at 1422 mm at 2400 s. Each step of the price buys a lower oil peak with a slower return of the level.

The preview makes the slug worse, presenting it through the held meter reading as a lasting rise, so the oil peaks at 238.1 m³/h. On the inlet step, where nothing needs absorbing, the shipped tight loops give the lowest oil standard deviation, 6.05 against 7.06 m³/h for the MPC and 8.45 m³/h for averaging, since passing a step straight on is the calmest answer to it, while the MPC moves the liquid valves least, 26 against 1275 and 269 %, at a pressure IAE of 268 against 17 bar·s.

6.6.10 The Wellstream Campaign

The 2400 s challenge brings three 12 m³ slugs, launched at 180, 1500 and 2040 s, a water cut rising to 35 and 40 % at 540 and 720 s, and an emulsion tightening in four steps to 1.8 times its usual stability between 900 and 1260 s. It asks for no trip, 9.0 to 11.5 barg, at most 250 m³/h of oil, BS&W and oil in water within their limits for 85 and 95 % of the time, no hold-tank overflow and at least 90 m³ of in-spec oil. Table 6.9 compares nine configurations. In the shipped configuration the plant exports 69.8 m³ in spec of 114.2 m³, keeps the BS&W within its limit 66.4 % of the time with a worst of 0.98 %, discharges 16.9 m³ of off-spec water with a worst of 264 mg/L, and passes 318 m³/h to the second stage, 564 s above its capacity. The suggested configuration, averaging, feedforward and the supervisor, exports 98.7 m³ in spec of 112.3 m³, 8.7 m³ more than the 90 m³ clause asks, brings the second bank in at 270.5 s, reaches 40 ppm of demulsifier at 1580.5 s, holds the worst BS&W

Table 6.9 Challenge Configurations Over 2400 s. Shares Are the Time Each Quality Stayed Within Its Limit

Configuration	In spec m^3	BS&W %	OiW %	Oil peak m^3/h	Pass
as shipped	69.8	66.4	63.8	318.5	no
suggested[a]	98.7	89.2	100.0	226.0	yes
averaging, supervisor	98.5	89.0	100.0	207.6	yes
supervisor only	87.3	84.4	100.0	318.5	no
averaging only	70.5	63.8	58.0	207.6	no
averaging, feedforward	70.0	63.1	54.9	226.0	no
tight, feedforward, supervisor	87.8	84.8	99.9	312.0	no
MPC, else as shipped	71.2	65.9	86.3	193.8	no
MPC, supervisor	101.2	93.6	100.0	193.4	yes

[a] averaging, feedforward and the supervisor

to 0.613 % and the worst overboard water to 22.7 mg/L, and keeps the pressure between 9.40 and 10.74 barg.

Each element does its own job. The supervisor alone keeps the overboard water in spec and lifts the BS&W share from 66.4 to 84.4 %, just short of the 85 % target, and the oil in spec to 87.3 m^3, short of 90 m^3, but leaves 318 m^3/h at the second stage, which among the PI settings only averaging protects. Averaging alone protects the second stage and fixes neither quality. Without the feedforward the averaging and the supervisor still pass, with 98.5 m^3 in spec, and the feedforward's contribution is a narrower pressure band, 9.40 to 10.74 barg against 9.26 to 10.97 barg, bought with 723 % of gas valve travel against 303 %. Figure 6.5 sets the nine configurations of Table 6.9 against the four clauses of the target that carry a number.

The MPC does not change the campaign's verdict. With everything else as shipped the MPC fails with 71.2 m^3 in spec, since the treating chemicals and the second bank are the supervisor's job, and with the supervisor on it passes with 101.2 m^3 and the pressure between 9.58 and 10.77 barg.

6.7 Technology in Practice

Figure 6.6 draws the three loops, the feedforward, the supervisor, the routing and the optional MPC of Section 6.5 with the hardware of a platform separator.

What Measures It

The level loop reads LT-100, a radar on the vessel top. Echo instruments can be fooled by a layer of foam on the liquid and have difficulty with interfaces that are not distinct, such as emulsions, and guided-wave radar, whose probe carries the signal into the liquid, is the only practical radar for a liquid-liquid interface [24]. In the model LT-100 adds waves that grow with the momentum of the inlet stream. The qualities depend on two analyzers. AT-100 reads the water in the export oil through a 20 s lag, and AT-101 reads the oil in the polished water through a 240 s sample delay. An online oil-in-water monitor is usually mounted on a side stream, and the length of its sample line adds a delay of its own [25].

> **TECHNOLOGY** **Sensor: The Interface Displacer**
>
> LT-101 is a displacer: it weighs an element too heavy to float that hangs in the liquid and reads the buoyant force on it as level. That force is proportional to the density of the liquid around the element, so a change of density reads as a change of level. For an interface the element must stay fully submerged, or the instrument cannot tell a low interface from a low total level [24]. An element in a cage beside the vessel can be isolated for service, one hung inside cannot [24], and an emulsion layer disturbs the reading [26]. The chapter gives LT-101 a 3 s lag, 3 mm of noise and, in case 8, a bias.

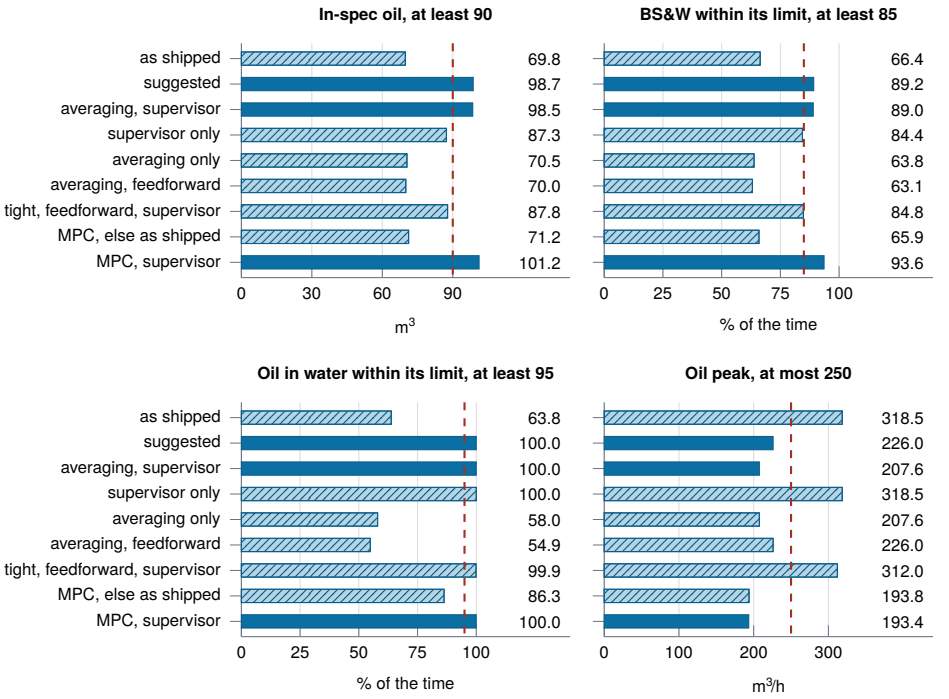


Figure 6.5 The challenge runs of Table 6.9 as bars: in-spec oil, the shares of time the BS&W and the oil in water stayed within their limits, and the oil peak, over 2400 s. Solid bars are the configurations that pass, hatched bars those that fail, dashed red lines are the clauses of the target, and the value of each bar stands at the right. Notice that every passing configuration pairs the supervisor with averaging or with the MPC, and that the supervisor alone misses the oil and BS&W clauses narrowly and the second stage widely.

What Moves It

Three control valves set the outlets: PV-100 on the gas, LV-100 on the oil and LV-101 on the water to the hydrocyclone. Fully open at design the oil valve passes 298.4 m^3/h and the water valve 134.3 m^3/h, while a 15 m^3 slug peaks at 1414 m^3/h. The dosing pumps, the heater, the second hydrocyclone bank, the recycle pump and the routing valve belong to the supervisor and the routing rule.

> **TECHNOLOGY** **Final Element: The Water Valve and Its Positioner**
>
> Packing friction and the force of the process on the plug keep a valve stem from following its actuator exactly, so a positioner compares the stem position with the command and drives the actuator until they agree [24]. With too much friction the stem moves in steps, called stiction, and ignores small reversals of the signal, worst in poorly maintained valves and in valves without a positioner [24]. Electronic positioners report position errors and total stem travel to maintenance and to the control system [24]. The chapter's valves follow their commands through a 3 s lag with no stiction band. Its not-following alarm makes the positioner's comparison of position and command: in case 6 the water valve seizes at 60 s and the alarm comes at 206 s.

Where the Controller Runs

The loops would run in the platform's control system. A distributed control system controls production within one geographic location through feedback and feedforward loops under a supervisory level, and its loops run with cycle times from milliseconds to minutes [27]. The app's loops execute every

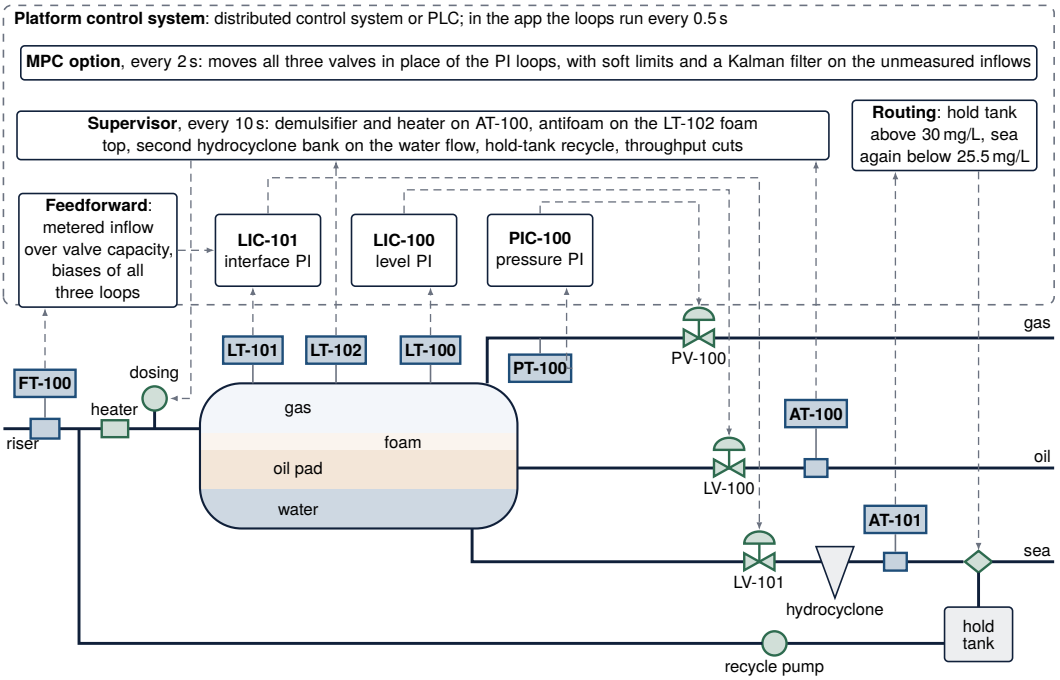


Figure 6.6 The loops of the separator simulator with their hardware. Lettered boxes are sensing devices with the chapter's tags: the level transmitters LT-100, LT-101 and LT-102 on the vessel, PT-100 on the gas line, the inlet meter FT-100 and the analyzers AT-100 on the oil and AT-101 on the polished water. Green symbols are final elements: the gas, oil and water valves, the inlet heater and chemical dosing, the routing valve to the sea or the hold tank, and the recycle pump. Gas goes to the compressor header and oil to the second stage. Dashed arrows are signals. Notice that only the two analyzers read quality, and that AT-101 commands a routing valve that the water it measured has already passed. Not to scale, and not a piping diagram.

0.5 s, its supervisor every 10 s and its MPC every 2 s, all inside that range and all far shorter than the 240 s by which AT-101 reports, so no scan rate makes the diversion timely. The chapter's structure maps onto three PI blocks with a feedforward bias computed from the inlet meter, a rule set in the logic layer for the chemicals, the heater, the second bank, the recycle and the throughput, a routing rule on AT-101 with a timed return, and, as an option, the MPC in a supervisory layer that moves the three valves in place of the PI blocks.

> **IN PRACTICE** **Compliance Is Judged in the Laboratory**
>
> In United States offshore waters the federal rule for produced water limits oil and grease to 42 mg/L on any one day and to 29 mg/L as the average of the daily values over 30 consecutive days [28]. On North Sea installations the oil in water is measured offline by the reference method of ISO 9377-2. The method requires at least two samples a day, samples are taken about three times a day [25]. The chapter's scorecard works differently from both: it judges the true oil in water at every instant against 30 mg/L.

What Is Modernizing It

Three developments touch this chapter. Electronic positioners count total stem travel and can predict when the stem packing will need replacing, flagging a maintenance alarm [24]. Online oil-in-water monitors, most of them fluorescence instruments, have served for monitoring, and a 2017 pilot plant

study used them to follow a hydrocyclone's efficiency as its inflow stepped [25], the dynamic reading that AT-101 lacks. A control-oriented separator model of 2018 adds virtual monitoring of the gas and liquid inflows and of the split of oil and water entering the water layer, quantities whose measurement is expensive, unreliable or impossible [13]. The Kalman filter of Section 6.5.5, which estimates the unmeasured inflows, is an estimator of the same kind.

6.8 Limitations

The wells deliver an imposed stream, so the application cannot represent the coupling between the riser and a topside choke controller on which active slug suppression relies [8].

The vessel is four well-mixed cells under a flat level, and its quality correlations are illustrative. It reproduces the direction and the time scale of each quality effect, but it cannot predict the BS&W of a particular crude or the efficiency of a particular liner [7, 18].

> **OPEN CHALLENGE** **Seeing Every Layer in the Vessel**
>
> A crude oil separator holds gas, oil, water, emulsion and sludge, and accurate measurement of its several interfaces is regarded as a challenge. Displacers, differential pressure transmitters and ultrasonic instruments cannot measure the emulsion or the foam, and gamma instruments, which do see the vertical distribution of the phases, carry hazardous radiation. Separator control stays simple for lack of such measurements, and a suitable instrument would give more efficient and compact separators and less chemical use [26]. Progress would be a measurement of the emulsion band and the foam reliable enough for a loop to act on.

There is no flare or relief path for the gas, so a header above the trip pressure ends the run, and the supervisor is a rule set rather than an optimizer or a vendor's logic.

The MPC's model leaves out droplets, foam and carryover, thin-layer draws, transmitter lags and waves, the wells and the supervisor, and a stuck stem. It holds the inflow over the horizon, so it cannot tell a slug from a lasting rise until its slow estimate moves, and its close validation reflects a model built from the simulator's own balance rather than one identified on a real vessel. The pressure keeps a fixed band with one slack for the whole horizon, so a predicted violation leaves any smaller later one unpriced.

> **OPEN CHALLENGE** **An Oil-in-Water Reading Fit for Feedback**
>
> Online oil-in-water monitors, most of them fluorescence instruments, serve only for monitoring. Their reading is only approximately linear and is calibrated to one range, one oil may need a different calibration from a slightly different oil, and a fouled view cell drifts. Their precision under changing conditions still needs verification, and none is installed as a feedback transmitter on North Sea installations [25]. Progress would be a reading trusted enough to adjust the water treatment before the discharge goes off spec, not after.

6.9 Conclusion

An offshore three-phase separator is an inventory whose levels are held for the sake of its outflows, and the simulator described here measures that distinction on one vessel. The oil and water valves act on the two levels through a triangular gain matrix, -0.0281 and -0.0126 millimeters per second per percent on the total level against -0.0167 on the interface, so the pairing is forced and a water valve that cannot act makes the level loop drain oil. A 15 m^3 slug is stored under any tuning, 12.8 m^3 of it at the peak under tight tuning and 14.4 m^3 under averaging, and the tuning decides only how fast it returns, at 317 m^3/h and 268 s over the second stage or at 219 m^3/h. Under both presets an overloaded hydrocyclone bank discharges 8.4 or 6.9 m^3 of off-spec water before the analyzer, four minutes late, diverts it, and a second bank or an interface loop averaged to 0.5 %/cm removes the loss. The campaign moves from 69.8 m^3 to 98.7 m^3 of in-spec oil with averaging, feedforward and the supervisor. An optional MPC lowers the slug's oil peak to 202.8 m^3/h against 219.1 and 220.8 m^3/h for the averaging loops, at a level IAE of 414 246 against 252 904 mm·s. The model imposes the

wellstream, mixes each cell and uses illustrative separation correlations. A fuller model would couple the riser to the separator pressure, add a relief path, replace the cells by a settling-zone model and average the discharge limit over time. The case that runs through the chapter is that a level controller chooses where a disturbance goes, not whether it arrives.

KEY POINTS

- A level controller chooses where a slug goes, not whether it arrives: the 15 m^3 slug of case 2 is stored in the vessel under any tuning.
- The tuning decides only how fast the stored liquid returns, at 317 m^3/h and 268 s over the second stage under tight tuning or at 219 m^3/h under averaging.
- The gain matrix is triangular, so the pairing is forced, and a water valve that cannot act makes the level loop drain oil.
- An overloaded hydrocyclone discharges 8.4 or 6.9 m^3 of off-spec water before the analyzer, four minutes late, diverts it, and a second bank or an averaged interface loop removes the loss.

Where else this applies. Volume 9, Chapter 7 spends a reservoir's storage to hold a flood under a downstream limit, and Volume 5, Chapter 7 diverts product on an analyzer that reports after the material has passed.

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6.10 Exercises

6.1 Concept check · 1 min

In case 2 a 15 m^3 slug reaches the separator over one minute. Why does neither tight nor averaging level tuning keep it out of the vessel?

(a) The slug arrives at up to 1414 m^3/h, while both outlet valves fully open pass only about 433 m^3/h at design pressure.

(b) LT-100 lags the level by 2 s, so the loop sees the slug too late to open the oil valve.

(c) The gas held back behind the slug lowers the pressure until the liquid valves pass almost nothing.

(d) The tight preset's 240 s integral time is four times the 60 s the slug takes to arrive.

6.2 Concept check · 2 min

In case 6 the water valve sticks at 60 s and the water cut then rises to 45 %. With the supervisor off, the total level stays on its setpoint while the interface climbs to its trip. Why?

(a) The interface loop winds up and its integral is passed to the oil valve, which then holds the interface high.

(b) The level loop holds the total level the only way left to it, by taking out more oil than arrives, so the water layer grows under a thinning pad.

(c) The supervisor is off, so the rising water cut fills the vessel until the high-high level trips.

(d) The relative gain array changes sign once the water valve sticks, so the level loop drives the interface up.

6.3 Concept check · 2 min

In case 2 under tight tuning, AT-101 sends the polished water to the hold tank at 399 s. Why does 8.4 m^3 of off-spec water still reach the sea?

(a) The routing valve waits 60 s after AT-101 passes 30 mg/L before it closes the overboard line.

(b) The hold tank is full, so the diverted water overflows to the sea.

(c) AT-101 reads through a 240 s sample delay. The true value passed 30 mg/L at 148 s, so the off-spec water had left before the diversion.

(d) The hydrocyclone reject is discharged untreated while the bank is overloaded.

6.4 Theory and calculation · 6 min

The level gains and the two presets follow from the vessel geometry. Use the chapter's values: the oil valve passes 298.4 m^3/h and the water valve 134.3 m^3/h fully open at design, the liquid surface is 29.4 m^2 at 1200 mm and the interface 22.4 m^2 at 500 mm.

(a) Compute the rate of change of the total level per percent of oil valve, and of the interface and the total level per percent of water valve, in mm/s. Why does the oil valve not move the interface? *Checkpoint:* 0.0282 mm/s, 0.0167 mm/s and 0.0127 mm/s.

(b) With $k = 0.0281$ mm/s per percent for the total level, compute $\tau_c = 1/(K_c k)$ and $\zeta = \frac{1}{2}\sqrt{\tau_I/\tau_c}$ for the tight preset (5.0 %/cm, 240 s) and the averaging preset (0.4 %/cm, 1500 s). *Checkpoint:* 71 s and 0.92, 890 s and 0.65.

(c) Compare both closed-loop time constants with the 60 s a slug takes to arrive. What does the comparison predict, and why does the tight loop not behave as its τ_c suggests during the arrival?

6.5 Theory and calculation · 6 min

Water drops dispersed in the oil pad must settle out before the oil leaves. At the design 49.5 °C the oil viscosity is 6.79 cP, its density 850 kg/m^3, and the density difference 175 kg/m^3.

(a) Compute the Stokes velocity $g\,\Delta\rho\,d^2/(18\mu)$ of the 540 and 60 µm water drops. *Checkpoint:* about 4.1 mm/s and 0.051 mm/s.

(b) For the 540 µm drop compute the particle Reynolds number $\rho_o v d/\mu$ and apply the correction of Equation (6.6). *Checkpoint:* $Re \approx 0.28$, about 3.86 mm/s.

(c) The oil flows at 149.8 m^3/h over the 22.4 m^2 interface. Compute this overflow rate and say which of the three classes (60, 180 and 540 µm) settle without first coalescing.

6.6 Theory and calculation · 8 min

A slug's arrival is a volume balance that no controller can change. Use the design values: normal inflow 214 m^3/h, both liquid valves fully open 433 m^3/h, and a surge volume of 26.4 m^3 between the 1200 mm normal level and the 2100 mm high-high trip.

(a) The 15 m^3 slug of case 2 arrives as a half-sine over 60 s. What is its peak flow? *Checkpoint:* about 1414 m^3/h.

(b) If both valves were wide open for the whole arrival, how much of the slug would they pass on, and what is the least volume the vessel must store? *Checkpoint:* 3.65 m^3 and about 11.4 m^3.

(c) The tight run stores 12.8 m^3 at its peak. Estimate the peak level from the surface widths, 29.4 m^2 at 1200 mm and about 29.9 m^2 at 1650 mm, and compare with the measured 1629.6 mm. *Checkpoint:* about 1630 mm.

(d) Repeat (b) for the 40 m^3 slug of the event button, which arrives over 90 s, and say what any tuning can do about it.

6.7 App challenge · 8 min

Run case 2, *Liquid slug*, at the default seed and a speed of 30, so a 1200 s run takes 40 s.

(a) Run to 1200 s as loaded (Level tuning Tight). Read the *Off-spec overboard* and *Carryover* tiles, export the CSV and find the largest value in the `oil_out_m3h` column. *Checkpoint:* 8.4 m^3, 335 L/MSm^3, 317 m^3/h.

(b) Reload the case with the reload button, set Level tuning to Averaging before Run, and repeat. *Checkpoint:* 6.9 m^3, 1772 L/MSm^3, 219 m^3/h.

(c) Keep the averaging level loop, set the Interface loop gain to 0.5 %/cm and its integral time to 1500 s (Level tuning then shows Custom), press Reset and run to 1200 s. Read the same two tiles, the worst value on the *OiW in spec* tile and the largest `water_out_m3h`. What did the interface loop change, and at what cost?

6.8 App challenge · 7 min

Run case 7, *Gas backpressure rise*, at the default seed and a speed of 10.

(a) Pause at any time between 400 and 900 s. Read the separator pressure on the *Pressure* tile, export the CSV and, in its last row, read the gas valve command `gas_valve_cmd_pct`, the integral term `ctrl_I_P` and the proportional term `ctrl_P_P`. *Checkpoint:* 11.52 barg, 100 %, integral 100.0 %, proportional about 23 %.

(b) Move the *Gas export header pressure* slider to 8.0 barg and run on for 300 s. Read the lowest pressure on the *Pressure* tile and, from the `P_barg` column, how long after your move the pressure comes back within 0.05 bar of 10.00 barg to stay.

6.9 App challenge · 9 min

Run the *Challenge, wellstream campaign* at the default seed and a speed of 30, so the 2400 s campaign takes 80 seconds. The verdict is taken at 2400 s, and the tiles keep counting after it, so read the result line the challenge records at 2400 s or the CSV row at `time_s` = 2400.

(a) Turn the Quality supervisor on, leave everything else as loaded, and run to 2400 s. Read the in-spec oil (`metric_oil_inspec_m3`), the BS&W share (or `metric_bsw_offspec_s`, the seconds off spec out of 2400 s) and the peak oil outflow. Which clauses of the target fail? *Checkpoint:* 87.3 m^3, 84.4 %, 318 m^3/h.

(b) Set Level tuning to Averaging as well, press Reset and run to 2400 s again. Read the same three values and the verdict.

(c) Explain what each element contributes, and why the feedforward of the suggested configuration is not needed to pass.

6.10 Application area · 4 min

In case 7 the compressor suction header rises to 11.3 barg, and the separator settles at 11.52 barg with its gas valve wide open, 0.48 bar below the high-high trip. A shift supervisor asks for a faster pressure loop. What is your answer, and what protects a real separator in this situation?

6.11 Application area · 4 min

After the case 2 slug the produced-water engineer has three proposals to stop off-spec water going overboard: a faster AT-101 with a 30 s sample delay, a second hydrocyclone bank in service, or the interface loop retuned to 0.5 %/cm and 1500 s. Rank them with the chapter's results and name a cost of each.

6.12 Review the agent · 5 min

An AI assistant reviewing the separator's control design writes: "The relative gain array of the level and interface loops is the identity to within 0.3 %, so the two loops do not interact. Each can be tuned,

alarmed and maintained on its own, and a fault in the water valve stays inside the interface loop: the level loop and the export oil quality are unaffected.” Find the flaw and say how you would check it in the app.