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CHAPTER 8

Selective Amine Sweetening With Delayed Analysis and Loading Protection

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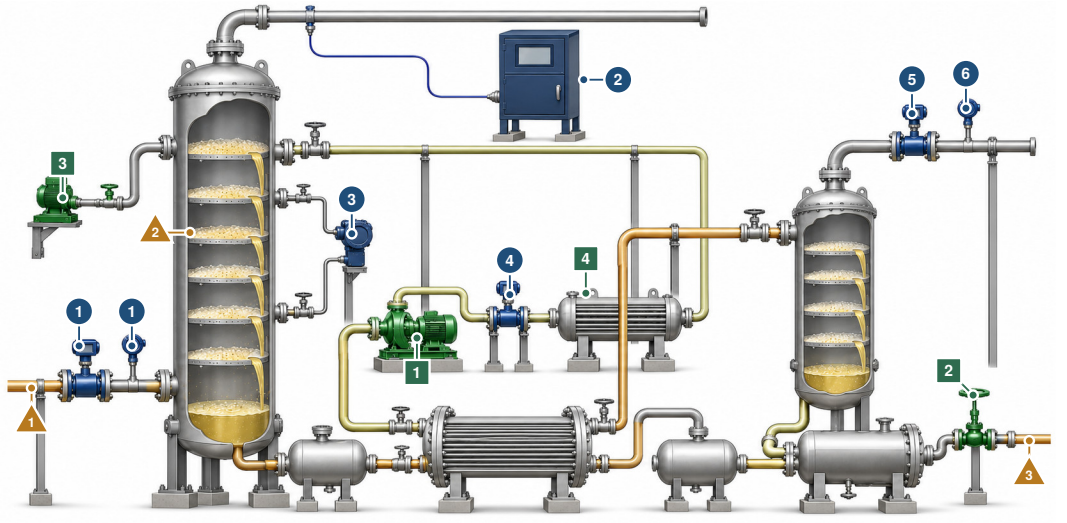
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CHAPTER 8

Selective Amine Sweetening With Delayed Analysis and Loading Protection



The controller moves 1 lean amine pump, the circulation 2 reboiler steam valve 3 antifoam injection 4 lean amine cooler

The controller reads 1 sour gas flow and temperature 2 hydrogen sulfide left in the sweet gas, minutes late 3 pressure drop across the absorber 4 lean amine flow 5 acid gas flow, which gives the loading 6 regenerator overhead temperature

What disturbs it 1 more gas, warmer gas or a sourer well 2 a hydrocarbon slug that makes foam 3 a dip in the steam supply

Notice the long sample line from the sweet gas to the analyzer cabinet, and the lean amine's road from the reboiler through the surge drum, the exchanger, the pump and the cooler back to the absorber's top. Illustration, not to scale.

IN PLAIN TERMS Washing a Sour Gas Out of Natural Gas

The main idea. Some natural gas carries hydrogen sulfide, a sour gas that buyers allow only in tiny traces. In a tall tower the gas rises through a falling liquid called amine that soaks it up. A column heated by steam then boils the sour gas out, so the liquid can be used again.

The challenge. The instrument that checks the cleaned gas reports each sample minutes after that gas has left. And the liquid can be loaded so full that it eats the plant's steel while the cleaned gas still passes its test.

Why it matters. A plant has to protect both the gas it sells and its own equipment, and each needs a different instrument.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	This page, the Did you know? box at the end of the Introduction, the two History boxes in Section 8.2, the Try it boxes and the second Did you know? box in Section 8.5, and Key points at the end of the Conclusion. No equations.
Study	40 min	The whole chapter in order, stopping at the three pause points, then Exercises 1 to 12.
Practice	15 min	This page, Section 8.5 with Figure 8.3, Section 8.6 and Section 8.7 with its Open challenge box.

The control question A sweetener must keep hydrogen sulfide in the sales gas under 4 ppm, but its analyzer reports each sample minutes after the gas has gone, and a cap on the rich amine loading protects the plant where that analyzer cannot see. Which measurement can protect which limit, and what does each defense cost in steam?

Learning objectives

- Explain why hydrogen sulfide approaches stage equilibrium in MDEA while carbon dioxide uptake follows the liquid holdup, and predict what a holdup change does to each.
- Compute the ratio circulation and the loading floor from the gas meter, the laboratory composition and the acid-gas meter.
- Predict when a sampled, delayed analyzer first reports an exceedance, and bound that delay.
- Show from runs that the rich loading can pass its cap while the sweet gas stays on specification, and choose the instrument that protects each limit.
- Compare the defenses of the twelve-hour challenge by the limit each holds and the steam each costs.

Prerequisites Sections 1.4.7 (absorption), 1.4.8 (the high selector), 1.4.9 (late and inferred measurements), 1.6.2 (the framework's PI) and 1.6.4 (the apps). Section 1.6.3 is needed only for the predictive option. Chapter 7 treats the same structures on one solute.

The app https://apmonitor.com/apps/amine-sweetening/

See also Volume 5, Chapter 3 for composition control through a slow analyzer, and Volume 5, Chapter 10 for a quality and a constraint that are both inferred. Volume 4, Chapter 2 for a protective override that rests at its clamp in healthy operation, and Volume 4, Chapter 6 for a safety limit that bounds throughput. Volume 9, Chapter 10 for a slow quality trim on a setpoint loop, priced in energy.



8.1 Introduction

A gas sweetener can meet its product specification while damaging its solvent circuit. In the teaching unit considered here, an increase in feed hydrogen sulfide at 30 min takes the rich amine over 0.5 mol/mol at 38.5 min, yet the sweet gas stays below 3.43 ppm of H_2S, inside a 4 ppm limit. Conversely, cutting the pump from 64 to 50 m^3/h sends the true gas over 4 ppm at 13.8 min, while the analyzer first reports it at 24.7 min. A feedback loop cannot respond to a measurement before the sample exists. A loading limit therefore needs a different instrument and a different action from a sales-gas limit.

The distinction is especially useful for a tertiary amine. Reaction kinetics reported for tertiary amines put carbon dioxide on a slower pathway than hydrogen sulfide [1, 2], and selective absorption measurements with aqueous methyldiethanolamine (MDEA) show why residence and interfacial transfer matter [3, 4]. Equilibrium models of acid gas in aqueous amines provide a more detailed basis for real design [5, 6]. The simulator of this chapter compresses that chemistry to six liquid stages and a teaching correlation. It lets the reader test which change buys carbon dioxide pickup, which preserves the H_2S specification, and which merely consumes steam.

The control problem is one of unequal information and timescales. Gas flow is metered in seconds, the sweet-gas analyzer samples every 10 min, the rich loading inference filters an acid-gas meter for 12 min, and the solvent takes tens of minutes to return from the regenerator. Ratio feedforward, analyzer feedback and a loading override consequently protect different parts of the same unit. Model predictive control (MPC), a recognized industrial approach [7], extends that comparison to constrained operation. The reaction chemistry, the equilibrium form, the PI loops and the optimizer are all established methods, applied here to one teaching unit. Section 1.4.9 places this unit among the plants of the volume whose binding limit is measured late or only inferred.

This chapter measures how selective absorption, delayed analysis, loading protection and steam availability interact in a reproducible MDEA sweetener, through nine cases that make those interactions visible. Section 8.2 places the simplified chemistry beside published equilibrium and rate work. Section 8.3 specifies the absorber stages, the regenerator, the solvent return path and the foam

state. Section 8.4 gives the measurements and the control laws: the PI loops, the gas ratio, the loading floor, the analyzer trim and the predictive option. Section 8.5 reports the nine cases, from a manual circulation cut to the twelve-hour graded shift. Section 8.6 sets the hardware of a real sweetener beside the model, Section 8.7 states what the synthetic model cannot predict, and Section 8.8 summarizes which measurement protects which limit.

> ✦ DID YOU KNOW? **Where the Hydrogen Sulfide Goes**
>
> In 2024 the United States produced an estimated 8.2 million metric tons of elemental sulfur, recovered at petroleum refineries, natural gas processing plants and coking plants, 81 plants in 25 states [8]. The acid gas a sweetener's regenerator sends toward a Claus unit is the gas plants' share, and Volume 11, Chapter 13 follows it there.

8.2 Selective Treating and Its Modeling History

An aqueous amine absorbs acid gases from natural gas and releases them when heated at lower pressure. Section 1.4.7 gives the single-solute absorber and its Kremser relation. Here two solutes share one solvent. Hydrogen sulfide, carbon dioxide and water interact with the amine differently, so a prediction based on one fixed removal fraction does not transfer from a lean, cool contactor to a loaded, warm one. The 1981 equilibrium model of Deshmukh and Mather represented both H_2S and CO_2 solubility in aqueous alkanolamines [5]. The later electrolyte-NRTL treatment of Austgen and coauthors gave another equilibrium framework for acid-gas amine systems [6]. Neither result makes a six-stage teaching absorber a plant-design model, but both establish that the two solutes share a solvent and influence its equilibrium.

> ⧖ HISTORY **1930: A Solvent That Gives the Gas Back**
>
> On 7 October 1930 Robert Roger Bottoms applied for a patent on separating acidic gases, chiefly carbon dioxide, sulfur dioxide and hydrogen sulfide, from industrial gas mixtures. The usual alkaline carbonates held little gas for their volume. He had found that a small group of amines unite with acidic gases at a low temperature and give them up as gas at a higher temperature, regenerated, while their own vapor pressure stays low. The absorbent could therefore circulate continuously in a closed cycle between a cool absorption stage and a hot regeneration stage, with heat interchangers to save heat, and he preferred triethanolamine for its higher boiling point [9]. Amine scrubbing has separated carbon dioxide from natural gas and hydrogen ever since [10].

The rate distinction was investigated separately, first for carbon dioxide and tertiary amines, as the second History box below tells. A rate-based 2004 model treated selective H_2S absorption and desorption in aqueous MDEA [4], while a separate 2004 study measured selective absorption of H_2S from mixed H_2S-CO_2 gas into MDEA and another amine [3]. Those works motivate keeping an explicit carbon-dioxide rate in the absorber rather than multiplying both gases by the same removal efficiency.

> ⧖ HISTORY **1988 and 1990: The Slow Path of Carbon Dioxide**
>
> In 1988 Versteeg and van Swaaij absorbed carbon dioxide into aqueous MDEA and two other tertiary alkanolamines through a liquid surface that looked completely smooth, in a stirred vessel, and inferred the reaction rate from the enhanced mass transfer. The reaction fitted a base-catalysis mechanism proposed earlier, and a Brønsted relation tied the logarithm of its rate constant to the strength of the amine as a base [1]. In 1990 Littel, van Swaaij and Versteeg measured three tertiary amines from 293 to 333 K, found the reaction first order in the amine, and traced the mechanism to Donaldson and Nguyen. They argued that most earlier work had overstated the part played by hydroxide ions, which are depleted near the gas-liquid interface [2].

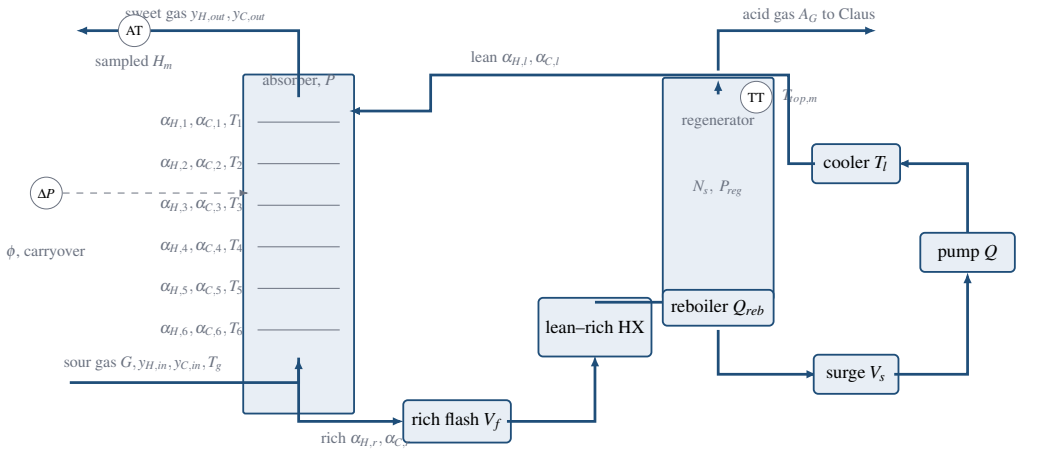


Figure 8.1 The simulated absorber and amine loop. Six absorber liquid stages carry H_2S and CO_2 loadings $\alpha_{H,n}$ and $\alpha_{C,n}$ and temperature T_n. Gas flow G, composition $y_{j,in}$ and temperature T_g enter below. Circulation Q returns lean solvent through the cooler. The rich flash, exchanger, regenerator and surge tank impose the return path seen by analyzer trim. AT reports a sampled and delayed H_2S value H_m, while the differential-pressure measurement catches foam. The diagram describes a teaching process model, not a piping design.

Published equilibrium data can also test the shape of a compact correlation without pretending to validate a complete plant. A 2020 patent tabulates H_2S partial pressures of 10, 30 and 100 kPa at loadings 0.21, 0.40 and 0.69 mol/mol for 50 wt% MDEA at 40 °C [11]. After the simulator's concentration factor is scaled from 45 to 50 wt%, its three values are 9.78, 31.34 and 98.17 kPa, errors of -2.23, $+4.46$ and -1.83%. This comparison tests three points on one solute's equilibrium curve. It does not check mixed-gas kinetics, hydraulic behavior, metal corrosion or the size of any dynamic upset.

The controller structures follow a common industrial progression. A fixed solvent rate is easy to operate but cannot follow a flow step. A measured gas-flow ratio acts before product analysis, while a product analyzer supplies a slower correction. A loading floor and a differential-pressure antifoam trigger add protection for limits the analyzer does not measure. PID tuning may be related to model reduction [12] and internal-model-control design [13], but the three loops here are shipped as declared teaching tunings. Chapter 7 applies the same progression of ratio feedforward, analyzer trim and economic MPC to a single solute. An economic MPC uses the same measurement packet to trade steam and pump work against predicted quality and loading constraints [7, 14, 15].

8.3 Unit, States and Constitutive Relations

Figure 8.1 follows the Unit view. Sour gas at 60 t/h, 60 bar absolute, 35 °C, 2 mol% H_2S and 4 mol% CO_2 rises through six lumped stages. The lean stream contains 45 wt% MDEA at a design flow of 64 m^3/h. Rich solvent leaves the absorber bottom, enters a flash drum and a lean–rich exchanger, then feeds a four-theoretical-stage stripping section over a reboiler. The acid gas overhead goes toward a Claus unit. A 40 m^3 surge tank, pump and cooler return lean solvent to the absorber top.

The model clock is minutes. Gas flow is converted from tonnes per hour to kmol per minute using the inlet mixture molecular weight, and the solvent's amine concentration is $c_A = \rho w_A / M_A = 3.92749\,\mathrm{kmol/m^3}$ with $\rho = 1040\,\mathrm{kg/m^3}$, $w_A = 0.45$ and $M_A = 119.16\,\mathrm{kg/kmol}$. Table 8.1 separates variables a learner may set from states and observations. Table 8.2 lists the full plant defaults and which are visible to the learner.

Table 8.1 Principal Variables at the Design Point

Quantity	Role	Initial	Range or test
G	disturbance, metered	60 t/h	30–90 t/h
$y_{H,in}$, $y_{C,in}$	disturbances	2, 4 mol%	0.5–5, 0–10 mol%
Q	manipulated, measured	64 m^3/h	0–110 m^3/h
$T_{top,SP}$	manipulated	106 °C	98–112 °C
H_m	controlled, delayed	2.64 ppm	4 ppm ceiling
α_r	state, displayed	0.42965	0.5 mol/mol cap
Q_{reb}	state, metered	4654 kW	6000 kW capacity
ϕ	state, foam index	0.45	1 carry threshold
V_s	state, surge volume	40 m^3	decreases on carry, pump starved below 0.5 m^3
ΔP	measured	120 mbar	1.3× clean alarm

8.3.1 Equilibrium, Transfer and the Six Stage Balances

The teaching equilibrium pressure of solute $j \in \{H, C\}$ over a stage is

$$
\begin{aligned}
p_j^{*} &= K_j \frac{\alpha_j \alpha_t}{1-\alpha_t} \exp(-b\alpha_t) \exp(\theta_j), \\
\theta_j &= \frac{\Delta H_j}{R}\left(\frac{1}{313.15} - \frac{1}{T+273.15}\right), \qquad \alpha_t = \alpha_H + \alpha_C .
\end{aligned}
\tag{8.1}
$$

The implementation floors $1-\alpha_t$ at 0.02 during excursions and nonnegative loadings at zero. At 40 °C, $K_H = 245$ kPa, $K_C = 100$ kPa and $b = 2.1$. The heats are 40 MJ/kmol for H_2S and 55 MJ/kmol for CO_2. The 40 °C curve has an approximately quadratic low-loading slope, then rises as free amine is exhausted. All four constants and the nonideality term are fitted teaching choices, rather than a regression supplied by the equilibrium papers.

For stage n, counted from the top, the incoming gas is from $n+1$. The model takes H_2S a fraction $E_H = 0.95$ toward equilibrium at each contacted stage, while CO_2 depends on an effective rate k_C and the liquid amine inventory:

$$
\begin{aligned}
N_{H,n} &= G_{n+1} E_H^{eff} \left(y_{H,n+1} - p_{H,n}^{*}/P\right), \\
K_{C,n} &= k_C c_A V_L (1-\alpha_{t,n}) f_c \\
&\quad \times \exp\left[-\frac{E_a}{R}\left(\frac{1}{T_n+273.15} - \frac{1}{313.15}\right)\right], \\
E_{C,n} &= \frac{K_{C,n} P}{G_{n+1} + K_{C,n} P}, \\
N_{C,n} &= G_{n+1} E_{C,n} \left(y_{C,n+1} - p_{C,n}^{*}/P\right), \\
G_n &= G_{n+1} - N_{H,n} - N_{C,n}, \\
y_{j,n} &= \frac{G_{n+1} y_{j,n+1} - N_{j,n}}{G_n}.
\end{aligned}
\tag{8.2}
$$

Here P is in kPa, N and G in kmol/min, $k_C = 10^{-4}\,(\text{min kPa})^{-1}$, $E_a = 30$ MJ/kmol, $V_L = 1.2$ m^3 per lumped stage, and $f_c = 1/(1+0.8\max(\phi-1,0))$ is foam's contact factor. Foam scales E_H by the same f_c. The top $6 - N_{contact}$ stages are dry if the learner lowers the feed point, so both rates there are zero. The gas contracts as it loses solute and has no separate holdup.

The stage loadings integrate the liquid counterflow and the transfers, while one thermal state per

stage forms the bulge:

$$\begin{aligned} c_A V_L \dot{\alpha}_{j,n} &= F_n(\alpha_{j,n-1} - \alpha_{j,n}) + N_{j,n}, \\ C_n \dot{T}_n &= \frac{Q_n \rho c_{p,L}}{60}(T_{n-1} - T_n) + G_{kg} c_{p,G}(T_{n+1} - T_n) \\ &\quad + \Delta H_H N_{H,n} + \Delta H_C N_{C,n}. \end{aligned} \tag{8.3}$$

F_n is kmol/min of circulating amine, Q_n is $\mathrm{m^3/h}$, $C_n = V_L \rho c_{p,L} C_{stage}$, $c_{p,L} = 3.6\,\mathrm{kJ/(kg\,K)}$, $c_{p,G} = 2.5\,\mathrm{kJ/(kg\,K)}$ and $C_{stage} = 1.3$. The top incoming liquid is lean solvent and the bottom incoming gas is the sour feed. At design $T_1 = 43.93\,^\circ\mathrm{C}$, $T_5 = 59.22\,^\circ\mathrm{C}$ and $T_6 = 55.01\,^\circ\mathrm{C}$. The gas and cold lean solvent cool the ends while absorption heats the lower interior.

8.3.2 Regenerator, Return Path and Foam

The rich flash drum of $10\,\mathrm{m^3}$ and exchanger line of $3\,\mathrm{m^3}$ each mix the loadings toward the stream arriving from the absorber at rate $F_r/(c_A V)$, and flash-drum temperature follows rich temperature at $Q_r/(60 V_f)$. At 1.9 bar absolute the reboiler temperature is the IAPWS-IF97 saturation temperature [16] plus a declared 3 K boiling-point elevation. A lean–rich exchanger of effectiveness 0.8 preheats the rich stream. The stripping section uses a four-stage Kremser fraction for each solute, the stripping counterpart of Equation (1.12):

$$\begin{aligned} V_b &= \frac{60 \max(0, Q_{reb} - Q_{loss})}{\lambda}, \quad S_j = \beta_j \frac{V_b}{F_r}, \\ f_j &= \frac{S_j - 1}{S_j^{N_s+1} - 1}, \quad \alpha_{j,out} = f_j \alpha_{j,feed}. \end{aligned} \tag{8.4}$$

The $S_j = 1$ limit is $1/(N_s + 1)$. In the implementation $Q_{loss} = 100\,\mathrm{kW}$, $\lambda = 39\,700\,\mathrm{kJ/kmol}$, $N_s = 4$, $\beta_H = 1.9$ and $\beta_C = 2.3$. A sensible-heat demand on the rich liquid and desorption heats reduce the steam left for the overhead. The overhead temperature target is the water dew point at water partial pressure $y_W P_{reg}$, with a teaching floor 15 K below the hot rich feed. Its state follows this target with a 2 min lag. The two rich-side loadings in the $8\,\mathrm{m^3}$ reboiler sump, two loadings in the $40\,\mathrm{m^3}$ surge tank and two in the $2.5\,\mathrm{m^3}$ lean line each obey a well-mixed flow balance. The lean cooler target is $T_{hot} - 0.9 u_c (T_{hot} - T_{cw})$, with 30 °C cooling water, filtered over 2 min. Pump flow and duty follow their commands with 0.2 and 1 min lags.

The foam state ϕ moves toward a load- and contamination-dependent target in 0.25 min. Hydrocarbon in the solvent grows if the lean amine is below the gas dew point, taken here as T_g, and drains with a 45 min time constant. Antifoam reaches the trays over 1 min and decays in 90 min. The clean pressure drop is $120(G/60)^2$ mbar. The foam correction raises it by $(1 + 0.8\phi^2)/(1 + 0.8(0.45)^2)$, while solvent carryover is $12 \max(\phi - 1, 0)^{1.5}\ \mathrm{m^3/h}$. The sweet-gas scrubber drains at $1.5\,\mathrm{m^3/h}$ and stops the run when its $1\,\mathrm{m^3}$ capacity fills. A separate stop follows 60 min continuously above rich loading 0.5. Neither stop is a certified equipment-protection prediction.

8.3.3 Initialization, Numerics and Scope

Each case starts from a steady solution for its own disturbances, circulation, overhead setpoint and lean temperature. The solver closes the lean solvent around the absorber, flash, exchanger, regenerator, sump, surge tank and cooler, then initializes every first-order state at its target. The integrated state has 18 absorber quantities, four foam and antifoam quantities, seven rich-side quantities, six lean-side quantities, pump flow, duty, overhead temperature and scrubber volume, plus ten boundary ledgers. The levers are clamped to their declared ranges after each step. The engine of Section 1.6.1 integrates with a classical fourth-order Runge–Kutta method in 1 s steps, while control runs every 5 s. The full disturbed-run ledger in the application tests closes H_2S and CO_2 to relative error below 10^{-10} and solvent volume below $10^{-9}\,\mathrm{m^3}$. Repeating the 31-seed challenge at 0.5 s retains every verdict.

Table 8.2 All Plant Parameter Defaults. V is visible on the parameter panel and H is hidden from the learner. Values are generic teaching choices, and the software uses the variable names shown.

Key	Value	Unit		Key	Value	Unit	
P	60	bar	V	tauQ	1	min	H
G0	60	t/h	H	tauTop	2	min	H
MWhc	17	kg/kmol	H	Qloss	100	kW	H
cpG	2.5	kJ/(kg K)	H	Vsurge0	40	m^3	V
VL	1.2	m^3	V	Vlean	2.5	m^3	H
EH	0.95		V	Tcw	30	°C	H
kC	10^{-4}	1/(min kPa)	V	epsC	0.9		H
EaC	30000	kJ/kmol	H	tauCool	2	min	H
Cstage	1.3		H	Q0	64	m^3/h	H
wMDEA	0.45		H	QpMax	110	m^3/h	V
rho	1040	kg/m^3	H	tauP	0.2	min	H
cpL	3.6	kJ/(kg K)	H	foamTend	1		V
KH	245	kPa	V	phi0	0.45		H
bAct	2.1		H	kHC	3		H
KC	100	kPa	H	tauHC	45	min	V
dHH	40000	kJ/kmol	H	kCond	0.006	per K min	H
dHC	55000	kJ/kmol	H	kAF	4		V
Vflash	10	m^3	V	tauAFin	1	min	H
Vexch	3	m^3	H	tauAF	90	min	H
Vreg	8	m^3	V	tauFoam	0.25	min	H
eps	0.8		H	Cf	12	m^3/h	V
Preg	1.9	bar	H	kEf	0.8		H
bpe	3	K	H	dp0	120	mbar	H
lamW	39700	kJ/kmol	H	Vscrub	1	m^3	V
Ns	4		V	scrubDrain	1.5	m^3/h	H
betaH	1.9		V	capLoad	0.5	mol/mol	V
betaC	2.3		H	capHold	60	min	V
QrebMax	6000	kW	V	dTapp	5	K	H
Vsuct	0.5	m^3	H				

The gas has no dynamic holdup. Six liquid cells stand for a many-tray absorber, and the gas-film efficiency and CO_2 uptake are teaching closures. Regeneration is quasi-steady in its stripping section and uses a simplified Kremser expression. Foam, corrosion and hydrocarbon condensation are phenomenological limits chosen to make a process-control lesson. There is no validated hydraulic prediction, corrosion-rate law, electrolyte species balance, absorber flooding map or Claus chemistry. The purpose of the states is to expose delay, selectivity and competing limits while keeping the mass transfers internally consistent.

8.3.4 State Transport and Boundary Ledgers

The generic solvent holdup equation makes the lags in Figure 8.1 explicit. For either gas j, a well-mixed rich-side vessel of volume V and flow Q_r obeys $V\dot{\alpha}_j = (Q_r/60)(\alpha_{j,in} - \alpha_j)$. The flash drum and exchanger use $V = 10$ and $3\,m^3$ in series. The regenerator sump uses $8\,m^3$ and the stripped outlet of Equation (8.4) as its incoming loading. The surge tank receives the sump outlet, and the lean line receives the surge outlet. Its loadings therefore satisfy

$$\begin{aligned} V_s\dot{\alpha}_{j,s} &= (Q_r/60)(\alpha_{j,r} - \alpha_{j,s}),\\ V_{lean}\dot{\alpha}_{j,l} &= (Q/60)(\alpha_{j,s} - \alpha_{j,l}),\\ \dot{V}_s &= (Q_r - Q)/60. \end{aligned} \tag{8.5}$$

Carryover makes $Q_r < Q$, so the surge volume falls. The pump draws on the tank, and over its last $V_{suct} = 0.5\,m^3$ it loses suction: the delivered flow is $Q = Q_p \min(1, V_s/V_{suct})$ for a pump flow Q_p, and the carryover cannot exceed Q. A drained tank therefore starves the circulation until the foam no longer carries solvent over, and its outflow then equals its inflow. The stage loop in Equation (8.3) receives $\alpha_{j,l}$ and closes the acid-gas balance. The rich flash temperature approaches the absorber-bottom temperature at rate $Q_r/(60V_f)$. The reboiler sump and surge loadings react to a duty change separately, so an overhead temperature move can precede an improvement in the gas by tens of minutes.

The regenerator heat closure accounts for water boil-up, rich-liquid sensible heating and desorption:

$$\begin{aligned} D_j &= F_r(\alpha_{j,feed} - \alpha_{j,out}), \quad A_G = D_H + D_C, \\ q_{sens} &= (Q_r/60)\rho c_{p,L}(T_{reb} - T_{rich,hot}), \\ q_{des} &= \Delta H_H D_H + \Delta H_C D_C, \\ S_{ov} &= \max[0, V_b - (q_{sens} + q_{des})/\lambda], \\ y_W &= S_{ov}/(S_{ov} + A_G). \end{aligned} \tag{8.6}$$

The last ratio is zero when its denominator vanishes. The overhead target is the greater of the water saturation temperature at $y_W P_{reg}$ and $T_{rich,hot} - 15\,\mathrm{K}$. A first-order 2 min state follows it. Gas absorption heat appears in each stage balance and solvent sensible heat in the regenerator duty. Heating supplied by the steam header is accumulated in an energy ledger. The ledgers integrate inlet H_2S and CO_2, gas outlet, acid-gas outlet and carryover with the same numerical step as their stage states. Thus their residuals reveal lost material if a transport or closure term is edited. They are diagnostic states, not additional equipment inventories.

A compact foam state connects the approach violation to the pressure measurement. With hydrocarbon contamination h_c, antifoam at the trays a_f and inlet gas at its assumed hydrocarbon dew point, the implementation uses

$$\begin{aligned} \dot{h}_c &= 0.006\max(T_g - T_l, 0)G/G_0 - h_c/45, \\ \phi^* &= 0.45\frac{(1+3h_c)}{(1+4a_f)}(G/G_0)^2\sqrt{Q/Q_0}, \\ 0.25\dot{\phi} &= \phi^* - \phi. \end{aligned} \tag{8.7}$$

The hydrocarbon source is zero if lean amine is warmer than sour gas. A manual or automatic antifoam shot first enters a one-minute delivery state, then the tray state decays in 90 min. These time constants and coefficients are teaching settings. They express a fast pressure response and a slow contamination inventory without representing a measured emulsion chemistry.

8.4 Measurements and Control

The simulated plant contains the true concentrations and temperatures, but a controller receives only a measurement packet. At each 5 s execution, gas flow has a 6 s lag and 0.2% multiplicative noise. Sour gas temperature, lean temperature, regenerator overhead and absorber differential pressure have 0.5, 0.3, 0.3 and 0.03 min lags. The acid-gas meter has a 0.5 min lag and 1% noise, while circulation has 0.3% noise. The sweet-gas analyzer samples every 10 min, spends 4.5 min in analysis and 0.5 min in its sample line, then reports with 0.05 ppm noise. A value displayed between reports is the last reported sample, not the current true gas. The true sample is retained separately to grade the challenge.

8.4.1 Fixed Flow, Gas Ratio and Loading Floor

In Auto, the circulation base command is either a fixed setpoint, a feedforward ratio or the MPC's command. The ratio uses measured gas flow G_m and the last laboratory feed composition $y_{H,lab}, y_{C,lab}$, not the current feed assay:

$$Q_{base} = \begin{cases} Q_{SP}, & \text{Fixed}, \\ 1000 r G_m(y_{H,lab} + y_{C,lab})/(M_{mix} c_A), & \text{Ratio}, \\ Q_{MPC}, & \text{MPC}. \end{cases} \tag{8.8}$$

The implemented load calculation converts G_m from t/h to kmol/h before multiplying by composition, and $r = 1.29$ mol MDEA per mol acid gas at design. The rich loading inference filters the measured

acid-gas molar flow A_m and circulation separately with $\tau = 12$ min. It adds an assumed lean loading of 0.004 mol/mol. For Fixed and Ratio only, the inferred loading produces a max-selected flow floor, the high-selector shape of Section 1.4.8:

$$\begin{aligned} \hat{\alpha}_r &= 0.004 + \frac{\bar{A}_m}{c_A \max(1, \bar{Q}_m)}, \\ Q_{floor} &= \frac{\bar{A}_m}{c_A \max(0.05, \alpha_{lim} - 0.004)}, \\ Q^* &= \min(110, \max(Q_{base}, Q_{floor})). \end{aligned} \tag{8.9}$$

The floor is active only when its switch is On. The pump follows Q^* with a 0.2 min time constant. A sourer well whose new composition has not reached the laboratory changes A_m after the absorber, so the floor supplies information the flow-only ratio lacks. The loading cap of 0.5 is a teaching corrosion guard. The learner may set the floor below it, at a default 0.45 and 0.42 in the suggested challenge.

8.4.2 Temperature, Analyzer and Antifoam Loops

The regenerator overhead temperature is held by the steam valve with the framework's velocity-form PI controller of Section 1.6.2 [12, 13]. Its proportional gain is 4% of valve per kelvin, integral time 6 min, and valve bounds 0–100%. A second PI holds lean amine at $T_g + 5$ K or at a fixed temperature by increasing cooler opening when the amine is too warm. Its gain is 3% per kelvin and integral time 4 min. Both use back-calculation with a tracking interval equal to each integral setting. Derivative time is zero. In Manual the three stations follow the operator's pump, steam and cooler commands and the inactive integrals track those commands, so the subsequent Auto transfer has no command jump.

The optional analyzer PI changes the regenerator temperature setpoint only on a new report, a cascade onto the temperature loop. It is reverse acting in the sense that measured H_2S above the 3 ppm target raises the temperature setpoint, with 1.5 K/ppm gain and 40 min integral time. The trim itself is bounded from -4 to $+6$ K and the resulting setpoint from 98 to 112 °C. It can therefore lower steam use during periods of ample quality margin. A differential-pressure ratio above 1.3 times clean triggers one antifoam shot in Auto, with at least 5 min between shots. These comparisons use filtered measured pressure, not the true foam state.

8.4.3 Two-Input Predictive Option

The MPC executes every 5 min. Section 1.6.3 describes the general setup, and this paragraph gives what is specific to this unit. It uses the controller's own copy of the steady absorber and regenerator map $m(Q, T_{SP}) = [\ln H, \alpha_r, Q_{reb}]$, updated with measured gas flow and the laboratory composition. The map is linearized about the current internal states by a 2 m^3/h circulation perturbation and a 0.5 K temperature perturbation. Three lags represent circulation to the sweet gas (5 min), overhead temperature (4 min) and the sump–surge–lean return, whose time constant is $\max[5, 60(V_r + V_s + V_{lean})/Q_m]$ min. The analyzer bias is corrected against the model state at the time the reported sample left the absorber, with a 0.3 update fraction. The loading bias takes the same fraction of the measured inference residual.

The quadratic program predicts 36 five-minute steps over three hours in move blocks spanning 1, 1, 2, 4, 8 and 20 prediction steps. It minimizes the linearized steam and pump duty plus moves while penalizing upper-limit slack on $\ln H$ and α_r. Pump work is estimated from 60 bar and 70% efficiency. The H_2S prediction limit is the learner's 4 ppm setting minus the declared 1 ppm margin, and rich loading is bounded by the lesser of the loading setpoint and the 0.5 cap. Circulation is bounded 30–110 m^3/h, setpoint 98–112 °C, and each move by 10 m^3/h and 1 K. When the steam valve has been wide open for 2 min, the temperature move is held and the map uses measured available duty. If the quadratic program fails or proposes a nonfinite or out-of-bounds move, the last bounded pair is retained until the next execution. This is a local control model, not the plant's six-stage dynamic

Table 8.3 Case Sequence and Main Student Action

No.	Event	Action or comparison
1	pump 64 to 50 m^3/h at 10 min	restore manually before stop
2	gas +20% at 30 min	Ratio then Fixed and Reset
3	gas warms 35 to 40 °C	enable analyzer trim
4	liquid holdup at 50–200%	compare H_2S and CO_2 profiles
5	feed H_2S 2 to 2.6%	engage loading floor
6	hydrocarbon slug at 30 min	enable antifoam on ΔP
7	lean setpoint 40 to 30 °C	restore gas-plus-approach
8	steam availability to 60%	trace delayed lean loading
9	sour well, slug, steam dip	meet 12 h scorecard

Table 8.4 Measured Landmarks in the Shipped Cases. The time column names the first relevant threshold or recovery, not an estimated settling time.

Case	Intervention or comparison	Time (min)	Engine observation
1	cut circulation to 50 m^3/h at 10	13.8 true, 24.7 report	true H_2S crosses 4 ppm, then the analyzer reports it
2	20% more gas on Ratio / Fixed	41.2 true on Fixed	2.66 / 5.04 ppm true peak
3	turn analyzer trim On at 75	154.7 analyzer recovery	report returns below 4 ppm after 79.7 min
4	double tray holdup at 10	120 readout	53.0% feed CO_2 absorbed, 2.25 ppm H_2S
5	sourer well at 30, loading floor at 45	38.5 cap, 51.3 return	rich loading peaks at 0.510 mol/mol
6	hydrocarbon slug at 30, antifoam Auto	30.167 alarm	206 mbar peak, no scrubber carryover
7	restore gas-plus-approach at 45	45.0 ΔP alarm	159 mbar peak, no carryover stop
8	steam availability 60% at 30	59.3 true, 64.7 report	6.62 ppm true peak at 129.5
9	suggested four-action line-up	720 completion	3.78 ppm worst sampled truth, 5.25 MW average

model. The app also keeps the learner's identified ratio or loading impression separate from the MPC's map.

8.5 Nine Cases on the Engine

Each case loads its own steady state and scripted events. Results in Tables 8.3, 8.4 and 8.5 are with the simulation engine at the shipped random seed and 1 s physics step, with operator actions entered at the times named. Rich loading is mol of H_2S plus CO_2 per mol MDEA. The analyzer is a delayed, noisy report, whereas the true gas is an immediate simulation quantity used for comparisons. The same case selected first, selected after another and rerun through Reset gives the same CSV in all nine load-path checks.

8.5.1 A Limit the Product Analyzer Cannot See

In case 1 the manual circulation cut takes true sweet-gas H_2S over 4 ppm at 13.8 min, rich loading past 0.5 at 14.7 min, and the analyzer over 4 at 24.7 min. Holding the cut gives 0.561 rich loading and approximately 23 ppm H_2S at one hour, followed by a corrosion stop at 74.5 min. Restoring 64 m^3/h at 50 min clears the loading cap at 53.8 min and the analyzer limit at 64.7 min. Holding smaller cuts finds the least circulation near the design point. About 57 m^3/h holds 4.00 ppm and 0.492 rich loading, whereas 55 m^3/h gives 5.85 ppm and 0.512 and ends in the corrosion stop. Both limits therefore bind at nearly the same circulation, and the result is no more precise than the synthetic equilibrium shape and the one modeled temperature profile that fix it. The delayed staircase explains why an operator who waits for the product report has less time to protect the rich line than the gas trend suggests.

The gas-rate step of case 2 separates fixed circulation from feedforward. Ratio raises circulation from 63.9 to 77.1 m^3/h and keeps the true H_2S peak at 2.66 ppm. Fixed circulation reaches 5.04 ppm true gas, crossing 4 at 41.2 min, while the analyzer does not cross until 54.7 min. The ratio's rich loading changes from 0.430 to 0.434, compared with 0.431 to 0.497 on Fixed. However, the ratio reads the last laboratory feed composition. In case 5 a sourer well raises feed H_2S from 2 to 2.6%, so rich loading crosses its 0.5 cap at 38.5 min while true gas stays below 3.43 ppm. Left alone, the

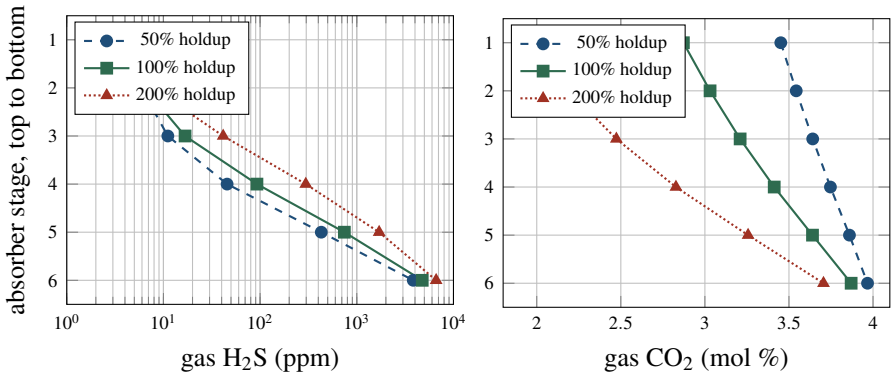


Figure 8.2 Gas profiles calculated from case 4 at 120 min, with 80 m^3/h circulation and three liquid holdups. Stage 1 is the top. H_2S uses a logarithmic ppm axis, while CO_2 uses mol%. The app's own Selectivity view also draws hollow equilibrium rings at each stage. Circles with dashed lines mark 50% holdup, squares with solid lines 100% and triangles with dotted lines 200%. The plotted points are simulation truth computed from the case, not analyzer samples.

unit stops at 98.4 min. Switching on the loading floor at 45 min brings the rich loading under 0.5 by 51.3 min and to 0.447 by 240 min, with 2.28 ppm sweet-gas H_2S. A product analyzer cannot be a substitute for a rich-loading estimate when these two limits separate.

> **TRY IT IN THE APP** **5 · The loading cap on a sourer gas**
>
> Load the case and press Run. Watch the Rich loading trend and the H_2S in sweet gas trend after the feed turns sourer at 30 min. The rich loading crosses its 0.5 cap at 38.5 min, yet the true H_2S stays below 3.43 ppm and the analyzer never reports a problem. Left alone, the corrosion stop ends the run at 98.4 min.

8.5.2 The Contact-Time Experiment

At 80 m^3/h circulation, case 4 varies tray liquid holdup without changing the number of stages. Halving it takes only 16.0% of feed CO_2, compared with 30.5% at design and 53.0% at double holdup. The corresponding sweet-gas H_2S values at 120 min are 3.26, 2.85 and 2.25 ppm. The latter moves slightly because the regenerator's steam duty changes with coabsorbed CO_2, from 4.84 MW at design to 5.81 MW at double holdup. The independent point is the nearly twofold difference in CO_2 pickup, not an assertion of strictly constant H_2S. Four stages in contact give 6.76 ppm H_2S because a complete approach-to-equilibrium stage has been removed. Figure 8.2 shows each gas concentration leaving the six stages at half, design and double holdup.

Pause. Try Exercise 8.2 before reading on.

8.5.3 A Slow Correction and Two Fast Alarms

Gas warming in case 3 makes true H_2S pass 4 ppm at 62.3 min. The analyzer reports the exceedance at 74.7 min. Enabling its trim at 75 min lifts the overhead setpoint toward 109 °C, moves reboiler duty from about 4.68 to 5.82 MW, and gets the analyzer below 4 ppm at 154.7 min. The sample delay is only part of that 80-minute recovery. Leaner solvent must also traverse the sump, 40 m^3 surge tank and cooler line.

A hydrocarbon slug is much faster. In case 6 the absorber pressure drop reaches its alarm ten seconds after the 30 min slug, at 30.167 min, peaks at 360 mbar untreated and fills the sweet-gas scrubber to a stop at 44.98 min. The delayed analyzer does not report more than 4 ppm until 44.7 min, so the pressure alarm leads it by 14.5 min. Automatic antifoam gives one shot, limits the pressure

Table 8.5 Challenge Results at the Default Seed

Configuration	Time (min)	Worst (ppm)	Peak rich (mol/mol)	Mean duty (MW)
Fixed, shipped	214.5	5.27	0.565	4.86
Ratio, floor, antifoam, trim	720	3.78	0.458	5.25
Same, no trim	720	3.63	0.458	5.54
Same, no antifoam	367.0	3.13	0.458	5.04

drop peak to 206 mbar and avoids carryover. Instantaneous true H_2S still peaks at 4.40 ppm between samples, while the analyzer peaks at 2.70 ppm. This outcome is allowed by a challenge that grades sampled gas rather than continuous truth.

> **TRY IT IN THE APP** **6 · Foam: a hydrocarbon slug, ΔP and antifoam**
>
> Press Run and watch the Absorber ΔP trend after the hydrocarbon slug at 30 min. The pressure drop passes its alarm ten seconds later and climbs to 360 mbar, and the scrubber fills until the run stops at 44.98 min. Set Antifoam on high ΔP to Auto on the Foam card, press Reset and run again: one shot holds the peak to 206 mbar with no carryover.

In case 7 lowering lean amine from 40 to 30 °C briefly improves absorption but condenses hydrocarbon, and leaving it there ends at 84.6 min. Restoring gas-plus-approach at 45 min lets the pressure drop briefly reach 159 mbar, just above its 156 mbar alarm, then avoids carryover.

Steam supply is a third constraint. In case 8 a dip to 60% availability at 30 min makes true H_2S pass 4 at 59.3 min and the analyzer pass it at 64.7 min. The true peak is 6.62 ppm at 129.5 min. A steady sweep of circulation from 30 through 110 m^3/h at that duty finds no flow holding 4 ppm, because low flow overloads the solvent while high flow receives too little stripping per mol. The case asks the learner to recognize an infeasible loop rather than keep moving the pump.

Pause. Try Exercise 8.1 before reading on.

8.5.4 The Twelve-Hour Shift

The final case introduces feed H_2S from 2 to 3% over hours 2–3, a hydrocarbon slug at hour 6 and a one-hour steam availability dip to 85% at hour 9. Its verdict requires every analyzer sample's true H_2S to be at most 4 ppm, continuous true rich loading at most 0.5, no stop and an average duty at most 5.35 MW. A learner who changes a disturbance, model parameter or tray holdup receives no grade. The shipped Fixed setting stops on corrosion at 214.5 min. Table 8.5 shows the main controlled comparisons.

Pause. Try Exercise 8.3 before reading on.

Figure 8.3 sets the four configurations of Table 8.5 against the four clauses of the target.

The suggested configuration selects Ratio, sets the loading floor at 0.42, enables automatic antifoam and analyzer trim. Its exact worst sample is 3.779 645 ppm, peak rich loading 0.458294 and mean duty 5247.400 kW over 720 min. Removing trim keeps the sampled gas below 4 ppm but raises mean duty to 5539.637 kW, above the 5350 kW ceiling. Removing antifoam ends at 367.0 min on carryover. The simulator tests repeat the shipped and suggested verdicts at the default seed and seeds 0–29, each at 1 s and 0.5 s: all 62 shipped runs fail and all 62 suggested runs pass. This is numerical robustness for the declared model and scripted shift, not a probabilistic reliability claim for a real sweetener.

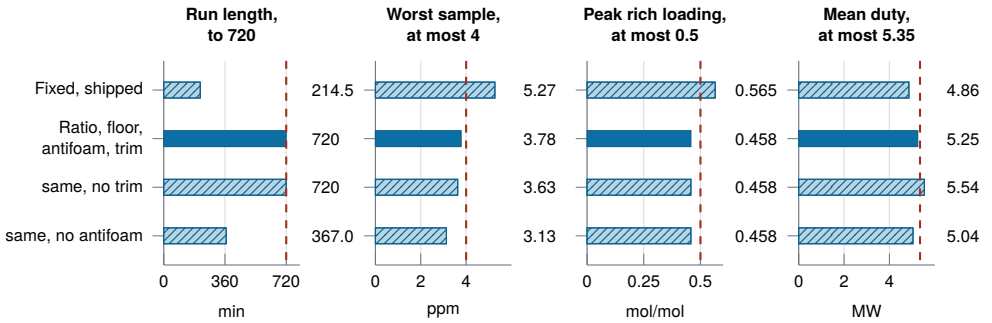


Figure 8.3 The challenge runs of Table 8.5 as bars: how long each run lasted, the worst sampled H_2S, the peak rich loading and the mean reboiler duty. The solid bars are the one configuration that passes, hatched bars those that fail, dashed red lines are the targets, and the value of each bar stands at the right. Notice that each configuration that fails breaks a different clause, and that the cleanest gas belongs to a run that ended early.

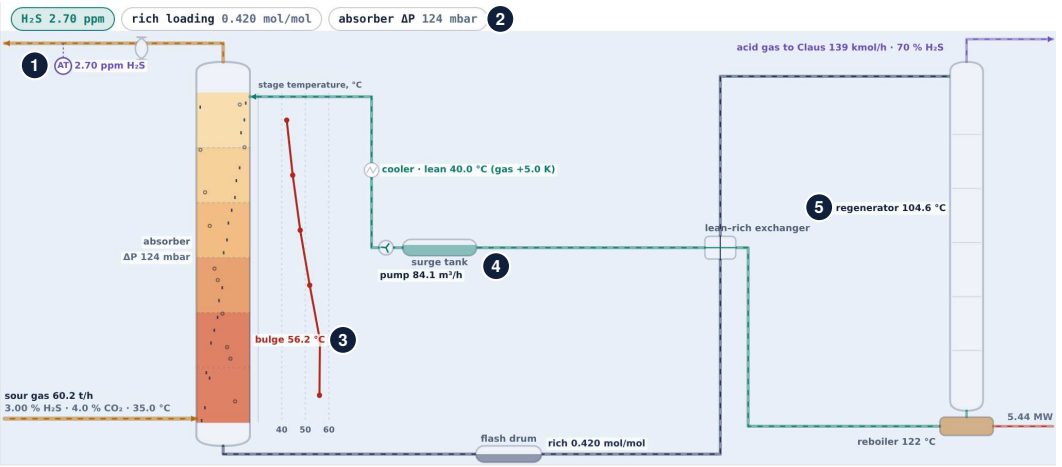


Figure 8.4 Suggested configuration at the end of the twelve-hour challenge, Unit view cropped to the plant drawing. (1) The analyzer AT on the sweet gas line with its current report, 2.70 ppm. (2) The status chips: the same report, the rich loading and the absorber pressure drop. (3) The absorber with the temperature of each stage, warmest in the lower interior where absorption heats the liquid. (4) The surge tank and the pump, which circulates about 84 m^3/h of lean amine. (5) The regenerator, its overhead at 104.6 °C, with the acid gas leaving above it toward the Claus unit and the reboiler below. The current report is not the grade: the challenge grades the complete run.

DID YOU KNOW? Feedback That Saved Steam

From the simulator (Table 8.5). Over the twelve-hour shift the analyzer trim left a slightly worse worst sample, 3.78 ppm against 3.63 ppm without it, and yet the unit used less steam, 5.25 MW against 5.54 MW. A loop that can only add heat when the gas is sour also takes it away when the gas is clean.

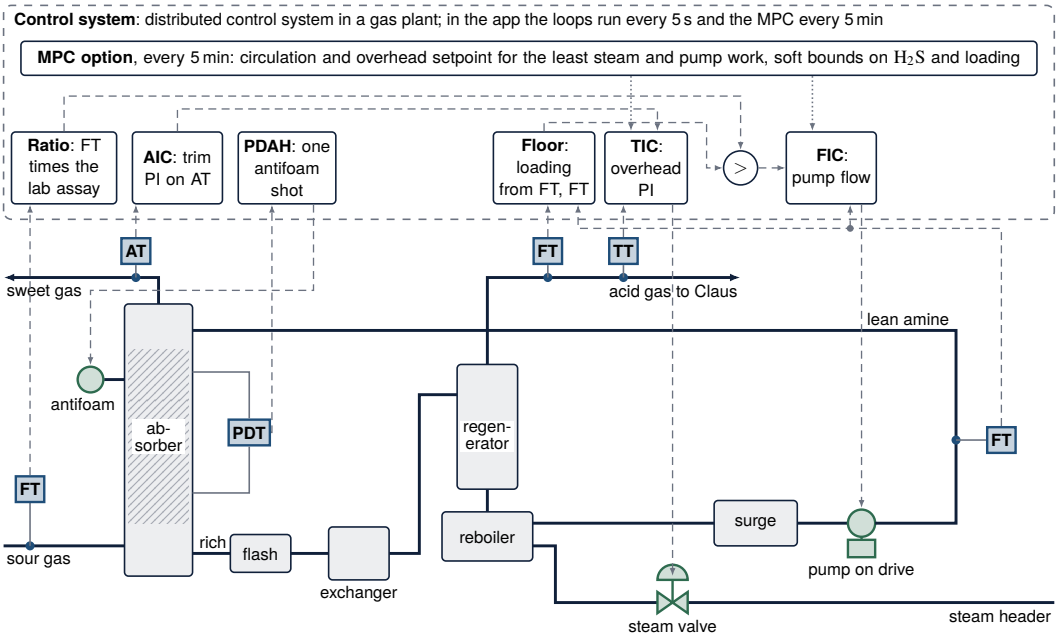


Figure 8.5 The loops of the sweetener simulator with their hardware. Lettered boxes are sensing devices with the chapter's tags: FT on the sour gas, AT on the sweet gas, PDT across the absorber, FT and TT on the acid gas overhead and FT on the lean amine. Green symbols are final elements: the lean amine pump on its drive, the reboiler steam valve and the antifoam pump. Dashed arrows are signals, dotted arrows the setpoints the optional MPC writes. Notice that AT reads the specification but not the loading cap, which only the acid gas meter and the lean flow meter infer, and that the floor meets the ratio at a high select. The lean cooler and its approach loop on the sour gas temperature are left out. Not to scale, and not a piping diagram.

8.6 Technology in Practice

Figure 8.5 draws the loops of Section 8.4 with the hardware of a sweetener in place of the schematic's symbols.

What Measures It

One instrument reads what the sales gas specification is about: the analyzer AT on the sweet gas. A process gas chromatograph, one common kind, separates a sample by its travel down a column, and cycle times of minutes are not uncommon even for online chromatographs in control loops [17]. Figure 8.6 shows the principle. The model's AT samples every 10 min with 0.05 ppm of noise. The loading floor reads two ordinary meters instead: the acid gas meter, with a 0.5 min lag, and the circulation.

> **TECHNOLOGY** **Sensor: The Sweet-Gas Analyzer**
>
> A 2018 review found the sulfur methods in use for natural gas accurate but slow, with few analyses, a long cycle and a delayed result [18]. An analyzer that separates its sample in time carries a dead time by principle, and enough dead time makes a feedback loop oscillate. An analyzer for hydrogen sulfide is checked against a span gas of known concentration, often 25 or 50 ppm, because analyzers drift more than pressure, level or flow transmitters [17]. A plugged sample line leaves it measuring stale sample with no way of knowing, so the trend goes quiet while the plant moves.

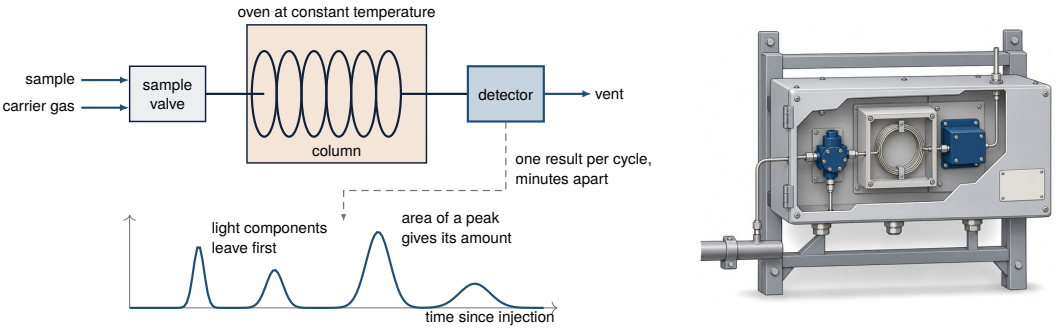


Figure 8.6 Principle of a process gas chromatograph, one kind of online analyzer for the sweet gas. A valve injects a sample into carrier gas, the column holds back each species for its own time, and the detector sees them leave one by one. Notice that a result exists only at the end of each cycle, which is the staircase the chapter's AT draws.

What Moves It

Four final elements carry the chapter's handles. The lean amine pump sets the circulation, the fast handle, from 0 to 110 m^3/h. The reboiler steam valve sets the duty that strips the solvent, the slow handle, and the steam header can limit it, as in case 8. The cooler holds the lean amine warmer than the gas, and the antifoam pump gives one shot on an alarm.

> **TECHNOLOGY** **Final Element: The Lean Amine Pump**
>
> The lean amine pump sets the circulation, the chapter's fast handle. A pump's flow can be set by throttling its discharge, by recycling to its suction, or by changing its speed with a drive. Changing the speed uses less energy than running at full speed and throttling, and it takes a control valve out of the line. A drive limits speed, current and the rate of acceleration and deceleration, and shuts down on overcurrent. A centrifugal pump, the most common kind in process plants, delivers less pressure as its flow rises [17]. In the chapter the pump follows its command through a 0.2 min lag and loses suction over the last 0.5 m^3 of the surge tank, so a drained tank shows on the trend as delivered flow falling below its command.

Where the Controller Runs

Inside a gas plant the loops would run on a distributed control system, which controls production within one location through feedback and feedforward loops under a supervisory level. Such loops run with cycle times from milliseconds to minutes [19]. The app's loops execute every 5 s and its MPC every 5 min, while the analyzer reports every 10 min, so no scan rate repairs the delay. The chapter's structure maps onto standard blocks: a ratio station that multiplies the gas meter by the laboratory composition, a high selector that lets the loading floor override it ahead of the FIC on the pump, a PID on the regenerator overhead with its setpoint trimmed by a PI on the analyzer, and a pressure drop alarm that fires the antifoam. The optional MPC sits in a supervisory layer above them.

IN PRACTICE **The Acid Gas Meter Is Required Anyway**

Under the United States performance standard for sulfur dioxide from onshore natural gas processing, written for plants built or modified from 1984 to 2011, a covered sweetening unit must measure its acid gas flow continuously and record it at least once an hour. At least one sample a day gives the hydrogen sulfide in that acid gas, and the sulfur produced each day is measured within 2 percent. Together they fix the sulfur recovery the plant must reach [20, 21]. The acid gas meter that the chapter's loading floor divides by the circulation is one such a plant already runs.

What Is Modernizing It

Three developments touch this chapter. Loading that the chapter infers from two meters is most often measured by wet titration in a laboratory, which can take two hours while the sample flashes carbon dioxide and the amine degrades. Near-infrared spectroscopy has been calibrated on a gas plant's solvent to read the amine, the carbon dioxide loading and the water at once, and its authors offer it to replace those methods [22]. Laser photoacoustic detectors read hydrogen sulfide in natural gas from a few ppm to several percent, despite the overlap of carbon dioxide's absorption, and are calibrated in place [23]. Model predictive control is established in industry [7], and the chapter's MPC adds a forecast of the loading and the sweet gas that does not wait for the next report.

8.7 Limitations

All vessel sizes, tunings, disturbances, foam laws and stop thresholds are generic teaching values. The three-point patent comparison supports only the rough shape of one H_2S equilibrium curve at 40 °C. The absorber's six cells do not resolve real tray hydraulics, mass-transfer area or gas-side holdup. The rate law compresses carbonate chemistry into one effective free-amine term, and the regenerator's quasi-steady stripping section cannot predict a moving temperature profile. Foam is one scalar state driven by hydrocarbon and antifoam, so the 10 s pressure alarm and 45 min scrubber stop are properties of this scripted model. A real unit needs measured fluid properties, a fitted hydraulic and kinetic model, and operating procedures for contamination and relief.

The challenge's quality requirement checks the true gas at analyzer sample instants, not continuously. Case 6 shows why that distinction matters: automatic antifoam allows a 4.40 ppm instantaneous peak while the analyzer sees at most 2.70 ppm. The feedback receives only reported samples and noisy process measurements, but the teaching overlay and grading can see the synthetic truth. The MPC uses a commissioned parameter copy and local map, so unmodeled foaming, solvent degradation and property drift can invalidate its forecast. No conclusion about industrial controller superiority is drawn from its local optimization or from the 62 deterministic seeded runs.

OPEN CHALLENGE **What Makes Amine Foam?**

Foaming is a stubborn problem of sour gas sweetening: in 2019 two incidents at gas plants cost solvent, put sweet gas off specification and cut the gas supply. Foam comes from contaminants in the feed gas or from amine degradation and corrosion, and identifying and quantifying the organic contaminants in the solvent remains a challenge. In a 2022 study with plant solvents, unsaturated fatty acids and alcohol ethoxylates promoted foam at 10 ppm, while linear hydrocarbons had little effect even at 2000 ppm [24]. The chapter's foam state, driven by hydrocarbon alone, is a teaching stand-in. Progress would be an online reading of the solvent's tendency to foam, so that antifoam goes in before the pressure drop rises.

8.8 Conclusion

The modeled sweetener couples a fast H_2S specification to a slower solvent inventory and to an analyzer that reports after each 10 min sample. At a circulation cut the true gas crosses 4 ppm at 13.8 min and the analyzer does so at 24.7 min. A sourer feed shows the other side of the problem: rich loading exceeds 0.5 while sweet gas remains below 3.43 ppm. Ratio circulation protects a metered

gas-rate change, an acid-gas-meter loading floor protects the rich circuit when the feed assay is stale, and differential pressure gives a response to foam long before product analysis can. Analyzer trim then trades additional margin for steam. In the declared twelve-hour challenge those four actions keep the worst sampled H_2S at 3.78 ppm, peak rich loading at 0.458 and average duty at 5.25 MW, while the shipped Fixed case stops on corrosion. The simulation's value is a reproducible comparison of which measurement can protect which limit, with its synthetic boundaries stated openly.

KEY POINTS

- A sweetener can keep its sales gas clean while overloading its own solvent: a sourer feed takes the rich loading over 0.5 while the gas stays below 3.43 ppm.
- At a circulation cut the true gas crosses 4 ppm at 13.8 min and the analyzer does so only at 24.7 min.
- Ratio circulation protects a metered gas-rate change, an acid-gas-meter loading floor protects the rich circuit when the feed assay is stale, and differential pressure answers foam first.
- Ratio, loading floor, antifoam and analyzer trim together keep the worst sampled H_2S at 3.78 ppm, peak rich loading at 0.458 and average duty at 5.25 MW, where Fixed stops on corrosion.

Where else this applies. Chapter 7 applies the same ratio feedforward and analyzer trim to a single solute, and Volume 4, Chapter 2 holds a protective override that rests at its clamp.

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8.9 Exercises

8.1 ⌕ Concept check · 2 min

In case 8 the steam available to the reboiler falls to 60 % at 30 min, and a steady sweep at that duty finds no circulation from 30 to 110 m^3/h that holds 4 ppm of H_2S. Why does neither more nor less circulation restore the specification?

(a) The analyzer reports each sample 5 min late, so every circulation move reaches the absorber after the gas has left.

(b) The amine pump is already at its 110 m^3/h capacity, so the circulation cannot be raised any further.

(c) The regenerator loop winds up against the open steam valve and holds its temperature setpoint at the upper bound.

(d) Less circulation loads each mol of amine closer to its capacity, while more circulation gets less stripping steam per mol and returns richer lean amine.

8.2 ⌕ Concept check · 2 min

In case 4 at 80 m^3/h, doubling the tray liquid holdup raises the share of feed CO_2 absorbed from 30.5 to 53.0 %, while the sweet-gas H_2S moves only from 2.85 to 2.25 ppm. Which statement explains the difference?

(a) Each stage takes H_2S a fixed 95 % of the way to equilibrium whatever its holdup, while CO_2 uptake grows with the amine inventory on the stage.

(b) More holdup cools the stages, and the larger heat of absorption of CO_2 makes its equilibrium pressure fall faster than that of H_2S.

(c) The extra liquid is drawn from the surge tank, so the circulation falls and the lean amine has less capacity left for H_2S.

(d) All the H_2S is absorbed on the bottom stage, so no change above it can move the H_2S leaving the top.

8.3 Concept check · 1 min

With automatic antifoam in case 6, the instantaneous true H_2S peaks at 4.40 ppm between two analyzer samples, while the analyzer never reports more than 2.70 ppm. Why can a run with such an excursion still meet the H_2S clause of the twelve-hour challenge?

(a) The challenge grades the analyzer's reports, and the trim holds them 1 ppm under the limit.

(b) The challenge grades the true H_2S only at the analyzer's sample instants.

(c) The challenge grades the average H_2S over the twelve hours, not its peak.

(d) The challenge forgives one sample over 4 ppm for each antifoam shot.

8.4 Theory and calculation · 7 min

The Ratio station sets the circulation from the gas meter and the laboratory's feed analysis, Equation (8.8), with $r = 1.29\,\text{mol/mol}$. Take the hydrocarbon gas at 17 kg/kmol (Table 8.2), H_2S at 34.08 kg/kmol and CO_2 at 44.01 kg/kmol.

(a) Compute the amine concentration c_A, the molar mass of the sour gas at 2 % H_2S and 4 % CO_2, and its molar flow at 60 t/h. *Checkpoint:* 3.927 kmol/m^3, 18.42 kg/kmol and 3257 kmol/h.

(b) Compute the acid-gas load and the Ratio circulation at design and after the 20 % gas step of case 2. Compare with the 63.9 and 77.1 m^3/h the chapter reports. *Checkpoint:* 195.4 kmol/h, 64.2 m^3/h and 77.0 m^3/h.

(c) In case 5 the feed H_2S rises to 2.6 % while the laboratory still reports 2 %. Compute the true acid-gas load, the mol ratio the unchanged circulation now gives, and the circulation that would restore 1.29 mol/mol.

8.5 Theory and calculation · 6 min

The equilibrium of Equation (8.1) can be checked against the three patent points of Section 8.2 for H_2S alone ($\alpha_C = 0$, so $\alpha_t = \alpha_H$).

(a) Compute p_H^* at 40 °C for loadings 0.21, 0.40 and 0.69 with $K_H = 245\,\text{kPa}$ and $b = 2.1$. *Checkpoint:* 8.80, 28.2 and 88.4 kPa.

(b) The amine concentration scales the equilibrium pressure, so multiply by 50/45 to compare with the patent's 10, 30 and 100 kPa for 50 % MDEA. Give the three errors. *Checkpoint:* 9.78, 31.34 and 98.17 kPa.

(c) In case 3 the lean amine warms from 40 to 45 °C with the gas. By what factor does p_H^* rise at a fixed loading, and what does that do to the sweet gas?

8.6 Theory and calculation · 6 min

In every case the analyzer draws a sample at 9.5, 19.5, 29.5 min and every 10 min after, and reports it 5 min later (0.5 min of sample line and 4.5 min of analysis), at 14.5, 24.5, 34.5 min and so on. The displayed value holds until the next report.

(a) For an exceedance that begins at an arbitrary time and persists, give the shortest and the longest delay until a report shows it. *Checkpoint:* 5 min and 15 min.

(b) The true gas passes 4 ppm at 13.8 min in case 1, 62.3 min in case 3 and 59.3 min in case 8. Predict when the analyzer first reports it in each case, and the delay.

(c) In case 6 the slug arrives at 30 min, the pressure-drop alarm sounds at 30.167 min and, without antifoam, the scrubber stops the run at 44.98 min. When does the first analyzer report of the upset arrive, and what is it worth to the operator?

8.7 App challenge · 8 min

Load scenario 1, "Manual: cut the amine circulation", default seed. Before Run, set the Amine pump (FIC card) to 56 m^3/h. The plant starts from the design steady state and the pump moves at $t = 0$. Run at speed 20 (each simulated minute takes 0.05 s) to 300 min or until the run stops, then export the CSV.

(a) Does the run end in a stop? Read the `exercise_stop` column, the time of the last row, and the first row where `truth_rich_loading` exceeds 0.5. *Checkpoint:* a corrosion stop at 104.1 min, cap first passed at 44.2 min (both ± 0.2 min).

(b) Press Reset, which keeps your settings, set the pump to 57 m^3/h and run to 300 min. Read `truth_h2s_ppm` and `truth_rich_loading` in the row at 300 min, and the largest `h2s_analyzer_ppm` of the run.

(c) Explain why the corrosion stop in (a) comes exactly when it does, and why 57 m^3/h is the least whole-number setting with no margin on either limit.

8.8 App challenge · 9 min

Load scenario 5, "The loading cap on a sourer gas", default seed. Before Run, turn the Loading limit On (FIC card) and leave its setpoint at 0.45. Run at speed 20 to 240 min and export the CSV.

(a) Read the first row with `loading_limit_active` equal to 1, the largest `truth_rich_loading` and the first later row where it is back under 0.5. *Checkpoint:* 45.8 min, 0.506 and 51.3 min.

(b) The true loading passed 0.5 at 38.5 min. Read `rich_loading_inferred` in that row and explain why the floor engaged seven minutes later.

(c) Press Reset, set the Loading limit setpoint to 0.42 and run again to 240 min. Read the largest `truth_rich_loading` and `circulation_m3h` at 240 min, and compare the circulation with the first run's.

8.9 App challenge · 9 min

Load scenario 9, "Challenge · a twelve-hour shift", default seed. Use speed 300, so that 720 min takes about 2.4 s. The run stops at 12 h or at a stop, and its verdict appears in What changed?

(a) Run as shipped. What ends the run, at what time, and which clauses of the target fail? *Checkpoint:* a corrosion stop at 214.5 min.

(b) Reload the scenario. Before Run, set Circulation control to Ratio, the Loading limit On with setpoint 0.42, Antifoam on high ΔP to Auto and the Analyzer trim On. Run to 12 h and read the verdict's worst sample, peak rich loading and average duty.

(c) Press Reset, turn the Analyzer trim Off and run again. Read the same three values and explain how a loop that raises the regenerator temperature when the gas is too sour saves steam.

8.10 Application area · 3 min

In case 7, on a cold night, someone lowers the lean amine setpoint from 40 to 30 °C because colder amine absorbs H_2S better.

(a) What happens over the next hour, and how does it end if nobody acts?

(b) Why does a sweetener hold its lean amine a few kelvin above the sour gas temperature, and what does that margin cost in absorption?

8.11 Application area · 4 min

In case 4 at 80 m^3/h, doubling the tray holdup raises the feed CO_2 absorbed from 30.5 to 53.0 % and the reboiler duty from 4.84 to 5.81 MW. The feed is 3257 kmol/h of gas with 4 % CO_2.

(a) Compute the extra CO_2 absorbed and the heat to desorb it at 55 MJ/kmol, and compare it with the rise in duty. *Checkpoint:* 29.3 kmol/h and 0.45 MW, about half of 0.97 MW.

(b) Name two costs of coabsorbed CO_2 for the plant, and two ways a selective unit limits it.

8.12 Review the agent · 5 min

An AI assistant reviews case 5 and writes: “The analyzer trim already protects the rich line. When the sourer gas overloads the amine, the H_2S slip rises, the trim raises the regenerator temperature, the leaner amine regains capacity, and the rich loading falls back under 0.5. A separate loading limit only duplicates the trim and costs circulation.” Find the flaw, and say how you would check it in the app.