INTERACTIVE CONTROL ENGINEERING
Principles and Applications

Volume 13 Control in Chemical Plants

CHAPTER 9

MTBE Reactive Distillation With Multiple Steady States and a Branch-Dependent Temperature Loop

Pages 210–232

Edited by John D. Hedengren

How to cite this chapter. "MTBE Reactive Distillation With Multiple Steady States and a Branch-Dependent Temperature Loop," in *Control in Chemical Plants*, John D. Hedengren, Ed., vol. 13 of *Interactive Control Engineering: Principles and Applications*. Advanced Process Solutions, LLC, 2026, ch. 9, pp. 210–232.

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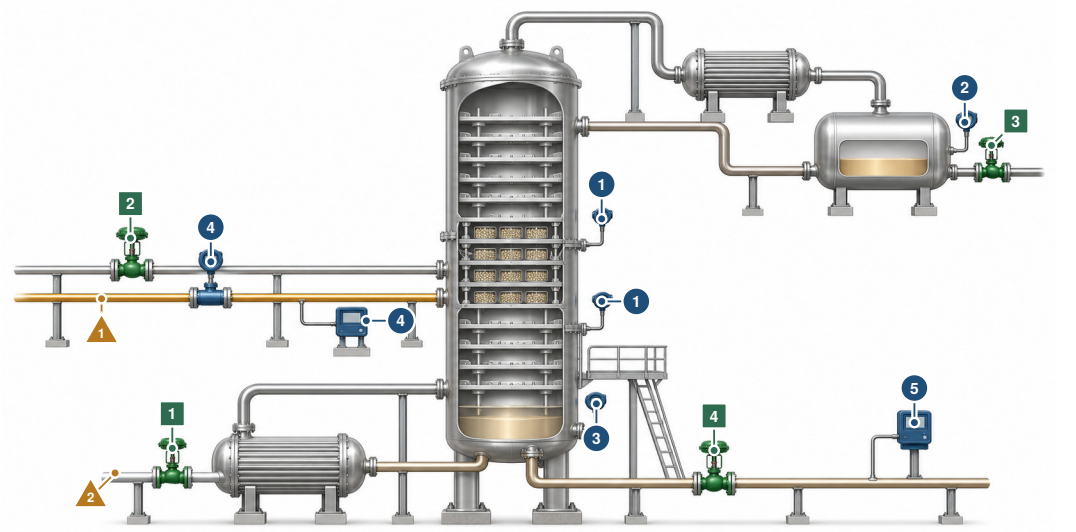
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CHAPTER 9

MTBE Reactive Distillation With Multiple Steady States and a Branch-Dependent Temperature Loop



The controller moves 1 reboiler steam valve, which sets the duty 2 methanol valve, in ratio to the C4 3 distillate valve, on the drum level 4 bottoms valve, on the base level

The controller reads 1 tray temperatures: catalytic tray 8 for the branch monitor, tray 12 for the loop 2 reflux drum level 3 base level 4 C4 flow meter and feed analyzer 5 bottoms analyzer

What disturbs it 1 a larger or leaner C4 feed 2 a dip in the steam supply

Notice the band of catalyst trays where the methanol must stay: with the same feeds and the same steam, the column can hold it there or lose it below. Illustration, not to scale.

IN PLAIN TERMS **One Column, Three Ways to Settle**

The main idea. This tall column makes a chemical called an ether. Two feeds react on trays that hold a catalyst, and the column separates the product as it forms. With the same feeds and the same heat, the column can settle in three very different ways, and which one it reaches depends on how it got there.

The challenge. The controller adds or removes heat by watching one tray low in the column. In one bad way to settle, that tray's temperature stops rising, so the controller keeps adding heat and makes things worse.

Why it matters. A loop that works well in one way can quietly push the column into another.

THREE WAYS TO READ THIS CHAPTER

Explore	13 min	the first page, the history boxes of Sections 9.1 and 9.2, the fact boxes of Sections 9.2 and 9.6, the two try-it boxes of Section 9.6 and the key points
Study	45 min	the whole chapter with its three pause points and the twelve exercises
Practice	15 min	the first page, Section 9.6, Section 9.7 with its three boxes, Section 9.8 and the open challenge

The control question At one set of feeds and one reboiler duty, an MTBE column can convert most of its isobutene, lose its methanol into the stripping trays, or fail to strip its C4. Which steady state does the column reach, and what does a stripping-tray temperature loop tuned on one of them do on the others?

Learning objectives

- Explain why the methanol's position decides the branch, and read the branches, folds and Hopf point of an S-curve against the duty.
- Compute the boilup, the vapor made by the heat of reaction and the temperature dependence of the equilibrium constant and the rate.
- Predict the hysteresis of a slow duty ramp from the S-curve and measure it on the running column.
- Identify an input multiplicity in a tray temperature and decide which setpoints a loop can hold on each branch.
- Evaluate a branch monitor and a duty-cutting supervisor, and choose a control tray and setpoint with margin on both branches.

Prerequisites Sections 1.4.5 (multiplicity in a reactive column), 1.4.2 (equilibrium-limited reactions), 1.4.6 (ratio control), 1.6.2 (velocity-form PID) and 1.6.4 (scenarios and the challenge). Chapter 8 uses the same stage stack.

The app https://apmonitor.com/apps/reactive-distillation/

See also Volume 7, Chapter 2 for folds and a Hopf point in a stirred tank, and Volume 7, Chapter 4 for a setpoint at the peak of the plant characteristic. Volume 5, Chapter 3 for composition control through a slow analyzer. Volume 6, Chapter 7 for the same stage stack in a recycle plant.

9.1 Introduction

Fifteen trays, eight of them carrying an acid resin, turn 775.8 kmol/h of methanol and 1976.4 kmol/h of a C4 cut holding 35.68 mol % isobutene into ether in the simulated column. At a reboiler duty of 42.5 MW the column can sit in three stable states. In one it converts 98.22 % of the isobutene and sends 99.94 mol % MTBE to the bottoms. In another the methanol has fallen through the catalyst into the stripping trays, only 90.05 % is converted, and the bottoms carry 16.91 mol % methanol. In the third the vapor is too weak to strip the C4, 94.89 % is converted and the bottoms hold 6.94 mol % C4. The feeds, the reflux ratio of 7 and the duty are the same in all three.

The simulator is built to correct a belief that most control courses leave in place, that a plant's handles fix its steady state, so that a controller tuned at one operating point meets the same plant wherever the handles return to it. Distillation alone can contradict that belief, since ideal two-product columns can have several steady states [1], and a reactor example shows that more than one set of inputs can give the same outputs, which decides whether a loop pairing is stable [2]. Reactive distillation combines both, and its multiplicity and oscillations are reviewed as part of its control problem [3]. In the column simulated here a duty ramped up at 1 MW per hour drops the conversion at 44.82 MW, and ramped down it recovers only at 40.88 MW. A tray-temperature loop that holds the high-conversion state through a feed step raises the duty without limit on the low-conversion state, and one tray temperature is reached at two duties.

> ⧖ **HISTORY** **1960 to 1991: Can a Plain Column Have Two States?**
>
> Multiple steady states in distillation were studied for three decades before 1991. Rosenbrock proved in 1960 and 1962 that a binary column with constant relative volatility and constant molar flows cannot have them, and a 1982 review concluded the same for any multistage column separating a binary mixture with constant molar flows. In 1991 a study showed, for the first time, multiplicity in columns with ideal thermodynamics. One kind came from reflux and boilup set in mass or volume units, as industrial columns usually set them, the other from the energy balance. In both, more reflux made the top of the column separate worse, at an unstable operating point [1]. The MTBE column adds a reaction to the trays and finds three stable states.

However, the literature presents these effects as steady-state analyses and simulation studies [3–5], and a student rarely meets a column that can be pushed across a fold and watched while its branches are drawn underneath. This chapter describes an MTBE column simulated in the browser, whose branches an independent steady-state solver computes and draws under the running plant, and measures what a duty ramp, a feed change, methanol excess, two start-up charges and a stripping-tray temperature loop do to the branch the column is on. The equilibrium-stage model, the Wilson equation [6], the activity-based kinetics [7, 8], continuation and the proportional-integral (PI) law are all standard. The measurements are made on one column at one seed. They show that the multiplicity emerges from parameters read from published sources, that the plant lines out within 0.007 percentage points of the solver's states in the comparisons of Table 9.4, and that the high branch is lost through a complex pair of eigenvalues at 43.50 MW rather than at a fold. The model is a 79-state column on the series' shared distillation module, with an integrator whose fixed points are exact steady states, and the chapter gives the equations, constants and defaults from which the column can be rebuilt. Nine cases come with completion rules that credit what a learner does.

Section 9.2 traces etherification on a distillation tray and the history of its multiplicity. Section 9.3 sets out the column as modeled, its trays, activity model, rate, instruments and integrator. Section 9.4 computes the branches with an independent solver, classifies their stability and explains why the methanol decides the branch and why one tray temperature is read at two duties. Section 9.5 describes the loops, the branch monitor and the supervisor. Section 9.6 measures the nine cases, from the hysteresis loop of a duty ramp to the graded challenge, and Section 9.7 names the real devices behind the loops. Section 9.8 states the limitations and Section 9.9 sums up. The exercises at the end of the chapter run the cases of Section 9.6.

9.2 Etherification on a Distillation Tray

An ether made from isobutene and methanol over an ion-exchange resin is limited by equilibrium, and in a fixed bed the conversion stops short of complete. Boiling the heavy ether away from the catalyst as it forms removes that limit, and etherification became one of the reaction classes of industrial reactive distillation. How the technique grew to more than 150 industrial columns is told in the history box below. The kinetics behind such designs were written in liquid-phase activities on the resin [7], and rate constants of that form are still used in reactor models [8].

> ⧖ HISTORY **From the 1920s to More Than 150 Columns**
>
> Reaction and separation in one column have been developed since the early 1920s, and the technique counts among the best success stories of process intensification. It overcomes the equilibrium limit of reactions such as esterification and etherification [9]. A 2007 survey reported more than 150 industrial reactive distillations operating worldwide at 100 to 3000 kilotonnes per year, most of them started up less than fifteen years before. Their reactions include hydrogenations, hydrodesulfurization, esterifications and etherification, and several commercial ways of packing a solid catalyst into a column had become available. The designs were scaled up from pilot plants by brute force and by modeling [10].

The column's second life began as a puzzle. Multiple solutions of an MTBE column were reported in 1993 [11], and a 1995 study asked why MTBE production by reactive distillation may yield them [12]. The analysis of columns at infinite length and infinite internal flows then predicted output multiplicities from the reactive vapor-liquid equilibrium alone, extended it to columns with a reactive core between nonreactive sections, and studied the physical causes of the MTBE multiplicities [4]. Theoretical analysis and experimental verification of steady-state multiplicities in MTBE and TAME columns appeared the same year [5], as did a nonequilibrium, rate-based model that showed multiple steady states in MTBE synthesis [13]. A 1996 dynamic simulation of a seventeen-stage column found the reported low- and high-conversion states together with unstable states between them, and its base

Table 9.1 Variables, Their Roles and Design Values (Case 3 at $t = 0$)

Symbol	Role	Design	Range
T_{12}	CV, control tray temperature (°C)	137.4	SP 70–155
x_B	CV (trim), bottoms MTBE (mol %)	99.94	SP 95–99.9
ℓ_D, ℓ_B	CV, drum and base levels (%)	50, 50	SP 20–80
Q	MV, reboiler duty (MW)	42.5	0–60
F_M	MV, methanol (kmol/h), $r_M F_{C4} z_{IB}$	775	0–1600
D, B	MV, distillate, bottoms (kmol/h)	1364, 694	0–3000, 0–2000
L	reflux, RD (kmol/h)	9546	—
r_M, R	settings, methanol ratio, reflux ratio	1.100, 7	0.9–1.3, 5–10
F_{C4}	DV, C4 feed (kmol/h)	1976	1600–2400
z_{IB}	DV, isobutene in the C4 (mol %)	35.68	28–42
s	DV, steam available (% of normal)	100	60–110
M_i, x_{ij}	states, holdups (kmol), fractions	15, profile	15 trays
M_D, M_B	states, drum, sump (kmol)	100, 150	cap 200, 300
X	output, isobutene converted (%)	98.22	—
$x_{D,M}$	output, methanol in distillate (mol %)	6.08	—
T_8	monitor tray temperature (°C)	77.6	saddle 93

case of feeds, reflux ratio and reactive stages [14] is the one later work, and this application, start from [15].

Control followed the nonlinear analysis. Two-point control of a reactive column for composition and conversion was studied in 1999 [16], a review chapter set the nonlinear dynamics of reactive distillation, including MTBE and TAME synthesis, beside control structure selection and control algorithms [3], and a monograph on reactive distillation gave a chapter to the control of MTBE and ETBE columns [17]. The application takes the simplest regulatory choice, one stripping-tray temperature on the reboiler duty, and shows what the branches do to it.

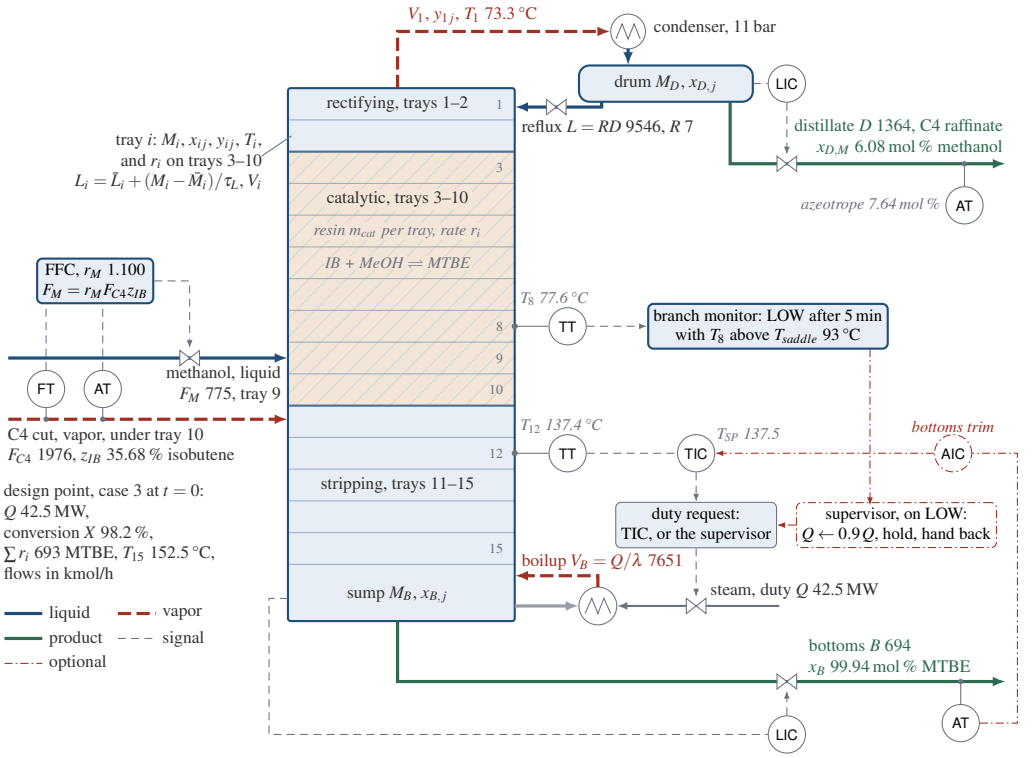


Figure 9.1 The MTBE column drawn after the Column view of case 3 at $t = 0$, the design point on the high branch at 42.5 MW. Methanol enters tray 9 as liquid and the C4 cut enters under tray 10 as vapor, the catalytic trays 3 to 10 are hatched, and the tray callout lists the states and flows of Equations (9.1) to (9.3). The temperature loop reads tray 12 and sets the reboiler duty, the methanol follows the measured C4 flow and the feed analyzer's isobutene, the two level loops set the distillate and bottoms, and the dash-dotted red elements (the bottoms trim, the monitor's supervisor and its duty override) are optional. Liquid and product streams are solid, vapor streams dashed and signals thin dashed. Flows in kmol/h. Process model only. Not to scale.

> ✦ **DID YOU KNOW? A Fifth or More Saved**
>
> In every industrial case of the 2007 survey, reactive distillation cut the variable cost, the capital and the energy by 20 percent or more against a reactor followed by a column [10]. A 2018 comparison put the energy saving of the classic reactive column at 15 to 80 percent [9].

9.3 The Column as Modeled

The simulated column has no plant behind it, but its shape and feeds are a published base case. A doctoral thesis on reactive distillation dynamics tabulates the base case of Schrans and coworkers [14], a total condenser, two rectifying, eight reactive and five stripping trays and a partial reboiler, with 215.5 mol/s of liquid methanol, 549 mol/s of C4 vapor at 35.68 % isobutene on stage 11, reactive stages 4 to 11, a reflux ratio of 7 and feeds at 11 atm, and its multiplicity figures put the methanol on stage 10 [15]. The application keeps that shape, numbers the trays 1 to 15 below the condenser, so that methanol enters tray 9 and the C4 vapor enters under tray 10, and holds every tray at 11 bar. The layout is shown in Figure 9.1.

Table 9.1 lists the variables by role. Flows are in kmol/h on an engine clock in minutes, so the code divides each balance by 60, a factor the equations below omit. The model integrates 79 states,

a holdup and three mole fractions on each of 17 stages (drum, 15 trays, sump), five flow lags, and six ledgers that count the inert, the isobutene group (isobutene plus MTBE) and the methanol group (methanol plus MTBE) in and out, the three quantities the reaction conserves.

9.3.1 Trays With a Reaction

Each tray holds liquid in phase equilibrium with the vapor it sends up. On a catalytic tray the reaction adds its stoichiometry to the component balances, as shown in Equation (9.1).

$$\begin{aligned} \frac{\mathrm{d}M_i}{\mathrm{d}t} &= L_{i-1} + V_{i+1} + F_i - L_i - V_i - r_i \\ \frac{\mathrm{d}(M_i x_{ij})}{\mathrm{d}t} &= L_{i-1}x_{i-1,j} + V_{i+1}y_{i+1,j} + F_i z_{ij} \\ &\quad - L_i x_{ij} - V_i y_{ij} + \nu_j r_i \end{aligned} \tag{9.1}$$

where j runs over isobutene, n-butene (the inert), methanol and MTBE, the last closing the fractions to one, $\nu = (-1, 0, -1, +1)$, r_i is the net rate of MTBE formation on tray i (zero off trays 3 to 10), and F_i is a feed on tray 9 or 10. One mole of liquid is lost per mole of ether formed. Constant molar overflow with one latent heat λ moves the flows, and the heat of reaction boils liquid on its own tray, as shown in Equation (9.2).

$$\begin{aligned} V_i &= V_{i+1} + (1-q_i)F_i + \nu_V r_i, \qquad V_{16} = V_B = Q/\lambda \\ L_i &= L_{i-1} + q_i F_i - (1+\nu_V)\, r_i, \qquad \nu_V = -\Delta H_r/\lambda \end{aligned} \tag{9.2}$$

where $q = 1$ for the liquid methanol and $q = 0$ for the C4 vapor. With $\Delta H_r = -37.7\,\mathrm{kJ/mol}$ [8] and $\lambda = 20\,\mathrm{kJ/mol}$, each mole of MTBE boils $\nu_V = 1.885$ moles, and the boilup is 180 kmol/h per MW. In the dynamic model these two equations are steady values about which a linearized weir moves the liquid, as shown in Equation (9.3).

$$L_i = \bar{L}_i + \frac{M_i - \bar{M}_i}{\tau_L} \tag{9.3}$$

where $\bar{L}_i$ and $\bar{M}_i$ are the flows and holdups of a reference set once from the base case's reflux and feeds and $\tau_L = 0.1$ min. The trays, the drum and the sump come from the stage stack the series shares, first written for its reactor-column-recycle plant and promoted to the framework once its dividing-wall column needed the same code (Volume 6, Chapter 7 and Chapter 8). This column is the stack's third user, and it plugs in through the stack's own interfaces. The activity model is the stack's bubble point. The reaction enters as a vapor feed of the tray's liquid with an equal liquid draw for the heat of reaction, a liquid draw of r_i for the mole lost, and one stoichiometric term added to the derivatives. The flows run the other way when MTBE decomposes.

9.3.2 Liquid Activity and the Bubble Point

Every tray's temperature and vapor follow from the bubble point with Wilson activity coefficients [6], as shown in Equation (9.4).

$$\begin{aligned} P &= \sum_j \gamma_j x_j P_j^{sat}(T), \qquad y_j = \gamma_j x_j P_j^{sat}/P \\ \ln\gamma_i &= 1 - \ln\sum_j x_j \Lambda_{ij} - \sum_k \frac{x_k \Lambda_{ki}}{\sum_j x_j \Lambda_{kj}} \\ \Lambda_{ij} &= \frac{V_j}{V_i}\,\mathrm{e}^{-a_{ij}/T} \end{aligned} \tag{9.4}$$

where $\ln P^{sat} = C_1 + C_2/T + C_3 \ln T + C_4 T^{C_5}$ in pascals (the DIPPR equation 101 form), solved for T by Newton's method from the fraction-weighted boiling points. The vapor-pressure coefficients, the

Table 9.2 Property Constants Read From the Sources (Fixed in the Source)

	isobutene	methanol	MTBE
C_1	102.5	81.768	55.875
C_2 (K)	−5021.8	−6876	−5131.6
C_3	−13.88	−8.7078	−4.9604
C_4	0.020296	7.1926×10^{-6}	1.9123×10^{-17}
C_5	1	2	6
V_j (cm^3/mol)	93.33	44.44	118.8
$a_{IB,j}$ (K)	0	49.4802	8.87958
$a_{M,j}$ (K)	1243.186	0	711.7
$a_{E,j}$ (K)	−0.01494	−197.9	0

rate: $a_0 = 6.3\times10^{12}$ mol h^{-1} g^{-1}, $E_a = 85.4$ kJ/mol, $\Delta H_r = -37.7$ kJ/mol, equilibrium $K(350\,\text{K}) = 28.5$, van 't Hoff with ΔH_r ($K = 271.2$ at 25 °C)

Wilson energies a_{ij} and the molar volumes V_j of isobutene, methanol and MTBE are those tabulated in a 2021 thesis [18] and appear in Table 9.2. The inert takes isobutene's properties.

The thesis prints the coefficient with V_i/V_j. The standard form [6] with V_j/V_i is used because only that reading of the tabulated energies gives the azeotropes the sources describe. With it the infinite-dilution coefficients at 350 K are 29.9 for methanol in isobutene, 4.02 for methanol in MTBE and 2.91 for MTBE in methanol, methanol and MTBE form a minimum-boiling azeotrope at 1 atm at 29.4 mol % methanol and 50.8 °C, and the C4 and methanol form an azeotrope at 11 bar at 7.64 mol % methanol and 73.1 °C. The printed reading gives 0.50 and 0.55 for the methanol and MTBE pair, a negative deviation with no azeotrope. At 11 bar the pure components boil at 75.2, 140.5 and 152.8 °C.

9.3.3 The Rate on the Resin

The net rate on a catalytic tray is written in activities $a = \gamma x$, as shown in Equation (9.5).

$$\begin{aligned} r_i &= m_{cat}\, k(T_i)\, \frac{a_{IB}\, a_M - a_E/K(T_i)}{(a_M+\varepsilon)^2} \\ k(T) &= a_0\, \mathrm{e}^{-E_a/RT} \\ K(T) &= K_{350}\, \exp\!\left[\frac{-\Delta H_r}{R}\left(\frac{1}{T}-\frac{1}{350\,\text{K}}\right)\right] \end{aligned} \tag{9.5}$$

where $m_{cat} = 1000$ kg of resin per tray, E is MTBE and M methanol. As $\varepsilon \to 0$ the fraction becomes the methanol-rich form $a_{IB}/a_M - a_E/(K a_M^2)$ with the constants a_0 and E_a of Table 9.2 [8]. $K_{350} = 28.5$ is the activity-based equilibrium constant of the 1990 kinetics [7] as tabulated in the thesis that supplies the column [15], and K falls as T rises because the reaction is exothermic.

The term $\varepsilon = 0.05$ keeps the rate finite where the methanol runs out, but it is not a small guard. Written out, the denominator is the adsorption form $(1 + K_{ads} a_M)^2$ with $K_{ads} = 1/\varepsilon = 20$ and the rate constant scaled by $1/\varepsilon^2$. At the design point it slows the rate on the catalytic trays to 0.48 to 0.81 of the $\varepsilon \to 0$ form, because the methanol activity there is only 0.11 to 0.44. The folds depend on it. At $\varepsilon = 0.02$ all six lie 0.9 to 3.0 MW lower (41.26, 38.34, 39.40, 37.23, 43.19 and 40.89 MW), while at $\varepsilon = 0.1$ only the under-boiled state remains at 42.5 MW (93.3 %). The catalyst mass, ε and λ are the three teaching values of the reaction and the flows. The folds survive each being changed but move with it. With 300 kg of resin per tray the curve folds at 48.10, 36.09, 53.46 and 52.80 MW, and with $\lambda = 16$ kJ/mol its six folds lie between 29.28 and 35.55 MW.

Table 9.3 Parameters With Their Status: A, Adjustable by the Learner. H, Hidden in the Parameter Panel. S, Set in the Source Code

Symbol	Meaning	Value	Unit	
m_{cat}	resin on each catalytic tray	1000	kg	A
Q_{max}	reboiler duty at full steam	60	MW	A
—	bottoms specification, conversion	98, 95	mol %, %	A
—	distillate methanol alarm	7.0	mol %	A
λ	latent heat (constant molar overflow)	20	kJ/mol	H
ε	methanol term, rate denominator	0.05	—	H
M_t	tray liquid at the weir reference	15	kmol	H
$M_{D,cap}$, $M_{B,cap}$	drum, base capacity	200, 300	kmol	H
τ_L, τ_Q	tray hydraulic lag, reboiler response	0.1, 2	min	H
P	pressure on every stage	11	bar	S
N	trays (rectifying, catalytic, stripping)	2, 8, 5	—	S
—	methanol, C4 feed trays	9, under 10	—	S
$\bar{L}$	weir reference reflux	9399.6	kmol/h	S
τ_F	feed, reflux and product flow lags	0.2	min	S

9.3.4 Drum, Sump, Actuators and Instruments

The drum holds what the total condenser returns, so its vapor in is y_1, and the sump boils at equilibrium as the partial reboiler, as written in Equation (9.6).

$$\begin{aligned} \frac{\mathrm{d}M_D}{\mathrm{d}t} &= V_1 - L - D \\ M_D \frac{\mathrm{d}x_{D,j}}{\mathrm{d}t} &= V_1\,(y_{1j} - x_{D,j}) \\ \frac{\mathrm{d}M_B}{\mathrm{d}t} &= L_{15} - V_B - B \\ \frac{\mathrm{d}(M_B x_{B,j})}{\mathrm{d}t} &= L_{15}\,x_{15,j} - V_B\,y_{B,j} - B\,x_{B,j} \end{aligned} \tag{9.6}$$

where $L = RD$. The delivered duty lags the request times the steam available with $\tau_Q = 2\,\mathrm{min}$, and the methanol, reflux, distillate and bottoms follow their setpoints with 0.2 min lags. A pump delivers only $\min(1, M/(0.02\,M_{cap}))$ of its flow as its vessel empties. The controllers see the plant only through a measurement packet, and a test in the application fails whenever the packet holds anything more. Thermowells on every tray lag 0.5 min with 0.05 K of noise, levels lag 0.1 min with 0.05 %, flows lag 0.05 min with 0.2 % of the flow, and the duty carries 0.02 MW. The series' analyzer module supplies three analyzers, one on the bottoms (MTBE, methanol, C4), one on the distillate's methanol and one on the feed's isobutene. Each samples every 10 min through a 1 min sample line and reports a cycle later with 0.02 mol % of noise. Each execution consumes a fixed count of random draws, which makes a seeded run repeat exactly.

9.3.5 Initialization and the Integrator

Table 9.3 gives the parameters. Each case opens lined out on the branch it names, at its own duty, feeds and ratios. The state comes from the steady-state solver of Section 9.4, started from a stored profile on that branch and walked to the case's settings, each tray holding its weir's steady liquid and the drum and base half full. The design point is a steady state of the dynamic model to 1.8×10^{-13} per minute.

The engine's classical fourth-order Runge-Kutta method (Section 1.6.1) at a 1 s step runs case 3 but fails one minute into the methanol-wetted start-up, where the reaction on a methanol-lean tray relaxes faster than the explicit step can follow. The application therefore supplies its own step. The transport is explicit, and on each catalytic tray the reaction is implicit through the rank-one Jacobian

of the rate, as shown in Equation (9.7).

$$\Delta\mathbf{x}_i = h\,\mathbf{f}_i + h^2\,\mathbf{u}_i\,\frac{\mathbf{g}_i^{\mathsf{T}}\mathbf{f}_i}{1 - h\,\mathbf{g}_i^{\mathsf{T}}\mathbf{u}_i}, \qquad u_{ij} = \frac{\nu_j + x_{ij}}{M_i} \tag{9.7}$$

where $\mathbf{f}_i$ is the tray's explicit derivative, $\mathbf{g}_i = \partial r_i / \partial \mathbf{x}_i$ at the tray's temperature and $h = 1\,\mathrm{s}$. This is the Sherman-Morrison solution of $(I - h\,\mathbf{u}\mathbf{g}^{\mathsf{T}})\Delta\mathbf{x} = h\mathbf{f}$, so $\Delta\mathbf{x} = 0$ exactly when $\mathbf{f} = 0$, and a fixed point of the step is a steady state of the equations. Where the linearized step would carry a fraction out of $[0, 1]$, the extent over the step is found by bisection on the interval that keeps every fraction inside. The stages are updated in holdup and component amount, so the inert and the two groups are conserved. Over the application's disturbed test run the ledgers close to 9.0×10^{-14} of what was fed, and one step from the solver's high, low and under-boiled states moves no state by more than 5×10^{-12}.

A step that would still carry a fraction more than 0.001 outside $[0, 1]$ is retaken as two half steps, split again while needed down to $h/32$. The first minutes of the methanol-wetted start-up need this, and there the lowest fraction is -7.1×10^{-4}, the methanol group closes to 3.6×10^{-3} kmol of 11 008 kmol fed over 4 h, and the column lands on the same state at $h/2$, $h/4$ and $h/10$. A step inside the tolerance is the single step, bit for bit. On the low branch at high duty (cases 4 and 8, and case 5 in Auto) fractions dip to at most -3.7×10^{-5}, inside the tolerance. Halving h leaves the jumps of case 1 at 44.816 and 40.884 MW.

The conversion is logged as the extent the reaction actually ran at over each step, summed over the catalytic trays and divided by the isobutene fed. Because the reaction relaxes within a fraction of a step, the rate re-evaluated at the stepped state jitters about that extent. In case 8 run at 143.5 °C, 300 min in, the applied extent gives 62.21 % at the 1 s step and 62.01 % at a quarter of it, while the re-evaluated rate reads 62.57 %.

9.3.6 Assumptions

The trays are equilibrium stages with an efficiency of one, and the reaction runs in the liquid of the catalytic trays with no resistance between vapor, liquid and resin, so the model is least reliable where the rate is fast, which is the case rate-based models address [13]. Constant molar overflow with one latent heat replaces an energy balance per tray, and the feeds are saturated. The inert is one component with isobutene's volatility, and no side reaction (dimethyl ether, isobutene dimers, tert-butyl alcohol) is modeled. The base case's inert is n-butane, its methanol enters at 320 K and its C4 at 350 K, it fixes the bottoms flow at 197 mol/s where the application fixes the duty, and it lists its feeds at 11 atm and its column at 10 atm [15]. The model holds 11 bar everywhere and takes both feeds as saturated. The pressure, the condenser and the flow loops are ideal. Its fifteen trays depart from the twelve first planned for the application because the fifteen-tray base case could be read, and a twelve-tray variant also folds in a prototype model built during development.

9.4 The Branches and Their Stability

9.4.1 An Independent Steady-State Solver

The branches are found by a second program. It writes the 51 steady balances (three fractions on 17 stages) again from Equations (9.1), (9.2) and (9.4) at constant holdup, with $x_D = y_1$ for the drum and the sump as an equilibrium stage, and it imports only the bubble point, the rate and an eigenvalue routine. It never calls the dynamic model's derivatives or the shared stage stack. The curve $\mathbf{f}(\mathbf{x}, Q) = 0$ is followed in the duty by pseudo-arclength continuation, as shown in Equation (9.8).

$$\begin{bmatrix} \partial_{\mathbf{x}}\mathbf{f} & \partial_Q\mathbf{f} \\ \mathbf{t}^{\mathsf{T}} & \end{bmatrix} \Delta\mathbf{z} = - \begin{bmatrix} \mathbf{f} \\ \mathbf{t}^{\mathsf{T}}(\mathbf{z} - \mathbf{z}_{pred}) \end{bmatrix}, \qquad \mathbf{z} = (\mathbf{x}, Q) \tag{9.8}$$

where $\mathbf{t}$ is the unit tangent and $\mathbf{z}_{pred}$ the predictor step along it. The Jacobian is numerical, the walk runs from 25 to 56 MW in arclength steps of 0.03, each fold's duty is refined by a walk at a tenth of

Table 9.4 The Dynamic Plant Against the Independent Solver

Comparison	Plant	Solver
41.0 MW, high, mean of the hour after 5 h (%)	98.237	98.230
45.5 MW, low, mean of the hour after 5 h (%)	81.548	81.548
42.5 MW, C4 start-up, 10–11 h (%)	98.218	98.219
42.5 MW, methanol start-up, 10–11 h (%)	90.039	90.041
derivatives at 8 solver states (per min)	$\leq 5.3 \times 10^{-11}$	
Hopf on the high branch (MW)	43.57	43.50
low branch held 10 h at 41.80 / 41.70 MW	low / gone	fold 41.75
high branch held 10 h at 46.10 / 46.20 MW	high / low	fold 46.15

the step and a parabola through the extreme, and each point is classified by the largest real part of the eigenvalues of the balances linearized with the dynamic model's holdups (15 kmol per tray, 100 kmol in the drum, 150 kmol in the sump). The curve takes 2.9 s headless and about 3 s in a browser with the run paused. Nothing logged, controlled or scored depends on it.

The solver and the plant agree where they can be compared without circularity, as listed in Table 9.4. Evaluated at the solver's states, the dynamic derivatives are zero to between 7×10^{-14} and 5×10^{-11} per minute. Moved off one solver state, the plant lines out on another. Started from a column refilled with the C4 cut or with methanol, neither of which is a solver state, it reaches the solver's high and low states at 42.5 MW.

9.4.2 Six Folds and a Hopf Point

At the published feeds the walk folds at 42.90, 40.46, 40.77, 38.35, 46.15 and 41.75 MW, as shown in Figure 9.2a. Three stable families result. The under-boiled branch, with too little vapor to strip the C4, runs up to its fold at 42.90 MW (a short stable sliver lies between the 40.46 and 40.77 MW folds). The high branch begins at its fold at 38.35 MW, and the low branch, with the methanol in the stripping trays, begins at its fold at 41.75 MW and continues to the end of the walk. Between 41.75 and 43.50 MW the high and the low branch coexist, the output multiplicity. At 42.5 MW the unstable saddles between the three stable states convert 95.24 and 95.43 %.

The high branch does not end at a fold. A complex pair of eigenvalues crosses the imaginary axis at 43.50 MW in the solver's constant-holdup linearization, with a period of 82 min, and between 43.55 and 43.60 MW in the full dynamic model's, whose real part goes from -2.8×10^{-3} to $+6.9 \times 10^{-3}$ per minute, so about 43.57 MW. A 10 h hold oscillates visibly only from 43.7 MW, where the conversion swings between 96.11 and 99.29 % over the last two hours. A short stable stretch of the high branch returns from 44.99 to 46.15 MW. Every fold reproduces at arclength steps of 0.05, 0.03, 0.02 and 0.005. At 0.01 one step straddles the 0.31 MW sliver between 40.46 and 40.77 MW and reports four folds. The exothermic stirred tank of Volume 7, Chapter 2 has the same ingredients in one vessel, ignition and extinction folds and a Hopf point on its hot branch.

9.4.3 Why the Methanol Decides the Branch

Methanol boils between the C4 and the MTBE, so the vapor rate decides where it sits. On the high branch it stays on the catalytic trays, where it reacts, and the bottoms are nearly pure ether. More boilup pushes it down. Once it is below the catalyst it cannot react, less MTBE is made, the heat of reaction boils less liquid, and the flows that put it there persist. On the low branch at 42.5 MW the bottoms carry 16.91 mol % methanol, and more duty pushes more down, so the conversion falls from 93.0 to 53.9 % between the low branch's fold and 56.17 MW. The branch monitor reads this on catalytic tray 8, which stays below 87.3 °C everywhere on the stable high branch and above 100.0 °C everywhere on the low branch.

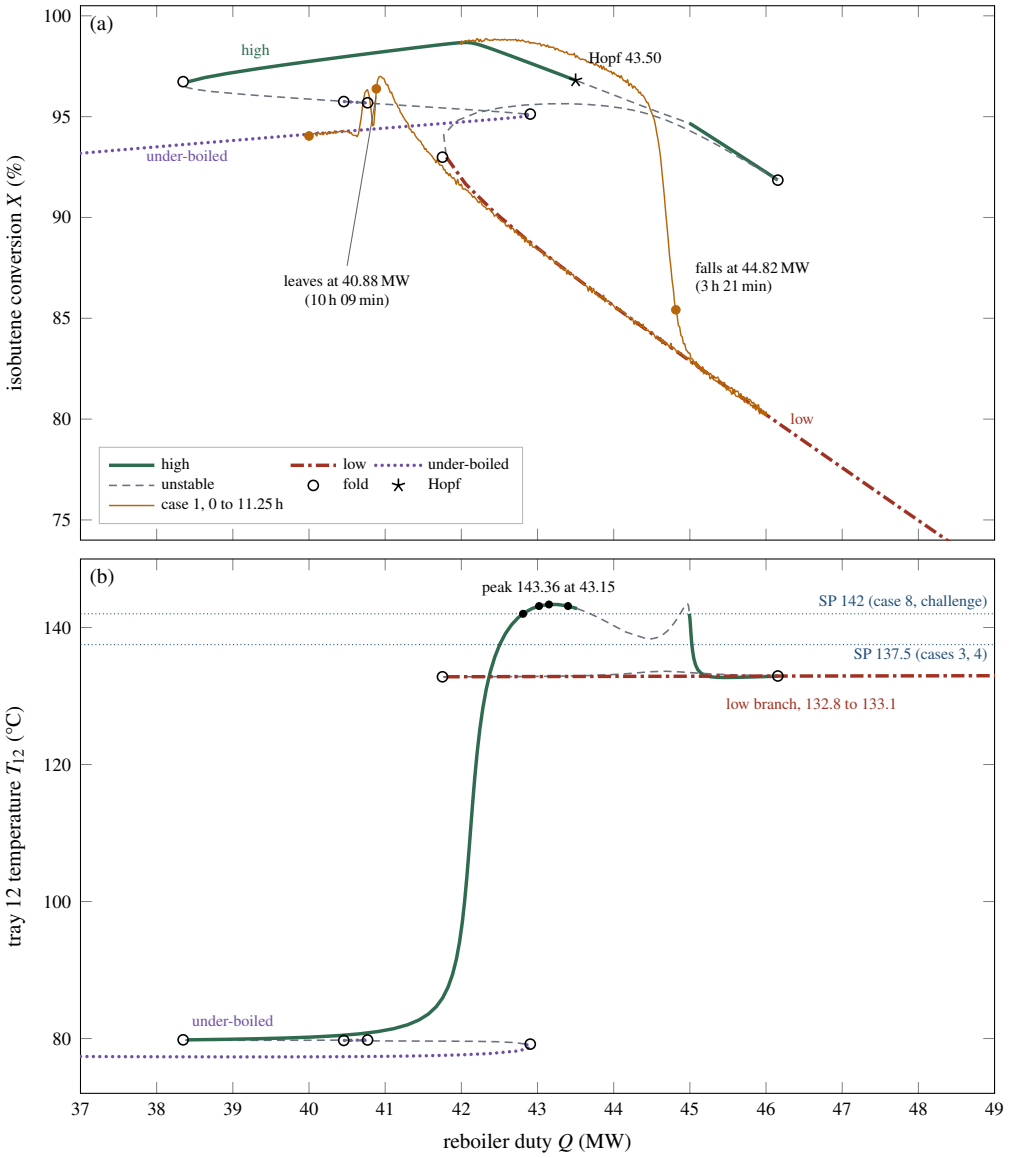


Figure 9.2 The S-curve at the published feeds from the application's own continuation. (a) Conversion against duty, stable branches heavy (high solid, low dash-dotted, under-boiled dotted), unstable states thin dashed, folds circled, the Hopf point starred, and the plant's path in case 1 from 42 MW up to 46 MW and down to 40 MW at 1 MW per hour, with the two jumps and the state at 11.25 h marked. (b) Tray 12 against duty on the same branches, with the two setpoints the cases use and the two duties at which tray 12 reads 143.13 °C on the high branch.

9.4.4 One Temperature at Two Duties

The stripping trays carry the temperature a loop can hold. On the high branch tray 12 rises with the duty from the C4's 75 °C toward the ether's 153 °C at 11 bar, peaks at 143.36 °C at 43.15 MW and falls after it, so 143.13 °C is read at both 43.02 and 43.4 MW, the input multiplicity of Figure 9.2b. On the low branch tray 12 holds methanol and MTBE and reads 132.81 to 133.07 °C at every duty from the fold to 56.17 MW, 133.10 at 58 and 133.13 °C at the reboiler's 60 MW. Tray 11 reads

128.87 to 130.43 °C there. A setpoint above that plateau cannot be reached on the low branch at all. The anti-lock brake of Volume 7, Chapter 4 holds its setpoint at the top of a friction curve, where the process gain passes through zero and reverses in the same way.

9.5 Loops as Implemented

9.5.1 The Tray-Temperature Loop and Its Helpers

Every loop runs the velocity-form PID law of Section 1.6.2, Equations (1.14) to (1.17), with its derivative term off and no output bias. The output is clamped after the sum, and the integral is pulled back toward the clamped value with a tracking time T_t equal to τ_I. The temperature loop (TIC) reads the thermowell of one stripping tray, 12 by default and 10 to 14 on offer, and sets the reboiler duty with action $a = +1$, because more duty heats the tray. In the convention of Section 1.6.2 that is a reverse-acting controller, although the app's text for case 8 calls it direct acting. Its defaults are $K_c = 0.15\,\mathrm{MW/K}$ and $\tau_I = 45\,\mathrm{min}$, it executes every $\Delta t = 0.1\,\mathrm{min}$, and its output runs from 0 to Q_{max}. Open loop at 42.5 MW, 0.2 MW more duty raises tray 12 by 3.42 K, two thirds of it in about 45 min. Integral action is off when τ_I reaches 600 min. In Manual the duty station is the operator's and the TIC tracks it, so a transfer in either direction is bumpless. When the control tray changes, a setpoint that sat within 1 K of the old tray's temperature moves to the new tray's, and any other is kept.

The level loops move the distillate and the bottoms with $a = -1$ (direct acting) at 40 kmol/h per percent and $\tau_I = 30\,\mathrm{min}$, the reflux follows as $L = RD$, and the methanol is set in ratio to the isobutene fed, $F_M = r_M F_{C4} z_{IB}$, with the measured C4 flow and the feed analyzer's isobutene or, as an option, the design 35.68 mol %. The optional bottoms trim (AIC) moves the TIC's setpoint by up to $\pm 15\,\mathrm{K}$ from the bottoms analyzer at 0.5 K per mol % and $\tau_I = 60\,\mathrm{min}$, executing on each report with the time since the last report as its control period. The analyzer is too slow to move the duty itself, which is why the TIC reads a tray, and Volume 5, Chapter 3 measures what such a delay costs a composition loop.

9.5.2 The Branch Monitor, the Supervisor and the Branch Names

The monitor reads catalytic tray 8 against a saddle temperature of 93 °C, between the high branch's 87.3 °C and the low branch's 100.0 °C. Five minutes above it reads LOW, and five minutes below it reads high again. With the supervisor on and the TIC in Auto, a LOW reading takes the duty from the TIC and cuts it to $f_{cut} = 0.9$ of the TIC's request, cuts it by 0.9 again after each hour the monitor still reads LOW, holds it until the monitor has read high for 30 min, and hands the duty back to the TIC, which has tracked it throughout. A path through methanol excess, duty and ratio was considered first. In a prototype a ratio cut left the column on the low branch for 10 h, so the supervisor cuts the duty instead.

A single cut lands below the low branch's fold at 41.75 MW only for a request under 46.4 MW, and two for one under 51.5 MW. Switched on at the start of case 4, at a duty of 42.50 MW, it cuts the TIC's first request, already raised by the proportional term, to 38.9 MW. The monitor reads high 13 min later and the column is on the high branch at 17 min. Switched on at 5 h, when the TIC asks for 47.79 MW, it cuts to 43.0 MW, above the fold, and an hour later to 38.7 MW, after which the monitor reads high at 6 h 14 min and the column is on the high branch at 6 h 18 min.

Three names for a branch appear in the application, and they are kept apart. The simulator's truth, used by the alarms, the challenge and the CSV, is low when the bottoms carry more than 6 mol % methanol and high otherwise. The readouts name the branch from the S-curve, low by the truth, otherwise the stable state at the plant's duty nearest it in conversion (high or under-boiled), with "past its stable end" and "between branches" when no such state exists, because the C4 in the bottoms cannot tell the high branch from the under-boiled one (the high branch carries 4.67 mol % C4 at 41 MW). The monitor is what an operator has and reads two states. The three can disagree. In case 5, 2 h after the methanol ratio is raised to 1.200, the bottoms carry 9.41 mol % methanol and 6.34 mol %

Table 9.5 The Nine Cases

#	Settings and events	Teaching point
1	Manual from 42 MW, ramp to 46 and back to 40 MW at 1 MW/h	hysteresis
2	Manual at 42.5 MW, learner moves to 41 MW	curve against plant
3	TIC on tray 12 at 137.5 °C, C4 feed +5 % at 1 h	the loop on the high branch
4	the same loop, started on the low branch	the loop on the low branch
5	Manual, learner raises the methanol ratio to 1.200	azeotrope, methanol down
6	Manual, C4 cut to 33 mol % isobutene at 1 h	a fold moves
7	Manual, two start-up charges	the path picks the branch
8	Manual at 43.4 MW, TIC setpoint 142 °C	input multiplicity
9	challenge, 8 h, C4 +5 % at 2 h, steam 85 % for 20 min at 5 h	the whole problem

C4, the truth and the readout say low, and the monitor still reads high with tray 8 at 75.3 °C, because the excess methanol reached the bottoms while the C4 was not stripped.

🕮 **Pause.** Try Exercise 9.3 before reading on.

9.5.3 Three Models

The plant is Section 9.3. The S-curve is a separate solution of its steady equations, read by the Branches view, the branch readout and the scenario texts. The controllers carry no process model. The monitor's saddle temperature and the supervisor's cut are the only places where knowledge of the branches enters the control system, and both are fixed numbers. The alarms, the specification of 98 mol % MTBE, the target of 95 % conversion, the reboiler's 60 MW and the distillate alarm at 7.0 mol % are teaching values. The real ones come from the unit's licensor, its steam system and the buyer's contract.

9.6 Nine Cases, Measured

Table 9.5 names the nine cases and Table 9.6 reads the app's own scorecard at the instant each is read. The cases, their completion rules and the challenge follow Section 1.6.4. Three cases carry most of the lesson. Case 1 draws the hysteresis loop before any controller is closed, case 4 shows a correct loop driving the column the wrong way, and case 7 shows that the start-up charge decides where the column lands. The measurements reported here were made headless at the default seed. The engine advanced through the same one-second physics steps as the page, each case was loaded through the page's own loading path, and every learner's move was applied at the time the text gives. Every case runs identically when loaded first, picked from the list after another case, or restarted with Reset.

9.6.1 A Hysteresis Loop on a Duty Ramp

Case 1 opens on the high branch at 42 MW, 98.67 % converted, and ramps the duty at 1 MW per hour from 30 min. The conversion eases to 95.53 % at 44.47 MW by 3 h, then falls, 92.29 at 44.63 MW and 85.76 % at 44.80 MW, and the column is on the low branch at 44.82 MW, 3 h 21 min into the run. On the way down it stays there, 82.82 % at 45.03 MW at 6 h, and it leaves at 40.88 MW at 10 h 9 min, so the two jumps are 3.93 MW apart. The ramp carries the column 1.3 MW past the Hopf point, because the oscillation that loses the high branch grows slowly, and 0.9 MW past the low branch's fold, as shown in Figure 9.2a and Figure 9.3. Both jumps are unchanged at half the step, and at seeds 1 to 3 the upward jump lies between 44.816 and 44.833 MW.

🕮 **Pause.** Try Exercise 9.1 before reading on.

Case 2 compares the plant with the curve. At 42.5 MW the curve lists under-boiled 94.9, high 98.2 and low 90.1 %. Moved to 41.00 MW, the plant holds within 0.1 percentage points of the solver's 98.230 % for 20 min by 87 min after the move, and its mean over the seventh hour is 98.220 %. The high branch at 41 MW reaches 4.71 mol % C4 in its bottoms by 7 h, and C4 IN BOTTOMS lights 53 min after the move and OFF SPEC 72 min after it. High conversion and an on-specification product are different things on this column.

Table 9.6 The Application's Scorecard Tiles at the Instants Each Case Is Read

Case	Settings and instant	Duty (MW)	Conversion (%)	Branch tile	Bottoms MTBE (mol %)	Control tray (°C)	Also
1	as shipped, 3 h	44.47	95.5	high (past end)	99.90	138.5	
1	as shipped, 3 h 21 min	44.82	85.4	low	93.79	132.9	monitor LOW
1	as shipped, 6 h	45.03	82.8	low	75.26	132.9	methanol 24.74 mol %
1	as shipped, 10 h 9 min	40.88	96.4	high	94.20	132.6	
1	as shipped, 11 h 15 min	40.00	94.0	under-boiled	85.89	77.4	C4 11.73 mol %
2	41 MW from 10 min, 7 h	41.00	98.3	high	95.29	81.2	C4 4.71 mol %
3	Auto, 8 h	44.75	98.1	high	99.94	137.4	
3	Manual, 8 h	42.50	97.8	high	92.93	80.4	C4 7.07 mol %
4	Auto, 5 h	47.76	75.6	low	69.58	132.9	monitor LOW
4	cut to 40 MW at 2 h, 8 h	40.00	94.1	under-boiled	84.55	77.3	C4 13.86 mol %
5	ratio 1.200 from 30 min, 2.5 h	42.50	94.8	low	84.25	77.3	monitor high
5	1.200 at 30, 1.100 at 50 min, 6.83 h	42.50	94.9	under-boiled	92.67	77.8	C4 6.94 mol %
6	fixed duty, 3 h	42.50	93.5	under-boiled	82.78	76.7	C4 16.55 mol %
6	44 MW from 91 min, 7.52 h	44.00	98.4	high	96.59	81.4	C4 3.41 mol %
7	C4 start-up, 2 h	42.50	98.8	high	99.75	112.5	
7	methanol start-up, 2 h	42.50	89.9	low	83.12	132.8	methanol 16.88 mol %
8	Auto, SP 142 °C, 8 h	42.81	97.8	high	99.96	141.9	
8	Auto, SP 143.5 °C, 6 h	54.97	57.7	low	53.21	133.3	



Figure 9.3 The hysteresis loop of case 1 at $t = 11.25$ h on the Branches view, in Manual, light theme, cropped to the plot, its status chips and its alarm strip. (1) The high branch, green (the same branches carry line styles in Figure 9.2a), with the six folds circled and the unstable states dashed. (2) The low branch, red. (3) The plant's path in amber, its chevrons pointing up the high branch, down onto the low branch at 44.82 MW, back along it and off it at 40.88 MW. (4) The plant at 40.00 MW on the under-boiled branch, violet, 94.0 % converted with 85.89 mol % MTBE and 11.73 mol % C4 in the bottoms. (5) The readout, with the curve's under-boiled 94.1 % and high 97.7 % at that duty.

TRY IT IN THE APP **1 · Ramp the duty up and back down**

Load the scenario, open the Branches view and press Run. Watch the plant's amber dot against the S-curve: it drops to the low branch at 44.82 MW on the way up and leaves it only at 40.88 MW on the way down.

9.6.2 One Loop, Two Branches

Case 3 runs the TIC on tray 12 at 137.5 °C and raises the C4 feed 5 % at 1 h. The loop takes the duty from 42.5 to 44.76 MW within the hour, tray 12 dips to 128.8 °C and is back within 1 K from 3 h 22 min, and the bottoms never fall below 99.90 mol %. On the fixed duty tray 12 falls to 80.4 °C and the bottoms to 92.93 mol % MTBE with 7.07 mol % C4, while the conversion hardly moves (97.83 against 98.09 % with the loop). The reaction section does not see the feed step, and the stripping section does.

Case 4 starts the same loop on the low branch, where tray 12 reads 132.8 °C, below its setpoint. The loop raises the duty past 45 MW at 2 h and to 47.76 MW at 5 h, tray 12 stays at 132.8 to 132.9 °C, and the conversion falls from 90.0 to 75.6 %. No duty on the low branch reaches 137.5 °C, which makes this the honest infeasible case of the set. Cut to 40 MW in Manual at 2 h, below the low branch's fold, the column leaves it, the monitor reading high 24 min later and the truth 27 min later, and it settles on the under-boiled branch.

Pause. Try Exercise 9.2 before reading on.

Case 8 starts on the high branch at 43.4 MW, past tray 12's peak, where the tray reads 143.13 °C. Switched to Auto at 142 °C, the loop cuts the duty, and the tray first gets hotter, 143.20 °C at 1 h and 143.35 °C at most, as the column climbs back over the peak. It then cools, and the TIC holds 142 °C at 42.81 MW on the rising side, within 0.5 K for 30 min by 2 h 57 min. At a setpoint of 143.5 °C, above the peak, the loop raises the duty, the tray cools, and the column falls onto the low branch 1 h 36 min in with the duty still climbing, 48.77 MW at 3 h and 54.97 MW at 6 h. Across seeds 0 to 3, and with the step halved, the holding run meets its rule between 2 h 57 min and 3 h 19 min, and the lost run falls between 1 h 36 min and 1 h 44 min.

> **TRY IT IN THE APP** **8 · One tray temperature, two duties**
>
> Load the scenario and switch the header to Auto. The loop cuts the duty, yet tray 12 first warms, to 143.35 °C at most, before it settles at 142 °C with 42.81 MW. Reload with the circular arrow, set the tray temperature setpoint to 143.5 °C and switch to Auto again. Now the loop raises the duty and the column falls to the low branch 1 h 36 min in.

9.6.3 Methanol, the Feed and the Start-Up

Case 5 raises the methanol ratio from 1.100 to 1.200 at 30 min. The distillate passes its alarm 3 min later and sits at the azeotrope, 7.63 mol % methanol, and the rest falls, past 3 mol % of the bottoms 20 min after the move. Left at 1.200, the column is on the low branch 2 h after the move. Put back to 1.100 at 50 min, the methanol leaves the bottoms within 55 min, but 6 h later the column is on the under-boiled branch, 94.90 % converted with 6.94 mol % C4, at the duty and ratio it started from. With the TIC in Auto the same excess takes the duty to 49.08 MW and the conversion to 72.11 % 5 h after the move.

Case 6 turns the C4 cut leaner, 33 mol % isobutene, at 1 h. The feed analyzer reports it and the methanol ratio uses it 20.1 min later. On the new curve the under-boiled branch reaches up to 43.47 MW, the high branch begins at 38.77 MW and the low branch at 44.95 MW, so 42.5 MW lies inside the under-boiled range. C4 in the bottoms passes 5 mol % at 1 h 31 min, and on the fixed duty it reaches 16.55 mol % by 3 h. Raised to 44 MW then, past the new fold, the column is above 98 % converted 97 min later and at 98.40 % after 6 h, with 3.41 mol % C4 still in the bottoms. The conversion dips to 84.2 % in the minute rows about 9 min after the feed change. The dip is physical rather than numerical, since it reappears at a quarter of the step (84.17 %) and at seeds 1 to 3 (82.81 to 84.01 %).

Case 7 refills every tray at 42.5 MW. Charged with the C4 cut, the column is on the high branch at 2 h, 98.8 % converted with 99.75 mol % MTBE in the bottoms. Charged with methanol, the resin wetted first, it is on the low branch at 2 h, 89.9 % converted with 16.88 mol % methanol in the bottoms, and it stays there. The case was first planned with the methanol-rich path landing high. The model

Table 9.7 The Challenge Over 8 h, Default Seed

Settings	Low x_B (mol %)	Low X (%)	Low branch	Verdict
tray 12, 142 °C (shipped)	67.58	73.0	from 6 h 32	fails
tray 11, 120 °C, supervisor (suggested)	99.70	97.2	never	passes
tray 11, 120 °C, no supervisor	99.70	97.2	never	passes
tray 12, 142 °C, supervisor	97.18	92.4	never	fails
tray 12, 137.5 °C	99.64	97.3	never	passes

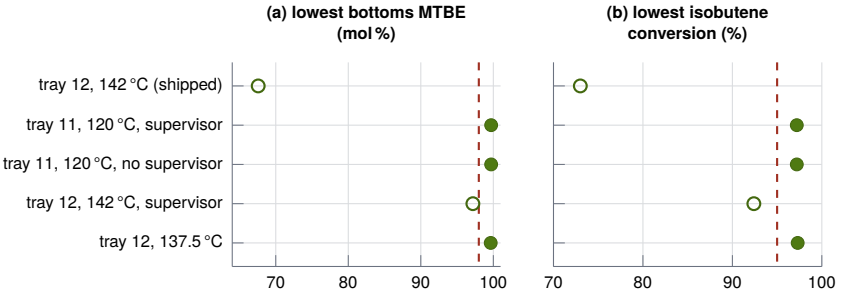


Figure 9.4 The challenge of Table 9.7 as a chart: (a) the lowest bottoms MTBE of each setting against the 98 mol % specification and (b) the lowest conversion against the 95 % target, both dashed. Filled dots pass and open dots fail. Notice that the supervisor keeps tray 12 at 142 °C off the low branch but still short of both lines, while the same loop at 137.5 °C, and tray 11 at 120 °C with or without the supervisor, clear both.

lands it low, and the case teaches what the model shows. At half, a quarter and a tenth of the step the methanol start-up lands on the same state.

> ✦ **DID YOU KNOW? Two Start-Ups, Two Columns**
>
> From the simulator: at the same 42.50 MW, feeds and reflux ratio, the column charged with the C4 cut is 98.8 % converted after 2 h, with 99.75 mol % MTBE in its bottoms. Charged with methanol it is 89.9 % converted, with 16.88 mol % methanol in its bottoms (Table 9.6).

9.6.4 The Challenge

The challenge runs 8 h under the TIC with tray 12 at 142 °C and no supervisor. The C4 feed rises 5 % at 2 h and the steam dips to 85 % for 20 min at 5 h. It passes when, at every 10 min sample of the true column from 30 min, the column is on the high branch with at least 98 mol % MTBE in the bottoms and at least 95 % converted. As shipped the column holds through the feed step, but after the steam dip the loop's catch-up overshoots tray 12's peak and the column falls to the low branch at 6 h 32 min. The loop then raises the duty to 51.2 MW by 8 h, and the bottoms fall to 67.58 mol %. The settings tried are listed in Table 9.7, and Figure 9.4 draws them as a chart.

The shipped setting fails on its margin, not on its tuning. Tray 12 peaks at 143.36 °C on the high branch, 1.4 K above the 142 °C setpoint, and the same gains on the same tray at the default 137.5 °C pass with 99.64 mol % and 97.3 % at their lowest. The suggested settings move the loop to tray 11 at 120 °C, which the high branch reaches and which lies below the low branch's 128.87 to 130.43 °C on that tray, so a loop on the low branch cuts the duty and returns the column by itself. They pass at the default seed as well as seeds 1 through 6, with 99.70 to 99.71 mol % and 97.2 to 97.3 % at their lowest, and pass at half the step. The supervisor never acts in a suggested run. With tray 12 at 142 °C the supervisor cuts the duty to 43.3 MW at 6 h 22 min and keeps the column off the low branch, but not on specification. No cut fraction from 0.7 to 0.98 passes on that setting. The shipped run fails at

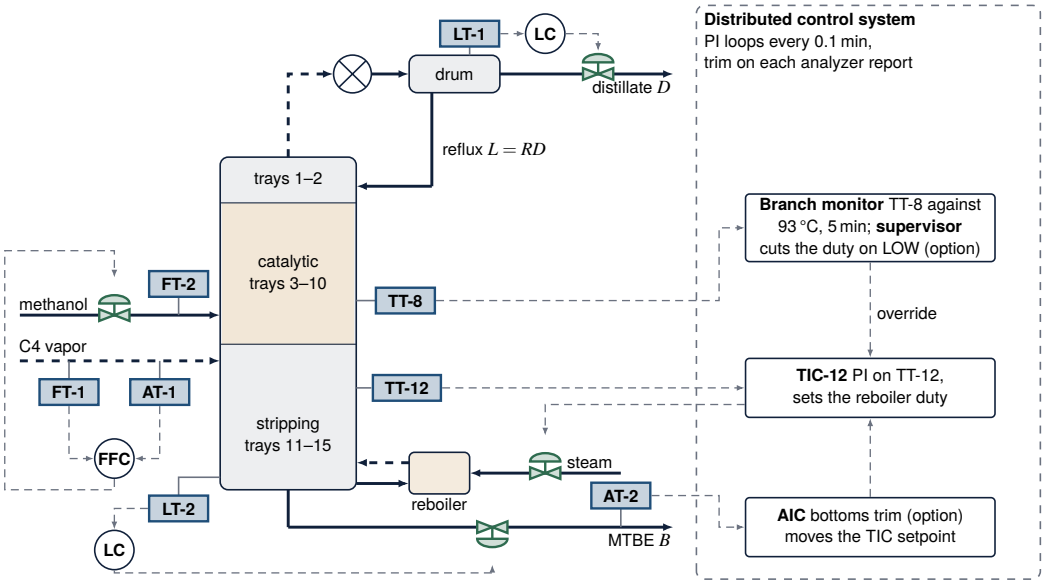


Figure 9.5 The loops of the MTBE column with their hardware. Lettered boxes are sensing devices: the thermowells on trays 8 and 12 (TT), the C4 flow meter (FT-1) and feed analyzer (AT-1), the methanol flow meter (FT-2), the bottoms analyzer (AT-2) and the two level transmitters, whose level controllers (LC) and the methanol ratio station (FFC) are drawn beside their devices. Valve symbols are final elements, thick dashed lines carry vapor and thin dashed arrows are signals. Notice that the temperature loop moves the steam valve on the reboiler, that the branch monitor reads a catalytic tray rather than the control tray, and that the methanol follows the C4 that is measured, not the C4 that is wanted. The distillate analyzer and the alarms are left out. Not to scale, and not a piping diagram.

seeds 1 to 6 as well, its lowest bottoms between 67.66 and 67.75 mol %. The scored samples begin to read low at 6 h 40 min, the first 10 min sample after the fall.

9.7 Technology in Practice

What Measures It

Figure 9.5 draws the loops of Section 9.5 with their devices. The temperature loop and the branch monitor read tray thermowells, modeled with a 0.5 min lag and 0.05 K of noise. They hold thermocouples or resistance thermometers (Chapter 4 and Chapter 8), and transmitters close together on a column can disagree where the flow patterns differ [19]. The methanol ratio, which decides the branch, rests on two flow meters and the feed analyzer.

TECHNOLOGY Sensor: A Coriolis Meter on the Methanol Feed

A Coriolis meter shakes one or more tubes that carry the fluid at their resonant frequency. The frequency reads the density, and the twist that the moving fluid adds, seen as a phase shift between two points on the tube, is proportional to the mass flow. The meter is very accurate but costly, has difficulty with gases and with mixed liquid and vapor, and errs when outside vibration reaches its tubes or gas bubbles collect in its bent ones [19]. Under a flow loop a meter that reads low makes the valve deliver more methanol than the ratio asks for, the excess of case 5. The model's flow meters lag 0.05 min with 0.2 % noise.

What Moves It

The reboiler duty is the temperature loop's handle, and in a plant it is the steam to the reboiler. The methanol, the distillate and the bottoms are liquid flows behind control valves, and the reflux follows the distillate in the ratio $L = RD$. In the model each of these flows follows its setpoint through a 0.2 min lag.

TECHNOLOGY Final Element: The Steam Valve on the Reboiler

A temperature loop on a heat exchanger usually throttles the heating steam with a control valve and leaves the process flow to the rest of the plant. An air-to-open steam valve closes as its signal falls, and that choice sets the controller's action. If the steam system fails, integral action drives the valve wide open in vain, and when the steam returns the saturated output sends too much and the temperature overshoots, unless the operator switches the loop to manual and brings the output down [19]. The model lumps valve and reboiler into a duty that follows the request times the steam available with a 2 min lag. Its challenge dips the steam to 85 % for 20 min, and the loop's catch-up then overshoots tray 12's peak.

Where the Controller Runs

A distributed control system runs nested and cascaded loops under a supervisory level, with cycle times from milliseconds to minutes [20]. The app executes its temperature and level loops every 0.1 min and its trim on each analyzer report, every 10 min, inside that range. The PI blocks, the ratio station and the trim belong to the regulatory layer. The branch monitor and the supervisor's duty cut are logic above it that overrides the temperature loop's output, and the loop's tracking of that output is what an industrial controller calls output tracking, which lets a loop pick up from a value it did not set [19].

IN PRACTICE One Temperature Loop to Hold the Profile

A column is first stabilized by its level and pressure loops. Without composition control its profile behaves almost like an unstable system that must be watched continuously, a heavy burden on the operators, so at least one composition loop is closed, for example on the boilup. The operator then tends to overpurify the uncontrolled product, which costs energy and capacity. A tutorial on column control recommends at least three temperature sensors in each section, so that pressure changes can be corrected and fast temperatures can feed a cascade or estimate the product compositions, and a reboiler that can change the boilup fast [21]. The tray-12 loop on the duty is this one-point control.

What Is Modernizing It

Model predictive control has a solid foundation in refining and petrochemicals [22]. For distillation a tutorial of 1997 noted that the cost of a dynamic model and of tuning had kept industry from a predictive controller on all five handles of a column, and that a first-principles model is probably better than an identified one [21]. The supervisor that knows where the fold lies, which the Conclusion names as a next addition, would rest on such a model. Soft sensors that estimate compositions from tray temperatures have distillation as their main target, and keeping their models up to date is the most critical issue their users report [23]. Reactive dividing-wall columns, which put the reaction of

this chapter inside the column of Chapter 8, promise further energy savings and are discussed as an open challenge after the limitations.

9.8 Limitations

The column's shape, feeds and pressure come from a published base case and its properties and kinetics from read sources, but the catalyst mass, the rate term ε and the latent heat are teaching values on which the fold duties depend, so the duties at which this column jumps are not predictions for a real one. The trays are equilibrium stages with constant molar overflow, the reaction has no mass-transfer resistance, the inert has isobutene's volatility, and no side reaction or energy balance per tray is modeled. The Wilson parameters are fitted values read at second hand, in the reading that gives the azeotropes the sources describe rather than the one printed.

The controllers carry no model and the supervisor's path is one declared move, where a real one would come from the unit's procedures. The monitor reads one tray and two states, and case 5 shows it reading high while methanol has reached the bottoms. Within a walk step of a fold the readout can name the wrong family (at 38.40 MW a plant still at 96.7 % reads under-boiled), a state no case reaches. On the low branch at high duty some fractions leave $[0, 1]$ by less than the step-splitting tolerance (cases 4 and 8 at 143.5 °C late in their runs). The disturbances arrive as steps. A C4 cut that turns leaner in one step is not how a real feed changes, but it separates the fold's movement from the loop's response.

> **OPEN CHALLENGE** **A Reactive Column Behind a Dividing Wall**
>
> Putting the reaction of this chapter inside the dividing-wall column of Chapter 8 promises 15 to 75 percent less energy. By 2018, however, experiments covered only five chemical systems, the models were uncertain, and complex control such as model predictive control had not been demonstrated on such a column. Progress would be experimental and pilot-plant studies with dynamic and rate-based models checked against them [9].

9.9 Conclusion

An MTBE column of fifteen trays, built on the series' shared stage stack with a Wilson activity model and an activity-based rate, has at 42.5 MW a high state converting 98.22 %, a low state converting 90.05 % with the methanol below the catalyst, and an under-boiled state converting 94.89 %. A solver that shares only the thermodynamics with the plant finds six folds from 38.35 to 46.15 MW and a Hopf point at 43.50 MW, and the plant lines out on its states within 0.007 percentage points in the comparisons of Table 9.4. Ramped at 1 MW per hour the column jumps at 44.82 and 40.88 MW. A tray-12 loop that holds the high branch through a feed step raises the duty to 47.76 MW on the low branch, where tray 12 never passes 133.13 °C, and a setpoint 1.4 K under the high branch's peak loses the challenge where tray 11 at 120 °C passes at seven seeds. The fold duties rest on three teaching values. The next additions to the model would be a rate-based tray model, side reactions, an energy balance per tray and a supervisor that knows where the fold lies. The simulator shows that a correct loop on a correct measurement can still drive a column away from the state it was tuned for.

KEY POINTS

- With the same feeds, reflux and duty, the column has three steady states.
- At 42.5 MW the high, low and under-boiled states convert 98.22, 90.05 and 94.89 %. Ramped at 1 MW per hour, the column jumps at 44.82 and 40.88 MW.
- On the low branch tray 12 never passes 133.13 °C, and the tray-12 loop raises the duty to 47.76 MW.
- Tray 12 at 142 °C loses the challenge on its margin, not its tuning.

Where else this applies. Tray 12's peak returns in Volume 7, Chapter 4 and Volume 2, Chapter 9.

References

[1] E. W. Jacobsen and S. Skogestad, "Multiple steady states in ideal two-product distillation," *AIChE Journal*, vol. 37, no. 4, pp. 499–511, 1991.

[2] L. B. Koppel, "Input multiplicities in nonlinear, multivariable control systems," *AIChE Journal*, vol. 28, no. 6, pp. 935–945, 1982.

[3] A. Kienle and W. Marquardt, "Nonlinear dynamics and control of reactive distillation processes," in *Reactive Distillation: Status and Future Directions*, K. Sundmacher and A. Kienle, Eds. Wiley, 2002, pp. 241–281.

[4] T. E. Güttinger and M. Morari, "Predicting multiple steady states in equilibrium reactive distillation. 2. Analysis of hybrid systems," *Industrial & Engineering Chemistry Research*, vol. 38, no. 4, pp. 1649–1665, 1999.

[5] K.-D. Mohl, A. Kienle, E.-D. Gilles, P. Rapmund, K. Sundmacher, and U. Hoffmann, "Steady-state multiplicities in reactive distillation columns for the production of fuel ethers MTBE and TAME: theoretical analysis and experimental verification," *Chemical Engineering Science*, vol. 54, no. 8, pp. 1029–1043, 1999.

[6] G. M. Wilson, "Vapor-liquid equilibrium. XI. A new expression for the excess free energy of mixing," *Journal of the American Chemical Society*, vol. 86, no. 2, pp. 127–130, 1964.

[7] A. Rehfinger and U. Hoffmann, "Kinetics of methyl tertiary butyl ether liquid phase synthesis catalyzed by ion exchange resin—I. Intrinsic rate expression in liquid phase activities," *Chemical Engineering Science*, vol. 45, no. 6, pp. 1605–1617, 1990.

[8] Z. Nawaz, "Methyl-tert-butyl-ether synthesis reactor modelling and optimization using an Aspen Custom Modeler," *Hungarian Journal of Industry and Chemistry*, vol. 45, no. 2, pp. 1–7, 2017.

[9] A. A. Kiss and M. Jobson, "Taking reactive distillation to the next level of process intensification," *Chemical Engineering Transactions*, vol. 69, pp. 553–558, 2018.

[10] G. J. Harmsen, "Reactive distillation: The front-runner of industrial process intensification," *Chemical Engineering and Processing: Process Intensification*, vol. 46, no. 9, pp. 774–780, 2007.

[11] R. Jacobs and R. Krishna, "Multiple solutions in reactive distillation for methyl tert-butyl ether synthesis," *Industrial & Engineering Chemistry Research*, vol. 32, no. 8, pp. 1706–1709, 1993.

[12] S. Hauan, T. Hertzberg, and K. M. Lien, "Why methyl tert-butyl ether production by reactive distillation may yield multiple solutions," *Industrial & Engineering Chemistry Research*, vol. 34, no. 3, pp. 987–991, 1995.

[13] A. P. Higler, R. Taylor, and R. Krishna, "Nonequilibrium modelling of reactive distillation: Multiple steady states in MTBE synthesis," *Chemical Engineering Science*, vol. 54, no. 10, pp. 1389–1395, 1999.

[14] S. Schrans, S. de Wolf, and R. Baur, "Dynamic simulation of reactive distillation: An MTBE case study," *Computers & Chemical Engineering*, vol. 20, pp. S1619–S1624, 1996.

[15] A. D. Estrada-Villagrana, "On the modeling of dynamics and operation of reactive distillation," Ph.D. dissertation, University of London (University College London), 2002. [Online]. Available: https://discovery.ucl.ac.uk/id/eprint/1317706/

[16] M. G. Sneesby, M. O. Tade, and T. N. Smith, "Two-point control of a reactive distillation column for composition and conversion," *Journal of Process Control*, vol. 9, no. 1, pp. 19–31, 1999.

[17] W. L. Luyben and C.-C. Yu, "Control of MTBE and ETBE reactive distillation columns," in *Reactive Distillation Design and Control*. Wiley, 2008, pp. 407–427.

[18] D. Porcelli, "Comparative techno-economic assessment between reactive and reactive-cyclic distillation for process intensification: theoretical framework and application to MTBE and MeOAc reactive distillation," Master's thesis, Politecnico di Milano, 2021. [Online]. Available: http://hdl.handle.net/10589/182157

[19] T. R. Kuphaldt, *Lessons in Industrial Instrumentation*, version 2.33 ed. Open textbook, Creative Commons Attribution 4.0 license, ibiblio.org/kuphaldt/socratic/sinst, 2024.

[20] K. Stouffer, M. Pease, C. Tang, T. Zimmerman, V. Pillitteri, S. Lightman, A. Hahn, S. Saravia, A. Sherule, and M. Thompson, "Guide to operational technology (OT) security," National Institute of Standards and Technology, Gaithersburg, MD, Special Publication 800-82r3, 2023.

[21] S. Skogestad, "Dynamics and control of distillation columns: A tutorial introduction," *Chemical Engineering Research and Design (Transactions of the Institution of Chemical Engineers, Part A)*, vol. 75, no. 6, pp. 539–562, 1997.

[22] S. J. Qin and T. A. Badgwell, "A survey of industrial model predictive control technology," *Control Engineering Practice*, vol. 11, no. 7, pp. 733–764, 2003.

[23] M. Kano and K. Fujiwara, "Virtual sensing technology in process industries: Trends and challenges revealed by recent industrial applications," *Journal of Chemical Engineering of Japan*, vol. 46, no. 1, pp. 1–17, 2013.

9.10 Exercises

9.1 Concept check · 2 min

In case 1 the duty ramps up at 1 MW per hour, and the column falls to the low branch at 44.82 MW. The S-curve says the high branch turns unstable at its Hopf point, 43.50 MW. Why does the fall come 1.3 MW later than the curve suggests?

(a) The reboiler responds with a 2 min lag, so the plant sees an older and lower duty
(b) The branch is lost through an oscillation that grows slowly, and the ramp outruns its growth
(c) The solver holds the tray holdups constant, which puts its Hopf point about a megawatt too low
(d) The low branch does not exist below 44.82 MW, so the column has no other state to go to

9.2 Concept check · 1 min

In case 4 the TIC holds tray 12 at a setpoint of 137.5 °C, and the column starts on the low branch with tray 12 at 132.8 °C. By 5 h the loop has raised the duty from 42.5 to 47.76 MW while tray 12 stays at 132.8 to 132.9 °C. Why?

(a) The integral has wound up against the reboiler's 60 MW limit and cannot come back
(b) The tray's gain to the duty is negative on the low branch, so the loop is in positive feedback
(c) On the low branch tray 12 holds methanol and MTBE near 133 °C at any duty
(d) The thermowell's 0.5 min lag hides the duty's effect from a loop that runs every 6 s

9.3 Concept check · 2 min

In case 5 the methanol ratio is raised to 1.200 at 30 min and left there. Two hours later the bottoms carry 9.41 mol % methanol and 6.34 mol % C4. The truth flag reads low, while the branch monitor still reads high with tray 8 at 75.3 °C. Which explains the disagreement?

(a) The monitor waits 5 min above its saddle before it reads LOW, and that time has not passed
(b) The truth flag is misled by the azeotrope, which carries the methanol out with the distillate
(c) The saddle temperature of 93 °C is set too high for a column fed at a ratio of 1.200
(d) Tray 8 stays near the C4's temperature because the C4 is not stripped, while methanol still falls

9.4 Theory and calculation · 6 min

The column runs at the design point, 42.5 MW, with a latent heat $\lambda = 20\,\mathrm{kJ/mol}$ and a heat of reaction $\Delta H_r = -37.7\,\mathrm{kJ/mol}$. It is fed 1976.4 kmol/h of C4 cut at 35.68 mol % isobutene, and the high branch makes 693 kmol/h of MTBE.

(a) Use Equation (9.2) to find the boilup V_B in kmol/h and the moles of vapor ν_V boiled by each mole of MTBE. *Checkpoint:* 7650 kmol/h and 1.885.

(b) Find the vapor the reaction adds in the catalytic section, and the reboiler duty that would boil the same amount. *Checkpoint:* 1306 kmol/h, the vapor of 7.26 MW.

(c) At the same duty the low branch converts 90.05 % of the isobutene and the high branch 98.22 %. How much less vapor does the reaction make on the low branch, in kmol/h and as reboiler duty? *Checkpoint:* 108.6 kmol/h less, the vapor of 0.60 MW.

9.5 Theory and calculation · 6 min

The rate of Equation (9.5) uses the equilibrium constant $K_{350} = 28.5$ with $\Delta H_r = -37.7\,\mathrm{kJ/mol}$ and $R = 8.314\,\mathrm{J/(mol\,K)}$, and the term $\varepsilon = 0.05$ in its denominator.

(a) Find K at 25 °C and at 100 °C. *Checkpoint:* 271.2 and 12.76.

(b) Write the denominator $(a_M + \varepsilon)^2$ as $\varepsilon^2(1 + K_{ads}a_M)^2$ and give K_{ads} and the factor by which the rate constant is scaled. *Checkpoint:* $K_{ads} = 20$, scaled by 400.

(c) Find the ratio of the rate to its $\varepsilon \to 0$ form, $a_M^2/(a_M+\varepsilon)^2$, at methanol activities of 0.11 and 0.44, for $\varepsilon = 0.05$ and for $\varepsilon = 0.02$. Give two decimals. *Checkpoint:* 0.47 and 0.81 at $\varepsilon = 0.05$, 0.72 and 0.91 at $\varepsilon = 0.02$.

9.6 Theory and calculation · 6 min

The supervisor cuts the duty to $f_{cut} = 0.9$ of the TIC's request when the monitor reads LOW, and again to 0.9 of the held value after each hour it still reads LOW. At the published feeds the low branch begins at its fold at 41.75 MW and the high branch at its fold at 38.35 MW.

(a) Find the largest request that one cut brings below 41.75 MW, and the largest that two cuts bring below it. *Checkpoint:* 46.39 MW and 51.54 MW.

(b) In case 4 the supervisor is switched on at 5 h, when the TIC asks for 47.79 MW. Find the duty after the first cut and after the second. Say for each whether the low branch and the high branch exist there. *Checkpoint:* 43.01 MW, where both exist, then 38.71 MW, where only the high branch of the two does.

(c) The cut is set to 0.80 instead. Find the duty after one cut from the same request, and the range of requests that one cut at 0.80 brings between the two folds. *Checkpoint:* 38.23 MW, below both folds. Requests from 47.94 to 52.19 MW.

9.7 App challenge · 8 min

Load scenario 1, Ramp the duty up and back down, and change no setting. With the default seed, run to 11 h 15 min (at the top speed of 120 min per second this takes about 6 s) and export the CSV file. Its time column is in hours, one row per minute.

(a) Find the first row in which the column `truth_branch` reads low. Give its time and the duty in `duty_MW`, within 0.02 MW. *Checkpoint:* 3.35 h (3 h 21 min) and 44.82 MW.

(b) Find the first later row in which `truth_branch` reads high again, its duty, and the width of the hysteresis loop. *Checkpoint:* 10.15 h (10 h 9 min), 40.88 MW, a loop 3.93 MW wide.

(c) The S-curve ends the high branch at its Hopf point, 43.50 MW, and the low branch at its fold, 41.75 MW. By how much does the ramp pass each before the column jumps? *Checkpoint:* 1.32 MW and 0.87 MW.

9.8 App challenge · 9 min

Load scenario 8, One tray temperature, two duties. The column starts on the high branch in Manual at 43.4 MW, with the tray temperature setpoint at 142.0 °C. Use the default seed and export the CSV file after each run.

(a) Switch the header to Auto before pressing Run, and run to 8 h. Read the highest value of `truth_T12_C` in the file, within 0.05 K, and the duty `duty_MW` at 8 h, within 0.02 MW. *Checkpoint:* 143.35 °C, 27 min in, and 42.81 MW.

(b) Press the reload button, set the Tray temperature setpoint to 143.5 °C, switch to Auto and run to 6 h. Find the first row in which `truth_branch` reads low, and read the duty at 3 h and at 6 h, within 0.05 MW. *Checkpoint:* 1.60 h (1 h 36 min), then 48.77 and 54.97 MW.

(c) Use Figure 9.2b to explain both runs. *Checkpoint:* One side of the tray-12 peak has a positive gain, the other a negative one, and 143.5 °C is above the peak.

9.9 App challenge · 10 min

Load the challenge, eight hours on the high branch. A C4 feed step comes at 2 h and a steam dip at 5 h, and the run stops itself at 8 h. Use the default seed. After each run, read the three So far tiles (on the low branch, lowest bottoms MTBE, lowest conversion) and the verdict.

(a) Run as shipped, with tray 12 at 142.0 °C and the supervisor off. *Checkpoint:* Low branch from 6 h 40 min, lowest bottoms 67.58 mol % MTBE, lowest conversion 73.0 %. Fails.

(b) In the TIC card choose Control tray 11, then set the Tray temperature setpoint to 120.0 °C. Leave the supervisor off, press Reset and run again. *Checkpoint:* Never on the low branch, 99.70 mol %, 97.2 %. Passes.

(c) Choose Control tray 12, then set the setpoint to 137.5 °C, press Reset and run again. What do the three runs say about the cause of the shipped failure? *Checkpoint:* Never on the low branch, 99.64 mol %, 97.3 %. Passes.

9.10 Application area · 4 min

The methanol ratio station computes the isobutene fed from the measured C4 flow and either the feed analyzer or the design 35.68 mol %. The analyzer samples every 10 min through a 1 min sample line and reports a cycle later.

(a) After a step in the isobutene of the C4 cut, what is the longest the station can run on the old value with the analyzer? *Checkpoint:* About 21 min. Case 6 measured 20.1 min.

(b) With the design fraction instead, the C4 cut turns to 33 mol % isobutene as in case 6. What methanol ratio does the column then receive at the shipped setting of 1.100? Compare it with case 5. *Checkpoint:* 1.189, close to the 1.200 that put methanol in the bottoms in case 5.

9.11 Application area · 4 min

An operations engineer proposes to copy the simulator's numbers into the procedure of a real MTBE column: "Keep the reboiler below 43.5 MW. If the conversion drops, cut the duty below 41.75 MW and wait."

(a) Which model values set these duties, and how far do the folds move when they change? *Checkpoint:* Catalyst mass, ε and λ. The folds move by megawatts.

(b) What would you watch on the real column instead of a duty to know that the high branch is near its end, and that the column has left it? *Checkpoint:* Tray 12's temperature levelling off as the duty rises, and the catalytic tray 8 temperature.

9.12 Review the agent · 5 min

An AI assistant reviews the failed challenge run and replies: "The column holds through the feed step and is lost after the steam dip, when the loop catches up too hard and overshoots. The setpoint of 142 °C is fine, since it is below the 143.36 °C peak. Halve the TIC gain to 0.075 MW/K and double the integral time to 90 min, and the column will pass." Find the flaw and say how you would check it in the app.