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CHAPTER 5

A Deepwater Flowline Simulator for Hydrate Control at the Weakest Point

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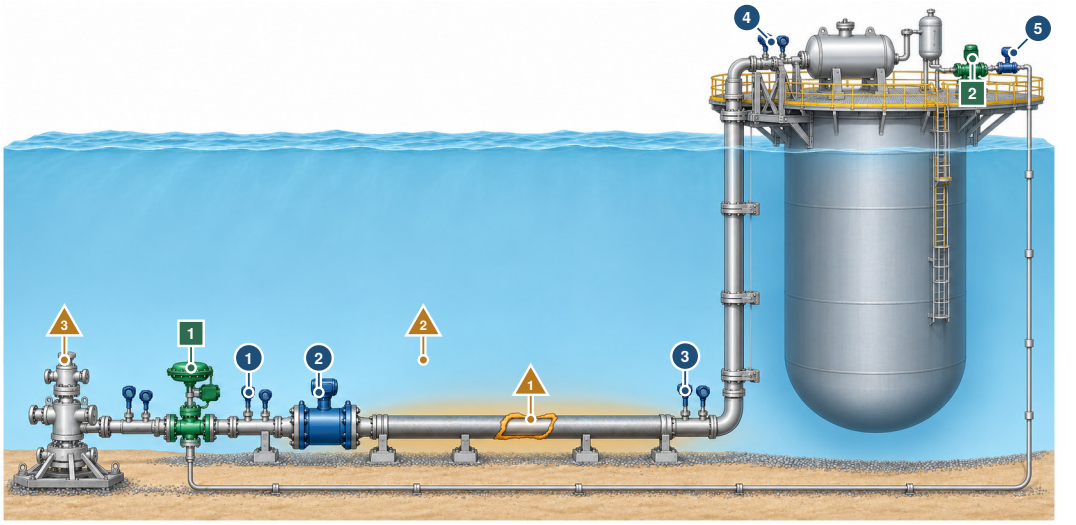
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CHAPTER 5

A Deepwater Flowline Simulator for Hydrate Control at the Weakest Point



The controller moves 1 subsea choke at the tree 2 methanol pumps on the platform
The controller reads 1 pressure and temperature after the choke
2 multiphase meter for the liquid flow and its water share 3 pressure and temperature at the riser base
4 pressure and temperature where the fluid arrives 5 methanol pump flow
What disturbs it 1 flooded insulation 2 colder seabed water 3 more water from the well

The weakest point is the foot of the riser, where the cooled fluid still carries the seabed pressure, and the methanol reaches it only after the long trip down the umbilical and along the whole line. Illustration, not to scale.

IN PLAIN TERMS The Coldest Pipe Is Not the Riskiest

The main idea. Oil, gas and water flow through a long, cold seabed pipe and up to a floating platform. Methanol added at the well keeps the gas and water from locking into solid crystals that could plug the pipe.

The challenge. Pressure lets the crystals form in warmer fluid, so the riskiest spot is the deep foot of the rising pipe, not its colder top. Methanol rides with the liquid and needs hours to get there, so a gauge there asks for it too late.

Why it matters. A dose sent ahead of the cold protects the line, while a dose sent after it comes too late.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	This page, the two History boxes and the first Did you know? box in Section 5.2, the first Try it box in Section 5.4, the second Try it box and the second Did you know? box in Section 5.6, and Key points in Section 5.9. No equations.
Study	60 min	The whole chapter in order, stopping at the three pause points, then Exercises 1 to 12.
Practice	20 min	This page, Section 5.6 with Figure 5.5, Section 5.7 and Section 5.8 with its Open challenge boxes.

The control question Gas hydrates form wherever the liquid in a subsea line is colder than an equilibrium that climbs with pressure and falls with the methanol in its water, so the constraint is a minimum over kilometers of pipe whose location moves. How is methanol dosed at the tree for a margin that is judged hours downstream, and what can an estimate built from a few transmitters tell the dose?

Learning objectives

- Locate the weakest point of a flowline from its temperature and pressure profiles, and explain why it is not where the fluid is coldest.
- Compute the liquid transit to the riser base from the line's liquid volume and the flow, and the methanol rate for a target concentration.
- Explain why the dose for a turndown or a water breakthrough must come from a feedforward on the predicted demand and the water rate, not from feedback.
- Estimate a stopped line's no-touch time from its lumped cooldown, and judge what two thermometers can and cannot say about lost heat.
- Plan a cold restart through the inhibition lead, the choke ramp and the flow held to the pumps, and grade it on exposure, methanol and oil.

Prerequisites Sections 1.4.3 (holdup and the transport delay of a liquid column), 1.4.8 (selectors and external reset), 1.6.2 (the framework's PID), 1.6.3 (for case M) and 1.6.4 (the apps), and the rate loop under an override on one choke in Chapter 4.

The app https://apmonitor.com/apps/subsea-flow-assurance/

See also Volume 5, Chapter 2 for control through a fuel delay, Volume 5, Chapter 7 for material judged after it has moved on, and Volume 5, Chapter 11 for a state that no instrument reaches, inferred from a model. Volume 4, Chapter 2 for a protective override, and Volume 4, Chapter 5 for a trim behind overrides.



5.1 Introduction

Many process constraints apply at the worst point of a distributed plant rather than at a transmitter. The hottest and the slowest vials of the freeze-dryer in Volume 8, Chapter 5 are a batch example. Transport-reaction processes such as tubular reactors are distributed parameter systems whose control is a subject of its own [1], a drinking-water network is judged by the disinfectant residual that reaches its consumers some time after a booster station has dosed it [2], and a subsea flowline by the smallest difference, anywhere along it, between the liquid temperature and the local hydrate equilibrium [3, 4]. The point that decides such a constraint moves as the operating state moves, and the actuator that protects it acts somewhere else.

A deepwater tieback carries a well's fluid from a subsea tree through an insulated flowline on the seabed and up a riser to a floating platform. Gas hydrates, crystalline solids in which water cages light gas molecules, form wherever free water is colder than an equilibrium temperature set by the pressure, and in deep water both the cold and the pressure are permanent [3]. Insulation keeps the stream warm while it flows and slows its cooling when it stops, and a thermodynamic inhibitor such as methanol lowers the equilibrium in the water it dissolves in [5]. The methanol is pumped on the platform, travels down an umbilical to the tree and then moves with the liquid.

The simulator addresses two beliefs, that the coldest fluid marks the greatest hydrate risk and that an inhibitor can be dosed by feedback on the margin it protects. On the line modeled here the coldest fluid is the fluid arriving at the platform, at 19.4 °C with a margin of +12.2 °C, while the smallest margin, +6.41 °C, sits at the foot of the riser, where the fluid is 3.9 °C warmer but still under 86.5 bar. A step of the methanol pump reaches half strength at that point 3.49 h later at the design rate. A loop that acts only once the estimated margin has fallen therefore doses liquid that has already gone past. A low-order model with one constant delay captures neither the moving minimum nor a delay that stretches as the flow falls.

The class is general. A dose applied at one node and judged at another after a transport delay is the structure of chlorine boosters in water networks [2], and control of a spatial profile rather

than of a point value is the subject of transport-reaction process control [1]. The canal of Volume 9, Chapter 5 has the same structure, a release at the head judged at the far end long after it was made. Three lessons carry across the class. The controlled variable is a minimum whose location moves, the dose belongs to a prediction of demand because feedback at the point of risk arrives a transit late, and an estimate of the profile built from a few sensors can explain the right effect by the wrong cause. However, control studies of pipeline-riser systems have treated the flow itself, such as the riser slugging that feedback on a choke can stabilize [6], while hydrate prevention has been treated as a design calculation of insulation and inhibitor volume [5, 7].

This chapter works with a deepwater flowline simulator in which the hydrate margin is computed slice by slice on the simulated truth, the methanol travels with the liquid, and the methanol loops see only an estimate built from six transmitters, the multiphase meter and the pump's flow meter, so that a turndown, a water breakthrough, an unmeasured heat loss, a trip or a cold restart can each be read as exposure below the hydrate curve. The hydrate correlations, the thermal model, ratio feedforward and override control are established practice. The model of the line is reduced in one particular way. It moves water cut and methanol exactly, as slices of liquid, while the temperatures ride on fixed segments, and it keeps a record of the truth that the instruments never see. The chapter gives it completely enough for the model to be written again from the text. The nine nonchallenge cases and the challenge separate what heat, chemistry, estimation and sequencing can and cannot guarantee.

Section 5.2 traces how hydrates became a control problem on the seabed. Section 5.3 builds the model of the flowline and riser: the thermal segments, the well and choke, the pressure and holdup, the slices of liquid and the hydrate margin. Section 5.4 draws its consequences for the weakest point, the liquid transit and the cooldown of a stopped line. Section 5.5 sets out the instruments, the profile estimator, the choke loops, the methanol feedforward with its trim and override, the shutdown and restart sequence and the optional predictive dosing. Section 5.6 reports the measured cases, the challenge and the comparison with predictive dosing. Section 5.7 sets the hardware of a real tieback beside the model, Section 5.8 states the limitations, Section 5.9 concludes, and the exercises of Section 5.10 run the cases.

5.2 Hydrates, Flowlines and Inhibitors

Hydrates became an engineering problem when natural gas began to travel long distances by pipe. The first History box below tells how the plugs in those lines were identified. By 1945 the formation of hydrates could be predicted from vapor–solid distribution coefficients [8] or from a chart of formation conditions against pressure and gas gravity [9]. The defenses that followed are still the ones in use, removing the water, keeping the gas warm, or adding an alcohol or a glycol that lowers the equilibrium in the free water, and the shortcut relation that carries Hammerschmidt's name is still used to estimate that depression [5]. The curve in the simulator descends from the gas-gravity route through a later correlation of the same kind.

> ⧖ HISTORY **1934: The Plugs Were Not Ice**
>
> Hydrates were first made in a laboratory in 1811, and for a long time they were a matter of scientific curiosity [10]. Before 1934 the crystals that blocked gas lines were blamed on various causes, with much apprehension and little definition. In 1934 Hammerschmidt showed that the plugs, which formed in cold weather above the freezing point of water, were hydrates and not ice [10–12]. He also gave a simple equation for the pressure and temperature at which they form, and he identified inhibitors, among them methanol and ethylene glycol, which are still in common use. The industry could then move from apprehension to avoidance, keeping its lines outside the conditions that such a calculation predicts [10].

Offshore production moved the problem onto the seabed and lengthened it, as the second History box below tells, and partial protection turned out to be a hazard of its own. Insulated lines protected

by methanol during shutdowns and restarts made the time a stopped line takes to cool into the hydrate region a design quantity [5], and the dynamic two-fluid model OLGA [13] brought transient multiphase simulation of such lines into engineering use.

> ⧖ HISTORY **1994 to 1996: Longer Lines in Deeper Water**
>
> In 1994 the fluids of a subsea well could be carried about 10 to 15 miles (16 to 24 km), while leases in about 4000 ft (1200 m) of water could need 50 to 60 miles (80 to 97 km). Chemical injection was regarded as the primary defense, and knowledge of insulation for deepwater lines was described as very limited [7]. Two years later methanol and ethylene glycol were the inhibitors most used offshore. Blockages had followed failures of the chemical injection system, unscheduled shutdowns at the host platform and too little inhibitor at well startup, the three events of cases 6, 7 and 8. Field experiments had shown under-inhibited lines blocking more readily than lines with no inhibitor, and laboratory tests at 1 to 5 percent by weight found both inhibitors speeding up hydrate formation [12].

The emphasis then moved from avoiding hydrates toward managing their risk [14]. Low dosage inhibitors, kinetic inhibitors that delay formation and anti-agglomerants that keep the crystals dispersed, were developed as alternatives to large volumes of methanol [15], and transient formation models now follow the growth of a hydrate phase rather than only its equilibrium [4, 16]. On the same hardware, the severe slugging of a pipeline-riser system has been analyzed as a problem of stabilization by feedback on a choke valve [6]. The simulator keeps to an insulated line protected by methanol from the platform, the arrangement in which the transport delay and the weakest point are plainest.

> ✦ DID YOU KNOW? **A Plug That Is Mostly Water**
>
> A 2021 review puts flowline hydrates at 85 mole percent water, with gas molecules smaller than pentane held in the water cages. Below about 1200 m of water the sea around a flowline is typically near 277 K, close to the 4 °C seabed of this chapter's line [10].

5.3 Model of the Flowline and Riser

The simulated line runs from a subsea tree at 1500 m through 5 km of seabed flowline and a vertical riser of 1.5 km to a spar, with a 0.25 m bore throughout. At the design rate of 1000 Sm^3/d of liquid with a 20 % water cut the choke is open 63.2 % and drops 25.1 bar, the fluid leaves it at 58.7 °C, and the platform holds the arrival at 20 bara. The layout, with its segments, umbilical and transmitters, appears in Figure 5.1.

The controlled, manipulated and disturbance variables and the states are sorted in Table 5.1. The integrator carries 73 states, the fluid and wall temperatures of 32 segments, the flow, the temperature at the wellhead, the two stages of the umbilical, and five running totals of liquid, methanol and energy that close the ledgers. The water share, methanol and exposure of the liquid live instead on 346 slices at the design rate, a discrete state moved after each integration step. Besides the sliders of Table 5.1, discrete events trip the well, request a planned shutdown or a restart, tag a parcel, drop the pump availability to 40 %, raise the water cut by 25 points, cool the seabed water by 2.5 °C, raise the arrival pressure by 25 bar, and fail or repair TT-103.

5.3.1 Segments, Heat and the Sea

The path is divided into 20 seabed segments of 250 m and 12 riser segments of 125 m. Each segment i holds a fluid node and a wall node that stands for the steel and the inner insulation, and the fluid

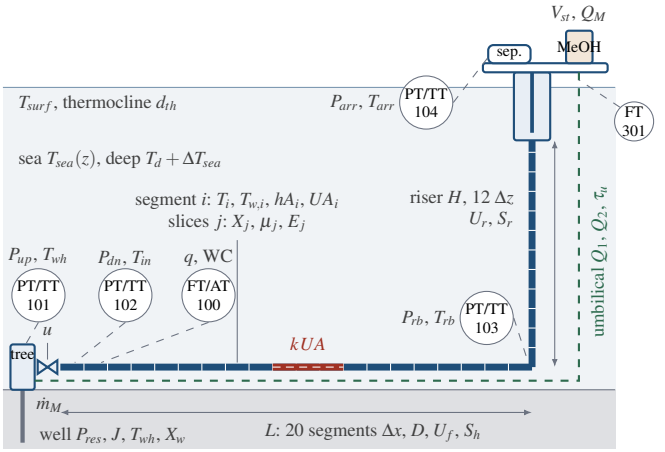


Figure 5.1 The modeled line, not to scale. The well feeds the tree, where the choke at opening u passes the liquid rate q with water share X_w into 20 seabed segments of length Δx and 12 riser segments of height Δz, each with fluid and wall temperatures T_i and $T_{w,i}$, a film hA_i and an insulation UA_i to the sea at $T_{sea}(z)$. The liquid carries its water share X_j, methanol μ_j and exposure E_j as slices j. The section marked kUA (red, with a dashed white center line) can lose its insulation by the factor k. The dashed umbilical takes the pump flow Q_M from the platform tank to the tree through the stages Q_1 and Q_2. PT/TT-101 to 104 measure pressure and temperature upstream and downstream of the choke, at the riser base and at the arrival, FT/AT-100 is the subsea multiphase meter and FT-301 the pump's flow meter.

Table 5.1 Flowline Variables by Role, With Design Values and Ranges

Variable	Role	Design value	Range
q_m	CV of FIC-100 (FT-100)	1000 Sm^3/d	SP 0–2000
$\hat{m}_{min}$	CV of the methanol trim	+6.41 °C, SP 3	SP 0–10
$P_{dn,m}$	CV of PIC-102 (PT-102)	90.4 bar	limit 80–160
u	MV, choke opening	63.2 %	0–100
Q_M	MV, methanol pump	0 m^3/h	0–4
X_w	DV, well water cut	20 %	0–80
P_{arr}	DV, arrival pressure	20 bara	10–60
ΔT_{sea}	DV, seabed water change	0 °C	±4
k	DV, insulation damage	1	1–10
a_p	DV, pump availability	100 %	0–100
b_{WC}, TT-103	DV, meter bias, failure	0, working	±15, 0/1
q, T_{wh}	states, flow, wellhead	1000 Sm^3/d, 60 °C	—
Q_1, Q_2	states, umbilical stages	0 m^3/h	—
T_i, $T_{w,i}$	states, 32 segments	56.0 to 19.4 °C	—
X_j, μ_j, E_j	slice records, 346 slices	0.2, 0, 0	—

carries its heat downstream by first-order upwind transport, as shown in Equation (5.1).

$$\begin{aligned} C_{f,i}\frac{\mathrm{d}T_i}{\mathrm{d}t} &= W_{i-1}\left(T_{i-1}-T_i\right)-hA_i\left(T_i-T_{w,i}\right) \\ C_{w,i}\frac{\mathrm{d}T_{w,i}}{\mathrm{d}t} &= hA_i\left(T_i-T_{w,i}\right)-UA_i\left(T_{w,i}-T_{sea,i}\right) \end{aligned} \tag{5.1}$$

Here $W_{i-1} = q\,c_v(X_{i-1})$ is the heat-capacity flow entering segment i, with $T_{-1} = T_{in}$ and $X_{-1} = X_w$ at the choke, and the other coefficients follow Equation (5.2).

$$\begin{aligned} c_v(X) &= X\rho_w c_w + (1-X)(\rho_o c_o + \mathrm{GOR}\,\rho_{gs} c_g) \\ C_{f,i} &= V_i H_i \left[X_i \rho_w c_w + (1-X_i)\rho_o c_o\right] \\ &\quad + V_i (1-H_i)\,\rho_{g,i} c_g \\ hA_i &= \pi D\,\Delta x_i \left[h_s + (h_f - h_s)\min(q/q_d,\,1.5)^{0.8}\right] \\ UA_i &= \pi D\,\Delta x_i\, U\left[1 + (k-1)\,\phi_i\right] \\ C_{w,i} &= C'_w\,\Delta x_i \end{aligned} \tag{5.2}$$

where c_v counts the gas that travels with the oil, $V_i = A\,\Delta x_i$ is the segment volume, H_i the liquid holdup, $\rho_{g,i}$ the local gas density, U the flowline or riser coefficient on the inner area and ϕ_i the share of segment i inside the damageable section. The film rises from natural convection at rest toward its design value with the Dittus–Boelter exponent. The sea is $T_{sea}(z) = T'_d + (T_{surf} - T'_d)\,\mathrm{e}^{-z/d_{th}}$ at the depth z of a segment center, with $T'_d = T_d + \Delta T_{sea}$, which gives 4.04 °C on the seabed and 18.0 °C in the top riser segment.

At the design rate the heat-capacity flow is 27.7 kW/K, of which the gas carries 1.7 kW/K, and the film and insulation in series conduct 5.78 W/(m·K), so the steady temperature approaches the sea over an e-folding length of 4.79 km. The discrete steady solution replaces the exponential by a factor $W/(W + ua_i)$ per segment, ua_i being the film and insulation of segment i in series, and runs 0.51 °C warm at the riser base against the analytic profile, a first-order error that falls to 0.26 °C with 40 seabed segments and 0.13 °C with 80.

5.3.2 Well, Choke and Flow

The well is a shut-in wellhead pressure $P_{si} = P_{res} - \Delta P_{tub} = 150$ bar behind a productivity index. One lumped liquid rate relaxes toward the rate q^* at which the well, the choke and the line balance, as shown in Equation (5.3), with pressures in bar and rates in Sm³/d.

$$\begin{aligned} P_{si} - \frac{q^*}{J} - \left(\frac{q^*}{K(u)}\right)^2 &= P_{dn,s} + K_f\,q^{*2} \\ \tau_h \frac{\mathrm{d}q}{\mathrm{d}t} &= q^* - q \\ K(u) &= K_{ch}\,\frac{R^{u-1} - R^{-1}}{1 - R^{-1}} \end{aligned} \tag{5.3}$$

Here $K(u)$ is an equal-percentage choke of rangeability R, offset so that zero opening passes no flow, $u \in [0,1]$ its opening, $P_{dn,s}$ the static part of the pressure just downstream of the choke and K_f the summed friction coefficient of the line. The choke actuator travels at 20 %/min. At the design rate the well draws down 34.5 bar, so the choke passes from $P_{up} = 115.5$ bar to $P_{dn} = 90.4$ bar, and a fully open choke would pass 1577 Sm³/d. The fluid entering the flowline follows the wellhead temperature less the Joule–Thomson cooling of the choke, as shown in Equation (5.4).

$$\begin{aligned} \frac{\mathrm{d}T_{wh}}{\mathrm{d}t} &= \phi_q\,\frac{T_{wh,f} - T_{wh}}{\tau'_{up}} \\ &\quad + (1-\phi_q)\,\frac{T_d + \Delta T_{sh} - T_{wh}}{\tau_{dn}} \\ T_{in} &= T_{wh} - \mu_{JT}\,(P_{up} - P_{dn}) \\ P_{up} &= P_{si} - q/J \end{aligned} \tag{5.4}$$

where $\phi_q = \min\bigl(1,\, q/(0.05\,q_d)\bigr)$ blends warm-up and cool-down and $\tau'_{up} = \tau_{up}\,q_d/\max(q,\,0.25 q_d)$ makes a slow restart warm the well more slowly. The well warms toward 60 °C over about an hour at

the design rate, cools toward 10 °C with a 10 h time constant when shut in, and loses 1.26 °C across the choke at design.

5.3.3 Pressure and Holdup

After each step the pressures are recomputed segment by segment, from the arrival pressure down. In each segment from the top, the gas density follows from its pressure with a constant compressibility, the in-situ gas volume per unit of liquid from the fixed gas-oil ratio, and the holdup from a constant slip ratio between the gas and liquid velocities, as shown in Equation (5.5).

$$\begin{aligned} \rho_{g,i} &= \frac{P_i M_g}{ZR\,(T_i + 273.15)}, \qquad r_i = \frac{\mathrm{GOR}\,\rho_{gs}(1 - X_i)}{\rho_{g,i}} \\ H_i &= \frac{1}{1 + r_i/S_i}, \qquad \rho_{m,i} = H_i \rho_{L,i} + (1 - H_i)\rho_{g,i} \\ \Delta P_i &= \rho_{m,i}\, g\, \Delta z_i + \frac{f\,\Delta x_i}{2D}\,\rho_{ns,i}\left(\frac{(1 + r_i)\,q}{A}\right)^2 \\ P_i &= P_{arr} + \textstyle\sum_{k>i} \Delta P_k + \frac{1}{2}\Delta P_i \\ P_{dn} &= P_{arr} + \textstyle\sum_k \Delta P_k \end{aligned} \tag{5.5}$$

Here $\rho_L = X\rho_w + (1 - X)\rho_o$, $\rho_{ns} = (\rho_L + r\rho_g)/(1 + r)$ is the no-slip density of the homogeneous friction term, Δz_i is zero on the seabed, and two fixed-point passes settle the gas density. At the design rate the riser column puts PT-103 at 86.5 bar, 66.5 bar above the platform, and the 5 km of seabed contribute 0.19 bar of friction (0.28 bar with the riser). Along the seabed the holdup rises from 0.53 at the choke to 0.56 as the cooling gas contracts, and the expanding gas thins the liquid up the riser from a holdup of 0.66 at its base to 0.33 at its top, so the line contains 172.6 m^3 of liquid. When the flow stops, the holdup and the fluid heat capacities keep their last values.

5.3.4 Water and Methanol as Slices of Liquid

The water share and the methanol belong to the liquid and travel with it. Upwind segments would smear a methanol front over several 250 m segments and dilute an under-dosed slug into the dosed liquid around it, so the model carries the liquid as a queue of slices of $\Delta V = 0.5\,\mathrm{m}^3$, 19 m of seabed pipe. Each slice j has a water share X_j, methanol μ_j in kilograms per cubic meter of liquid and its own exposure. After every step the liquid that entered is pushed in at the choke with the well's water share, the methanol that reached the water during the step is shared among the new slices by volume, and whatever exceeds the line's liquid volume $\sum_i V_i H_i$ is delivered to the platform. A slice is placed by its cumulative liquid volume from the choke, so a change made at the tree arrives at any point once all the liquid between the tree and that point has been pushed past it. The methanol reaches the tree through two first-order stages and loses a fixed share to the oil and gas, as shown in Equation (5.6).

$$\begin{aligned} \tfrac{1}{2}\tau_u \frac{\mathrm{d}Q_1}{\mathrm{d}t} &= Q_M - Q_1, \qquad \tfrac{1}{2}\tau_u \frac{\mathrm{d}Q_2}{\mathrm{d}t} = Q_1 - Q_2 \\ \dot{m}_M &= \rho_M\, Q_2\,(1 - f_{loss}) \\ W_j &= \frac{100\, r_j}{1 + r_j}, \qquad r_j = \frac{\mu_j}{\rho_w X_j} \end{aligned} \tag{5.6}$$

where $\dot{m}_M$ is the methanol that reaches the water and W_j the aqueous concentration of slice j in wt %, the quantity the equilibrium sees. The two stages of 7.5 min deliver 59 % of a step after 15 min and 91 % after 30 min. The pump draws from a 120 m^3 tank and stops when it is empty, and the well's water cut approaches its setting through a first-order change with a 1 h time constant.

5.3.5 Equilibrium, Margin and Exposure

The uninhibited equilibrium belongs to one representative natural gas of specific gravity 0.65. It is written $T_{eq,0} = a + b \ln P$ with P in bar and fitted by least squares to seven points of the Motiee gas-

gravity correlation between 20 and 200 bar, which it reproduces within 0.41 °C. Methanol in the water depresses it by the Hammerschmidt relation, used up to about 25 wt %, or by the Nielsen–Bucklin relation, used up to about 50 wt %, as shown in Equation (5.7).

$$\begin{aligned} T_{eq,0}(P) &= a + b \ln P \\ \Delta T_H &= \frac{1297\,W}{32.04\,(100 - W)}, \qquad \Delta T_{NB} = -72 \ln x_w \\ m_{ij} &= T_i - T_{eq,0}(P_i) + \Delta T(W_j) \end{aligned} \tag{5.7}$$

Here $a = -14.63\,^{\circ}\mathrm{C}$, $b = 7.073\,^{\circ}\mathrm{C}$, x_w is the mole fraction of water in the aqueous phase and m_{ij} the margin of slice j in segment i, both depressions in °C. The curve gives 6.56 °C at 20 bar and 17.94 °C at 100 bar, and 20 wt % of methanol depresses it by 10.12 °C by Hammerschmidt and by 9.47 °C by Nielsen–Bucklin. The controlling margin m_{min} is the lowest m_{ij} over every slice carrying free water, a water share above 0.005, so one segment may contain dosed and under-dosed liquid together, and the under-dosed part sets its margin. A negative margin is exposure, not a plug. Each segment accumulates the subcooling of its wet liquid weighted by the share of its liquid volume below the curve, as shown in Equation (5.8).

$$\begin{aligned} \frac{\mathrm{d}E_i}{\mathrm{d}t} &= \sum_{j \in i} \frac{v_{ij}}{V_{L,i}} \max(0, -m_{ij}) \\ \mathrm{PRI} &= 1 - \mathrm{e}^{-\max_i E_i / E_{ref}} \end{aligned} \tag{5.8}$$

The sum runs over the wet slices in segment i, v_{ij} is the part of slice j inside it, $V_{L,i} = V_i H_i$, and E_i is counted in °C·h. The plug-risk index PRI is an explicitly illustrative mapping of the worst segment, with $E_{ref} = 12\,^{\circ}\mathrm{C{\cdot}h}$. The scorecard reads exposure and the worst margin from this record of the truth, never from the instruments.

5.3.6 Grid, Step and Starting State

Table 5.2 gives every parameter value. The 73 states advance by classical fourth-order Runge–Kutta steps of 10 s, the holdup, the heat capacities and the pressures are held fixed through each step, and the slices move after it. The fastest thermal mode, fluid exchanging heat with its own wall, decays in 90 to 143 s during flow, and at the 1577 $\mathrm{Sm^3/d}$ of a fully open choke the top riser segment is swept in 112 s, so the upwind transport runs at a Courant number of 0.089. Halving the step moves the riser-base temperature of case 2 at 12 h by 0.000 01 °C and its worst margin by 0.000 06 °C. Refining the seabed to 40 segments lowers the design margin from +6.41 °C to +6.17 °C and brings the first exposure of case 2 14.7 min earlier, and 80 segments give +6.04 °C. Over 12 h of flow the energy held in fluid and wall matches the inflow less the outflow and the loss to the sea within 10^{-9} of the inflow, once a tracked revaluation of the heat capacities, under 10^{-4} of the inflow, is included, and every kilogram of methanol and cubic meter of liquid is either in the line or delivered, two of the 57 checks the application passes.

A flowing case starts from the discrete steady solution of Equation (5.1) at its flow, water cut and dose, iterated with the hydraulics and the Joule–Thomson cooling of the choke until the inlet temperature settles, with the choke at the opening that holds that flow, so the reset state has zero derivatives. A cold case starts from the same state at 800 $\mathrm{Sm^3/d}$ dosed at 30 wt %, closes the choke and integrates 24 h of cooldown before the run begins, which leaves the fluid of the well at 14.5 °C.

5.3.7 Assumptions

The hydraulics are reduced. A single liquid rate follows the balance of Equation (5.3) with a declared 120 s response, the pressures carry no dynamics of their own, and a constant slip ratio fixes the holdup, which therefore does not rise at low flow and admits neither terrain nor severe riser slugging.

Table 5.2 Flowline Parameters, Marked Visible Where the Panel Adjusts Them, Hidden Where It Does Not and Fixed Where the Code Sets Them

Symbol	Meaning	Value	Class
L, H	flowline, riser length	5.0 km, 1500 m	visible
D	inside diameter	0.25 m	visible
N_h, N_r	seabed, riser segments	20, 12	hidden, fixed
—	damageable section	2.25–3.0 km	visible
U_f, U_r	overall U, inner area	7.5 W/(m^2·K)	visible
C'_w	wall per meter	110 kJ/(m·K)	visible
h_f, h_s	film, design flow, rest	400, 60 W/(m^2·K)	hidden
T_d, T_{surf}	seabed, surface water	4, 22 °C	visible
d_{th}	thermocline scale	250 m	hidden
GOR	gas-oil ratio, all free	100 Sm^3/Sm^3	visible
S_r, S_h	slip, riser, seabed	1.6, 1.0	vis., hid.
ρ_o, c_o	oil	850 kg/m^3, 2100 J/(kg·K)	hidden
ρ_w, c_w	produced water	1025 kg/m^3, 4000 J/(kg·K)	hidden
c_g, Z	gas	2300 J/(kg·K), 0.85	hidden
f	Darcy friction	0.02	hidden
γ, ρ_{gs}	gas gravity, standard	0.65, 0.796 kg/Sm^3	fixed
P_{res}, ΔP_{tub}	reservoir, well column	250, 100 bar	visible
J	productivity index	29 Sm^3/(d·bar)	visible
$T_{wh,f}$, ΔT_{sh}	flowing, shut-in excess	60, 6 °C	vis., hid.
τ_{up}, τ_{dn}	well warm-up, cool-down	1, 10 h	visible
μ_{JT}	Joule–Thomson, choke	0.05 °C/bar	visible
K_{ch}, R	choke capacity, range	720 Sm^3/d/$\sqrt{\text{bar}}$, 25	vis., hid.
—	choke travel rate	20 %/min	visible
τ_h, τ_{WC}	flow response, water cut	120 s, 1 h	visible
q_d, q_{plat}	design, platform limit	1000, 2500 Sm^3/d	hid., vis.
Q_{max}, τ_u	pumps, umbilical	4 m^3/h, 15 min	visible
V_{st}, f_{loss}	storage, loss to oil	120 m^3, 10 %	visible
ρ_M	methanol density	791 kg/m^3	fixed
P_{MAOP}, E_{ref}	MAOP, index scale	130 bar, 12 °C·h	visible
ΔV	slice volume	0.5 m^3	fixed

A stopped line keeps its phases in place, so the liquid in a shut-in riser never falls back to load its base. A two-fluid transient model resolves all three effects [13].

The gas is a fixed 100 Sm^3 per Sm^3 of oil, all of it free and of constant compressibility, so no gas returns to solution or comes out of it, and the choke is the only place where the stream cools on expansion. Oil and water have constant properties and neither compresses nor shrinks, which makes the liquid rate equal to the standard rate.

One fluid node and one wall node represent each segment, heat does not conduct along the pipe, and the energy moves by first-order upwind transport, the source of the 0.51 °C warm error at the riser base. The thermocline keeps a fixed exponential shape, and a cold current lowers only its deep value.

The hydrate curve belongs to one representative gas, fitted between 20 and 200 bar, and is illustrative rather than a design curve for any field. The inhibition relations are shortcut methods, the produced water carries no salt, and a fixed 10 % of the methanol leaves with the oil and gas at every pressure, temperature and gas rate. Exposure is thermodynamic, so an under-dosed slug counts as partly protected, although under-inhibited systems have been seen to block more readily than uninhibited ones [12].

5.4 The Weakest Point and the Liquid Transit

The margin at a point is a race between two profiles, as shown in Figure 5.2. Along the seabed the pressure falls only from 90.4 to 90.2 bar, so the uninhibited equilibrium holds near 17.2 °C while the fluid cools from 58.7 to 23.8 °C toward the 4.04 °C sea. Up the riser the fluid keeps cooling, from 23.3 °C in the first riser segment to 19.4 °C at the top, but the pressure falls by 64.6 bar over the same

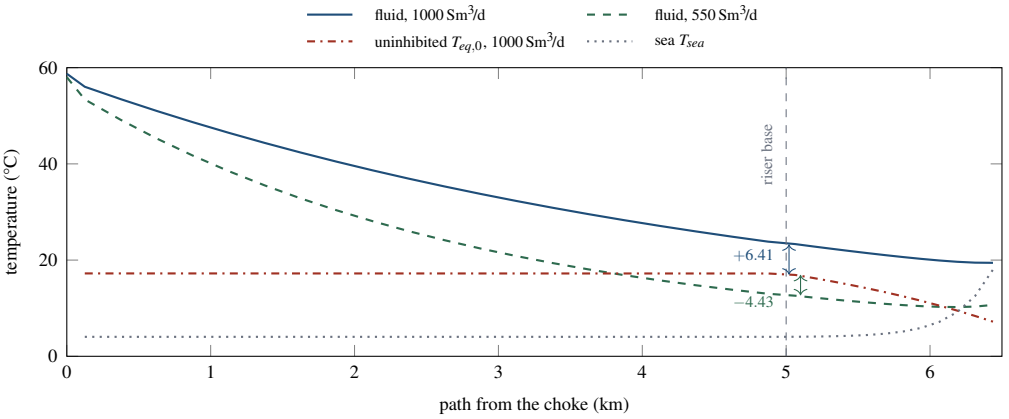


Figure 5.2 Steady fluid temperature, uninhibited hydrate equilibrium and sea temperature along the path at 1000 Sm³/d and 550 Sm³/d, from the model's own steady initialization. The fluid is drawn solid at 1000 Sm³/d and dashed at 550 Sm³/d, the equilibrium dash-dotted and the sea dotted. The equilibrium at 550 Sm³/d lies within 0.12 °C of the one drawn. The arrows give the uninhibited margin in the first riser segment, where both flows reach their minimum.

climb and takes the equilibrium from 16.9 down to 7.2 °C. The minimum of $T - T_{eq}$ therefore falls where the fluid has spent longest cooling but still carries the full seabed pressure, in segment 21 at 5.06 km and 1437.5 m depth, at +6.41 °C. The coldest fluid, at the platform, keeps +12.2 °C.

The equilibrium barely depends on the flow, because the pressure along the seabed is the riser's head plus the platform's pressure, and at the riser base it moves only from 16.91 to 17.02 °C between 1000 Sm³/d and 550 Sm³/d. The fluid temperature carries the whole flow dependence. The uninhibited riser base settles at 23.3 °C at 1000 Sm³/d, 16.6 °C at 700 Sm³/d and 12.6 °C at 550 Sm³/d, so the steady uninhibited margin falls from +6.41 °C to −0.43 °C and −4.43 °C. Without methanol the line cannot hold its margin setpoint at any of the lower rates.

🕮 **Pause.** Try Exercise 5.1 before reading on.

Transport sets the timing. The seabed holds 134.7 m³ of the line's 172.6 m³ at the design rate, so a change made at the tree reaches the riser base 3.23 h later and the platform 4.14 h later, and at 550 Sm³/d the riser base about 5.9 h later. A step of the methanol pump in manual reaches half strength at the riser base after 3.49 h, the umbilical adding about a quarter of an hour. A parcel tagged at reset arrives after 4.15 h at 19.42 °C, its coldest, and its own worst margin, +6.39 °C, was recorded at 5.13 km as it left the first riser segment.

Table 5.3 Transmitters, Lags and Noise

Tag	Point	Lag	Noise, 1σ
PT/TT-101	upstream of the choke	5, 30 s	0.05 bar, 0.05 °C
PT/TT-102	downstream of the choke	5, 30 s	0.05 bar, 0.05 °C
PT/TT-103	riser base	5, 30 s	0.05 bar, 0.05 °C
PT/TT-104	arrival at the spar	5, 30 s	0.02 bar, 0.05 °C
FT-100	multiphase meter, liquid	30 s	1.5 % of reading
AT-100	same meter, water cut	60 s	2 % absolute, bias
FT-301	pump discharge, topsides	5 s	0.5 % of reading

TRY IT IN THE APP 1 · Warm steady operation

Load the case, press Run and open the Profiles tab. Compare the fluid temperature with the hydrate equilibrium along the whole path. The gap is narrowest in the first riser segment, at +6.41 °C, while the fluid reaching the spar, the coldest of the line, keeps +12.2 °C.

A stopped line has a time scale of its own. With the film at natural convection, the fluid first passes its heat to the wall with a time constant of 14 to 16 min, and fluid and wall then cool together toward the sea with the lumped time constant $(C_f + C_w)/UA$, 8.2 h on the seabed and 8.8 h at the riser base. The design line, if it stopped, would have 3.28 h before its first segment reached the curve by the estimator's prediction.

5.5 Instruments, Estimator and Control

The engine is that of Section 1.6.1. A control period of 20 s, two physics steps, serves the loops, the estimator and the sequence alike, and the historian writes one row for each simulated minute. The hydraulics, the slices and the exposure record are brought up to date after each integration step. Speeds range from 60 to 7200 times real time, and at the default of 900 an hour of plant time takes 4 s, so a 24 h case runs in about a minute and a half.

5.5.1 Instruments

The loops never see a segment of the plant. Each transmitter reads the true value at its own point through an exact first-order lag and adds colored noise, correlated over 30 s on the pressures and the pump meter, 60 s on the thermometers, 120 s on the liquid rate and 300 s on the water cut, with the lags and amplitudes of Table 5.3. A failed TT-103 reports nothing, and the estimator is told so rather than fed a guess. The measured water cut passes a 300 s filter before the dose uses it.

5.5.2 The Profile Estimator

The methanol loops and the sequence act on a second copy of the segment model that knows only the declared design, its insulation, geometry and fluids, and the design seawater temperatures, whatever the Parameters panel says. It is driven by FT-100, the filtered water cut, TT-102 as its inlet temperature, the FT-301 pump flow through its own copy of the umbilical stages and PT-104, it carries its own slices, and it advances by forward Euler in two 10 s substeps per control period. Three corrections pull it toward the plant. Its riser pressures are scaled to pass through PT-104 and PT-103, and its seabed pressures are shifted to PT-103 with the mismatch at PT-102 spread linearly back to the choke. The residual at TT-103 is distributed along the seabed in proportion to the distance from the choke, and the residual at TT-104 is distributed the same way up the riser, both with a 300 s time constant. While the line flows, factors θ_f and θ_r multiply the design U of the flowline and the riser, adapted at 4×10^{-5} per °C per second of the riser-base and riser residuals and bounded between 0.3 and 6, with θ_r adapting only while the riser-base residual is under 0.1 °C. Two thermometers fix the total heat the line loses and say nothing about where it is lost. The kiln of Volume 5, Chapter 11 meets

the same gap in a core temperature that no instrument reaches. At reset the estimator starts from its own steady profile at the measured flow, inlet temperature and pump rate, or, after a shut-in, from a line assumed to have cooled everywhere by as much as the riser-base reading shows and to carry the pre-dose throughout.

The estimator also predicts. It marches the steady profile toward which the present flow is heading, with the adapted factors and the design sea, which gives the steady uninhibited margin $\hat{m}_{ss}$, and it predicts the no-touch time, the time left before the first wet segment reaches its inhibited equilibrium if the flow stops, from a lumped cooldown of each segment, as shown in Equation (5.9).

$$t_{nt} = \min_i \frac{C_{f,i} + C_{w,i}}{\theta\, UA_i} \ln \frac{\hat{T}_{m,i} - T_{sea,i}}{T_{eq,i} - T_{sea,i}} \tag{5.9}$$

Here $\hat{T}_{m,i}$ is the heat-capacity-weighted mean of the estimated fluid and wall temperatures and $T_{eq,i}$ the segment's inhibited equilibrium, with $t_{nt} = 0$ once $\hat{T}_{m,i} \le T_{eq,i}$ and no limit while $T_{eq,i}$ lies below the sea.

5.5.3 The Choke Loops

FIC-100 holds the liquid rate on FT-100 by moving the choke, with $K_c = 0.03\,\%$ per $\mathrm{Sm^3/d}$ and $\tau_I = 240\,\mathrm{s}$. PIC-102 watches PT-102 against a 120 bar limit below the 130 bar MAOP, with $K_c = 5\,\%$ per bar and $\tau_I = 120\,\mathrm{s}$. A low select hands the choke to the smaller of the two requests and of a ceiling that the restart sequence ramps, $u = \min(u_Q, u_P, u_{ceil})$. The loop that loses follows what was applied. The integral of FIC-100 is set so that its output equals the applied opening, and the integral of PIC-102 is set to the applied opening itself, so that its output sits above it by its own proportional term and takes the choke exactly when the pressure crosses its limit. At reset both choke loops start at the opening that holds the initial state and the trim at whatever concentration the pump already delivers beyond the feedforward, so no case begins with a bump. This is the low selector with external reset of Section 1.4.8. The three loops of the application are instances of the framework's velocity-form PID of Section 1.6.2, Equations (1.16) to (1.19), with the control period $\Delta t_c = 20\,\mathrm{s}$, a zero bias and the back-calculation tracking time equal to τ_I. The derivative is switched off in all three loops ($\tau_D = 0$), and no output carries a rate limit of its own, although the choke actuator travels at 20 %/min. Every loop uses $e = \mathrm{SP} - \mathrm{PV}$ with a positive gain, so a low rate opens the choke, a high pressure closes it and a low margin adds methanol. In manual the operator's choke opening and pump rate go straight to the actuators, and every loop tracks them by setting its integral term to whatever makes its own output equal the applied value, so switching back to automatic moves nothing.

5.5.4 Methanol Feedforward, Trim and Override

The pump command is a high select of three requests, limited by the pumps still running and by the methanol left in storage, as shown in Equation (5.10).

$$\begin{aligned} W_{ff} &= W^{-1}\big(m_{SP} - \min(\hat{m}_{ss}, \hat{m}_{now})\big) \\ Q_L &= \frac{r(W_{ff} + \Delta W)\,\rho_w\, q_{w,m}}{\rho_M (1 - f_{loss})} \\ r(W) &= W/(100 - W) \\ Q_M &= \min\big(\max(Q_L, Q_{ovr}, Q_{seq}),\ a_p Q_{max}\big) \end{aligned} \tag{5.10}$$

Here W^{-1} inverts the depression relation in use and $\hat{m}_{now}$ is the uninhibited margin of the estimated line as it stands, so the feedforward doses for the worse of the line as it will become and as it is. The dose is proportioned to the measured water rate $q_{w,m}$, the FT-100 rate times the filtered water cut, or, as an option, to the liquid rate with the water cut taken as its 20 % design value. The trim ΔW is a PI on the estimated minimum margin with $K_c = 0.5\,\mathrm{wt\,\%}$ per °C and $\tau_I = 4\,\mathrm{h}$ against a 3 °C setpoint, limited between zero and the concentration the available pumps can still add, so it may add methanol

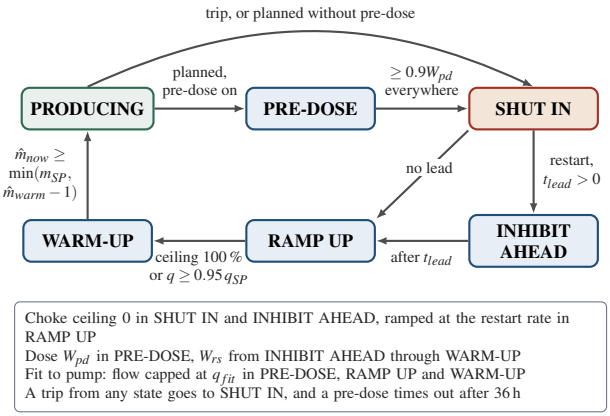


Figure 5.3 Shutdown and restart sequence. The conditions are evaluated on the estimate every 20 s, $\hat{m}_{warm}$ is the steady uninhibited margin at the target flow with the well at its flowing temperature, and q_{SP} stands for the smaller of the setpoint and q_{fit}.

but never remove the feedforward's. The low-margin override Q_{ovr} runs the available pumps at full capacity whenever the estimated margin drops under 1 °C, and lets go 0.5 °C above it, and Q_{seq} is the dose of the sequence. The loop is live only in automatic with the well producing and flowing above 5 % of design. Whenever the override or the sequence requests more methanol than the loop would, the trim freezes at its present value, the conditional integration that keeps a loop behind a selector from winding up [17].

5.5.5 Shutdown and Restart

The sequence is the state machine of Figure 5.3. A trip commands the choke shut from any state. A planned shutdown in automatic, with the pre-dose on, first runs the pumps at the pre-dose concentration $W_{pd} = 30\,\text{wt}\,\%$ until the estimate shows at least nine tenths of it in every segment, then closes the choke. A restart in automatic runs the pumps for the lead t_{lead} with the choke still shut, ramps a ceiling on the choke at the restart rate, and doses the restart concentration $W_{rs} = 30\,\text{wt}\,\%$, first for the target flow and, once the ramp is complete, for the measured flow, until the estimated uninhibited margin reaches the smaller of m_{SP} and the warm steady margin at the target flow less 1 °C. With the fit-to-pump option on, the flow setpoint during pre-dose, ramp and warm-up is capped at the rate at which the available pumps deliver the target concentration, as shown in Equation (5.11).

$$q_{fit} = \frac{a_p Q_{max}\, \rho_M (1 - f_{loss})}{r(W)\, \rho_w\, \text{WC}_m / 100} \tag{5.11}$$

With 4 m³/h, 30 wt % and a 20 % water cut this is 778 Sm³/d, and it moves with the measured water cut WC_m. In manual a restart hands the choke and the pump to the operator at once.

5.5.6 Plant, Estimator and Loop Models

The chapter keeps three models distinct. The plant is the model of Section 5.3, 73 states and the slices, run on the true environment. The estimator's model is the same segment equations on the design environment and the declared default parameters, whatever the learner sets, corrected through six transmitters, and it is the model consulted by the original methanol loops and sequence when the original structure is selected. The feedforward's model is the estimator's steady prediction, and the no-touch prediction of Equation (5.9) is a lumped cooldown that ignores the fast exchange between fluid and wall. No model is identified inside the application. The flow loop faces the 120 s flow lag behind a rate-limited choke, and after the case 2 cut the liquid rate comes within 5 % of its new

setpoint in 17.8 min and stays within 3 % of it from 20 min, the remaining wander being the FT-100 noise that the loop follows. The methanol loop faces a transport delay of hours between its dose and the margin it acts on, which no PI tuning can shorten.

5.5.7 Predictive Methanol Dosing

An additional economic MPC selects only the methanol rate, following the receding-horizon formulation used in industrial control [18] and set up in general in Section 1.6.3. Its sixteen states are fourteen pump-equivalent rates $z_1,\dots,z_{14}$ in m³/h, an uninhibited margin h and a bias b_m in °C. The nominal reduction is

$$\begin{aligned} 450\dot{z}_1 &= v - z_1, & 450\dot{z}_2 &= z_1 - z_2, \\ \dot{z}_i &= \frac{12 q_m}{V_R}(z_{i-1} - z_i), & i &= 3,\dots,14, \\ 7200\dot{h} &= \hat{m}_{ss} - h, & \dot{b}_m &= 0, \\ y &= h + g z_{14} + a + b_m. \end{aligned} \tag{5.12}$$

Here v is the candidate pump rate and q_m the measured liquid rate in m³/s. The nominal observer supplies $\hat{m}_{ss}$, the steady uninhibited minimum at current flow, using the existing known bounded flow target when stopped. If unavailable, h supplies that target. Declared default geometry and steady holdup give $V_R = 138.750\,234\,\mathrm{m}^3$ through the riser-base cell and $172.633\,921\,\mathrm{m}^3$ for the full line. The twelve residence cells replace sharp slice transport. With measured water rate $q_{w,m}$, let $\alpha = \rho_M(1 - f_{loss})/(3600\rho_w q_{w,m})$ and $D(v) = \Delta T[100\alpha v/(1+\alpha v)]$. The slope $g = D'(z_{14})$ and intercept $a = D(z_{14}) - g z_{14}$ linearize the selected inhibition relation. The implemented forward difference uses a ratio increment 10^{-5}. Water cut is floored at 0.1 % and water rate at 10^{-7} m³/s for this map.

A separate profile observer uses the original instrument packet and the inherited declared predose prior for a cold line, with base physical coefficients frozen at their defaults, as the original observer's are. Its inherited thermometer nudging and estimated heat-loss multipliers remain active when enabled. It receives no sea measurement, true profile or future event. Both profile observers and the reduced states advance in Manual and under classical control, using actual pump history. Initial z_i equal the measured pump rate, h starts at the observer's uninhibited margin and $b_m = 0$. Each 20 s scan propagates the reduction in substeps no longer than 5 s. A bounded residual update follows the nominal observer's inferred minimum $\hat{m}_o$, rather than the true minimum,

$$b_m^{+} = \mathrm{clip}_{[-30,30]}\{b_m + \lambda_b[\hat{m}_o - h - D(z_{14}) - b_m]\}. \tag{5.13}$$

Here $\lambda_b = 1 - e^{-20/1800}$, with gain one at priming. This is a residual-bias correction, related to disturbance augmentation [19], without a Kalman gain or an offset-free performance guarantee under mismatch.

Every 120 s, six scans, the model is discretized by an exact zero-order hold on a 300 s grid. The affine intercept is incorporated by shifting h by a. The 6 h horizon has 72 samples and twelve held moves of lengths $[1,1,1,2,3,4,5,7,9,11,13,15]$. The program is

$$\begin{aligned} \min_{v,s} \quad & 0.15\sum_{j=1}^{12}(v_j - v_{j-1})^2 \\ & + 0.04\sum_{k=1}^{72} v_{\beta(k)} + 400 s^2 + s \\ \text{subject to} \quad & 0 \le v_j \le v_{avail}, \quad |v_j - v_{j-1}| \le 0.4, \\ & y_k + s \ge r - (r - \hat{m}_o)_+ e^{-300k/7200}, \\ & s \ge 0. \end{aligned} \tag{5.14}$$

Table 5.4 Cases and What Each Teaches

#	Scenario and event	Teaching point
1	Warm, 1000 Sm^3/d	where the weakest point is
2	Cut to 550 Sm^3/d at 1 h, no feedforward	a transit of delay
3	500 Sm^3/d, water 20 to 45 %, liquid basis	dose the water
4	800 Sm^3/d, sea 3.5 °C colder at 1 h	what the estimate blames
5	Insulation ×6, 2.25–3.0 km, at 1 h	where no sensor looks
6	350 Sm^3/d, pumps to 25 % at 1 h	rate and dose limits
7	Trip at 1 h, no methanol	the no-touch time
8	Cold restart at 0.5 h, no lead, 20 %/min	inhibit before flow
M	Turndown and planned stop, MPC	reduced-model comparison
9	36 h cold restart challenge	graded restart

The index $\beta(k)$ selects the block, v_0 is the previous applied rate clipped into $[0, v_{avail}]$, and $(\cdot)_+$ denotes its positive part. Numerical weights apply in the stated rate and temperature units. There is one global slack s for the entire horizon. Pump availability and storage set v_{avail}, with zero at shut-in or empty storage. The 0.4 m^3/h bound applies per decision or future block boundary. The recovery funnel and margin band are soft. Pressure is handled by the original choke override, not by a QP pressure constraint.

Normally $r = m_{SP}$. Preview can change it only after a planned shutdown request enters pre-dose, to the larger of m_{SP} and the nominal uninhibited margin plus $\Delta T(W_{pd})$ and a declared forecast error. No future restart is available. The sequence owns non-producing doses, and the low-margin override, pump and storage caps retain priority. Acceptance checks optimal status, finite arrays, every held move, slew, slack and recomputed future predictions. Rejection holds the first applied rate before protections, then returns the classical dosing law. A valid recovery plan also holds its first move. Exact trim tracking permits a negative concentration correction below feedforward. Subsequent fallback scans can rise to the classical feedforward floor, and a zero-water inverse cannot encode a positive pump. While MPC remains selected, its nominal observer feeds the sequence, override, fallback and reported estimates even after failure. The original observer carries the same declared defaults, and over 120 runs of 36 h, 100 of them with a physical parameter changed, the two estimates agree at every step, so fallback applies the original dosing law to the same estimate. Retained forecasts describe the last valid plan, separately from actual ownership and the nonacting classical candidate terms.

5.6 Measured Cases

The cases and the lesson each carries are in Table 5.4, and the measured outcome of each is in Table 5.5. Unless a case names a change, the feedforward doses on the water rate, the trim, the low-margin override, the pressure override and the pre-dose are on, the margin setpoint is 3 °C, the lead 30 min, both doses 30 wt % and the restart ramp 5 %/min, and the flow is held to the pumps. Every value comes from a headless run of the engine with its fixed seed, 20261103, and times count hours of simulated time from reset. A setting named for a case is changed after the case is loaded and before it runs, and carrying the same setting through a reset gives the same run. Where the transmitter noise decides a result, the spread over three other seeds is given beside it. The application lists case M as its ninth scenario, "MPC versus feedforward at turndown", and the challenge after it without a number. This chapter keeps the numbering of Table 5.4, in which case 9 is the challenge.

5.6.1 The Weakest Point and a Turndown

Case 1 is the design state of Section 5.4 and needs no methanol. Its +6.41 °C at the riser base is the whole budget of the line, and each later case removes part of it by a different route. In case 2 the platform asks for 550 Sm^3/d at 1 h, and the riser base starts a slow slide from 23.3 °C toward

Table 5.5 Measured Outcome of Each Case

Case	Measured outcome
1	design margin +6.41 °C, segment 21, transit 4.14 h
1, planned shutdown	pre-dose 5.75 h, 22.7 m^3, +2.99 °C at 30 h
2, trim alone	exposed 8.55 h, −4.43 °C at 24 h, 132 °C·h, 47.4 m^3
2, feedforward on	worst +1.03 °C at 7.15 h, 28.3 m^3
3, liquid basis	9.0 wt % at 12 h, worst −1.73 °C, 36.9 °C·h
3, water basis	worst +1.54 °C, pump to 3.49 m^3/h, 63.7 m^3
4, corrections on	worst +1.68 °C, θ_f 1.12 at 24 h
4, corrections off	at 12 h estimate +3.16 °C, true +0.63 °C
5, flowing	exposed 5.59 h, worst −2.19 °C, 19.4 °C·h
5, trip at 12 h	predicted 6.68 h, curve at 2.875 km after 1.36 h
6, as shipped	245 °C·h, worst −3.21 °C
6, setpoint 1000 at 2 h	398 Sm^3/d, 227 °C·h
6, setpoint 100	after 1 min 9.45 °C·h, at 2 h 49.4 °C·h
7, trip	predicted 3.28 h, plant 3.64 h, 3066 °C·h by 24 h
8, no lead	exposed after 12.5 min, worst −4.14 °C, 12.1 °C·h
8, lead, slow ramp	worst +1.17 °C, +2.19 °C
8, lead, Nielsen–Bucklin	worst +0.003 °C, no exposure

the 12.6 °C of the new steady state. The feedforward is off, so methanol can come only from the trim and the override. The trim begins to dose at 4.71 h, once the estimate has sunk below the 3 °C setpoint, and from 7.19 h the override holds the pumps at full capacity, yet each dose enters liquid that needs about 5.9 h more to reach the riser base. The first exposure comes at 8.55 h, 7.55 h after the cut. The heavy dosing then lands around 16 h on liquid that no longer needs it (+20.5 °C), the pumps shut off as the estimate recovers, and the liquid that entered undosed in that pause arrives last, so the day closes at −4.43 °C with 132 °C·h of exposure and 47.4 m^3 of methanol spent. Switched on, the feedforward starts the pump 2.3 min after the cut, on the steady demand the estimator foresees, 14.7 wt % and 1.29 m^3/h at 2 h, the methanol rides in the same liquid as the cold, and the margin bottoms at +1.03 °C (7.15 h) on 28.3 m^3. Over three other noise seeds the trim alone gathers 128 to 130 °C·h and the feedforward bottoms between +1.04 and +1.06 °C, so the comparison does not rest on the noise.

🕮 **Pause.** Try Exercise 5.2 before reading on.

5.6.2 More Water and a Colder Sea

Case 3 holds 500 Sm^3/d at 17.9 wt % (1.31 m^3/h), enough for the 3 °C margin, with the ratio fixed to the liquid rate. From 1 h the well's water cut climbs from 20 toward 45 % with a 1 h time constant. The water rate rises by more than a factor of two while the pump barely moves from 1.3 m^3/h, so the aqueous concentration at the riser base thins from 17.9 to 9.0 wt % by 12 h, while the denser column lifts the pressure at the riser base from 88.0 to 106.1 bar by 24 h, and the equilibrium with it. The extra water brings heat as well, and the riser base warms from 11.2 °C before the breakthrough to 14.2 °C by 24 h, but the margin still reaches −1.73 °C at 12.57 h and the line gathers 36.9 °C·h. A ratio on the water rate raises the pump with the water, to 3.49 m^3/h at most, keeps the margin at +1.54 °C or above (+1.21 to +1.76 °C over three other seeds), and spends 63.7 m^3 against 55.8 m^3. The price of protection scales with the water and not with the oil.

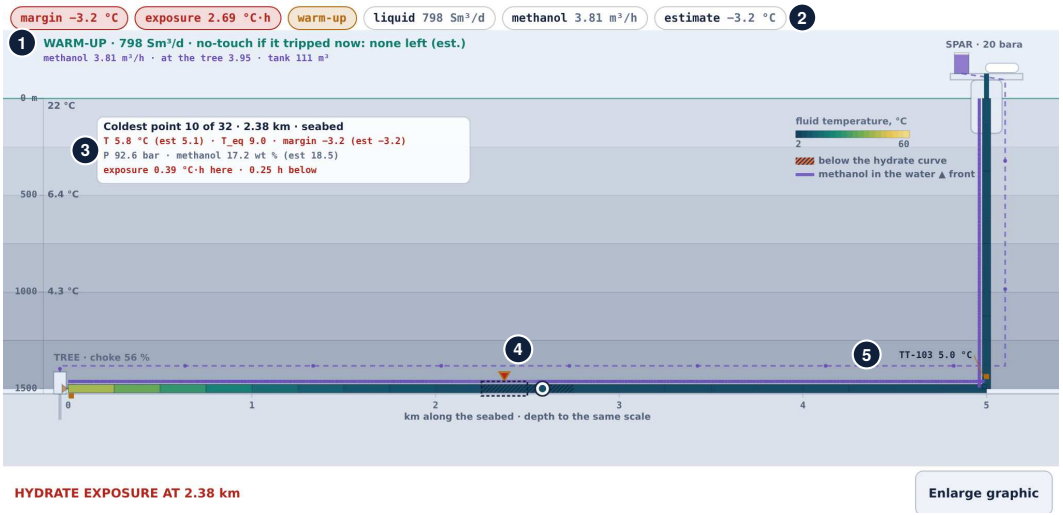


Figure 5.4 Case 8, delayed-injection restart, 3.00 h into the run and 2.5 h after the choke began to open with no inhibitor lead, cropped to the plant view. (1) The header: the sequence is in warm-up at 798 Sm^3/d, by the estimate no no-touch time would be left if the well tripped now, and the pump runs at 3.81 m^3/h with 3.95 m^3/h reaching the tree. (2) The badges: a margin of −3.2 °C and 2.69 °C·h of exposure. (3) The readout of segment 10: 5.8 °C against an equilibrium of 9.0 °C, a margin of −3.2 °C (estimate −3.2 °C), 92.6 bar and 17.2 wt % of methanol in its water (estimate 18.5). (4) Segments 10 and 11, from 2.25 to 2.75 km, are hatched below the hydrate curve, the true and estimated coldest points are both marked in segment 10, and the ringed tagged parcel at 2.58 km marks the front of the liquid that entered after the restart. The new fluid warms the first segments from 42.6 °C while the line beyond 2 km lies between 4.8 and 6.1 °C. (5) TT-103 at the riser base reads 5.0 °C. The status line at the bottom reports hydrate exposure at 2.38 km.

> **TRY IT IN THE APP** **3 · Higher water cut**
>
> Load the case and press Run with the ratio on the liquid rate. The pump stays near 1.3 m^3/h while the water rate more than doubles, and the margin reaches −1.73 °C. Press Reset, set Methanol ratio taken against to Water rate and run again. The pump follows the water, to 3.49 m^3/h at most, and the margin stays at +1.54 °C or above.

Case 4 runs 800 Sm^3/d on 2.3 wt % (0.23 m^3/h) with the riser base at 19.0 °C, and at 1 h a cold current drops the seabed water by 3.5 °C. Nothing tells the estimator. With its corrections on, the profile is pulled through TT-103 and TT-104, the colder line shows up in the present-state margin of the feedforward, the pump climbs to 0.92 m^3/h by 24 h, the riser base settles near 16.5 °C, and the true margin touches +1.68 °C at 5.29 h. The flowline factor rises to $\theta_f = 1.12$ over the day, since a colder sea and 12 % more heat loss through the insulation look the same to two thermometers. With the corrections off, the estimate still reads +3.16 °C at 12 h against a true +0.63 °C, the true margin reaches +0.52 °C at 14.98 h, and the pump stays at or below 0.42 m^3/h.

Pause. Try Exercise 5.3 before reading on.

5.6.3 A Flooded Section and a Pump Shortfall

In case 5 seawater floods the insulation between 2.25 and 3.0 km at 1 h and multiplies its conductance by six. The wall downstream of the damage releases its stored heat for some hours, so at 4 h the truly coldest point is segment 14 at 3.375 km, just past the flood, where the estimate still places it

in segment 21. Methanol starts at 4.71 h, when the estimate first calls for it, and the override runs the pumps at full capacity from 5.55 h, too late for the liquid already on its way. Exposure begins at 5.59 h in segment 18 at 4.375 km, reaching the last seabed segment by 5.70 h and the riser base at 5.06 km by 5.92 h, for 19.4 °C·h in all and a worst margin of −2.19 °C at 8.08 h. The estimator attributes the loss to the whole flowline, $\theta_f = 1.44$ by 24 h. A trip at 12 h then finds an estimated line carrying 10.5 to 27 wt % of methanol from the trim and the override, and the estimator gives it 6.68 h of no-touch time. The flooded section reaches its own curve 1.36 h after the trip, at 2.875 km, far from any thermometer, whereas the undamaged line of case 1 tripped at the same time first reaches the curve in the last seabed segment after 3.63 h, against a prediction of 3.34 h.

Case 6 models a late-life well at 350 Sm^3/d with 30 % water and a platform limited to 400 Sm^3/d of liquid, dosed at 23.6 wt % (1.95 m^3/h). A pump failure at 1 h leaves 1.00 m^3/h. The ratio now calls for 1.97 m^3/h on average, from 1.70 to 2.29 m^3/h as the measured water rate varies, and the loop saturates and stays there. Exposure starts 8.4 h after the failure at 3.875 km, reaches the last seabed segment at 11.07 h and the riser base at 5.06 km at 11.59 h, and totals 245 °C·h by 24 h with a worst margin of −3.21 °C. A setpoint of 1000 Sm^3/d at 2 h runs into the platform limit at 398 Sm^3/d and still collects 227 °C·h. For the lower-rate comparison, the scenario is reloaded at 350 Sm^3/d, run for one minute, then cut to 100 Sm^3/d. That step shrinks the water needing dose but lets the line cool further. Another 24 h gives 9.45 °C·h, with exposure beginning near 15.2 h and a worst margin of −0.67 °C in the last seabed segment. Made at 2 h, after an hour of under-dosing, the same cut leaves 49.4 °C·h with −5.51 °C at 3.125 km. Choosing 100 Sm^3/d before Run instead initializes a line already settled and dosed at that rate, which remains protected at +2.90 °C, and Reset gives the identical startup. A high startup target is capped at the platform capacity, so a 1000 Sm^3/d target in this case starts at 400 Sm^3/d. These are different starting histories from a live rate change. The pumps set the methanol per kilogram of water and the platform sets the flow that keeps the line warm, so no setting of these loops protects the line as it stands at the failure. The application reports the deficit as exposure instead of lending the pumps a capacity they lack.

5.6.4 The No-Touch Time

Case 7 trips the well at 1 h with no methanol in the line. At the trip the estimator gives the line 3.28 h, and the last seabed segment meets its curve 3.64 h after the trip, 0.36 h later than the lumped estimate, because the fluid in the plant hands its heat to the wall before the two cool together. From then on the uninhibited line is simply exposed. At 24 h the riser base is at 5.6 °C under an equilibrium of 16.9 °C, the last seabed segment holds the lowest margin, −11.85 °C, and the exposure has reached 3066 °C·h. The scripted trip of case 7 fires again after every reset and overrides a pre-dose, so the planned shutdown is run on the same design state in case 1. Fired there at 1 h, a planned shutdown pre-doses for 5.75 h, throttling the flow to as little as 703 Sm^3/d to let the pumps reach the dose, and spends 22.7 m^3 before the estimate reports 27 wt % or more in every segment. Only then does the choke close, and the stopped line still has +2.99 °C at 30 h, 23.25 h later. The length of the pre-dose depends on the noise, 5.8 to 9.4 h over three other seeds, because a slice dosed just under 27 wt % while the throttled flow wanders has to reach the platform before the choke may close.

> ✦ DID YOU KNOW? **A Clock That Can Run Fast or Slow**
>
> From the simulator (Table 5.5). On the intact line of case 7 the estimator gives a no-touch time of 3.28 h, and the plant takes 3.64 h. After the flood of case 5 it gives 6.68 h, and the flooded section reaches its curve after 1.36 h.

5.6.5 A Cold Restart

Case 8 opens on a line that was pre-dosed to 30 wt % at 800 Sm^3/d and then left shut in for 24 h, so the riser base sits at 5.1 °C with +5.05 °C of margin and the fluid in the well has cooled to 14.5 °C. At 0.5 h the choke begins to open at 20 %/min, and the pumps start at that instant with no lead. The

Table 5.6 Challenge Runs of 36 h Against the Target

Configuration	Exp. (°C·h)	Worst (°C)	Oil (Sm^3)	MeOH (m^3)	Met
as shipped	155	−4.82	548	103.1	no
suggested[a]	0	+1.38	706	81.9	yes
suggested, flow held to pumps	0	+1.30	529	119.6	no
suggested, no feedforward	1.13	−0.30	706	86.7	no
suggested at 1000 Sm^3/d	0	+0.46	753	74.2	yes

[a] 30 min lead, feedforward on, flow not held to the pumps, 900 Sm^3/d

ceiling reaches fully open within 5 min and the sequence enters warm-up at 0.58 h, after which the dose follows the measured flow, still small, and the pump drops from 4.00 to 0.46 m^3/h before rising again with the flow. Through the umbilical only 59 % of a step has arrived after 15 min, so the first new liquid meets seabed-cold pipe under-dosed. The estimate goes negative 11.0 min after the restart and the truth 12.5 min after it, in the first segment.

From there the under-dosed slug carries its exposure along the line. At 3.00 h it fills segments 10 and 11, from 2.25 to 2.75 km, with its leanest slice at 17.2 wt % and the fluid at 5.8 °C under an equilibrium of 9.0 °C, as shown in Figure 5.4. Behind it comes liquid with the restart dose, 28 to 32 wt %, and ahead of it the pre-dosed contents of the line at 30 wt %. As the slug reaches the foot of the riser the margin falls to −4.14 °C at 4.96 h in the last seabed segment, and the case ends with 12.1 °C·h. A 30 min lead lets the umbilical deliver before the choke opens and keeps the margin at +1.17 °C or better. A 5 %/min ramp without a lead keeps +2.19 °C or better by another route, since the flow grows only as fast as the methanol can follow. Whichever variant is run, the warm-up ends 15.9 h after the restart and 62.1 to 62.6 m^3 have been pumped, about half the tank. The 30 wt % dose also lies past the range of the Hammerschmidt relation. Nielsen–Bucklin gives 15.5 °C of depression there instead of 17.3 °C, and with it the 30 min lead restart keeps only +0.003 °C. The size of the under-dosed slug depends on the noise in the first minutes of flow. Over three other seeds the restart without a lead gathers 3.9 to 6.7 °C·h, the 30 min lead keeps +0.03 to +1.08 °C, and the Nielsen–Bucklin run dips to between −0.07 and −0.96 °C, an uncertainty that only a design margin on the dose can absorb.

5.6.6 The Challenge

The challenge repeats the cold restart at 0.5 h and adds a water breakthrough from 20 to 40 % at 6 h and a platform cut to 600 Sm^3/d at 18 h, over 36 h. Meeting it requires that no wet liquid be exposed, that the flowline stay under its 120 bar limit, that no more than 90 m^3 of methanol be pumped and that at least 650 Sm^3 of oil reach the platform, and Table 5.6 compares five configurations against that target. The shipped settings, which omit the lead and the feedforward and hold the flow to the pumps, expose the line 12.5 min after the restart and end at 155 °C·h, 548 Sm^3 of oil and 103 m^3 of methanol. The suggested settings, a 30 min lead, the feedforward on, the flow no longer held to the pumps and a 900 Sm^3/d setpoint, finish the warm-up at 14.5 h, keep the margin at +1.38 °C or more, and deliver 706 Sm^3 for 81.9 m^3 with the flowline pressure never above 106.1 bar. Restoring the hold on the flow leaves the line cold 5.1 h longer and costs oil and methanol together, since the warm-up lasts until the line is warm and the pumps run at capacity throughout it. Dropping the feedforward leaves the 18 h turndown to the trim, which answers it late enough to expose the riser base from 30.2 h. A 1000 Sm^3/d setpoint passes as well, with more oil and less methanol, but its worst margin is only +0.46 °C, which the target does not penalize. That margin is within the noise. Over three other seeds the 1000 Sm^3/d setpoint fails once, with 0.1 °C·h of exposure, while the suggested settings pass every time with worst margins of +0.06 to +0.91 °C. Figure 5.5 sets the five configurations side by side against the limits of the target.

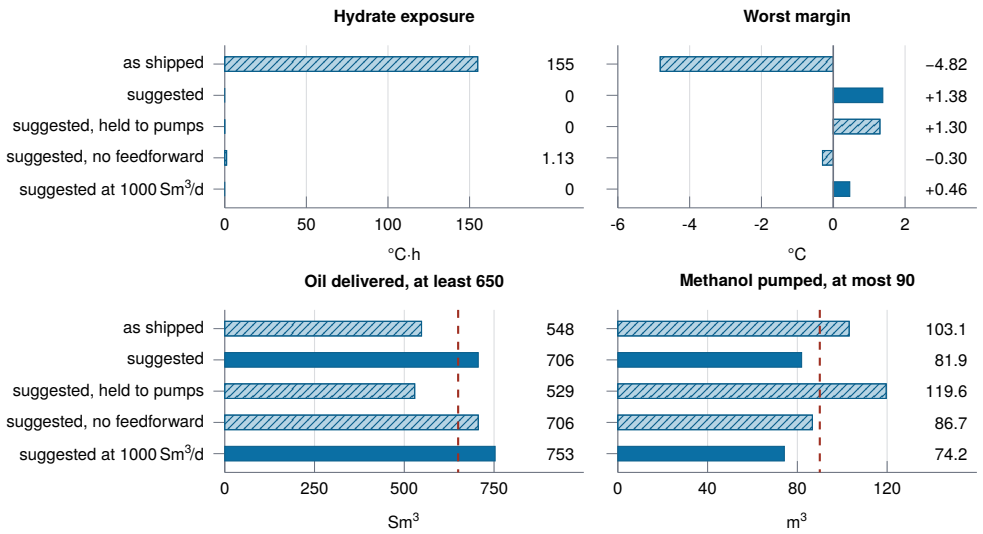


Figure 5.5 The challenge runs of Table 5.6 as bars: exposure, worst margin, oil delivered and methanol pumped over 36 h. Solid bars meet the target, hatched bars miss it, dashed red lines are the oil floor and the methanol cap, and the value of each bar stands at the right. Notice that holding the flow to what the pumps can dose, a cautious rule, costs oil and methanol together, and that of the two runs that pass, the faster setpoint keeps the thinner margin.

The predictive controller made 1080 solves over 36 h in Chrome 157 on the measurement host. Mean times were 56.481 µs for DenseQP alone, 370.648 µs for solve and acceptance, 352.130 µs for model construction and 723.519 µs per decision. Complete controller work, including both observers, took 970.500 ms. Normalized by simulated duration this is 0.000 748 843 % of one core at 1× and 5.391 67 % at 7200×. A short actual 1× window advanced no decisions beyond priming. Actual top-speed playback ran near 60 frames/s without natural frame-budget stops. Guard Off, On and forced exhaustion produced matching 720-step, 60-solve records, with 359 forced stops. The 25 ms guard bounds work within a frame without dropping reached steps or decisions. These measurements show no natural pacing benefit.

5.6.7 Comparison With Predictive Dosing

Table 5.7 adds paired 36 h runs at seed 20261103, with identical instruments and fixed MPC settings. F denotes the feedforward-and-trim structure with the feedforward on and its ratio on the water rate, rather than the feedforward-off setup of case 2 or the liquid-basis setup of case 3. I uses that same law with one PI derived before the cross-case runs. A nominal pump step from 1 to 1.5 m³/h gives gain 0.493 370 °C per wt %, delay 12 575 s and time constant 915 s. The IMC rule $K_c = \tau/[K(\lambda + \theta)]$, $\lambda = \theta$, $\tau_I = \tau$ gives 0.073 741 2 wt % per °C and 915 s for every case [20]. Tables 5.5 and 5.6 keep the windows and settings of the earlier sections.

Case M cuts production at 1 h, requests shutdown at 12 h and requests restart at 30 h. F, I and MPC use 77.818922, 77.809399 and 93.316 154 m³, respectively. F and I have no exposure and a minimum of +1.025 663 °C, whereas MPC reaches −1.739 696 °C and 8.300 350 °C·h. The latter sums segment/slice depths as in Equation (5.8). Integrating only the negative minimum gives the distinct 3.023 019 °C·h. The reduced prediction smears a lean front and the economic objective spends its soft margin. The worst MPC margin occurs at 40 620 s, before shutdown, as shown in Figure 5.6. Both structures close at 124 660 s (34.63 h). The 30 h restart request is ignored during pre-dose, so this case does not demonstrate a completed restart. Separate planned and cold-restart runs test accepted restart commands.

Table 5.7 Additional 36-Hour Comparisons With Water Feedforward, Frozen PI and MPC

Case and law	Minimum (°C)	Exposure (°C·h)	Methanol (m^3)	Margin IAE (°C·h)	Dose travel (m^3/h)	At cap (%)	Mean solve[a] (µs)
Turndown							
F	+1.026	0.000	44.101	34.83	55.91	0.00	—
MPC	−1.740	8.300	105.310	138.85	73.40	36.90	303.0
I	+1.026	0.000	44.812	35.91	56.08	0.00	—
Water cut							
F	+1.544	0.000	92.166	15.96	115.12	0.00	—
MPC	−4.993	62.760	106.136	93.99	47.75	38.52	526.0
I	+1.540	0.000	93.102	18.62	116.05	0.00	—
Cold sea							
F	+1.685	0.000	30.186	12.77	50.25	0.00	—
MPC	−0.134	0.050	79.592	108.56	83.93	22.95	499.2
I	+1.675	0.000	31.053	16.47	51.21	0.00	—
Planned stop/restart							
F	+3.306	0.000	69.981	184.96	55.16	26.91	—
MPC	+3.306	0.000	69.981	184.96	55.16	26.91	523.3
I	+3.306	0.000	69.981	184.96	55.16	26.91	—
Cold restart							
F	−4.141	12.121	63.731	189.19	59.88	21.45	—
MPC	−4.141	12.121	67.535	188.37	72.58	22.84	508.3
I	−4.141	12.121	63.267	187.72	58.90	21.45	—
Pump shortfall							
F	−3.248	486.835	36.925	172.90	2.41	97.22	—
MPC	−3.248	486.548	37.469	172.86	6.14	97.22	520.2
I	−3.248	486.836	36.925	172.90	2.41	97.22	—
Insulation damage							
F	−2.189	19.430	59.713	55.89	70.00	10.69	—
MPC	−2.237	18.955	88.077	104.68	79.51	43.18	508.3
I	−2.191	19.926	60.142	56.36	69.87	10.80	—
TT fault							
F	+0.826	0.000	36.228	51.62	55.79	12.44	—
MPC	−0.510	1.158	68.204	90.57	84.03	19.72	503.9
I	+0.815	0.000	36.485	52.91	55.71	12.48	—
M							
F	+1.026	0.000	77.819	164.76	115.37	0.00	—
MPC	−1.740	8.300	93.316	198.25	117.23	16.99	581.7
I	+1.026	0.000	77.809	164.74	115.34	0.00	—
Challenge, main setup							
F	−4.141	12.121	116.858	124.37	111.51	27.95	—
MPC	−4.696	57.719	120.000	142.64	70.91	47.98	519.3
I	−4.141	12.121	116.858	124.37	111.51	27.95	—

F uses the shipped trim tuning with the feedforward on and its ratio on the water rate. I applies the single predetermined IMC tuning. Preview Off, On, and On with a +3 °C error reproduce every physical row. Every MPC row made 1080 solves and none was rejected, while F and I make no solves. Margin IAE is the shared scorecard integral of setpoint minus the selected observer's estimate in absolute value, divided by 3600. Dose travel is the sum of absolute applied-rate increments. At cap is physical pump-cap occupancy, distinct from the original command-shortfall saturation flag. [a]Fresh Node solve-plus-acceptance wall means vary with host load and are not DenseQP-only or Chrome playback timings.

Preview Off, On and On with a +3 °C error give identical physical results throughout the primary matrix. Candidate targets can change in pre-dose, but sequence ownership leaves zero applied preview

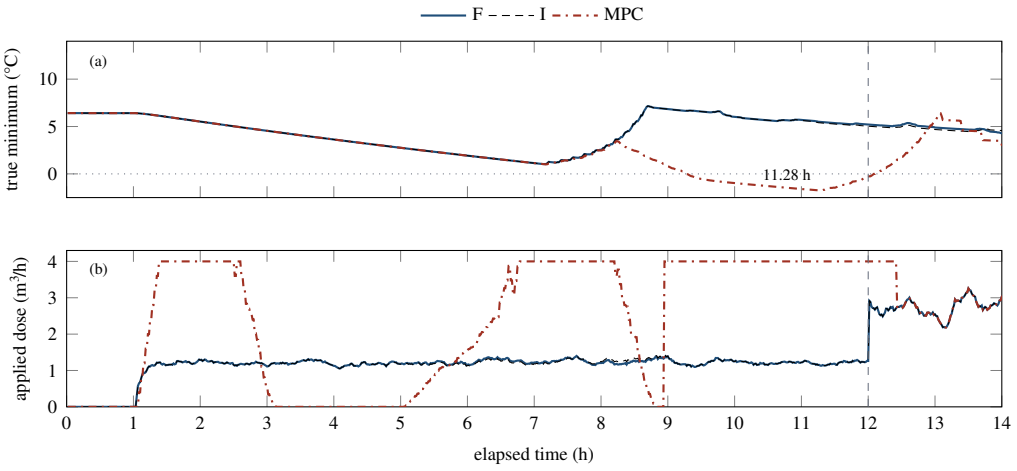


Figure 5.6 Case M through 14 h on common time axes, F solid, I densely dashed and MPC dash-dotted. F and I nearly coincide in true minimum (a), while MPC exposes the lean front despite its larger applied dose (b). The dashed vertical line is the 12 h shutdown request. All curves include the original overrides and sequence, which owns pre-dose actuation. Values are sampled each minute, including the 40 620 s decisive minimum.

benefit. On the unchanged suggested challenge, F and I pass with 81.945284 and 81.669 589 m^3. MPC also avoids exposure and delivers the same 706.130 866 Sm^3 of oil at the same 106.127 bar maximum, but its 102.055 818 m^3 fails the 90 m^3 cap. On the exact original turndown setup, MPC reduces exposure from 276.379 to 8.300 °C·h over 36 h while methanol rises from 75.341 to 105.310 m^3. On the exact liquid-basis water-cut setup it increases exposure from 51.727 to 62.760 °C·h and methanol from 96.416 to 106.136 m^3. The comparison reports these losses as measured.

The 180 primary, 42 diagnostic, 12 exact-setup and 32 forced-fallback rows cover 4821120 finite, physically bounded steps. Halving the physics step changes primary worst margins by at most 0.019 46 °C, exposure by 0.114 68 °C·h and methanol by 1.8443 %, without reversing paired primary rankings. With noise removed, original-versus-fixed PI methanol ordering reverses for turndown and insulation damage. Changed-input diagnostics establish neither numerical convergence nor universal rankings. Twenty corrupted actual solver returns are rejected. Replay of 900 actual packets from each warm and cold history reproduces the nominal observer exactly, whereas a conditionally advanced observer fails that check.

5.7 Technology in Practice

Figure 5.7 draws the choke loops, the profile estimator, the methanol dosing and the sequence of Section 5.5 with the hardware of a deepwater tieback.

What Measures It

The choke loops read the multiphase meter and PT-102. The hydrate margin that the methanol loops protect lives only in the estimator, which the thermometers at the riser base and the arrival pull toward the plant. The dose also rests on the meter's water cut, which matters more as a field matures and the water cut of its wells rises [21]. In the model AT-100 lags 60 s, with 2 % absolute noise and a settable bias.

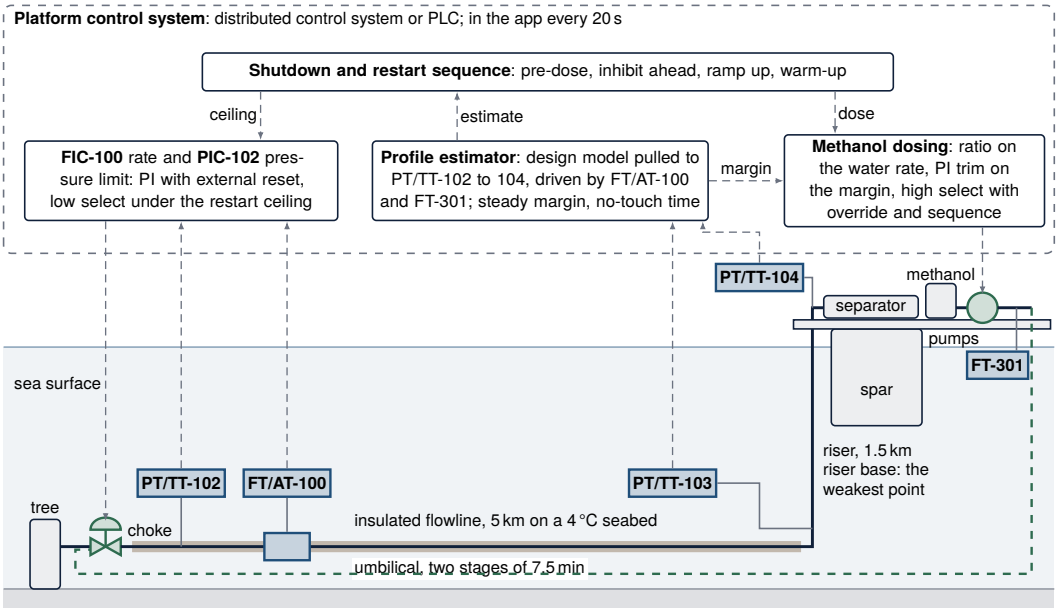


Figure 5.7 The loops of the flowline simulator with their hardware. Lettered boxes are sensing devices with the chapter's tags: the pressure and temperature transmitters PT/TT-102 after the choke, PT/TT-103 at the riser base and PT/TT-104 at the arrival, the subsea multiphase meter FT/AT-100 and the pump's flow meter FT-301. The subsea choke and the methanol pumps are the final elements, the dashed green line is the umbilical and dashed arrows are signals. Notice that no transmitter reads the hydrate margin: every methanol decision passes through the estimator, and the dose leaves the platform hours before it reaches the riser base. Not to scale, and not a piping diagram.

> **TECHNOLOGY** **Sensor: The Temperature Transmitter at the Riser Base**
>
> TT-103 at the riser base is the main witness of the margin estimate. A resistance thermometer is a winding of pure metal wire, usually platinum, whose resistance always rises with temperature [22]. Where it must be replaceable without depressurizing the pipe it sits in a thermowell, whose mass adds a first-order lag. A 4 to 20 mA signal reveals a broken wire by the loss of current, and transmitters that follow the NAMUR levels report a failed sensor below 3.6 mA or above 21 mA [22]. The chapter gives TT-103 a 30 s lag and 0.05 °C of colored noise, and a failed TT-103 reports nothing, so the estimator knows that it is blind there.

What Moves It

Two final elements share the line. The subsea choke at the tree sets the flow for FIC-100 and gives way to PIC-102 near the pressure limit, and in the model its actuator travels at 20 %/min. The methanol pumps on the platform set the dose, and the umbilical carries it down to the tree, where it enters the liquid it has to protect.

TECHNOLOGY Final Element: The Methanol Metering Pump

Metering pumps inject small quantities of a chemical into a process stream. When the dose must follow the treated flow, a 4 to 20 mA signal sets the output between zero and full flow, and many such pumps use a plunger that delivers the chemical in discrete pulses rather than as a steady flow [22]. The chapter's ratio on the water rate is that proportioning. Its pumps deliver 4 m^3/h at most into an umbilical that passes 59 % of a step to the tree after 15 min. When a pump fails in case 6, no setting of the loops protects the line.

Where the Controller Runs

The loops would run in the platform's control system. A distributed control system controls production within one geographic location, usually through feedback and feedforward loops, and loops in such systems run with cycle times from milliseconds to minutes [23]. The app's 20 s control period sits inside that range and is far shorter than the hours the methanol needs to reach the riser base, so no scan rate can make feedback on the margin timely. The chapter's structure maps onto two PID blocks with external reset feeding a low select on the choke, a ratio block with a PI trim and a high select on the pump, a sequence for shutdown and restart, and the profile estimator in a supervisory layer above them.

IN PRACTICE The No-Touch Clock

When a subsea line stops, a 2021 review describes a no-touch time of about half a day, in which the platform tries to resume production while the pressurized line cools toward hydrate conditions at the seabed. For a stop longer than that, operators act to keep hydrates out, for example by displacing the line with dead oil, called bullheading, or by depressurizing it below the hydrate pressure at seabed temperature [10]. The chapter's design line has 3.28 h by its estimator, and the application offers no depressurization.

What Is Modernizing It

Three developments touch this chapter. Low dosage inhibitors, kinetic inhibitors and anti-agglomerants, are an alternative to thermodynamic inhibitors and are used in the field [15]. A 2021 review places them beside alcohols, glycols and salt among the chemical methods of hydrate management, and finds industry trending toward safe operation inside the hydrate region [10]. Virtual flow meters infer the phase rates from ordinary field instruments and empirical algorithms. They cost far less than other multiphase meters but need much calibration before start-up, and a 2019 review expects them to progress [21]. Fiber-optic sensing along a pipeline reads the temperature around it all the way along the fiber [24], the profile that the two thermometers of case 5 cannot give.

5.8 Limitations

The hydraulics are one lumped rate over quasi-steady pressures with a constant slip ratio. Terrain and severe riser slugging, which on a real line are control problems of their own [6] and reach the separator of Chapter 6 as slugs, are absent, and the liquid in a shut-in riser stays where it stopped.

The first-order energy transport on 250 m segments puts the design margin 0.38 °C above its 80-segment value.

The hydrate curve is one representative gas, illustrative and fitted between 20 and 200 bar, the shortcut inhibition relations are used beyond their range at the 30 wt % restart dose, and the share of methanol that partitions into the hydrocarbons is fixed at 10 %.

Exposure is thermodynamic. Nothing forms or obstructs the flow, the plug-risk index is an illustrative mapping whose kinetic uncertainty is an order of magnitude, and a transient formation model would be needed to say whether a given exposure plugs the line [16].

OPEN CHALLENGE When Does Exposure Become a Plug?

Thermodynamics now predicts hydrate formation to within about 10 % in pressure and 1 K in temperature, while kinetic studies give up at least an order of magnitude of that accuracy. Practice has moved from avoiding the hydrate region toward managing operation inside it, and a 2021 conceptual model of how a plug forms on a restart still needs scientific verification [10]. A 2022 review calls for kinetic models of hydrate formation in real crude oils, tested in flow loops [25]. Progress would be a validated prediction of when a given exposure blocks a line.

The estimator knows only the design insulation and sea temperature, and two thermometers are all it has to correct them. Distributed temperature sensing, low dosage inhibitors [15] and depressurization of a shut-in line are not offered.

OPEN CHALLENGE Finding Heat Loss Along Kilometers of Pipe

An optical fiber laid with a pipeline turns the line into a thermometer. A laser pulse scatters inside the fiber, the ratio of two Raman components of the light gives the local temperature, and the travel time gives the place [24]. Over long distances the spatial resolution is limited to the order of meters and worsens with distance, and a cleaner signal costs a longer averaging time [24]. In case 5 two thermometers spread a local flood over the whole flowline. Progress would be a profile fine and fast enough along a subsea line to locate the damage before a shutdown finds it.

The predictive reduction is not an exact forecast of the slice plant. Four nominal pump steps have transient residuals up to 1.5522 °C and RMS 0.3690 °C, although steady gains agree to roundoff. Its bias follows an inferred margin and cannot identify unmeasured local insulation damage. Under forced fallback on changed geometry or physical properties, the nominal and original observers differ by 0 °C, since both carry the declared defaults and meet the changed plant as model mismatch. Neither a positive predicted band nor successful QP solution guarantees the true margin or the challenge's cumulative dose budget.

5.9 Conclusion

The hydrate margin of a deepwater flowline is a minimum over 6.5 km of pipe. The simulator computes it on the truth, slice by slice, while its methanol loops work from an estimate built on six transmitters and two meters. At the design rate the smallest margin, +6.41 °C, sits at the riser base while the coldest fluid keeps +12.2 °C at the platform, and a change made at the tree reaches the riser base 3.23 h later. A turndown dosed by feedback on the estimated margin ends at −4.43 °C with 132 °C·h of exposure, while the feedforward from the predicted demand holds +1.03 °C with 28.3 m^3 of methanol instead of 47.4 m^3. A ratio on the liquid rate lets a water breakthrough thin the riser base to 9.0 wt %, a flooded section of insulation meets its curve 1.36 h after a trip for which the estimate allows 6.68 h, and the first liquid of a restart with no inhibitor lead is exposed 12.5 min after the choke opens, where a 30 min lead keeps +1.17 °C. The model keeps quasi-steady hydraulics, one representative hydrate curve and no kinetics. A fuller model would add a two-fluid hydraulic model with slugging, hydrate formation kinetics with the effect of under-inhibition, salt in the water and distributed temperature sensing. The application is an accessible place to practice sending a dose ahead of its transit and finding a constraint that no instrument measures.

The predictive comparison exposes a failure of model reduction. Case M spends 93.316 m^3 with 8.300 °C·h exposure, while water feedforward spends 77.819 m^3 with none.

KEY POINTS

- The coldest fluid is not the greatest risk: at the design rate the smallest margin sits at the foot of the riser, where cooled fluid still carries the full seabed pressure.
- Methanol travels with the liquid, so a change made at the tree reaches the riser base 3.23 h later, and feedback on the margin there doses liquid that has already gone past.
- A feedforward on the predicted demand holds +1.03 °C through the case 2 turndown, where feedback alone ends at −4.43 °C.
- Two thermometers fix how much heat the line loses and say nothing about where it is lost.

Where else this applies. Volume 9, Chapter 5 judges a release at the head long after it was made, and Volume 5, Chapter 11 infers a core temperature that no instrument reaches.

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5.10 Exercises

5.1 Concept check · 1 min

At the design rate of 1000 Sm^3/d, where along the line does the smallest hydrate margin sit, and why there?

(a) At the platform arrival, because the fluid is coldest there at 19.4 °C.

(b) At the foot of the riser, where the fluid has cooled longest but still carries the seabed pressure.

(c) Just downstream of the choke, where the Joule–Thomson cooling of the choke acts.

(d) At the top of the riser, where the pressure falls toward the 20 bara of the platform.

5.2 Concept check · 2 min

In case 2 the platform cuts the flow to 550 Sm^3/d and only the trim on the estimated margin and the low-margin override can add methanol. Why does the riser base still fall below the hydrate curve?

(a) The trim gain of 0.5 wt % per °C is too low, and a larger gain would hold the margin.

(b) The estimator cannot see the riser base, so the trim acts on a margin that is wrong.

(c) Methanol added once the estimated margin falls enters liquid that reaches the riser base about 5.9 h later.

(d) The pumps lack the capacity to protect the line at the lower flow.

5.3 Concept check · 2 min

In case 4 the seabed water turns 3.5 °C colder and nothing tells the estimator. With its corrections on, the flowline heat-loss factor θ_f climbs to 1.12 over the day although the insulation is intact. Why?

(a) The insulation conducts more heat as the sea around it cools.

(b) The film coefficient falls because the flow drops at the colder sea.

(c) TT-103 drifts with the colder water and pulls the estimate down.

(d) Two thermometers fix how much heat the line loses but not why, so a colder sea is read as more heat loss through the insulation.

5.4 Theory and calculation · 6 min

Transport sets the timing of every dose in this line. Use the chapter's model values.

(a) The seabed flowline holds 134.7 m^3 of liquid at the design rate. How long does a change made at the tree take to reach the riser base at 1000 Sm^3/d, and at 550 Sm^3/d with the same liquid volume? *Checkpoint:* 3.23 h and about 5.9 h.

(b) The umbilical is two first-order stages of 7.5 min each. What fraction of a step of the pump rate reaches the tree after 15 and after 30 min, and after how many minutes has half of it arrived? *Checkpoint:* 59 %, 91 % and about 12.6 min.

(c) The chapter measures a methanol step in manual at half strength at the riser base 3.49 h after the pump moves. Add your results of (a) and (b) and account for the difference.

5.5 Theory and calculation · 6 min

Case 6 runs at 350 Sm^3/d with 30 % water, dosed at 23.6 wt %, and at 1 h the pumps fall to 1.00 m^3/h. Use Equation (5.10) with $\rho_w = 1025\,kg/m^3$, $\rho_M = 791\,kg/m^3$ and $f_{loss} = 10\,\%$.

(a) What pump rate delivers 23.6 wt % to the water before the failure? *Checkpoint:* about 1.95 m^3/h.

(b) What aqueous concentration can 1.00 m^3/h deliver at the same water rate? *Checkpoint:* about 13.7 wt %.

(c) By how much does the Hammerschmidt depression fall between the two concentrations, and what does that say about the exposure that follows?

5.6 Theory and calculation · 5 min

The estimator predicts the no-touch time of a stopped line with Equation (5.9), a lumped cooldown of fluid and wall together.

(a) Take the last seabed segment at the design rate: fluid at 23.8 °C, uninhibited equilibrium 17.2 °C, sea 4.04 °C and the lumped time constant 8.2 h. Ignore the difference between fluid and wall. How long after a trip does this segment reach its curve? *Checkpoint:* about 3.3 h.

(b) In case 7 the estimator gives 3.28 h at the trip and the plant's last seabed segment meets its curve after 3.64 h. Is the estimate safe here, and why does the plant take longer?

(c) After the insulation damage of case 5 a trip at 12 h is given 6.68 h, yet the flooded section reaches its curve after 1.36 h. What in the equation was wrong for that section?

5.7 App challenge · 8 min

Load scenario 2, "Lower production rate", default seed, and use speed 900 (a run of 24 h takes about a minute and a half).

(a) Press Run as shipped, with Feedforward from the predicted demand Off, and pause after 24 h. Read the Worst margin tile. The exposure and methanol tiles keep counting after 24 h, so export the CSV and read `exposure_total_Ch` and `metric_meoh_used_m3` in the row at `time_s` 86 400. *Checkpoint:* about –4.43 °C, 132 °C·h, 47.4 m^3.

(b) Press Reset, set Feedforward from the predicted demand to On before Run, run past 24 h again and read the same three values.

(c) In the CSV of the first run, find the first row in which `margin_true_C` is negative and its location in `margin_true_at_km`. Explain both runs with the transit at 550 Sm^3/d.

Give the values to 0.05 °C, 1 °C·h and 0.2 m^3.

5.8 App challenge · 9 min

Load scenario 8, "Delayed-injection restart", default seed, and use speed 3600 (each 8 h run takes about eight seconds). The choke opens at 0.5 h. Make every change before pressing Run, and pause at or after 8 h. The two tiles no longer change after about 6 h.

(a) Run 8 h as shipped (lead 0 min, ramp 20 %/min). Read the Hydrate exposure and Worst margin tiles. *Checkpoint:* about 12.1 °C·h and –4.14 °C.

(b) Press Reset, set Restart inhibition lead to 30 min, and run 8 h. Read the same tiles.

(c) Reload the scenario with its reload button, which restores the lead of 0 min, set Choke ramp on restart to 5 %/min, and run 8 h.

(d) Reload again, set the lead to 30 min and Methanol depression to Nielsen–Bucklin, and run 8 h. What does the Worst margin tile say about the 30 wt % restart dose?

Give the margins to 0.02 °C.

5.9 App challenge · 10 min

Load the Challenge, "cold restart and water breakthrough", default seed, and use speed 7200 (each 36 h run takes about 18 seconds). The target is no exposure, the flowline below 120 bar, at most 90 m^3 of methanol and at least 650 Sm^3 of oil.

(a) Run past 36 h as shipped and pause. Oil and methanol keep counting, so export the CSV and read, in the row at `time_s` 129 600, `exposure_total_Ch`, `metric_worst_margin_C`, `metric_oil_Sm3`, `metric_meoh_used_m3` and `metric_worst_P_bar`. *Checkpoint:* about 155 °C·h, 548 Sm^3, 103.1 m^3.

(b) Press Reset and, before Run, set Restart inhibition lead to 30 min, Feedforward from the predicted demand On, Hold the flow to what the pump can dose Off and Production setpoint, liquid, to 900 Sm^3/d. Run past 36 h and read the same five columns.

(c) Press Reset, set Hold the flow to what the pump can dose back On, run past 36 h, and read oil and methanol in the same row. Use Equation (5.11) to explain them for a water cut of 20 and of 40 %.

Give oil to 2 Sm^3, methanol to 0.2 m^3 and the margin to 0.02 °C.

5.10 Application area · 4 min

The model counts exposure thermodynamically, so an under-dosed slug counts as partly protected. Field experiments have seen hydrate blockages form more readily in under-inhibited lines than in lines with no inhibitor.

(a) In case 8 without a lead, the leanest slice of the slug carries 17.2 wt % against a restart dose of 30 wt %. How should an engineer read the case's 12.1 °C·h of exposure in the light of that field experience?

(b) The restart dose of 30 wt % lies past the range of the Hammerschmidt relation. What would you do before writing it into a procedure?

5.11 Application area · 4 min

The line carries thermometers only at the riser base and the arrival.

(a) In case 5 the insulation floods between 2.25 and 3.0 km. Why does neither thermometer locate the damage, and which measurement would?

(b) Until such a measurement exists, what operating rule would you attach to the estimator's no-touch time after a trip?

5.12 Review the agent · 5 min

An AI assistant reviews case M, the turndown with a planned shutdown, and writes: "Under MPC the line used 93.3 m^3 of methanol against 77.8 m^3 for feedforward and trim. The MPC carries more inhibitor through the turndown, so it gives the larger margin. Switch the line to MPC for safety." Find the flaw and say how you would check the claim.