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CHAPTER 7

Glycol Dehydration Simulator With an Equilibrium Floor and a Reboiler Ceiling

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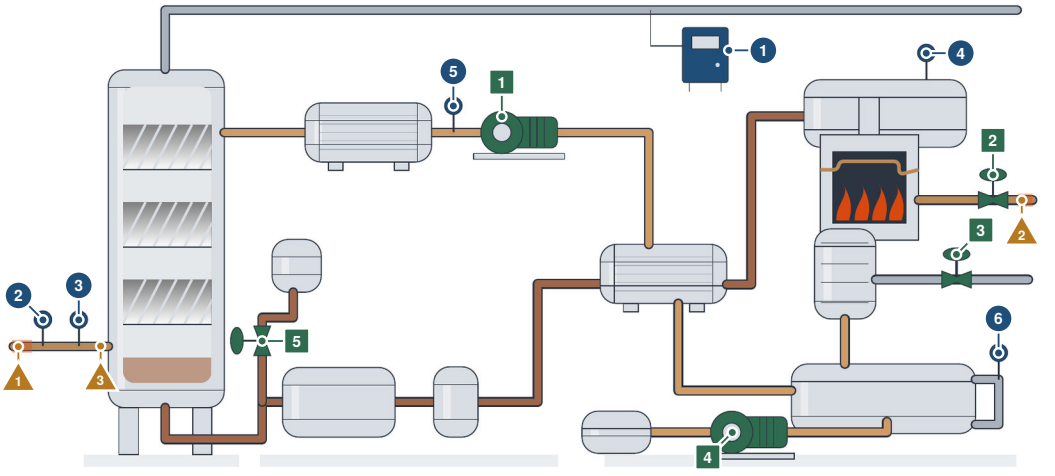
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CHAPTER 7

Glycol Dehydration Simulator With an Equilibrium Floor and a Reboiler Ceiling



The controller moves 1 glycol pump, the fast handle 2 reboiler fuel valve 3 stripping gas valve 4 glycol makeup pump 5 antifoam injection

The controller reads 1 water left in the dry gas, ten minutes late 2 wet gas flow 3 wet gas temperature 4 reboiler temperature 5 glycol circulation flow 6 surge drum level

What disturbs it 1 more gas, or warmer gas 2 a limit on the reboiler's fuel 3 a slug of liquid hydrocarbon

Notice that the analyzer cabinet samples the dry gas far along its outlet line, and that glycol made purer in the reboiler must pass the stripping column, the surge drum and the exchanger before it reaches the contactor. Illustration, not to scale.

IN PLAIN TERMS Drying Gas With a Liquid That Drinks Water

The main idea. Gas from wells carries water that must come out before it enters the pipeline. In a tall tower the gas bubbles up through glycol, a liquid that soaks up water. A heater then boils the water out so the glycol can be used again.

The challenge. More glycol dries the gas within minutes, but only down to a limit set by how dry the glycol is. Drying the glycol further reaches the tower only after about half an hour, burns fuel, and stops before the glycol breaks down.

Why it matters. Wet gas forms icy solids that block pipes, so nearly all gas that is sold passes through such a unit.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	This page, the first Did you know? box in the Introduction, the two History boxes in Section 7.2, the Try it boxes and the second Did you know? box in Section 7.6, and Key points at the end of the Conclusion. No equations.
Study	55 min	The whole chapter in order, stopping at the three pause points, then Exercises 1 to 12.
Practice	15 min	This page, Section 7.6 with Figure 7.4, Section 7.7 and Section 7.8 with its Open challenge box.

The control question One water specification on the dry gas has two handles: glycol circulation, which acts in minutes but only down to a floor set by equilibrium with the lean glycol, and glycol purity, which moves that floor but reaches the contactor only as the surge drum turns over and is capped by the reboiler ceiling. When is each handle worth its energy, and what goes wrong when a loop reaches for the wrong one?

Learning objectives

- Derive the floor of a two-stage contactor with finite stage efficiency and decide whether any circulation can meet a specification.
- Compute the purity that stripping gas buys below the reboiler from the Kremser relation, and its energy cost.
- Explain why a ratio feedforward on the water load holds a gas step but not a warmer inlet, and what an analyzer trim adds.
- Explain why more circulation makes the gas wetter when the reboiler is short of fuel, and check it on the graded day.
- Weigh the energy of circulation, heat and stripping gas against the water specification, as the economic MPC does.

Prerequisites Sections 1.4.7 (absorption, the Kremser relation and the lean floor), 1.4.8 (selectors and external reset), 1.4.9 (late analyzers), 1.6.2 (the framework's PID) and 1.6.4 (the apps). Section 1.6.3 is needed only for the MPC.

The app https://apmonitor.com/apps/glycol-dehydration/

See also Volume 4, Chapter 3 for limiters at a selector whose integrators track the applied fuel, and Volume 4, Chapter 2 for a protective override that waits at its clamp. Volume 9, Chapter 8 and Volume 9, Chapter 6 for economic predictive control that prices its inputs. Volume 5, Chapter 3 for composition control through a slow analyzer, and Volume 5, Chapter 10 for a product quality inferred and corrected by a late laboratory.

7.1 Introduction

Gas from the production separators arrives carrying all the water it can hold. In the generic unit simulated here, 60 t/h of natural gas, about 60 million standard cubic feet per day, saturated at 35 °C and 60 bar brings 58.2 lb/MMscf of water, 66.2 kg/h in all, into a packed contactor. Against 24.3 L/min of triethylene glycol (TEG) at 99.04 wt%, 22 liters for every kilogram of water arriving, the gas leaves with 6.73 lb/MMscf, a water dew point of −1.6 °C at the contactor pressure, just under a 7 lb/MMscf specification. Doubling the circulation does not halve what is left. From 15 L/min of glycol regenerated at 190 °C, 30 L/min lowers the water from 9.67 to 6.83 lb/MMscf, and 50 L/min still leaves 5.79 lb/MMscf.

The water has to come out because, together with the gas, it forms solids in the pipe well above its own freezing point. Natural gas hydrates are crystalline compounds of water and gas that block valves and lines under pressure, and by 1942 the remedy in practice was to dry the gas upstream of the plant or the line [1]. In 1950 most gas companies took gas only below 7 lb/MMscf, so that virtually all gas sold had to be dehydrated [2], and by 1973 glycols, triethylene glycol above all, were the preferred absorbents [3]. Dehydration is therefore a step that virtually every sales gas passes through, and the specification it serves is the one the simulator keeps as its teaching value.

> **DID YOU KNOW? Far Drier Than the Contract**
>
> In a 2015 test on the transmission system of Spain the gas carried only 4 to 8 parts per million of water by volume, much drier than the European specification, a water dew point below −8 °C at 7 MPa [4]. The 7 lb/MMscf of this chapter is a dew point of −1.0 °C at 60 bar.

The simulator is built around three beliefs that the unit contradicts. The first is that more solvent always removes more water. The gas can be dried only toward the water it would carry in equilibrium

with the lean glycol at the top of the contactor, so with the 45 °C inlet of case 5 and glycol regenerated at 190 °C no circulation brings the water below 8.41 lb/MMscf, and beyond about 570 L/min the glycol, kept 5 K warmer than the gas, heats the contactor and the water rises again. The second belief is that a fixed ratio of glycol to water load holds the dry gas steady. A ratio holds the share of the water removed, so when the inlet warms 2 K and brings 11 % more water, the ratio adds 11 % more glycol and the water left climbs from 6.68 to 7.53 lb/MMscf. The third is that a hotter reboiler always buys purer glycol. The reboiler sits at its bubble point, 99.13 wt% at the 204 °C ceiling in this model, and the last 0.8 wt% has to come from stripping gas, which took the energy of the unit from 154 to 598 kW in case 6.

These features belong to classes of problems that reach well beyond gas processing. Every absorption and regeneration loop, the amine units that sweeten the same gas among them (Chapter 8), delivers a product bounded by the purity of its recycled solvent, and the purity limit of the conventional glycol loop has produced a family of enhanced regeneration schemes of its own [5]. A quality held by a fast inexpensive input and a slow expensive one with a hard limit is a constrained multivariable problem of the kind commercial model predictive control packages are built for [6], and pricing the inputs directly in the objective is the subject of economic predictive control [7]. A ratio of solvent to load used as a feedforward, trimmed by an analyzer, and a high-limit override selected against a temperature loop on a fired vessel are standard structures of process control [8].

However, the material a student meets treats these pieces apart. The equilibrium literature of the TEG, water and gas system is written for contactor design [3, 9], parametric and economic studies of the dehydrator are steady-state simulations [10, 11], and the predictive controller reported for a dehydration unit regulates a feed pressure and a heater temperature on identified first-order models [12]. This chapter quantifies, with a browser simulator of a TEG dehydrator in which the contactor, the still, the surge drum and a delayed moisture analyzer are integrated together, how fixed circulation, a ratio feedforward on the water load, an analyzer trim, a reboiler loop under a high-limit override and an economic model predictive controller (MPC) meet a pipeline water specification through gas and temperature disturbances, foam, a pump trip and a fuel limit. It states the model fully enough for it to be rebuilt.

The correlations are teaching values, and ratio control, override selection and linear MPC are established methods. Every result is measured on a single generic unit at the default random seed. The floor of the contactor is the equilibrium over the lean glycol plus the share of the inlet water that two 90 % stages let through. Under a reboiler fuel limit, extra circulation lowers the purity it was meant to make up for, so an analyzer trim takes the worst sample from 7.04 to 10.47 lb/MMscf. The high-limit override lets the reboiler pass 204 °C by 0.21 K on a sudden loss of load. The model has seventeen states and nine ledger states whose water and glycol balances close to 6.4×10^{-13} of what entered, and a measurement boundary keeps the stage compositions, the lean purity and the foam away from every controller. Each of the nine cases is graded by a completion rule.

Section 7.2 follows gas dehydration from hydrates to enhanced regeneration. Section 7.3 states the model, whose contactor floor is the two-stage, finite-efficiency form of the Kremser relation of Section 1.4.7. Section 7.4 sets the two handles against their two limits, and Section 7.5 states the controllers as coded. Section 7.6 measures the nine cases, Section 7.7 sets the hardware of a real dehydrator beside the model, Section 7.8 lists what the model leaves out, and the exercises in Section 7.10 put the cases to work.

7.2 Dry Gas for the Pipeline

Dehydration began as the cure for the gas hydrate, a solid that blocks gas lines, as the first History box below tells. A subsea flowline that cannot be dried is protected by inhibitor instead (Chapter 5).

HISTORY 1934 and 1942: Ice That Was Not Ice

Before 1934 the plugs that blocked gas lines were blamed on various causes, with a great deal of apprehension. That year Hammerschmidt [13] found that the crystalline plugs forming above the freezing point of water were hydrates of water and gas [14], and with that he brought the subject to the gas industry [1]. In 1942 Carson and Katz described hydrates as white crystalline compounds that exist under pressure well above the freezing point and plug valves and pipes in part or entirely. The cure in practice was to dehydrate the gas before it entered the plant or the pipeline. No method yet predicted when a wet gas would form hydrates, and their equilibrium constants let those conditions be estimated from the composition of the gas [1].

The drying itself was done in several ways. A field study of 1951 named four classes of process then in use, adsorptive, absorptive, chemical reaction and refrigeration, and tested a wellhead unit that dried the gas by expansion through an orifice, noting that the indirect processes spent part of the gas on regeneration and that most of them resisted automation [15]. Calcium chloride was the chemical route. A wellhead unit of 1961 passed the gas through a bed of anhydrous pellets whose brine then absorbed more water on trays below and was dumped into a pit as expendable, and in the San Juan basin and the Big Piney field such units still worked beside glycol dehydrators, although field crews disliked recharging them and could check their performance only by inspecting the bed or running a dew-point test [16].

Absorption into a liquid glycol won on cost, and the second History box below follows the doubts of 1950 to 1973 about how dry it could make the gas.

HISTORY 1950 to 1973: How Dry Can Glycol Make It?

In 1950 adsorption on activated bauxite, alumina or silica gel could make gas virtually bone dry, but a small unit of that kind cost substantially more than an absorption unit that met the pipeline specification, so the search for better absorbent liquids intensified [2]. By 1961 drying with aqueous triethylene glycol had become prominent, yet many doubted that it could dry gas from 120 °F wellheads to the dew point near 32 °F that a contract of 7 lb/MMscf required, a doubt dating from the days when suppliers would not guarantee depressions beyond 65 to 75 °F [9]. In 1973 the published dew points over the glycol still disagreed, and the data above 99.8 wt%, the purity modern contactors needed for depressions of more than 100 °F, were scant and contradictory. Designers answered the doubt with circulation rates higher than necessary, a practice ill suited to offshore platforms where space and power are scarce [3].

Low dew points then moved the problem to the regenerator. At atmospheric pressure a reboiler at 400 °F (204 °C) gives at most about 98.8 wt% while low dew points need up to 99.9 wt%. A hotter reboiler is ruled out, because TEG decomposes thermally at 404 °F (207 °C) and even a 400 °F reboiler can decompose glycol at its hotter film temperatures, so the extra purity comes from stripping gas, best introduced in a short column after the glycol leaves the reboiler [10]. Stripping with nitrogen, part of the dry product gas or a volatile hydrocarbon in the DRIZO process, the Stahl column and the Coldfinger process are among the schemes reviewed for getting past the purity limit of the conventional loop [5], and the trade of circulation, trays and stripping gas against processing cost has been posed as an optimization of the simulated unit [11]. The same loop has an environmental side. Aromatic hydrocarbons are highly soluble in TEG and leave with the regenerator's vent, which is usually open to the atmosphere [10], and condensing the vapor and burning the noncondensable gas in the reboiler was found to be the most cost-effective control [17]. A multivariable predictive controller built on first-order models has been compared with proportional-integral loops on a dehydration unit's feed pressure and heater temperature [12].

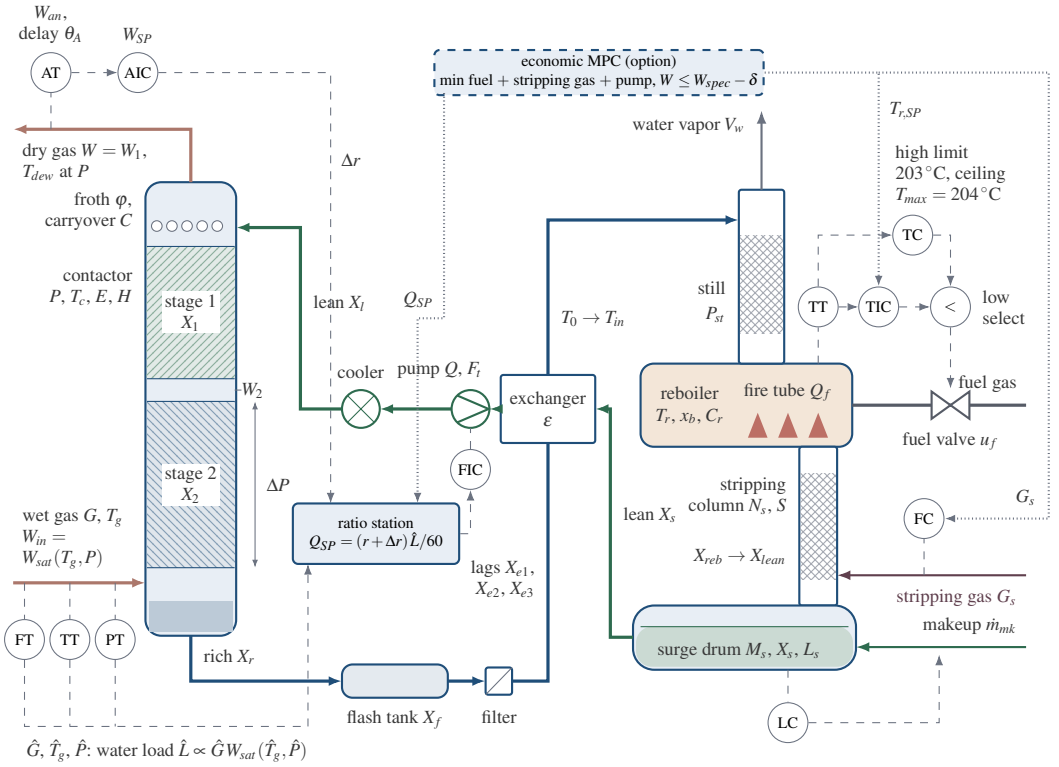


Figure 7.1 TEG dehydration unit as modeled, after the application's wide Unit view. Wet gas G at T_g, saturated with W_{in}, rises through two stages holding X_1 and X_2 at contactor temperature T_c and efficiency E, and leaves with W past the analyzer AT, which reports W_{an} after the delay θ_A. The rich glycol X_r passes the flash tank X_f, the filter, three lags X_{e1} to X_{e3} and the cold side of the lean–rich exchanger of effectiveness ε to the still on the reboiler (T_r, duty Q_f from the fuel valve u_f), which boils off V_w. The stripping column with N_s stages and stripping gas G_s takes X_{reb} to X_{lean}, the surge drum holds M_s at X_s and level L_s, and the pump returns Q through the lean line X_l. The ratio station sets Q_{SP} from the water load $\hat{L}$ and the analyzer trim Δr, the TIC and the high-limit override meet at a low select on u_f, the FC holds G_s, the LC switches the makeup $\dot{m}_{mk}$, and the optional MPC (dotted) sets Q_{SP}, $T_{r,SP}$ and G_s. The contactor level and flash tank pressure loops are not modeled. The drawing shows the process model and is neither an instrument diagram nor to scale.

7.3 A Contactor and Its Regenerator as Modeled

The simulated unit is a generic TEG dehydrator for 60 t/h of a gas of 0.846 kg/Sm^3 at 60 bar, 1182 Sm^3/min or 60.2 million standard cubic feet per day, as shown in Figure 7.1. Wet gas saturated at the inlet temperature enters the bottom of a packed contactor of two theoretical stages and leaves the top past a moisture analyzer. The rich glycol passes a flash tank, a filter and the cold side of the lean–rich exchanger into a still on a fired reboiler at atmospheric pressure, flows down a stripping column into the surge drum, and returns across the exchanger through a pump and a cooler to the top of the contactor. Water contents are carried in milligrams per standard cubic meter at 15 °C and shown in pounds per million standard cubic feet at 60 °F, with 1 lb/MMscf = 16.05 mg/Sm^3. The clock is the minute.

Each variable in Table 7.1 has a role in the loops. Seventeen physical states are integrated, the water per kilogram of TEG on the two stages X_1 and X_2, in the flash tank X_f and in three transport lags X_{e1} to X_{e3}, the reboiler temperature T_r, the TEG in the surge drum M_s and its water ratio X_s, the

Table 7.1 Dehydrator Variables, Their Roles and Design Values (Case 3 at $t = 0$)

Variable	Role	Design	Range
W	CV, water in dry gas (true)	6.73 lb/MMscf	spec 7 lb/MMscf
W_{an}	measured W, 10 min late	6.73 lb/MMscf	2-min samples
T_r	CV, reboiler	200.0 °C	SP 150–204 °C
L_s	CV, surge drum level	60 %	low 30, trip 10
Q	MV, circulation	24.28 L/min	0–50 (standby 16)
r, Δr	MV, ratio and trim	22 L/kg, 0	5–60 L/kg
u_f	MV, fuel valve	44.2 %	0–100 %
G_s	MV, stripping gas	0	0–50 Sm^3/h
$\dot{m}_{mk}$, antifoam	MV, on or off	Auto, off	60 kg/h, on
G	DV, gas flow	60 t/h	30–90 t/h
T_g	DV, inlet temperature	35 °C	20–50 °C
a_f, a_s	DV, fuel, stripping supply	100 %	20–100, lost
pump, h	DV, standby pump, slug	main, 0	16 L/min, 1.5
X_1, X_2	states, stages	0.0177, 0.0466	kg/kg
X_f, $X_{e1..3}$	states, rich transit	0.0466	kg/kg
M_s, X_s	states, surge drum	784.4 kg, 0.00971	—
Q_f	state, absorbed duty	110.6 kW	0–250 kW
φ, a	states, foam, antifoam	0.45, 0	carryover above 1
T_c, E	outputs, contactor	36.09 °C, 0.90	—
T_{dew}	output, dew point at P	−1.61 °C	—
w_{lean}, w_{rich}	outputs, purities	99.04, 95.55 wt%	—
ΔP, losses	outputs, foam signs	25 mbar, 1.12 kg/h	—
energy	output, fuel + strip + pump	151.5 kW	budget 250 kW

lean line X_l, the delivered circulation Q, the absorbed burner duty Q_f, the stripping gas flow G_s, the foam index φ, the liquid hydrocarbon in the glycol h, the antifoam at the packing a and the makeup flow $\dot{m}_{mk}$. Nine more states are ledgers that integrate every boundary flow of water and TEG, so both balances can be checked to round-off. The gas side, the reboiler composition and the stripping column are algebraic at each instant.

7.3.1 Water in the Gas and Its Dew Point

The inlet gas carries the saturated water content of the Bukacek form, a two-term algebraic fit of the McKetta–Wehe chart, and the dew point is its inverse at the contactor pressure, as shown in Equation (7.1).

$$W_{sat}(T,P) = 16.05\left[47\,484\,\frac{p_v(T)}{P} + 10^{6.69449-3083.87/T_R}\right]$$
$$W_{in} = W_{sat}(T_g,P), \qquad W_{sat}(T_{dew},P) = W \tag{7.1}$$

where W_{sat} is in mg/Sm^3, P and the vapor pressure of water p_v are in psia and T_R is the temperature in degrees Rankine. Above 0 °C p_v is the region 4 saturation line of IAPWS-IF97 [18], and below it the Magnus form over supercooled water, so a dew point under 0 °C is that of metastable liquid water. The inlet at 35 °C carries 58.18 lb/MMscf and at 45 °C 96.32 lb/MMscf, 1.66 times as much. Against a published fit of the McKetta–Wehe chart for sweet gas [19] the form gives 0.0, −0.2 and −0.4 % at 35, 38 and 45 °C and 60 bar. A water content of 7 lb/MMscf is a dew point of −1.0 °C at 60 bar.

7.3.2 Water Held by the Glycol

The gas in equilibrium with a TEG solution carries the water activity of the solution times the saturated content at the contactor temperature, with a one-parameter Margules coefficient, as shown in Equation (7.2).

$$W_{eq}(X) = \gamma_w x_w W_{sat}(T_c,P), \qquad \ln\gamma_w = A(T)(1-x_w)^2$$
$$A(T) = 0.256 - \frac{228.7\,\mathrm{K}}{T}, \qquad x_w = \frac{X/M_w}{X/M_w + 1/M_T} \tag{7.2}$$

where X is the water per kilogram of TEG, x_w its mole fraction and $M_w = 18.015$ and $M_T = 150.17$ the molar masses. The coefficient is a teaching correlation, not a fit, with $\gamma_\infty = 0.615$ at 35 °C and 0.800 at 204 °C. Because the activity is nearly proportional to the water left in the glycol, each tenfold cut in that water buys about the same step in dew point, so the depression rises steeply with purity. At a 35 °C contactor the equilibrium dew point at 60 bar is −7.7, −13.4, −22.8, −42.6 and −67.1 °C over 98.5, 99.0, 99.5, 99.9 and 99.99 wt%, a depression from 42.7 to 102.1 K. Against published readings and a published fit of the TEG–water dew-point chart of the Gas Processors Suppliers Association, drawn from the measurements of Parrish, Won and Baltatu, these dew points lie within about 1 K from 98.5 to 99.9 wt% and about 3 K drier at 99.99 wt%. The largest difference among the readings is at 99.9 wt%, 100 °F and 1000 psia, where the model gives −41.5 °C and the chart −40 °C. The measurements above 99.8 wt% are the ones the literature found least consistent [3].

7.3.3 Two Stages and the Floor They Leave

Each stage holds H of TEG and passes a share E of the way to equilibrium on the gas side, and its water ratio follows from a balance on the glycol, as shown in Equation (7.3).

$$\begin{aligned} W_2 &= (1-E)\,W_{in} + E\,W_{eq}(X_2) \\ W &= (1-E)\,W_2 + E\,W_{eq}(X_1) \\ H\frac{\mathrm{d}X_1}{\mathrm{d}t} &= F_t X_l - (F_t - v)X_1 + G(W_2 - W) \\ H\frac{\mathrm{d}X_2}{\mathrm{d}t} &= F_1(X_1 - X_2) + G(W_{in} - W_2) \\ T_c &= T_g + \frac{Lc_{pL}\,\Delta T_\ell + h_{abs}N}{G_m c_{pG} + Lc_{pL}} \end{aligned} \tag{7.3}$$

where G is the gas in Sm^3/min (with the water contents in kg/Sm^3 in these balances), $F_t = \rho Q/(1+X_s)$ the TEG pumped, v the TEG vaporized into the gas at its partial pressure over the top stage, $F_1 = F_t - C_T - v$ the TEG leaving the top stage after the carryover C_T, L the solution flow, $\Delta T_\ell = 5$ K the lean glycol's approach above the gas, N the water absorbed and G_m the gas mass flow. The contactor temperature is found in two passes, the second with the absorption of the first. At design $T_c = 36.09$ °C, the stages hold 0.0177 and 0.0466 kg/kg, the gas leaves stage 2 with 17.89 lb/MMscf and stage 1 with 6.73 lb/MMscf, 88.4 % of the inlet water is absorbed, and the gas in equilibrium with the lean glycol would carry 3.05 lb/MMscf.

With unlimited circulation both stages sit at the lean composition and the outlet tends to $W^* + (1-E)^2(W_{in} - W^*)$, with W^* the equilibrium over the lean glycol, which is the floor no circulation can buy. Two stages at $E = 0.9$ pass 1 % of the inlet water's excess over W^*. This is the floor of Equation (1.12) at an unlimited absorption factor, with each ideal stage replaced by one of efficiency E.

Pause. Try Exercise 7.1 before reading on.

7.3.4 The Still at Its Bubble Point

The reboiler boils the rich glycol down to the composition whose bubble point at the still pressure is its temperature, as shown in Equation (7.4).

$$\begin{aligned} P_{st} &= x_b\,\gamma_w(x_b, T_r)\,p_{sat}(T_r) + (1-x_b)\,p_{TEG}(T_r) \\ p_{TEG}(T) &= p_0 \exp\Big[-\beta\Big(\frac{1}{T} - \frac{1}{T_b}\Big)\Big] \\ X_{reb} &= \min[X_r,\ X(x_b)], \qquad V_w = F_2\,(X_r - X_{reb}) \end{aligned} \tag{7.4}$$

where p_{sat} is the IAPWS-IF97 saturation pressure, $P_{st} = 1.013\,25$ bar, p_{TEG} a Clausius–Clapeyron teaching fit through the normal boiling point of TEG, $p_0 = 101.325$ kPa at $T_b = 558.15$ K (285 °C)

with $\beta = 8800\,\mathrm{K}$, $X_r = X_{e3}$ the rich glycol arriving and $F_2 = F_1$ its TEG flow. The bubble point is solved by six Newton steps from the infinite-dilution guess, a fixed count. The reboiler makes 98.76 wt% at 190 °C, 99.04 at 200 °C, 99.11 at 203 °C and 99.13 at 204 °C, with $\gamma_w = 0.823$ at design. These purities are 0.48, 0.36 and 0.34 wt% above the 98.0, 98.5 and 98.8 wt% that a published process simulation gives at 360, 380 and 400 °F (182.2, 193.3 and 204.4 °C) at one atmosphere [10], so this reboiler leaves 0.72 to 0.75 times the water that one does. The fit was kept because it meets the targets of the plan for the application, about 98.5 wt% at 190 °C and 99.1 wt% at 204 °C, and because a refit to the published values would move every case. With 98.68 wt% at 200 °C, the published value interpolated, the design ratio of 22 L/kg would leave 7.71 lb/MMscf and the specification would need about 28 L/kg. The vapor pressure of TEG lies 22 % under Stull's data at 200 °C and moves the purity by 0.016 wt%.

7.3.5 Stripping Below the Reboiler

Dry gas blown up the stripping column removes a further share of the water, from the Kremser relation for N_s theoretical stages, as shown in Equation (7.5).

$$X_{lean} = X_{reb}\,\frac{S-1}{S^{N_s+1}-1}, \qquad S = \frac{\gamma_w\, p_{sat}(T_r)}{P_{st}} \cdot \frac{g/V_m}{\rho_h/M_T} \tag{7.5}$$

where $g = G_s/(0.06\,Q)$ is the stripping gas in $\mathrm{Sm^3}$ per cubic meter of glycol, $V_m = 23.645\,\mathrm{Sm^3/kmol}$, $\rho_h = 1010\,\mathrm{kg/m^3}$ the hot glycol density and $N_s = 2$. At 203 °C and 24.3 L/min the equilibrium ratio is 13.45, and 5, 10, 20 and 45 $\mathrm{Sm^3/h}$ give S = 0.29, 0.58, 1.16 and 2.61 and 99.35 wt%, 99.53, 99.74 and 99.91 leaving the column. Stripping gas also takes from the reboiler 0.9 of the heat that warms it from ambient to T_r (q_s below), and it is counted at its heating value, $36\,\mathrm{MJ/Sm^3}$ or 10 kW per $\mathrm{Sm^3/h}$.

7.3.6 The Reboiler's Heat Balance

The reboiler temperature is a state whose energy balance carries the duty, the sensible heat of the rich glycol after the exchanger, the heat of boiling with reflux and the losses, as shown in Equation (7.6).

$$\begin{aligned} C_r\frac{\mathrm{d}T_r}{\mathrm{d}t} &= Q_f - F_2(1+X_r)\,c_{pL}(T_r - T_{in}) - V_w\lambda\,(1+R) \\ &\quad - UA\,(T_r - T_{amb}) - q_s \\ T_{in} &= T_0 + \varepsilon\,(T_r - T_0), \qquad T_0 = T_c + 30\,\mathrm{K} \end{aligned} \tag{7.6}$$

where every term is in kJ/min, so a duty in kW enters multiplied by 60, T_0 is the rich glycol after the reflux coil, q_s the heat taken by the stripping gas, and the other symbols are listed in Table 7.2. At design the burner delivers 110.6 kW, of which 46.3 kW heats the rich glycol arriving at 159.8 °C, 46.8 kW boils off 58.6 kg/h of water and 17.5 kW is lost, 44.2 % of a 250 kW burner and 147.5 kW of fuel burned at a firing efficiency of 0.75. At a fixed duty the reboiler's own time constant is 112 min. More circulation means more glycol to heat, so at a fixed duty it lowers T_r and the purity with it, which is the coupling that Manual operation and the fuel limit expose.

7.3.7 The Glycol Loop, Losses and Foam

The rich glycol passes the flash tank and three equal lags for the filter, exchanger and lines, $H_f\dot{X}_f = F_2(X_2 - X_f)$ and $(H_{tr}/3)\dot{X}_{ei} = F_2(X_{e,i-1} - X_{ei})$, together 16.4 min of residence at design. The surge

drum and the loop's losses close the circuit, as shown in Equation (7.7).

$$\begin{aligned} \frac{\mathrm{d}M_s}{\mathrm{d}t} &= F_{ret} + \dot{m}_{mk} - F_t, \qquad F_{ret} = F_2 - v_s - r_d \\ M_s \frac{\mathrm{d}X_s}{\mathrm{d}t} &= F_2 X_{lean} - X_s (F_{ret} + \dot{m}_{mk}) \\ H_l \frac{\mathrm{d}X_l}{\mathrm{d}t} &= F_t (X_s - X_l) \\ C &= C_0 \frac{G}{G_0} + C_f \max(0, \varphi - 1)^{1.5} \\ \tau_\varphi \frac{\mathrm{d}\varphi}{\mathrm{d}t} &= \varphi_0 \, \tau_f \left(\frac{G}{G_0} \right)^2 - \varphi, \qquad \tau_f = \tau_{f0} \frac{1 + k_h h}{1 + k_a a} \end{aligned} \tag{7.7}$$

where v_s is the TEG leaving the still overhead after a 98 % reflux recovery, $r_d = k_d[\exp((T_r - T_{max})/4\,\mathrm{K}) - 1]$ the decomposition above the ceiling T_{max}, C the solution carried over with the gas, h the liquid hydrocarbon from a slug, cleared with a time constant of 60 min, and a the antifoam reaching the packing over 5 min. The surge drum level is $L_s = 100 M_s (1 + X_s)/(\rho V_s)$ in percent. The foam lowers the stage efficiency, $E = E_0/[1 + k_E \max(0, \varphi - 1)]$, and raises the pressure drop, $\Delta P = \Delta P_0 (G/G_0)^2 (1 + 0.8\varphi^2)/(1 + 0.8\varphi_0^2)$. At design the unit loses 0.49 kg/h of TEG by carryover, 0.02 kg/h into the gas and 0.61 kg/h from the still, 1.12 kg/h in all, and the surge drum holds 784.4 kg of TEG at 60 %, a turnover of 29.7 min.

7.3.8 Actuators, Instruments and Energy

The pump, burner, stripping gas valve and makeup pump follow their commands through first-order lags of 0.2, 1.0, 0.3 and 0.5 min. The pump delivers at most 50 L/min, or 16 L/min on the standby pump, the stripping gas at most 50 $\mathrm{Sm^3}$/h, and the burner at most 250 kW times the fuel available. The moisture analyzer draws a sample every 2 min and reports it 10 min after it left the gas, 8 min of sample line and 2 min of analysis, with 0.05 lb/MMscf of noise. The gas meter has a 6 s lag and 0.2 % of noise, the inlet temperature a 30 s lag and 0.05 K, the reboiler thermocouple an 18 s lag and 0.1 K, the circulation meter 0.3 % of noise and the level 0.2 percentage points. The noise is seeded as described in Section 1.6.1, so two runs that differ in one setting see identical noise. The energy the challenge judges is the fuel burned, the stripping gas at its heating value and the pump's shaft work, 0.164 kW per L/min against 59 bar, 151.5 kW at design. A burner trip at 210 °C and a pump trip at a 10 % surge level latch and stop the run.

7.3.9 Parameters, Start and Integration

Table 7.2 gives every parameter. None was measured on a plant. They were chosen as typical of a TEG unit of this size and so that the design point closes. A case starts lined out at its own settings, with the circulation its architecture asks for and the reboiler at its setpoint, the contactor solved by Newton's method on the two stage balances, the still and the surge drum iterated to a consistent lean composition, and the stations of Manual lined up with the automatic operating point. At design the derivatives of the compositions and of the reboiler temperature are below 2×10^{-16} of their states, and the surge drum falls only by the losses until the makeup pump runs. Integration uses fourth-order Runge–Kutta steps of 2 s, the controllers execute every 6 s and a row is logged every minute, on the engine of Section 1.6.1. Halving the step moves no lesson number by more than 1.05×10^{-6} of its value and no crossing time or verdict. At the end of every case, as shipped and with its learner moves, the water ledger closes to 6.4×10^{-13} and the TEG ledger to 2.1×10^{-14} of what entered. A simulated hour costs well under 0.1 s of computing in a JavaScript engine, with or without the MPC.

7.3.10 Assumptions and Where They Fail

The contactor is two well-mixed stages with a gas-side efficiency, not a packed bed with mass-transfer coefficients, and the gas holds no water, so the outlet answers a stage at once. That is enough for the

Table 7.2 Model Parameters (A Adjustable in the Application, H Hidden From the Learner, F Constant in the Code)

Symbol	Meaning	Value	Unit	
P	contactor pressure (absolute)	60	bar	A
G_0, ρ_G	design gas, density at 15 °C	60, 0.846	t/h, kg/Sm^3	H
c_{pG}, c_{pL}	gas, glycol heat capacity	2.4, 2.5	kJ/(kg K)	H
E_0	stage efficiency (Murphree, gas)	0.90	—	A
H	TEG holdup per stage	55	kg	A
ΔT_ℓ	lean glycol above inlet gas	5	K	A
h_{abs}	heat of absorption	2400	kJ/kg	H
ρ, ρ_h	lean, hot glycol density	1100, 1010	kg/m^3	H
H_f, H_{tr}	flash tank, transit holdup (TEG)	270, 165	kg	A
H_l	lean line and cooler holdup	55	kg	H
V_s	surge drum volume	1.2	m^3	A
Q_{max}, Q_{sb}	main, standby pump	50, 16	L/min	A
τ_P, η_P	pump lag, efficiency	0.2, 0.6	min, —	H
$\dot{m}_{mk}$, τ_{mk}	makeup rate, lag	60, 0.5	kg/h, min	A, H
L_{lo}, L_{trip}	low alarm, pump trip level	30, 10	%	A
—	Margules constants of $A(T)$	0.256, −228.7	—, K	F
β, T_b	TEG vapor pressure slope, boiling point	8800, 285	K, °C	F
P_{st}	still pressure	1.01325	bar	A
$Q_{f,max}$	burner capacity (absorbed)	250	kW	A
η_F, τ_F	firing efficiency, burner lag	0.75, 1	—, min	H
C_r	reboiler heat capacity	3000	kJ/K	A
ε	lean–rich exchanger effectiveness	0.70	—	A
—	reflux coil heating ($T_0 - T_c$)	30	K	H
λ, R	heat to boil water, reflux	2300, 0.25	kJ/kg, —	H
UA, T_{amb}	reboiler loss, ambient	0.1, 25	kW/K, °C	H
N_s	stripping column stages	2	—	A
$G_{s,max}$, τ_G	stripping gas valve, lag	50, 0.3	Sm^3/h, min	A, H
—	still TEG recovery	0.98	—	H
T_{max}, T_{trip}	ceiling, burner trip	204, 210	°C	A
k_d	decomposition scale	2	kg/h	H
LHV	fuel and stripping gas	36	MJ/Sm^3	H
τ_{f0}, φ_0	foaming tendency, design foam	1.0, 0.45	—	A, H
k_h, k_a, k_E	slug, antifoam, efficiency gains	2.5, 3, 0.6	—	H
τ_h, τ_a, τ_φ	slug, antifoam, foam times	60, 5, 3	min	A, H, H
C_0, C_f, ΔP_0	mist, foam carryover, clean drop	0.5, 113, 25	kg/h, kg/h, mbar	H, A, H

floor, the diminishing return on circulation and plausible sizes, though not for sizing a real contactor. The same temperature serves both stages. The equilibrium scales the saturated content by the water activity, the activity coefficient, the vapor pressure of TEG and the two theoretical stripping stages are teaching correlations, and the reboiler is purer than published simulations by the amounts stated above. The saturated content is that of sweet gas, without corrections for gravity, salt, carbon dioxide or hydrogen sulfide, and below 15 °C the dew point extrapolates the Bukacek form below its stated range. The still is quasi-steady at its bubble point and holds no water, the flash tank and the lines carry composition at constant holdups with no flashed hydrocarbon, and the contactor level and the flash tank pressure are taken as held by their own fast loops, which are not modeled and have no faceplates. Foam, carryover, vaporization and decomposition are synthetic laws chosen for about 1 kg/h of losses at design and about 220 kg/h at the foam peak of case 7. The 204 °C ceiling, the 210 °C burner trip, the 10 % level trip and the 7 lb/MMscf specification are teaching values. The ceiling sits just under the 207 °C decomposition temperature a published design study gives for TEG [10], while real limits come from the glycol supplier's data, the unit's design standard and its burner management system, and the water specification from the transport contract [2].

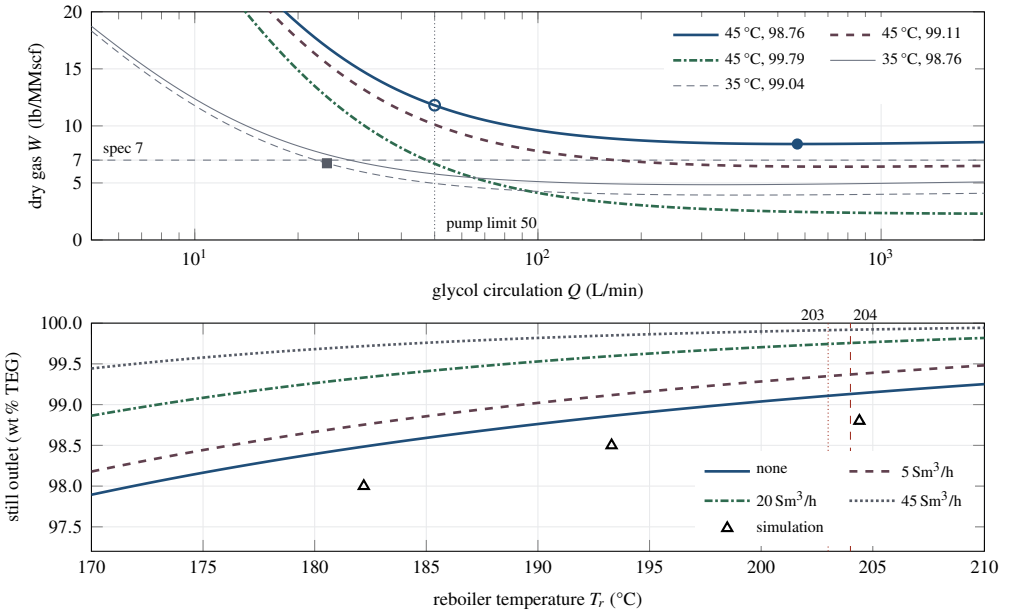


Figure 7.2 The two handles from the application's own functions. Top, steady water in the dry gas against circulation for the 45 °C inlet of case 5 and the 35 °C design inlet, each at the lean purity in wt % the legend names. The 45 °C curves are thick (98.76 solid, 99.11 dashed, 99.79 dash-dotted), and the 35 °C curves are thin and gray (98.76 solid, 99.04 densely dashed). The horizontal dashed line is the specification and the vertical dotted line the pump limit. The filled dot is the 45 °C floor at 98.76 wt%, 8.41 lb/MMscf near 570 L/min, the ring is the state of Figure 7.3, and the square is the design point. Bottom, glycol leaving the still against reboiler temperature at 24.3 L/min with no stripping gas (solid) and with 5 (dashed), 20 (dash-dotted) and 45 Sm^3/h (dotted), beside the 203 °C override (dotted vertical) and the 204 °C ceiling (dashed vertical). Triangles are a published process simulation at one atmosphere [10].

7.4 A Fast Handle, a Slow Handle and Two Limits

The two handles act through different holdups. Circulation reaches the outlet through the stages, 2.08 min of glycol each at design, so in case 1 a step from 15 to 30 L/min at 10 min takes the water under 7 lb/MMscf at 17 min. Purity reaches the outlet only as the surge drum turns over. In case 4 the glycol leaving the still is at 99.11 wt% by 30 min while the glycol entering the contactor is still at 98.88 wt%, and the water crosses under the specification 32 min after the reboiler step.

The steady water in the dry gas against circulation and the purity the still delivers against reboiler temperature, computed with the application's own functions, are shown in Figure 7.2. At the design inlet, 99.04 wt% glycol at 24.3 L/min gives 6.73 lb/MMscf and the least water any circulation reaches is 3.94 lb/MMscf, near 390 L/min. On the 45 °C inlet with 98.76 wt% glycol the least is 8.41 lb/MMscf near 570 L/min, above the specification, and with unlimited glycol the water returns to 8.87 lb/MMscf because the glycol, 5 K warmer than the gas, warms the contactor. At 50 L/min the contactor is at 46.8 °C, where the gas in equilibrium with the lean glycol already carries 6.83 lb/MMscf, and even with perfect stages the least would be about 7.2 lb/MMscf. The floor is a property of the equilibrium and the stage efficiency, so of the operator's handles only purity moves it. At 99.11 wt%, the most the reboiler gives under its override, the least water is 6.43 lb/MMscf, and at the 99.79 wt% that 50 Sm^3/h of stripping gas makes, 50 L/min reaches 6.69 lb/MMscf.

The lower panel shows the ceiling. Heat alone moves the still outlet from 98.76 wt% at 190 °C to 99.11 at 203 °C, a gain of 0.35 wt%, and past that point each further Sm^3/h of stripping gas buys less

purity than the last. At 203 °C the first 5 Sm^3/h raise the purity by 0.24 wt% for 47 kW, while the step from 20 to 45 Sm^3/h raises it by 0.17 wt% for 251 kW. The two limits therefore bound a cheap region and an expensive one. A specification below the floor cannot be met by circulation at all, and above the ceiling every tenth of a percent of purity is paid for in stripping gas.

At a fuel limit the handles stop being independent. When the burner is wide open, every extra liter of glycol is a liter the reboiler cannot heat to its setpoint, so the purity falls and the floor rises. A loop that answers a wet analyzer with more circulation then makes the gas wetter, the opposite of its intent, which is what the challenge of Section 7.6 tests.

🕮 **Pause.** Try Exercise 7.3 before reading on.

7.5 The Controllers in the Code

The controllers execute every $\Delta t_c = 0.1$ min, three physics steps, and read nothing of the plant but a packet holding the analyzer's last report, the gas meter, the inlet temperature and pressure, the reboiler thermocouple, the flows, the level, the contactor pressure drop and the pump's motor contacts. An application test fails if any other key appears in it. The header's Manual and Auto switch the pump and the fuel valve together, and in Manual both sit at their stations while every loop tracks them, so a transfer back to Auto is bumpless (Section 1.6.2).

7.5.1 The Common PID

The reboiler loop and the trim use the framework's velocity-form PID of Section 1.6.2, written in this chapter's symbols in Equation (7.8), with σ for the action a of Equation (1.16).

$$
\begin{aligned}
e_k &= \sigma\,(\mathrm{SP}_k - \mathrm{PV}_k), \qquad P_k = K_c e_k \\
s_k &= s_{k-1} + P_k - P_{k-1}, \qquad \hat{u}_k = u_0 + s_k + I_{k-1} \\
u_k &= \min\!\big[\max(\hat{u}_k, u_{lo}), u_{hi}\big] \\
I_k &= I_{k-1} + \Big[\frac{K_c}{\tau_I} e_k + \frac{u_k - \hat{u}_k}{T_t}\Big]\Delta t
\end{aligned}
\tag{7.8}
$$

where $\sigma = \pm 1$ sets the direction, $T_t = \tau_I$, and integral times of 600 min and longer turn the integral off. Neither loop uses derivative action. The reboiler loop (TIC) acts with $\sigma = +1$ on the fuel valve, so a reboiler 1 K under its setpoint opens the valve 3 points, with $K_c = 3\,\%/\mathrm{K}$, $\tau_I = 45$ min, limits 0 and 100 % and $\Delta t = \Delta t_c$.

7.5.2 The High-Limit Override

A proportional override with external reset feedback acts 1 K under the ceiling and meets the TIC at a low select, as shown in Equation (7.9).

$$
\begin{aligned}
u_{HL} &= \mathrm{clip}\big[K_{HL}(T_{HL} - \tilde{T}_r) + \tilde{u}_f,\ 0,\ 100\big] \\
u_f &= \min(u_{TIC}, u_{HL}), \qquad \tau_{fb}\frac{\mathrm{d}\tilde{u}_f}{\mathrm{d}t} = u_f - \tilde{u}_f
\end{aligned}
\tag{7.9}
$$

where $K_{HL} = 10\,\%/\mathrm{K}$, $T_{HL} = 203\,^\circ\mathrm{C}$, $\tilde{T}_r$ is the thermocouple through a 0.5 min filter and $\tilde{u}_f$ the applied fuel command through the lag $\tau_{fb} = 2$ min. When the override is selected the TIC tracks its output. Because the feedback is the valve actually applied, the override holds the reboiler just under the limit when it is in command and stays out of the way below it, the external-reset form of Section 1.4.8. A jet engine's fuel control selects among several limiters on the same principle (Volume 4, Chapter 3). After a setpoint step to 204 °C in case 4 the thermocouple peaks at 203.7 °C and settles at 202.7 °C. The override does not hold the ceiling on a sudden loss of load. With the setpoint at 204 °C before the pump trip of case 8, the true reboiler reaches 204.21 °C and stays above 204 °C for 2.3 min, decomposing 2.6 g of TEG, and the gas returning to 60 t/h in case 3

gives 204.12 °C for 1.8 min. The override acts 1 K below the ceiling through a filter on an 18 s thermocouple, while the burner answers in a minute and the load vanishes in seconds. In Manual nothing holds the ceiling, and a fuel valve wide open from 5 min trips the burner at 13.4 min.

7.5.3 Ratio Feedforward and Analyzer Trim

Circulation is fixed at a setpoint, set in ratio to the water load the instruments infer, trimmed by the analyzer, or left to the MPC, as shown in Equation (7.10).

$$\begin{aligned} \hat{L} &= \frac{10^{-3}\,\hat{G}\,W_{sat}(\hat{T}_g,\hat{P})}{\rho_G}, \qquad Q_{SP} = \frac{(r+\Delta r)\,\hat{L}}{60} \\ \Delta r &= \mathrm{PI}(W_{an} - W_{SP}) \\ r_{lo} - r \le \Delta r &\le \min(r_{hi},\ 60\,Q_{cap}/\hat{L}) - r \end{aligned} \tag{7.10}$$

where $\hat{L}$ is the water load in kg/h from the gas meter $\hat{G}$ in t/h and the measured inlet temperature and pressure, $r = 22\,\mathrm{L/kg}$ by default, $r_{lo} = 5$ and $r_{hi} = 60\,\mathrm{L/kg}$, and Q_{cap} the capacity of the running pump. The ratio is a feedforward on both disturbances. The trim is the PID of Equation (7.8) with $\sigma = -1$, $K_c = 3\,\mathrm{L/kg}$ per lb/MMscf, $\tau_I = 20\,\mathrm{min}$ and a target W_{SP} of 6.5 lb/MMscf, below the specification for the analyzer's 10 min delay. A slow analyzer limits composition loops in the same way on a distillation column (Volume 5, Chapter 3). It executes once per fresh report over the time since its last execution, and its upper bound is the ratio the pump can deliver, so it cannot wind up against a saturated pump. Switched off, it tracks no correction, so switching it on is bumpless.

7.5.4 Economic Predictive Control

With MPC selected, a receding-horizon quadratic program sets the circulation, the reboiler setpoint and the stripping gas every 2 min over a 2 h horizon, as shown in Equation (7.11). It specializes the framework's predictive controller of Section 1.6.3 with linear energy prices on the inputs.

$$\begin{aligned} \min_{u} \ & \sum_{k=1}^{60} c^{\top} u_k + \sum_{j} \Delta u_j^{\top} S\,\Delta u_j + 10^{3}\varepsilon^{2} + 10^{4}\varepsilon \\ \text{s.t.} \ & \hat{W}_k = W_{map}(\bar{z}) + K(z_k - \bar{z}) + b \le W_{spec} - \delta + \varepsilon \\ & z_{k+1} = A_d z_k + B_d u_k + c_d, \qquad u_{lo} \le u_k \le u_{hi} \end{aligned} \tag{7.11}$$

where $u = [Q,\ T_{r,SP},\ G_s]$ and the states z are those inputs lagged through what each passes on its way to the outlet, the circulation through $\tau_Q = 4\,\mathrm{min}$, the reboiler setpoint through $\tau_T = 10\,\mathrm{min}$ and then the surge drum's turnover, and the stripping gas through the surge drum. The map W_{map} is the controller's own copy of the steady contactor and still of Section 7.3, fed by the measured gas, inlet temperature and pressure with the parameters in force when the case started, a Wiener model linearized by central differences at every execution, so the gain K falls toward zero as the circulation approaches the floor. The linear costs c are each input's marginal energy in kW of fuel, about 2.8 kW per L/min of circulation for reheating and pumping, the fuel to hold a hotter reboiler, and 10 kW per $\mathrm{Sm^3/h}$ of stripping gas. The water bound is soft, with a margin $\delta = 1\,\mathrm{lb/MMscf}$ and one slack ε. Move suppression on the block increments Δu_j is $S = \mathrm{diag}(2, 2, 10)$, a weight of 10^{-6} on the inputs themselves keeps the program strictly convex, the bounds are 5 to Q_{cap}, 170 to 203 °C and 0 to 50 $\mathrm{Sm^3/h}$, the moves are limited to 6 L/min, 1 K and 6 $\mathrm{Sm^3/h}$ per execution, and the 60 steps are blocked as 1, 1, 2, 4, 8, 14 and 30. The bias b is updated from each analyzer report against the model's value when the sample left the tap, $b \leftarrow b + 0.2(e - b)$, so the comparison is made at the instant the sample describes and the delay does not appear as a model error.

When the fuel valve has stood at 99.5 % or more for 30 s, the MPC holds the reboiler setpoint where it is, adds the thermal path of circulation through the limited duty to its model, and caps the circulation at what the burner can heat to within 1 K of the setpoint, approached at 1.5 L/min per

Table 7.3 The Nine Cases

#	Case, preset and events	Teaching point
1	Fixed 15 L/min, 190 °C, map view	the operating map
2	Fixed 24.3 L/min, gas +30 % at 30 min	a disturbance, a late analyzer
3	Ratio, gas +30 % at 30 and back at 120 min, inlet +2 K from 150 min	feedforward and trim
4	Ratio, 190 °C, regeneration view	the reboiler ceiling
5	Ratio, 190 °C, inlet 35 to 45 °C over 30–90 min	the floor
6	Ratio, 203 °C	stripping gas and its price
7	70 t/h, makeup off, drum 40 %, slug at 30 min	foam and inventory
8	Ratio, main pump trips at 30 min (standby 16 L/min)	purity without circulation
9	Challenge, 24 h, fixed 24.3 L/min, 200 °C	the whole problem

execution. If the program fails, the last inputs are held. The program is condensed and solved by the framework's shared dense quadratic program solver (`shared/src/framework/core/linmpc.js` and `qp.js`). In the challenge it solves 720 times with no fallback.

7.5.5 Three Models Kept Apart

The plant is the whole of Section 7.3. The identified model is whatever a learner fits to a step, such as the 2.08 min stage holdups behind a circulation step, the 29.7 min surge drum behind a purity step and the 112 min reboiler at a fixed duty. The controllers' model is the MPC's copy of the steady map with lagged inputs and commissioned parameters, corrected only by the analyzer bias, which sees neither the foam nor any parameter edited during the run. The burner and pump trips read the simulator's truth and are teaching guardrails, not certified protection. The exported CSV file pairs each instrument column with the true quantity behind it, and every true column carries the prefix `truth_`, so a controller replayed from the file is kept from reading it.

7.6 Nine Cases on the Running Engine

The nine cases appear in Table 7.3. Each begins from the defaults of Section 7.5, Ratio at 22 L/kg, the reboiler at 200 °C, no stripping gas, the makeup on Auto and the design gas, unless its row states otherwise. Every number below comes from the engine stepped headlessly at the default seed exactly as the browser steps it, with a move named with a time made at that minute of the run (Section 1.6.4 describes how a case is named and run). Opening a case first, selecting it after another case and restarting it with Reset all produce one trajectory. The measured outcomes are collected in Table 7.4.

7.6.1 The Map, the Gas Rate and the Ratio

Case 1 opens at 15 L/min, 13.6 L per kilogram of water, and 98.76 wt% glycol from a 190 °C reboiler, with the gas at 9.67 lb/MMscf. Doubling the circulation takes off 2.84 of those lb/MMscf, and the next 20 L/min only 1.04 more. Raising the reboiler to 204 °C at 15 L/min reaches 8.83 lb/MMscf, because too little glycol carries the water away whatever its purity. The case runs in Auto with the circulation on Fixed for a reason the learner meets in Manual. There the fuel valve is held too, and 30 L/min on the pump cools the reboiler from 190 to 154 °C and leaves 12.2 lb/MMscf, worse than the start.

In case 2 the gas rises 30 % at 30 min and the water load from 66.2 to 86.1 kg/h, so the fixed 24.3 L/min falls from 22 to 16.9 L/kg. The true water passes 7 lb/MMscf one minute later and settles near 7.82 lb/MMscf, while the analyzer, reading gas that left 10 min earlier, reports OFF SPEC at 43 min. About 29.5 L/min is the least circulation that restores the specification.

Table 7.4 Measured Outcomes by Case, Default Seed (Water in lb/MMscf)

#	Setting	Outcome
1	as shipped	9.67, dew point 4.0 °C
	30 or 50 L/min at 10 min	under 7 at 17 min, 6.83 or 5.79 at 240 min
	204 °C at 15 or 25 L/min	8.83 or 6.43
	Manual, pump 30 L/min	reboiler 154 °C, 12.2
2	as shipped	over 7 at 31 min, peak 7.87, OFF SPEC at 43 min
	28, 29.5, 30 L/min at 60 min	7.20, 6.99, 6.92 at 240 min
3	Ratio through the gas step	pump 24.4 to 31.4 L/min, peak 6.86
	warm-up of 2 K	6.68 to 7.53, analyzer over 7 at 175 min
	Ratio + trim at 190 min	analyzer under 7 at 243 min, 6.61 at 360 min
4	204 °C at 10 min	202.7 °C, water under 7 at 42 min, 6.54, 99.10 wt%
5	as shipped	13.4 at 120 min
	ratio 30 L/kg at 100 min	pump at 50 L/min, 11.95
	then 204 °C, then 50 Sm^3/h	10.12, then 6.69 at 99.79 wt%, 741 kW
6	0, 5, 10, 20, 45 Sm^3/h	6.54, 5.87, 5.35, 4.75, 4.27 at 154, 201, 249, 347, 598 kW
7	as shipped	foam index 2.57, ΔP 38 to 185 mbar, 22.3, 219 kg/h carried over
	left alone	133 kg lost by 120 min, level under 30 % at 110 min
	antifoam, makeup at 45 min	under 7 at 53 min, 52 kg lost, drum back at 90 min
8	as shipped	pump 24.4 to 15.9 L/min, 8.62 at 240 min
	204 °C at 45 min	8.45, 128 kW
	204 °C, 15 Sm^3/h at 45 min	under 7 at 139 min, 6.73, 275 kW

TRY IT IN THE APP **2 · Gas flow +30 % at fixed circulation**

Load the case and press Run. Watch the two lines of the Water in dry gas trend after the gas steps up at 30 min. The true water passes 7 lb/MMscf one minute later, but the analyzer, reading gas that left the contactor 10 min earlier, reports OFF SPEC only at 43 min.

Case 3 meets the same step with the ratio, which moves the pump from 24.4 to 31.4 L/min as soon as the meter sees the gas, and the water peaks at 6.86 lb/MMscf. The warm-up is different. At 37 °C the gas brings 11 % more water and the ratio adds 11 % more glycol, which keeps the share removed but lets the water left grow in proportion, and the warmer contactor raises the equilibrium as well. The trim switched on at 190 min raises the ratio to 29.4 L/kg and brings the analyzer back under 7 lb/MMscf at 243 min.

Pause. Try Exercise 7.2 before reading on.

7.6.2 Purity, the Floor and the Ceiling

In case 4 a reboiler step to 204 °C reaches 202.5 °C by 23 min and is held at 202.7 °C by the override. The water crosses under the specification at 42 min and settles at 6.54 lb/MMscf with 99.10 wt% glycol for about 10 kW more fuel. Case 5 warms the inlet to 45 °C, which raises the load from 66.2 to 109.6 kg/h and the water to 13.4 lb/MMscf by 120 min. A ratio of 30 L/kg takes the pump to its 50 L/min and the water only to 11.95 lb/MMscf, against the floor of Section 7.4. The state at 360 min is shown in Figure 7.3. Purity moves the floor, 204 °C to 10.12 lb/MMscf and 50 Sm^3/h of stripping gas to 6.69 lb/MMscf, at 741 kW. In case 6 the first 5 Sm^3/h of stripping gas buys 0.67 lb/MMscf of water for 47 kW, the last 25 Sm^3/h buy 0.48 lb/MMscf for 251 kW, and at 45 Sm^3/h the stripping gas alone costs 450 kW, 3.1 times the reboiler's fuel. The dew point at 60 bar falls from −2.0 to −8.3 °C.

7.6.3 Foam and a Lost Pump

Case 7 runs at 70 t/h with the makeup pump off. The hydrocarbon slug at 30 min takes the foam index to 2.57 within 9 min, the contactor pressure drop from 38 to 185 mbar and the stage efficiency to 0.46, so the water jumps to 22.3 lb/MMscf while 219 kg/h of glycol goes over the top. Left alone, the foam lasts until 140 min, 133 kg of TEG is lost by 120 min and the drum passes its 30 % alarm at 110 min. Antifoam and makeup at 45 min clear the foam and the specification by 53 min, after 52 kg has gone.

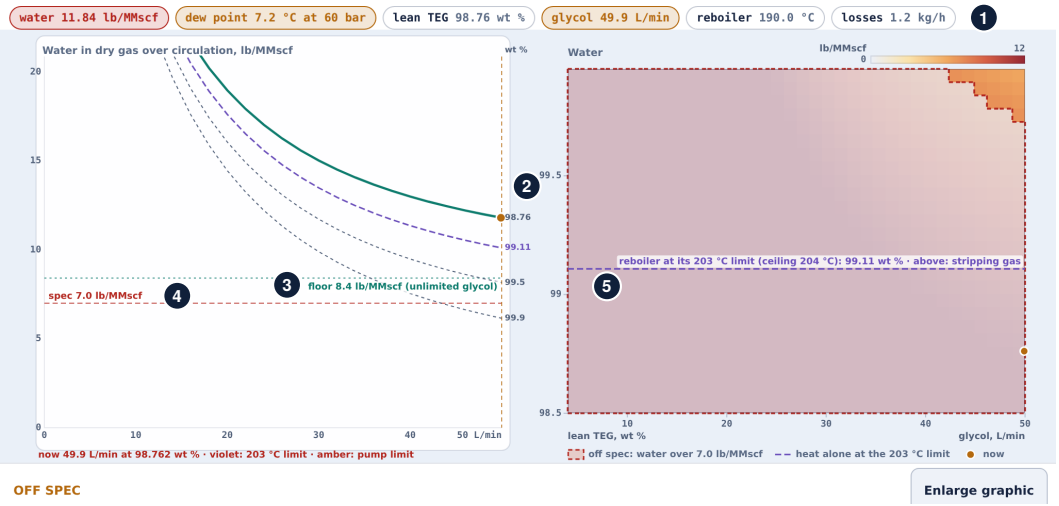


Figure 7.3 The equilibrium floor in case 5 at $t = 360$ min, Dew-point map view cropped to the map, with the Circulation ratio raised to 30 L/kg before the run (the case ships with 22 L/kg). The inlet gas has warmed to 45 °C and carries 109.2 kg/h of water, and the pump is at its limit, 49.9 L/min or 27.5 L/kg. (1) The status chips: the reboiler is back at 190.0 °C, the lean glycol is at 98.76 wt%, and the dry gas carries 11.81 lb/MMscf (analyzer 11.84 lb/MMscf, dew point 7.2 °C at 60 bar). The status strip under the map reads OFF SPEC. (2) The bold solid curve ends at the pump line (amber, dashed). (3) The floor at 8.4 lb/MMscf (teal, dotted) lies above (4) the 7.0 lb/MMscf specification (red, dashed). The thinner dashed curves for 99.11 (violet, long dashes), 99.5 and 99.9 wt% lie below the bold one, and only the last crosses the specification within the pump's range. (5) On the right panel the map over circulation and purity is off specification except at high circulation with purities well above the long-dashed violet line, the 99.11 wt% that heat alone reaches at the 203 °C limit.

> **TRY IT IN THE APP** **7 · Foaming, carryover and the glycol inventory**
>
> Press Run and watch the contactor's pressure drop after the hydrocarbon slug at 30 min. It climbs from 38 to 185 mbar as the foam builds, and the water in the dry gas jumps to 22.3 lb/MMscf. At 45 min turn Antifoam injection On and set the Makeup pump to Auto. The water is back under 7 lb/MMscf at 53 min, after 52 kg of glycol has gone.

The main pump trips at 30 min in case 8 and the standby delivers at most 16 L/min, two thirds of design, 14.5 L/kg. The plan for the application called for half circulation, but at 12 L/min no purity holds the specification, the least being 8.20 lb/MMscf at 204 °C and 50 Sm^3/h, so the lesson of holding the water by purity would fail. On 16 L/min the reboiler at 204 °C alone settles near 8.45 lb/MMscf. With 15 Sm^3/h of stripping gas as well, at 99.78 wt%, the water returns under 7 lb/MMscf at 139 min, 94 min after the moves, and reaches 6.73 lb/MMscf at 275 kW against 128 kW.

7.6.4 A Day Under an Energy Budget

The challenge runs 24 h. The gas ramps from 60 to 80 t/h between 6 and 10 h, the inlet warms to 38 °C between 12 and 13.5 h and cools to 35 °C by 16 h, and then the reboiler's fuel is limited to 55 % of the burner. The target is the true water of every analyzer sample at or under 7 lb/MMscf, the reboiler never above 204 °C, no trip and at most 250 kW of energy on average. Two features depart from the plan for the application, each for a measured reason. The plan asked for a hot afternoon 10 K above the inlet, which no setting can meet, since with every handle at its limit all day the worst

Table 7.5 The Challenge Over 24 h. Worst Analyzer Sample in lb/MMscf, Samples Over 7, Reboiler Peak and Average Energy

Settings	Worst	Over	°C	kW	Verdict
shipped (fixed 24.3 L/min, 200 °C)	10.37	506	200.4	165	fails
Ratio	8.04	321	201.0	180	fails
Ratio + trim	10.48	242	202.0	188	fails
Ratio + trim, 204 °C	10.47	195	203.2	187	fails
and 10 Sm^3/h all day	6.94	0	203.2	263	fails (energy)
and 15 Sm^3/h from 16 h	7.04	5	203.2	230	fails
and 8 from 12, 12 Sm^3/h from 16 h	6.81	0	203.2	229	passes
every handle at its limit	4.56	0	203.1	711	fails (energy)
suggested (MPC)	6.73	0	203.2	232	passes

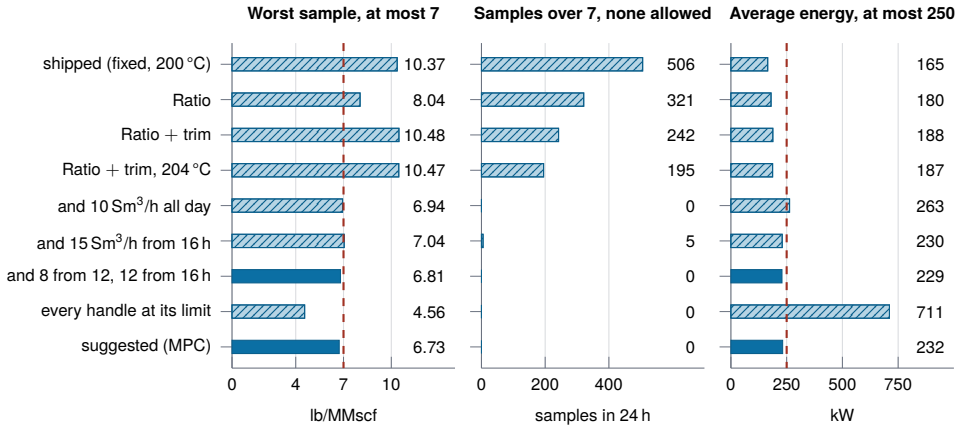


Figure 7.4 The challenge runs of Table 7.5 as bars: the worst analyzer sample, the samples over 7 lb/MMscf and the average energy over 24 h. Solid bars are the settings that pass, hatched bars those that fail, dashed red lines are the limits of the target, and the value of each bar stands at the right. Notice that the two settings that pass add stripping gas only where it is needed, while every handle at its limit holds the water best and fails on energy.

sample is 8.57 lb/MMscf with 49 samples over. It also asked for minimum energy without a number, and without a budget brute force passes, since every handle at its limit holds every sample at or under 4.56 lb/MMscf at 711 kW. The variants appear in Table 7.5. At the top playback speed of 300 min per second the 24 h challenge plays in about 5 s.

Figure 7.4 sets the nine settings of Table 7.5 against the two limits of the target that carry a number and the count of samples over the specification.

Fixed circulation fails as the gas ramps, from 428 min, and the ratio alone holds the morning but not the warm afternoon, from 750 min, because it keeps the share removed rather than the water left. Ratio and trim at 204 °C miss the afternoon by 0.04 lb/MMscf with the pump at its limit and then fail badly under the fuel limit, where the worst sample reaches 10.47 lb/MMscf. The trim answers the wet analyzer with more glycol that the starved reboiler cannot heat, the purity falls and the trim asks for more. Stripping gas added where nothing cheaper works, 8 Sm^3/h from 12 h and 12 from 16 h, passes at 229 kW, while 10 Sm^3/h left open all day meets the water target but spends 263 kW, over the budget. The MPC finds a plan of that kind by itself. It holds the reboiler setpoint at its 203 °C limit and raises the circulation from a mean of 28.9 L/min in the first six hours to 38.6 after the gas ramp. Before 16 h it uses stripping gas only in the hot afternoon, with the pump at or near its limit, apart from up to 6 Sm^3/h in the first 10 min while it raises the reboiler setpoint. Under the fuel limit it trades circulation down to a mean of 31.3 L/min for up to 27.1 Sm^3/h of stripping gas while the

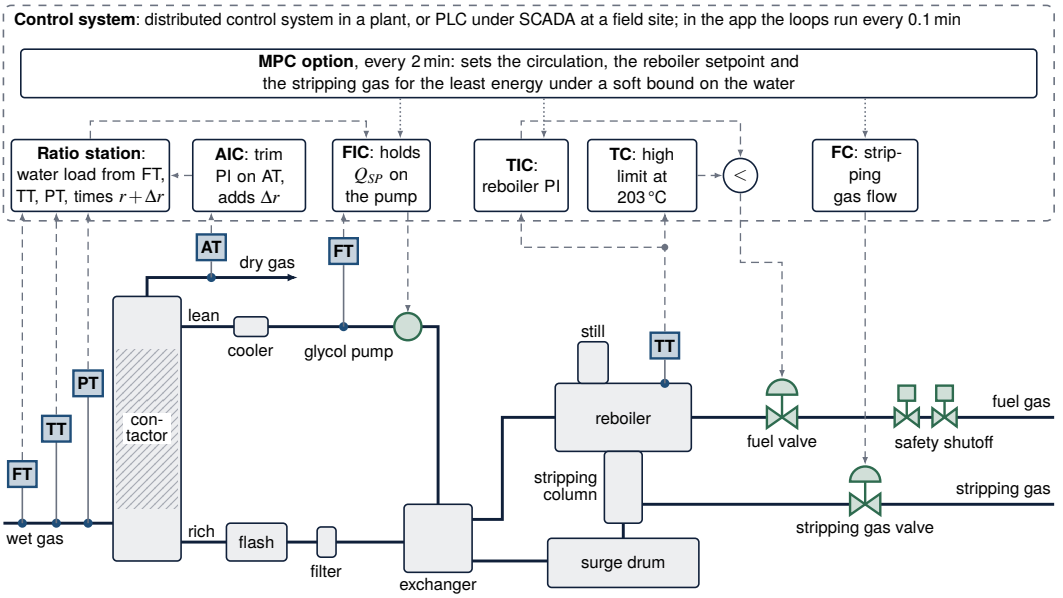


Figure 7.5 The loops of the dehydrator simulator with their hardware. Lettered boxes are sensing devices with the chapter's tags: FT, TT and PT on the wet gas, AT on the dry gas, FT on the lean glycol and TT on the reboiler. Green symbols are final elements: the glycol pump, the fuel valve with the two safety shutoff valves of the fuel train, and the stripping gas valve. Dashed arrows are signals, dotted arrows the setpoints the optional MPC writes. Notice that only AT reads the water the specification is about, and that the reboiler's two controllers meet at a low select before the fuel valve. The makeup pump, its level switch and the antifoam are left out. Not to scale, and not a piping diagram.

reboiler falls to 190.0 °C and takes 3.75 h to recover. Every sample stays at or under 6.73 lb/MMscf, with 232 kW on average, 188 kW of it fuel. At seeds 1 and 2 the MPC passes the same way, at 231.6 and 231.9 kW, and the shipped settings fail from 428 min. The budget makes the challenge an economic problem, and the hand-timed plan that passes uses 2.5 kW less than the MPC because its moves were placed with the day's schedule in view. A data hall whose cheapest operating point sits on a constraint that moves with the weather poses the same economic problem (Volume 9, Chapter 8).

> ✦ DID YOU KNOW? **Feedback That Raised the Worst Case**
>
> From the simulator (Table 7.5). On the graded day, adding the analyzer trim to the ratio cut the samples over the specification from 321 to 242 but raised the worst sample from 8.04 to 10.48 lb/MMscf. The trim lowered the count and deepened the worst miss.

7.7 Technology in Practice

Figure 7.5 draws the loops of Section 7.5 with the hardware of a dehydrator in place of the schematic's symbols.

What Measures It

One instrument reads the quantity the specification is about: the moisture analyzer AT on the dry gas. Many analyzers stand some distance from the process and receive a sample through a system of tubes, heaters, filters, pumps and regulators, and problems with process analyzers quite often stem from sample systems that are badly built or maintained. A plugged sample line leaves an analyzer

reading stale sample with no way of knowing it [20]. The model gives AT a sample every 2 min reported 10 min after it left the gas, 8 min of that in the sample line. The feedforward reads ordinary transmitters: the gas meter with a 6 s lag, the inlet temperature with 30 s and the reboiler thermocouple with 18 s.

> **TECHNOLOGY Sensor: The Moisture Analyzer**
>
> Hygrometers for natural gas work on several principles: a chilled mirror that finds the dew point, an electrolytic cell, a laser spectrometer, and polymer or aluminum oxide sensors. Condensation and spectroscopic instruments work only at low pressure, so they are fed through pressure-reducing sample lines. In a 2015 comparison in natural gas at up to 6 MPa, the instruments saw a step in humidity almost at once, the electrolytic analyzer needed up to two hours to settle, and every instrument was slower when the gas dried than when it wetted. Most aluminum oxide probes drifted downward, reading drier as time went on [4], which on a trend looks like a unit slowly improving by itself. The chapter's AT carries 0.05 lb/MMscf of noise and no drift.

What Moves It

Three final elements carry the two handles. The glycol pump sets the circulation, the fast handle, through a 0.2 min lag up to 50 L/min, or 16 L/min on the standby pump. The fuel valve sets the reboiler duty, the slow handle, and the stripping gas valve adds the expensive end of the purity handle up to 50 Sm^3/h.

> **TECHNOLOGY Final Element: The Reboiler's Fuel Train**
>
> The fuel valve u_f is the modulating valve of a fuel gas train. Upstream of it, two safety shutoff valves with a vent between them, a double block and bleed, isolate the fuel when a burner management system sees low or high fuel pressure or a lost flame. The shutoff valves are electrically actuated and close by spring when power is lost, and an ultraviolet flame sensor is used because it cannot be fooled by the glow of a hot firebox. The same system purges the firebox and sequences the ignition at start-up [20]. In the chapter the fuel valve acts through a 1 min burner lag, the override reaches it through the low select, and the burner trip at 210 °C stands in for the burner management system as a teaching guardrail.

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. At a remote field site a programmable logic controller (PLC) or a remote terminal unit controls the local process and reports to a supervisory control and data acquisition (SCADA) center. Such loops run with cycle times from milliseconds to minutes [21]. The app's loops execute every 0.1 min and its MPC every 2 min, both far shorter than the analyzer's 10 min, so no scan rate repairs the delay. The chapter's structure maps onto standard blocks: a PID for the reboiler and a proportional high limit with external reset meeting at a low selector, a ratio station that multiplies the computed water load, a PID trim on the analyzer that adds to the ratio, and, as an option, the MPC in a supervisory layer that writes the circulation, the reboiler setpoint and the stripping gas.

> **IN PRACTICE A Rule of Thumb Written Into Law**
>
> Under the United States emission standards for oil and gas production, a glycol dehydrator at an area source outside urban areas must compute its optimum circulation from the gas flow, the water it removes and the industry rule of thumb of 3.0 gallons of glycol per pound of water, times 1.15 for a margin of safety, and must not circulate more. A unit that cannot meet its sales gas moisture specification at that rate calculates and documents an alternate rate [22]. The rule belongs to the standards for hazardous air pollutants: the glycol absorbs other constituents of the gas along with the water, and the unit's process vents are the reboiler vent and the flash tank vent [23].

What Is Modernizing It

Two developments touch this chapter. Laser absorption analyzers shine a tunable laser through the sample and read the gas from the light its molecules absorb [20]. In the 2015 comparison of hygrometers in natural gas the spectroscopic and electrolytic analyzers showed no appreciable drift, where most aluminum oxide probes drifted [4]. Regeneration is being reworked for energy: in a simulated plant, routing the flash tank's gas to the regenerator as stripping gas instead of to the flare allowed less circulation and cut the reboiler duty by 36.2 % [24]. The economic MPC of Section 7.5 prices the same handle in kilowatts of fuel and opens it only where nothing cheaper is left.

7.8 Limitations

The unit is generic, and none of its sizes or correlations was fitted to a plant. The contactor is two well-mixed stages, so the circulation that meets a specification here is a teaching number, not a design. For 7 lb/MMscf from gas at 90 °F and 500 psia over 98.8 wt% glycol the model needs 27.9 L/kg with perfect stages and 79 L/kg with its efficiency of 0.9, where a published simulation of two equilibrium stages with the glycol at the gas temperature needs about 3 gal per pound of water, or 25 L/kg [10]. The reboiler is 0.34 to 0.48 wt% purer than the same simulation, a fit kept because it meets the targets of the plan for the application while a refit would move every case, and the equilibrium is about 3 K drier than the chart at 99.99 wt%. The saturated water content ignores acid gas and gravity, the dew point below 0 °C is that of supercooled water, and the hydrate point of the same gas lies higher. Hydrocarbon absorption, flash gas and the aromatic emissions of the still are absent [17].

The contactor level and the flash tank pressure have no loops, the high-limit override passes the ceiling by 0.21 K on a sudden loss of load, and nothing protects the ceiling in Manual. The challenge departs from the plan for the application in two measured ways, a milder afternoon and an energy budget, because the original afternoon is infeasible and the original objective is passed by brute force, and the pump trip leaves two thirds of the circulation for the same kind of reason. The MPC's model is the plant's own steady map with first-order dynamics, so it meets model error only through foam, a changed parameter and the analyzer, and its bias learns slowly through a 10 min delay. Disturbances arrive as scheduled steps, ramps and pulses.

> **OPEN CHALLENGE** **A Moisture Reading Fit for the Loop**
>
> Moisture instruments for natural gas are usually calibrated at atmospheric pressure in nitrogen or air, far from the conditions of the process. Turning a water content into a dew point depends on the composition, temperature and pressure of the gas, and the extrapolations can move the dew point by up to 10 °C where 1 to 3 °C is wanted [4]. A 2020 study still saw a gap between the analyzers available and what industry asks for: a response fast enough for online use in natural gas, valid across gas mixtures with a single calibration [25]. Progress would be a reading at line pressure fast and trusted enough to close the dew point loop on it.

7.9 Conclusion

This chapter studied how a glycol dehydrator meets one water specification with a handle that is fast but bounded by equilibrium and a handle that is slow, capped and expensive. The simulator computes both from a seventeen-state model whose water and glycol ledgers close to round-off. Circulation lowers the water from 9.67 to 6.83 lb/MMscf when it doubles, but on a 45 °C inlet with 98.76 wt% glycol no circulation reaches 7 lb/MMscf, the least being 8.41 lb/MMscf, so only purity can meet it. Heat buys purity up to 99.11 wt% under the override, and stripping gas the rest at 10 kW per Sm^3/h. A ratio on the water load holds a gas step at a peak of 6.86 lb/MMscf but lets a warmer inlet through, a trim recovers it slowly through a 10 min analyzer, and under a fuel limit the trim makes the gas wetter. An economic MPC holds every sample of a graded day at or under 6.73 lb/MMscf at 232 kW on average. The correlations are teaching values, the reboiler is about 0.4 wt% purer than published simulations and two plant loops are left out. A fuller model would add a packed-bed contactor, the contactor level and flash pressure loops, aromatic emissions and a reboiler refitted to measured

purities. The simulator shows that a specification can lie below what any amount of the fast handle can reach.

KEY POINTS

- Pumping more glycol dries the gas only toward a floor set by how dry the glycol is, so on a 45 °C inlet with 98.76 wt% glycol no circulation reaches 7 lb/MMscf.
- Heat buys purity up to 99.11 wt% under the override, and stripping gas the rest at 10 kW per Sm^3/h.
- A ratio on the water load holds a gas step at a peak of 6.86 lb/MMscf but lets a warmer inlet through, and a trim recovers it slowly through a 10 min analyzer.
- Under a fuel limit the trim makes the gas wetter, while an economic MPC holds every sample of the graded day at or under 6.73 lb/MMscf.

Where else this applies. Chapter 8 sweetens the same gas with a solvent whose regenerated purity bounds the product, and Volume 9, Chapter 8 prices its inputs in an economic predictive controller on a constraint that moves with the weather.

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7.10 Exercises

7.1 Concept check · 2 min

In case 1 the reboiler holds 190 °C, so the lean glycol stays at 98.76 wt%. Doubling the circulation from 15 to 30 L/min takes the water in the dry gas from 9.67 to 6.83 lb/MMscf, far from half. Which explanation is right?

(a) The outlet approaches a floor set by equilibrium with the lean glycol and by what two stages of efficiency 0.9 let through

(b) The stage holdups of about two minutes delay the response, so the water has not settled when it is read

(c) The extra glycol cools the reboiler, so the lean glycol gets wetter and cancels part of the gain

(d) The analyzer reports gas that left the contactor ten minutes earlier, so it hides part of the fall

7.2 Concept check · 1 min

Case 3 runs on Ratio. From 150 min the inlet gas warms from 35 to 37 °C and brings about 11 % more water, and the ratio raises the circulation by the same 11 %. What does the water in the dry gas do?

(a) It stays near 6.68 lb/MMscf, because the glycol per kilogram of water is unchanged

(b) It rises, because a fixed ratio keeps the share removed and the warmer contactor raises the equilibrium

(c) It falls, because the extra glycol cools the contactor below the temperature of the incoming gas

(d) It rises on the analyzer only, because the inlet temperature transmitter lags the true inlet

7.3 Concept check · 2 min

The challenge is run on Ratio + trim with the reboiler setpoint at 204 °C. At 16 h the reboiler fuel is limited to 55 % of the burner, the analyzer reads wet and the trim raises the circulation ratio. What follows?

(a) The water returns under the specification within one analyzer delay, because circulation is the fast handle

(b) The high-limit override takes the fuel valve and holds the reboiler at 203 °C until the limit clears

(c) The gas gets wetter, because the burner cannot heat the extra glycol and the purity falls, so the trim asks for more

(d) Nothing changes, because the trim stops at the ratio that the fuel-limited burner is able to heat

7.4 Theory and calculation · 7 min

The reboiler sits at its 203 °C override and makes 99.11 wt% glycol. At 24.3 L/min the equilibrium ratio $\gamma_w p_{sat}(T_r)/P_{st}$ in Equation (7.5) is 13.45. Use $V_m = 23.645\,\mathrm{Sm^3/kmol}$, $\rho_h = 1010\,\mathrm{kg/m^3}$, $M_T = 150.17$ and $N_s = 2$.

(a) Find the stripping gas per cubic meter of glycol g and the stripping factor S for 20 $\mathrm{Sm^3/h}$. *Checkpoint:* $g = 13.72\,\mathrm{Sm^3/m^3}$ and $S = 1.16$.

(b) Find the share of the reboiler's water that stays in the glycol leaving the column, the water ratio X_{lean} and the purity leaving the column. *Checkpoint:* 0.285, 0.002 56 kg/kg and 99.74 wt%.

(c) Repeat for 5 $\mathrm{Sm^3/h}$ and 45 $\mathrm{Sm^3/h}$, and compare the purity bought per $\mathrm{Sm^3/h}$ by the first 5 $\mathrm{Sm^3/h}$ with that bought by the step from 20 to 45 $\mathrm{Sm^3/h}$. *Checkpoint:* 99.35 and 99.91 wt%, about 7 times less per $\mathrm{Sm^3/h}$ for the last step.

7.5 Theory and calculation · 7 min

At design the inlet gas carries $W_{in} = 58.18\,\mathrm{lb/MMscf}$, the gas leaves stage 2 with 17.89 lb/MMscf and stage 1 with 6.73 lb/MMscf, the stage efficiency is $E = 0.9$, and the gas in equilibrium with the lean glycol would carry $W^* = 3.05\,\mathrm{lb/MMscf}$.

(a) Use the gas-side relations of Equation (7.3) to find the water that gas in equilibrium with each stage's glycol would carry, and the share of the inlet water absorbed. *Checkpoint:* $W_{eq}(X_2) = 13.41$ and $W_{eq}(X_1) = 5.49\,\mathrm{lb/MMscf}$, 88.4 % absorbed.

(b) Estimate the floor with unlimited circulation at the design contactor temperature, and explain why the least water any circulation reaches in the model, 3.94 lb/MMscf near 390 L/min, is higher. *Checkpoint:* 3.60 lb/MMscf.

(c) In case 5 at 50 L/min the inlet is at 45 °C ($W_{in} = 96.32\,\mathrm{lb/MMscf}$) and $W^* = 6.83\,\mathrm{lb/MMscf}$. Estimate the floor the same way and say whether a bigger pump can meet 7 lb/MMscf. *Checkpoint:* 7.72 lb/MMscf, above the specification.

7.6 Theory and calculation · 7 min

Use the reboiler balance of Equation (7.6) at the design point: $T_r = 200\,^\circ\mathrm{C}$, $T_c = 36.09\,^\circ\mathrm{C}$, $\varepsilon = 0.70$, 58.6 kg/h of water boiled off with $\lambda = 2300\,\mathrm{kJ/kg}$ and $R = 0.25$, $UA = 0.1\,\mathrm{kW/K}$, $T_{amb} = 25\,^\circ\mathrm{C}$, a firing efficiency of 0.75 and 46.3 kW to heat the rich glycol at 24.28 L/min.

(a) Find the rich glycol's temperature entering the reboiler, the heat to boil the water and the loss, and from them the absorbed duty and the fuel burned. *Checkpoint:* 159.8 °C, 46.8 kW and 17.5 kW, 110.6 kW absorbed and 147.5 kW burned.

(b) Find the fuel that heating the rich glycol costs per L/min of circulation (the sensible heat only) and add the pump's 0.164 kW per L/min. Compare the sum with the cost the MPC places on circulation. *Checkpoint:* About 2.7 kW per L/min.

(c) In the challenge the burner is limited to 55 % of 250 kW while the gas runs at 80 t/h. Assume the boil-off grows in proportion to the gas, the loss is unchanged and each L/min still takes the design sensible heat. Estimate the most circulation the burner can hold at 200 °C. *Checkpoint:* About 30 L/min.

7.7 App challenge · 8 min

Run case 1, *The operating map: set circulation and purity yourself*, at the default seed. It ships with the Circulation setpoint at 15 L/min and the Reboiler temperature setpoint at 190 °C. For each setting below, reload the case, make the setting before Run, run 60 min at speed 20 (3 s), and read the column `truth_water_lbMMscf` of the exported CSV at 60 min. The Water (analyzer) tile carries the analyzer's noise and may differ by up to 0.06 lb/MMscf.

(a) Circulation setpoint 20, 30 and 50 L/min. Give the water for each, and the water removed per extra L/min over each interval, starting from 9.67 lb/MMscf at 15. *Checkpoint:* 8.24, 6.83 and 5.79 lb/MMscf (each within 0.03).

(b) Reboiler temperature setpoint 204 °C with the circulation left at 15 L/min. Give the water, the Lean TEG tile and the Reboiler tile, and say why purity alone does not meet 7 lb/MMscf here. *Checkpoint:* 8.81 lb/MMscf, 99.107 wt%, 202.9 °C.

(c) Circulation setpoint 25 L/min and reboiler 204 °C together. Give the water. *Checkpoint:* 6.43 lb/MMscf (within 0.03).

7.8 App challenge · 8 min

Run case 3, *The ratio feedforward on the water load*, at the default seed. Dew point control ships on Ratio at 22 L/kg.

(a) Run 360 min as shipped at speed 60 (6 s) and export the CSV. Read the circulation, column `circulation_Lmin`, at 29 and 60 min. Then read the column `truth_water_lbMMscf`: its largest value between 30 and 120 min, and its values at 150 and 360 min. *Checkpoint:* About 24.2 and 31.4 L/min (within 0.3), a peak of 6.86 lb/MMscf, then 6.68 and 7.52 lb/MMscf (within 0.02).

(b) Reload the case, select Ratio + trim in Dew point control before Run, and run 360 min again. Read `truth_water_lbMMscf` at 150 min, its largest value between 150 and 360 min, and `circulation_ratio_Lkg` at 360 min. Explain why this run holds the warm-up when the run in which the trim is switched on at 190 min lets the analyzer stay above 7 lb/MMscf until 243 min. *Checkpoint:* 6.40 lb/MMscf, a peak of 6.97 lb/MMscf near 180 min, and 29.6 L/kg (within 0.1).

7.9 App challenge · 9 min

Run case 9, the Challenge, *a day on the dehydrator*, at the default seed. Each run is 24 h at speed 300 (about 5 s). The run stops at 1440 min and its verdict appears, and the So far tile shows the worst sample and the average energy.

(a) Run as shipped. Give the worst sample, the number of samples over 7 lb/MMscf and the average energy. *Checkpoint:* 10.37 lb/MMscf, 506 samples, 165 kW.

(b) Reload, select Ratio + trim and set the Reboiler temperature setpoint to 204 °C before Run. Give the same three values, and read `circulation_Lmin`, `reboiler_C` and `truth_lean_teg_wtpct` at 950 and 1440 min in the CSV. Explain what happened after the fuel limit at 960 min. *Checkpoint:* 10.47 lb/MMscf, 195 samples, 187 kW. From 39.6 to 49.9 L/min, from 202.8 to 161.0 °C, from 99.11 to 97.28 wt%.

(c) Reload and select MPC before Run. Give the verdict, and read the largest `stripping_gas_Sm3h` and the lowest `reboiler_C` after 960 min. *Checkpoint:* 6.73 lb/MMscf and 232 kW, passed. About 27.1 Sm^3/h and 190.0 °C (within 0.3).

7.10 Application area · 4 min

Case 7 runs at 70 t/h with the makeup pump off and the surge drum at 40 %. The drum holds 784.4 kg of TEG at 60 %, and its low alarm is at 30 %.

(a) How much TEG can the unit lose before the low alarm? *Checkpoint:* About 131 kg.

(b) At the peak carryover of 219 kg/h, how long would that take? The case passes the alarm about 80 min after the slug. Why longer? *Checkpoint:* About 36 min.

(c) What does an operator see first, and which two actions put it right?

7.11 Application area · 3 min

A sales contract asks for at most 7 lb/MMscf of water. The export line runs at 60 bar and its coldest point is at 4 °C.

(a) What water dew point at 60 bar does the model give for 7 lb/MMscf, and does gas on the specification drop free water in this line?

(b) What does the chapter say about hydrates, and what should be checked instead of the dew point?

(c) Why does the reboiler stop at 204 °C, and where does purity beyond the ceiling come from?

7.12 Review the agent · 5 min

An AI assistant reads case 5 with the inlet at 45 °C. As shipped, the pump runs at about 40 L/min and the water reaches 13.4 lb/MMscf. With the ratio raised to 30 L/kg the pump sits at its 50 L/min limit and the water falls to 11.95 lb/MMscf. The assistant writes: “The last 10 L/min removed 1.45 lb/MMscf. A second pump in parallel gives 100 L/min, five more such steps, so the water would fall by about 7.3 lb/MMscf to about 4.7 lb/MMscf, well under the specification. Buy the pump.” Find the flaw, and say how you would check the claim in the app and in the chapter.