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CHAPTER 14

A Refinery Fuel Gas Header That Should Never Import and Flare at Once

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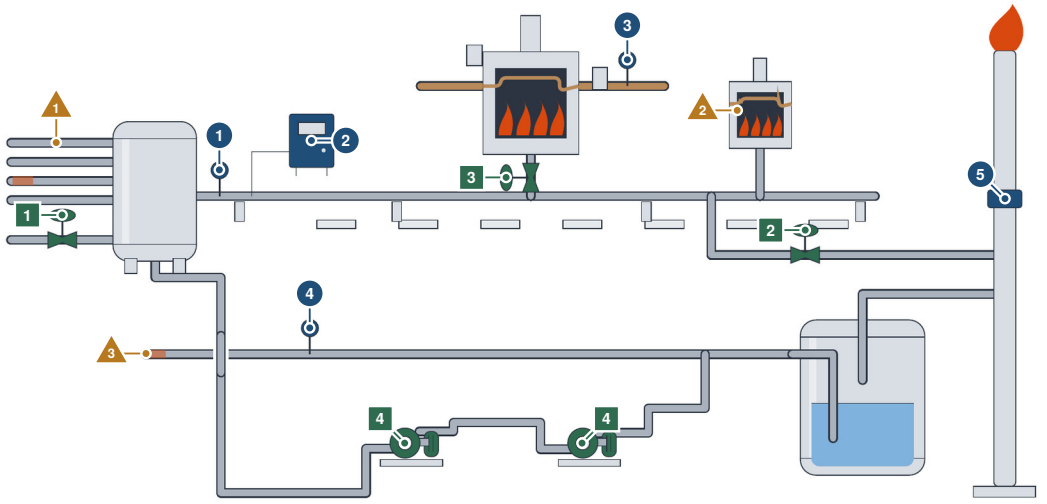
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CHAPTER 14

A Refinery Fuel Gas Header That Should Never Import and Flare at Once



The controller moves 1 natural gas makeup valve 2 flare valve on the same controller output 3 fuel valve of heater H-1 4 two recovery compressor stages

The controller reads 1 fuel gas header pressure 2 Wobbe meter on the mixed gas 3 outlet temperature of H-1 4 flare header pressure 5 flow meter at the flare, for the record

What disturbs it 1 the four source gases: a coker drum switch, an FCC trip, a purge rise 2 heater H-20 lights 3 relief load into the flare header

One controller output opens either the makeup valve or the flare valve, and the recovery stages take gas from the flare header ahead of the water seal and return it to the mix drum. Illustration, not to scale.

IN PLAIN TERMS Buying Gas and Burning It at Once

The main idea. A refinery burns the gas its own units make and buys natural gas to make up the rest. One controller holds the pressure in the shared pipe. It opens a valve that buys gas or a valve that sends spare gas to the flare, an open flame that burns it.

The challenge. If the two valves overlap, the controller can keep both open. The plant then buys gas and burns gas at the same time, while the pressure looks normal. The pipe holds less than a minute of gas, so any upset moves the pressure fast.

Why it matters. A refinery should never pay for gas while it burns its own as waste.

THREE WAYS TO READ THIS CHAPTER

Explore	11 min	This page, the Did you know? and History boxes in Section 14.2, the Try it boxes and the second Did you know? box in Section 14.5, and Key points in Section 14.8. No equations.
Study	45 min	The whole chapter in order, stopping at the three pause points, then Exercises 1 to 12.
Practice	15 min	This page, Section 14.5 with Figure 14.3, Section 14.6 and Section 14.7 with its Open challenge box.

The control question A refinery fuel gas header holds well under a minute of its throughput, and one pressure controller splits its output between a natural gas makeup valve and a flare valve that pass money in opposite directions. How should that split range, the flare gas recovery and the heaters' firing be set so that the refinery never buys gas while it flares its own?

Learning objectives

- Calculate the integrating gain of a gas header from its volume and temperature, and the time an unbalanced flow takes to move its pressure.
- Explain why an overlap in a split range imports and flares while the pressure stays on setpoint, and why a dead band costs almost nothing on an integrating header.
- Compute the heating value and Wobbe index of a fuel gas mixture, and predict how much heat a burner at fixed pressure loses when hydrogen is added.
- Set the load and unload thresholds of a staged recovery compressor from where the loaded stages hold the flare header.
- Compare feedback, flow feedforward and MPC on a measured consumer surge, and say why an MPC on two valves still needs a positioner interlock.

Prerequisites Sections 1.4.2 (heaters, fuel heating value and the Wobbe index), 1.4.7 (split ranges and constraint control), 1.6.2 (velocity form) and 1.6.4 (scenarios). Section 1.6.3 is needed only for the MPC. Chapter 11 treats the drum switch that this header's coker gas follows.

The app https://apmonitor.com/apps/fuel-gas-header/

See also Volume 4, Chapter 5 for split ranges on heated and cooled barrel zones and Volume 4, Chapter 9 for valve-position control on a site with an import limit. Volume 3, Chapter 4 for the air side of a heater burning fuel gas and Volume 3, Chapter 6 for feedforward from a measured load. Volume 6, Chapter 7 for the choice of which flow of an inventory loop is held fixed.

14.1 Introduction

A refinery burns its own waste. The catalytic cracker's gas plant, the coker, a hydrotreater's recycle purge and the reformer's surplus hydrogen leave the units as gases nobody can sell as liquid, and a mix drum and header deliver them to every fired heater on the site. In the generic system simulated here those four sources send 18 500 Nm^3/h (normal cubic meters at 0 °C and 1.013 25 bar absolute), a recovery compressor returns 900 Nm^3/h of relief gas, and 1009 Nm^3/h of natural gas makes up the 250 MW the heaters burn. The 60 m^3 header at 3.5 bar g holds 10.4 kmol, which is 41 s of that throughput. When the coker switches drums and sends 3000 Nm^3/h less, the header falls 0.97 bar a minute and passes 3.0 bar g 45 s after the switch began.

The simulator is built around two beliefs it is meant to correct. The first is that a split range is a wiring detail. One pressure controller output opens the makeup valve below the middle of its range and the flare valve above it, and the two valves pass money in opposite directions. Configured with the two valve ranges overlapping by 4 % of output, the controller holds the header on setpoint while buying natural gas and flaring fuel gas at the same time, for 14.4 min of a 30 min case. The pressure trend shows nothing wrong. The second belief is that the heat a burner releases follows the heating value of its gas. At a fixed burner pressure it follows the Wobbe index, the higher heating value divided by the square root of the specific gravity, and adding 10 % hydrogen to the design gas lowers the heating value 7.1 % but the Wobbe index only 2.7 %. The class of problem is wider than refining. A single output split across two actuators with opposite costs appears in heating and cooling of one zone (the barrel zones of Volume 4, Chapter 5), in acid and base dosing, and in pressure held between a vent and a supply, and split-range control is a common structure in the process industry whose systematic design is still being worked out [1–3]. A header whose quality changes the response of every consumer at once has the same shape wherever gases of different origin are blended into one supply, and gas quality criteria for such interchange were argued for engines in 1986 [4].

However, the literature a student meets keeps the pieces apart. Fuel gas systems are scheduled by mixed-integer optimization over hours [5–7], flare gas recovery is evaluated by design studies and economics [8, 9], and gas interchangeability is a combustion subject [10]. This chapter puts the split range, the recovery compressor and the heaters' response to gas quality into one simulated refinery fuel gas header running on one clock, and measures what an overlap, a dead band, a staging threshold, a hydrogen-rich purge and three control architectures do to it. The ideal-gas balance, the split range, the proportional-integral (PI) loop, the Wobbe index and the model predictive controller (MPC) are all standard. The findings are measurements on one generic system at one seed. With the PI loop every dead band of zero or more gave no import and flare in the case built to show it, and only a dead band of exactly zero left 4.5 s in the 8 h challenge, so the overlap rather than the narrowness of the band is the fault. An MPC whose plans never open both valves still imports and flares for 7.9 to 9.3 min in 8 h unless an interlock waits for the positioners. The model has 23 states, its pressure rate matches the integrating gain computed from the declared volume to a relative 10^{-9}, and it is given here down to its last default so that it can be rebuilt. Its controllers see only instruments and never the simulator's state. Nine cases, the last a challenge, carry the lessons, and their completion rules look at the learner's own moves and at the state the header reaches after them.

Section 14.2 follows the domain, from flaring and flare gas recovery to the Wobbe index. Section 14.3 sets out the header, the gas properties, the split range, the flare header and the heaters as modeled. Section 14.4 describes the pressure loop, the flow feedforward, the MPC, the compressor staging and the heater loop with its Wobbe feedforward. Section 14.5 measures the nine cases and the challenge, Section 14.6 sets the hardware of a real header beside the model, Section 14.7 states the limitations and Section 14.8 draws the conclusions. The exercises at the end of the chapter run the cases.

14.2 Fuel Gas, Flares and the Wobbe Index

Fuel gas is a byproduct of refining and the primary energy source of a refinery, which burns what its units make and purchases what they do not [7]. The flare is the other end of that balance. Flaring is widely used by the fossil fuel industry to dispose of gas it cannot use [11], and an industrial survey of the practice covers the principles of combustion, the types of flare and case studies of their operation [12]. Recovering that gas instead became a design subject in its own right. A 2012 study examined reforming the flare gas of a gas refinery into usable energy with no routine flaring [13], the technical and economic case for recovering flare gas in several gas-processing plants was evaluated in 2017 [8], and a flare gas recovery system built on liquid ring compressors was designed and simulated in 2020 [9]. What a flare emits when it does burn has also been measured rather than assumed. Airborne sampling across three basins that account for more than 80 % of United States flaring found flares destroying 91.1 % of their methane, against the 98 % generally assumed, once unlit flares are counted [11].

> **✦ DID YOU KNOW? Refineries Burn Their Own Gas**
>
> In 2024, United States refineries burned 213,576 thousand barrels of still gas, counted at 6 million British thermal units per fuel oil equivalent barrel, and 1,031,147 million cubic feet of natural gas [14]. Still gas is the mixture of methane, ethane and other light gases that distillation, cracking and reforming produce.

The plant-wide view of fuel gas came from optimization. A mixed-integer linear model for multi-period scheduling of a refinery's fuel gas system was published in 2008 [5], the energy configuration and operation of refinery fuel gas networks were optimized together in 2015 [6], and a 2018 study made such a schedule robust to the fluctuation of fuel gas generation and consumption that leaves a theoretical plan infeasible on the day [7]. Those fluctuations are what the regulatory layer absorbs, and the header pressure loop, its split range between makeup and flare and its relation to the recovery compressor sit below the schedule. Split-range control is used to extend one controlled variable's

operating range across more than one manipulated variable, and a systematic design procedure that weighs the different dynamic effect and cost of each input was proposed in 2019 [1]. A generalized form with one controller per input and a baton passed between them, and model predictive control as the alternative that needs a detailed model, followed in 2020 [2].

Gas quality has its own history, from a 1977 utility study of hydrogen in burners to the Wobbe index as a criterion in 1986, and the History box below tells it. Interchangeability indices for premixed burners are still measured experimentally [10]. A refinery header sees the same problem every time a hydrotreater purges harder, because hydrogen-rich purge gas reaches every heater at once.

> **HISTORY 1977 and 1986: How Much Hydrogen a Burner Takes**
>
> A 1977 utility study asked how much hydrogen could be blended into natural gas and burned in typical appliances with no adjustment. It burned blends of 8 to 31 % hydrogen in eleven pilot burners and twenty-three main burners [15]. A burner passed only if its heat input changed little and its flames neither lifted, flashed back, yellowed nor burned incompletely. The heat input index of the study was a ratio of Wobbe numbers, the heating value divided by the square root of the specific gravity. Main burners in the open failed above 20 to 22 % hydrogen, limited by flashback when turned down [15]. In 1986 the Wobbe index was argued as the gas quality criterion for interchanging fuels in engines, because a change of composition at the same index left the air-to-fuel ratio and the combustion velocity nearly unchanged [4].

14.3 The Fuel Gas System as Modeled

No refinery stands behind the simulated system, and every size, flow, composition, price and threshold is a teaching value. Four sources and a natural gas makeup valve feed a mix drum and header of volume V, which supply one fully simulated heater, H-1, a bank of eighteen heaters lumped behind one demand, and a twentieth heater, H-20, out for maintenance until case 8 lights it. A flare valve on the header sends surplus gas to the flare stack downstream of the water seal. A separate flare header gathers the relief load of the units behind a 60 mbar g water seal, and a recovery compressor with two on/off stages returns that gas to the mix drum before it can lift the seal. The layout, every symbol of the equations below and the values of the challenge at 2 h are shown in Figure 14.1.

The model integrates 23 states. Eleven are physical: the kilomoles n_i of hydrogen, methane, an ethane-and-heavier lump C_{2+} and nitrogen in the header, the kilomoles n_F in the flare header, the makeup and flare valve stems x_{MU} and x_{FL}, H-1's burner pressure p_b, its firebox heat Q_f and outlet T_{out}, and the lumped heaters' firing demand h_L. Twelve are ledgers that integrate what crosses the boundaries (each lump's and the flare header's net inflow, the gas into and out of the header, the volume flared and imported, the carbon dioxide from the flared carbon and the energy flared and imported), so that conservation and every scorecard total can be checked exactly. Time is in minutes, flows in Nm^3/h, header pressure in bar gauge, flare header pressure in mbar gauge, heating values in MJ/Nm^3 on the higher heating value, and heat in MW. Table 14.1 lists the variables by role.

14.3.1 The Header and Its Integrating Gain

The header is one well-mixed ideal-gas volume at a fixed temperature, and each lump balances what the sources, the recovered gas and the makeup bring in against what the heaters and the flare valve take out at the header's own composition, as shown in Equation (14.1).

$$\begin{aligned} c\,\frac{\mathrm{d}n_i}{\mathrm{d}t} &= \sum_k F_k y_{k,i} + F_{RC}\,y_{rel,i} + F_{MU}\,y_{NG,i} \\ &\quad - \left(F_h + F_L + F_{su} + F_{FV}\right)\frac{n_i}{n} \\ p &= \frac{nRT}{V} - p_a, \qquad n = \textstyle\sum_i n_i \end{aligned} \tag{14.1}$$

where $c = 22.414 \times 60$ converts Nm^3/h to kmol/min, k runs over the FCC dry gas, the coker gas, the hydrotreater purge and the reformer net gas with compositions y_k, F_{RC} is the gas the recovery

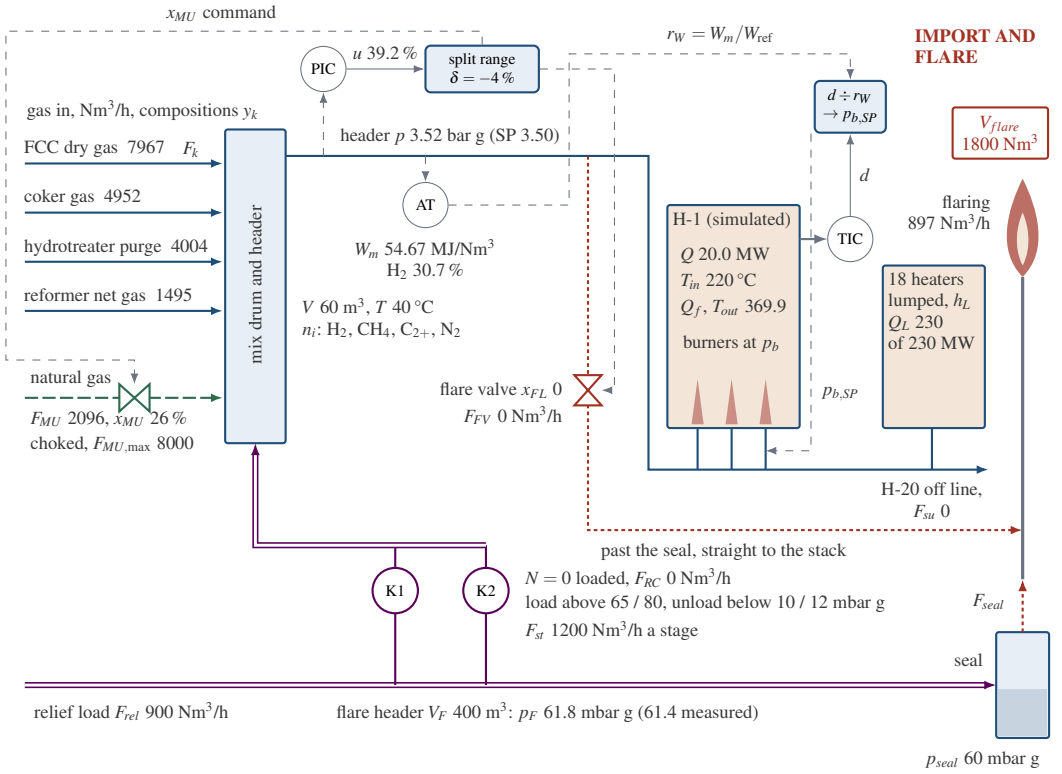


Figure 14.1 The fuel gas system as modeled. (a) Drawn after the System view of the challenge as shipped at $t = 2$ h: the four sources and the natural gas makeup into the mix drum, the PIC and its split range with a 4 % overlap, the Wobbe meter (AT) and the feedforward to the burner pressure of H-1 and the lumped bank, the header's flare valve discharging past the seal, and the flare header whose stages load above the seal, so the whole 900 Nm³/h relief load lifts the seal and burns (897 Nm³/h metered at the tip). Flows in Nm³/h at the meters unless marked. Fuel gas is drawn solid, natural gas long-dashed, gas to the flare dotted, relief gas as a double line and signals thin dashed. Process model only, not to scale. (b) The Split range view of case 2 at 12 min: one output, two valves, the overlap shaded, both valves open at $u = 48.5$ %, the makeup valve solid and the flare valve dash-dotted, with the suggested 6 % dead band thin (makeup dashed, flare dotted) for comparison, and the flare header's ladder with the seal and each stage's load (▲) and unload (▽) thresholds.

Table 14.1 Variables by Role at the Design Point

Symbol	Role	Design	Range
p	CV, header pressure (bar g)	3.50	SP 2.5–4.5
T_{out}	CV, H-1 outlet (°C)	370.0	SP 340–390
u	MV, split-range output (%)	41.07	0–100
x_{MU}, x_{FL}	MV, makeup and flare valves (%)	12.6, 0	0–100
d	MV, H-1 firing demand (%)	100	0–130
N	MV, recovery stages loaded	1	0–2
F_k	DV, sources (% of design)	100	0–200
F_{rel}	DV, relief load (Nm^3/h)	900	0–4000
d_L	DV, other heaters' firing (%)	100	70–120
s	DV, H-20 lit (%)	0	0–100
n	state, gas in the header (kmol)	10.40	—
y_{H_2}	output, hydrogen (mol %)	32.09	—
HHV, SG	output, heating value, specific gravity	44.097, 0.6501	—
W	output, Wobbe index (MJ/Nm^3)	54.69	alarm 52.5
p_F	output, flare header (mbar g)	16.25	seal 60
F_{MU}	output, makeup (Nm^3/h)	1009	0–8000
F_{flare}	output, flared (Nm^3/h)	0	—
Q, Q_L	output, heat released (MW)	20, 230	—
$t_{I\&F}$	output, import and flare (min)	0	—

compressor returns at the relief composition y_{rel}, F_{MU} the natural gas makeup at y_{NG}, F_h, F_L and F_{su} the fuel of H-1, the lumped bank and H-20, F_{FV} the flow through the header's flare valve, $T = 40\,°C$ and $p_a = 1.013\,25$ bar. Summing the four balances gives the integrator that every controller of this header fights, as shown in Equation (14.2).

$$\frac{\mathrm{d}p}{\mathrm{d}t} = K\,(F_{in} - F_{out}), \qquad K = \frac{RT}{V}\cdot\frac{1}{c}\cdot 10^{-2} \tag{14.2}$$

with R in J/(mol K), V in m^3, and the factor 10^{-2} turning kPa into bar per kmol. At $V = 60\,m^3$, $K = 3.2267 \times 10^{-4}$ bar/min per Nm^3/h, so 1000 Nm^3/h of imbalance moves the header 0.323 bar a minute, and at 240 m^3 it is 8.067×10^{-5}. The application's own test steps the FCC gas down by 800 Nm^3/h at both volumes and finds the engine's pressure rate equal to K times the step to a relative 10^{-9}. Nothing on the right side of Equation (14.2) answers the pressure. The sources send what their units make, the makeup valve is choked from a 20 bar absolute supply, and each heater's burner-pressure loop holds its own flow until its fuel valve is wide open. The header has no self-regulation until a heater starves, which for H-1 begins when the header falls to 2.216 bar g.

Pause. Try Exercise 14.1 before reading on.

14.3.2 Composition, Heating Value and the Wobbe Index

The gas properties follow from the four lumps by mole-fraction averages, as shown in Equation (14.3).

$$\begin{aligned} \mathrm{HHV} &= \textstyle\sum_i y_i H_i, \qquad SG = \sum_i y_i M_i / 28.96 \\ W &= \mathrm{HHV}/\sqrt{SG} \end{aligned} \tag{14.3}$$

where H_i is 12.75, 39.8, 92.0 and 0 MJ/Nm^3 and M_i is 2.016, 16.043, 38.5 and 28.013 kg/kmol for the four lumps, and the C_{2+} lump carries 2.6 carbon atoms a molecule. Table 14.2 gives each stream. The design gas, mixed from the sources, the recovered relief gas and the makeup, is 32.09 % hydrogen with $\mathrm{HHV} = 44.097\,MJ/Nm^3$, $SG = 0.6501$ and $W = 54.690\,MJ/Nm^3$. Pure hydrogen and methane come out at W of 48.32 and 53.47 MJ/Nm^3. The purge, at 42.48 MJ/Nm^3, lies below both, because a little heavy gas raises a light gas's specific gravity sharply.

Hydrogen lowers the heating value and the specific gravity together, so the Wobbe index moves much less than the heating value. Adding a fraction a of pure hydrogen to the design gas gives

Table 14.2 Stream Compositions (Mole Fractions of the Four Lumps) and Properties. Teaching Values

Stream	H_2	CH_4	C_{2+}	N_2	Nm^3/h	HHV	SG	W
FCC dry gas	0.14	0.32	0.44	0.10	8000	55.00	0.869	59.01
coker gas	0.10	0.48	0.38	0.04	5000	55.34	0.817	61.23
hydrotreater purge	0.85	0.09	0.04	0.02	4000	18.10	0.182	42.48
reformer net gas	0.90	0.04	0.05	0.01	1500	17.67	0.161	44.04
relief load	0.20	0.40	0.30	0.10	900	46.07	0.731	53.88
natural gas	0	0.93	0.06	0.01	1009	42.53	0.605	54.70
header (design)	0.321	0.327	0.293	0.059	20409	44.10	0.650	54.69

$\mathrm{d}\ln W/\mathrm{d}a = -0.711 + 0.447 = -0.264$ at $a = 0$, the first term from the heating value and the second from half the fall in specific gravity. Adding 5, 10 and 20 % hydrogen lowers the heating value 3.55, 7.11 and 14.22 % and the Wobbe index only 1.33, 2.66 and 5.35 %, as shown in Figure 14.2a. Natural gas, at 54.70 MJ/Nm^3, has the design gas's Wobbe index to within 0.01 MJ/Nm^3. That equality is a coincidence of the chosen teaching compositions and not a property of refinery gas. Three candidate designs during the build gave header indices of 54.69, 55.17 and 54.09 MJ/Nm^3, and nothing was tuned toward the natural gas value.

14.3.3 Makeup, Flare Valve and the Split Range

One output u drives both valves through the split range of Equation (14.4).

$$\begin{aligned} x^*_{MU} &= \mathrm{clip}\Big(\frac{50 - \delta/2 - u}{50 - \max(0, \delta/2)}\Big), \\ x^*_{FL} &= \mathrm{clip}\Big(\frac{u - 50 - \delta/2}{50 - \max(0, \delta/2)}\Big) \\ \frac{\mathrm{d}x}{\mathrm{d}t} &= \mathrm{clip}\Big(\frac{x^* - x}{\tau_x},\ \pm r_v\Big) \\ F_{MU} &= F_{MU,\max}\, x_{MU} \\ F_{FV} &= F_{FL,\max}\, x_{FL}\, (p + p_a)/(p_0 + p_a) \end{aligned} \tag{14.4}$$

where clip limits to $[0, 1]$, δ is the dead band in percent of output, x^* the command, τ_x the stem's lag (5 s for the makeup and 3 s for the flare valve), $r_v = 10\,\%/\mathrm{s}$ the stroking limit, $F_{MU,\max} = 8000\,\mathrm{Nm^3/h}$, $F_{FL,\max} = 15\,000\,\mathrm{Nm^3/h}$ at the design pressure p_0, and the stems are held at their stops. A positive δ leaves a band of output around 50 % in which neither valve opens. A negative δ is an overlap in which both do, and the case 2 and challenge settings as shipped carry $\delta = -4\,\%$, so the makeup shuts at 52 % and the flare valve opens at 48 %, as shown in Figure 14.1b. Both valves are choked, the makeup from its supply and the flare valve into the flare, so neither flow depends on the header except through the flare valve's absolute upstream pressure.

14.3.4 Flare Header, Water Seal and Recovery Compressor

The flare header holds its gas behind the water seal, and a loaded compressor stage recycles through its spillback whatever its suction cannot supply, as shown in Equation (14.5).

$$\begin{aligned} c\,\frac{\mathrm{d}n_F}{\mathrm{d}t} &= F_{rel} - F_{RC} - F_{seal}, \qquad p_F = \frac{n_F R T}{V_F} - p_a \\ F_{RC} &= N\, F_{st}\, \mathrm{clip}\big((p_F - p_{\min})/\Delta p_{sb}\big) \\ F_{seal} &= k_{seal}\, \max(0,\ p_F - p_{seal}) \end{aligned} \tag{14.5}$$

where p_F is in mbar gauge, $V_F = 400\,\mathrm{m^3}$, N is the number of loaded stages, $F_{st} = 1200\,\mathrm{Nm^3/h}$ per stage, $p_{\min} = 5\,\mathrm{mbar}\,g$, $\Delta p_{sb} = 15\,\mathrm{mbar}$, $k_{seal} = 500\,\mathrm{Nm^3/h}$ per mbar and $p_{seal} = 60\,\mathrm{mbar}\,g$. With

N stages loaded and enough capacity the flare header settles at $p_{\min} + \Delta p_{sb} F_{rel}/(N F_{st})$, which is 16.25 mbar g for one stage at 900 Nm^3/h and 15.0 mbar g for two at 1600 Nm^3/h. With no stage loaded the 900 Nm^3/h relief load lifts the seal and holds the flare header at $60 + 900/500 = 61.8$ mbar g. The flared flow is $F_{flare} = F_{seal} + F_{FV}$. The header's flare valve discharges past the seal, so the recovery compressor never takes back what the split range flares. Many plants route that valve into the flare header, where a compressor with spare capacity would recirculate it, and the simplification keeps the split range's flaring and the compressor's recovery separately measurable.

14.3.5 Burners, H-1 and the Lumped Heaters

Every burner manifold sits behind a fuel valve, and valve and burner tips both pass gas as the square root of the difference of squared pressures over the specific gravity. The flow at a burner pressure p_b and the heat it releases are shown in Equation (14.6).

$$\begin{aligned} F &= F_0\,\phi(p_b)\sqrt{SG_0/SG}, \qquad \phi(p_b) = \sqrt{\frac{p_b^2 - p_a^2}{p_{b0}^2 - p_a^2}} \\ Q &= \mathrm{HHV}\,F/3600 = Q_0\,(W/W_0)\,\phi(p_b) \\ p_{b,\max} &= \sqrt{\frac{r^2 P^2 + p_a^2}{r^2 + 1}}, \qquad r^2 = \frac{p_{b0}^2 - p_a^2}{u_0^2\,(P_0^2 - p_{b0}^2)} \end{aligned} \tag{14.6}$$

where pressures are absolute, $P = p + p_a$ is the header's absolute pressure and P_0 its design value, F_0, Q_0, SG_0 and W_0 are design values, $p_{b0} = 2.2$ bar absolute, $u_0 = 0.6$ is the fuel valve opening at design, and $p_{b,\max}$ is the burner pressure with the fuel valve wide open, 2.978 bar absolute at design ($r^2 = 0.682$). At a fixed burner pressure the heat is proportional to W, which is why the Wobbe index rather than the heating value is the property a burner answers to.

Pause. Try Exercise 14.2 before reading on.

H-1's outlet loop sets a firing demand d, a fast inner loop makes the burner pressure follow the setpoint the demand asks for, and the heat passes a firebox lag and a coil to the outlet, as shown in Equation (14.7).

$$\begin{aligned} p_{b,SP} &= \sqrt{p_a^2 + (p_{b0}^2 - p_a^2)\,\big(d/(100\,r_W)\big)^2} \\ \tau_{pb}\frac{\mathrm{d}p_b}{\mathrm{d}t} &= \min(p_{b,SP},\ p_{b,\max}) - p_b \\ \tau_{fb}\frac{\mathrm{d}Q_f}{\mathrm{d}t} &= \eta Q - Q_f \\ \tau_p\frac{\mathrm{d}T_{out}}{\mathrm{d}t} &= \frac{1000\,Q_f}{\dot{m}c_p} - (T_{out} - T_{in}) \end{aligned} \tag{14.7}$$

where r_W is the Wobbe ratio the feedforward applies (1 with it off), $\tau_{pb} = 3$ s, $\tau_{fb} = 40$ s, $\tau_p = 90$ s, $\eta = 0.85$, $T_{in} = 220$ °C and $\dot{m}c_p = 113.33$ kW/K, sized so that $Q_0 = 20$ MW heats the coil to 370 °C. One percent of firing is 1.5 K at the outlet. H-1 is starved when $p_{b,SP}$ exceeds $p_{b,\max}$. The eighteen lumped heaters use the same burner law with $Q_0 = 230$ MW, and their outlet loops are one integral action on their heat, $\mathrm{d}h_L/\mathrm{d}t = \max(0.005, h_L)(Q_{L,dem} - Q_L)/(Q_{L,dem}\tau_L)$ with $\tau_L = 3$ min and $Q_{L,dem} = 230\,\mathrm{MW}\,d_L/100$, held when they starve. H-20, when lit to a fraction s, burns at a fixed burner pressure, $F_{su} = s\,(3600\,Q_{SU}/\mathrm{HHV}_0)\sqrt{SG_0/SG}$ with $Q_{SU} = 18$ MW, so it draws 1473 Nm^3/h at the design gas.

14.3.6 The Coker's Drum Switch

A delayed coker switches its effluent to a cold drum at the end of each cycle, and the new drum condenses part of the vapor. The application reproduces that as a teaching shape rather than importing the coker model of Chapter 11. At a switch the coker gas falls to 40 % of its rate over 30 s, stays there

20 min and recovers linearly over the next 40 min. Switches a scenario publishes are known from $t = 0$, so the MPC may preview them. One fired from the panel joins the plant's schedule when it happens and is never announced to the MPC.

14.3.7 Instruments and What Is Counted

Instruments sit between the plant and every controller. The header pressure has a 1 s lag and 0.003 bar of noise, the flare header 1 s and 0.3 mbar, every flow meter a 2 s lag and 0.3 % noise, and the ultrasonic meter at the flare tip 2 %. The Wobbe meter is a combustion calorimeter with a hydrogen cell that samples every 10 s, analyzes for 10 s behind a 10 s sample line and reports with 0.03 MJ/Nm^3 of noise. H-1's outlet reads through 15 s of delay, a 5 s lag and 0.1 K of noise, and the valve positioners report their stems. The flared volume, its carbon dioxide and the import-and-flare time are integrated from the true flows, as shown in Equation (14.8).

$$\begin{aligned} V_{flare} &= \int F_{flare}\, dt \\ m_{CO_2} &= \int \tfrac{44.01}{22.414}\left(F_{seal} C_{rel} + F_{FV} C\right) dt \\ t_{I\&F} &= \int \left[F_{MU} > 50\right]\left[F_{flare} > 50\right] dt \end{aligned} \tag{14.8}$$

where C is carbon atoms per molecule, 1.18 for the relief gas, and the brackets are 1 when true. Import and flare is therefore counted from the flows, both above 50 Nm^3/h at the same instant, and never inferred from the valve positions. The carbon dioxide assumes complete combustion with no destruction efficiency and no methane slip, a teaching assumption that measured flares do not meet [11]. Gas is valued at 6 $/GJ for natural gas bought and for fuel gas flared, a teaching price.

14.3.8 Parameters, Initialization and Numerics

Table 14.3 gives every parameter with its default. A case opens lined out at its own settings and disturbances. The flare header takes the smallest stage count its load and unload thresholds allow, a bisection on u finds the split-range output at which makeup or flare valve closes the header's balance at the setpoint, the heaters' demands are set so that each delivers its duty with the Wobbe meter lined out on the starting gas, and the manual stations are placed on those values so that Manual from $t = 0$ holds. At design the output sits at 41.07 % with the makeup valve 12.6 % open. Fourth-order Runge-Kutta steps of 0.5 s advance the states, the controllers execute every 1 s, and the log keeps a row every 5 s. Each lump, the flare header and the metered totals close over a disturbed hour to better than 10^{-9} kmol. Halving the step moves no verdict of the challenge and no figure of it by more than 0.002 bar or half a second of import and flare, and in case 1 it moves the time to 3.0 bar g from 45.0 to 44.8 s.

14.3.9 Assumptions

The header is one well-mixed isothermal volume, so pressure waves, transport delay from the drum to a burner and temperature changes on compression are absent, and a composition change reaches every burner within the 41 s residence time. Each source sends what its unit makes whatever the header pressure, which holds while the units control their own pressure upstream and fails if the header rose high enough to back gas into them. Gas is four lumps. Their heating values and molar masses are teaching values close to those of the pure components, and the C_{2+} lump's 92.0 MJ/Nm^3 sits nearer a mean carbon number of 2.7 than the 2.6 its molar mass implies, by the application's technical review. The standard calculation of heating value, density and Wobbe index from a full composition is ISO 6976, which the model does not use. The burner and valve law is an isothermal subsonic one, and the makeup and flare valves are treated as choked. Heater efficiency is constant on the higher heating value, so the latent heat in the water a hydrogen-rich fuel makes is not tracked. Only H-1 is simulated in full, the eighteen lumped heaters share one integral loop, and H-20 has no starvation check, which no case reaches. Every safety-related number, the seal, the stage thresholds,

Table 14.3 Parameters and Defaults. A, Adjustable in the Parameters Panel. C, a Control on a Card. F, Fixed in the Source

Symbol	Meaning	Value	Unit	
V	header volume (30, 60, 120, 240)	60	m^3	C
T, p_0	header temperature, design pressure	40, 3.5	°C, bar g	A
$F_{MU,\max}$, τ_{MU}	makeup valve capacity, lag	8000, 5	Nm^3/h, s	A
$F_{FL,\max}$, τ_{FL}	flare valve capacity, lag	15000, 3	Nm^3/h, s	A
r_v	valve stroking limit	10	%/s	A
V_F, p_{seal}	flare header volume, water seal	400, 60	m^3, mbar g	A
k_{seal}	flow over the seal	500	$Nm^3/h/mbar$	A
F_{st}	recovery capacity per stage	1200	Nm^3/h	A
$p_{\min}$, Δp_{sb}	spillback floor, span	5, 15	mbar	A
Q_0, η	H-1 firing at design, efficiency	20, 0.85	MW, —	A
T_{in}, $T_{out,0}$	H-1 inlet, design outlet	220, 370	°C	A
τ_{fb}, τ_p	firebox lag, coil time constant	40, 90	s	A
p_{b0}, u_0	design burner pressure, valve opening	2.2, 0.6	bar a, —	A
τ_{pb}	burner pressure loop	3	s	A
$Q_{L,0}$, τ_L	lumped heaters' firing, reset time	230, 3	MW, min	A
Q_{SU}	H-20 firing when lit	18	MW	A
F_k	FCC, coker, purge, reformer at design	8000, 5000, 4000, 1500	Nm^3/h	A
—	coker gas after a switch	40	%	A
—	natural gas price, fuel gas value	6, 6	$/GJ	A
H_i, M_i	lump heating values, molar masses	§14.3.2		F
y_k	stream compositions	Table 14.2		F
—	flowing threshold for $t_{I\&F}$	50	Nm^3/h	F

the makeup capacity and the WOBBE LOW alarm at 52.5 MJ/Nm^3, is a teaching value. API Standard 521 governs the design of real pressure-relieving and flare systems, and a plant's relief and flare studies set its numbers.

14.4 Controllers as Implemented

Within a physics step the controllers act first, then the states advance, then the plant-side bookkeeping (ramps, the coker's schedule, the import-and-flare count) runs, and the outputs are written last. The controllers execute every $\Delta t_c = 1$ s on the instruments of Section 14.3.7. One of the application's tests whitelists what the controllers may read, and another fails if the flow feedforward or the MPC reads the natural gas supply's availability, a disturbance no instrument measures.

14.4.1 The Header Pressure Loop and the Split Range

The pressure controller is the shared velocity-form PID of Section 1.6.2, used here without derivative action. Its measurement is the header pressure p_m, its output bias u_b in Equation (1.18) is the feedforward output u_{ff}, which is zero for the plain split range, its output is limited to 0 to 100 %, and its tracking time T_t equals τ_I. A high header raises the output toward the flare valve, so the loop is direct acting on u, with $a = -1$ and the error $p_m - p_{SP}$. The defaults are $K_c = 60$ % of output per bar and $\tau_I = 2$ min, an integral time of 60 min removes integral action, and the default dead band is 6 %. The output passes through Equation (14.4) to the two valve commands. In Manual the learner sets u and the PI tracks it, so a return to Auto is bumpless, as Section 1.6.2 describes.

14.4.2 Flow Feedforward

The second architecture adds a feedforward from the meters. The metered need is $\Phi = F_{h,m} + F_{L,m} + F_{su,m} - \sum_k F_{k,m} - F_{RC,m}$, and u_{ff} is the output that would deliver it, mapped back through the split range, $u_{ff} = 50 - \delta/2 - (50 - \max(0, \delta/2))\,\Phi / F_{MU,\max}$ for $\Phi \geq 0$ and the flare valve's mirror image for $\Phi < 0$. The capacity used is the makeup valve's declared one. Because u_{ff} jumps from one edge of the dead band to the other whenever Φ changes sign, the feedforward carries the meters' noise across the band. After the purge step of the challenge, when the header needs only about 125 Nm^3/h

of makeup and the summed meters carry several tens of $\mathrm{Nm^3/h}$ of noise, the output crosses 50 % 240 times in 3 h, against 4 times under the PI alone. The Manual helper *Balance the header* sets u to the same value once.

14.4.3 Model Predictive Control on Both Valves

The third architecture replaces the split range with the MPC option of Section 1.6.3. Every 2 s an MPC solves for both valve commands over 90 s on the header's integrator with its declared volume, each stem's lag and a disturbance, as shown in Equation (14.9).

$$\begin{aligned} \dot{p} &= K\left(F_{MU,\max}\, x_{MU} - F_{FL,\max}\,\tfrac{P}{P_0}\, x_{FL} + w\right) \\ \tau_{MU}\dot{x}_{MU} &= c_{MU} - x_{MU}, \qquad \tau_{FL}\dot{x}_{FL} = c_{FL} - x_{FL} \end{aligned} \tag{14.9}$$

where c are the commands and w is the metered imbalance (sources and recovered gas minus heaters) plus a bias. An observer runs the same model every 1 s on the commands sent and corrects it with the measured pressure, $\hat{p} \leftarrow \hat{p} + 0.2\,\varepsilon$ and $b \leftarrow b + 0.02\,\varepsilon/(K\Delta t_c)$ with $\varepsilon = p_m - \hat{p}$, which makes the controller offset-free. With the coker preview on, w over the horizon also carries the coker's metered gas scaled by the published switch shape. The continuous model becomes an exact zero-order-hold step of 2 s, and the quadratic program over 45 steps in 11 graduated move blocks is Equation (14.10).

$$\begin{aligned} \min\ & \textstyle\sum_k w_p (p_k - p_{SP})^2 + 10\, w_p (p_N - p_{SP})^2 \\ & + w_{\Delta u} \textstyle\sum_j \|\Delta c_j\|^2 + 10^4 s^2 \\ & + w_\$ \textstyle\sum_k (\gamma_{MU} c_{MU,k} + \gamma_{FL} c_{FL,k}) \\ \text{s.t. } & 0 \le c_{MU} \le \bar{c}_{MU}, \quad 0 \le c_{FL} \le \bar{c}_{FL} \\ & |p_k - p_{SP}| \le 0.15 + s, \quad s \ge 0 \end{aligned} \tag{14.10}$$

where $w_p = 100$ per $\mathrm{bar^2}$, $w_{\Delta u} = 1$, $w_\$ = 1$, and γ is the money each valve's gas is worth per decision step at full opening, natural gas bought for the makeup and fuel gas burned for the flare. Because both valves cost money and act on the pressure in opposite directions, the optimum never opens both. The stems lag the plan, however, so an interlock sets $\bar{c}_{FL} = 0$ while the makeup is commanded open or its positioner reads more than 0.2 % of travel, and $\bar{c}_{MU} = 0$ in the mirror case. The series' shared solver handles the program with the dual method of Goldfarb and Idnani [16], only the first planned move reaches the valves, as in industrial receding-horizon practice [17], and a solve that fails, is not finite or leaves its bounds is rejected, after which the tracked split-range PI takes the valves without a bump. On the challenge with the suggested staging and feedforward the MPC never failed in 8 h.

The interlock is necessary, and the measured reason is the stems. With the MPC's plan alone, which never opens both valves, the lagging stems pass gas both ways at the hand-overs, and the challenge counts 7.88 to 9.33 min of import and flare in 8 h across five seeds. An interlock on the commands alone still leaves 3.00 to 3.47 min. Both fail the challenge's 1 min limit, and the interlock on the positioners' feedback brings it to zero. An earlier record of the build gave half a second to 2.5 s for the case without interlock, which was not reproduced.

Pause. Try Exercise 14.3 before reading on.

14.4.4 Recovery Compressor Staging

The two stages load and unload on the measured flare header pressure, where the compressor takes its suction, and not on the fuel gas header controller's output. With k stages loaded the next loads when $p_{F,m}$ rises above its load threshold L_{k+1}, and the last unloads when $p_{F,m}$ falls below its unload threshold U_k. A sequencer from the series' shared core holds every start for a minimum run of 2 min and every stop for a minimum rest of 2 min, with 15 s between any two changes. The defaults are $L = 30$ and 45 mbar g and $U = 10$ and 12 mbar g, all below the seal, so the stages load before gas reaches the flare. An earlier design of the application put the stages on the controller output, loading

Table 14.4 The Nine Cases

#	Case and events	Teaching point
1	Manual, coker switch at 3 min	an integrator
2	$\delta = -4$ %, other heaters -4 % at 5 to 20 min	overlap and dead band
3	FCC trips at 5 min	a balance the makeup cannot close
4	H-1 on Man, purge +50 % at 5 min	hydrogen and the Wobbe index
5	purge +50 % at 5, back at 30 min	Wobbe feedforward
6	relief to 1600 Nm^3/h at 5 to 50 min, $U_2 = 40$	staging and hysteresis
7	Manual, coker switch at 3 min, 60 or 240 m^3	volume and gain
8	H-20 lights at 5 min	measured disturbance
9	Challenge: 8 h, coker at 1, FCC -40 % at 3, purge at 5 h	the whole system

before its flare valve, but the compressor's suction is the flare header, and a stage on the fuel gas header's output would have no gas to take.

14.4.5 The Heater Loop and Wobbe Feedforward

H-1's outlet loop uses the same shared PI, reverse acting on the measured outlet, with $K_c = 1\,\%$ of firing per kelvin, $\tau_I = 2$ min and an output of 0 to 130 %. Its output is a firing demand, not a fuel flow, and the burner-pressure loop of Equation (14.7) turns it into a burner pressure. With the Wobbe feedforward on, every heater's demand, H-1's and the lumped bank's, is divided by $r_W = \text{clip}(W_m/W_{\text{ref}},\ 0.7,\ 1.3)$ before it becomes a burner pressure, $W_{\text{ref}} = 54.69\,\text{MJ}/\text{Nm}^3$ being the design gas's index. Because the heat at a fixed burner pressure goes as W in Equation (14.6), this division is exact for a correctly measured W. On a volumetric fuel-flow loop the exact ratio would be the heating value instead. Chapter 3 meets an unmeasured change of heating value with its outlet loop alone, and Volume 3, Chapter 4 adds the air side of a heater burning fuel gas. The application has no Wobbe blending loop. Natural gas is already the pressure loop's makeup, so any more of it than the balance needs could only leave through the flare, a structural reason that does not depend on the coincidence of the two indices.

14.4.6 Three Models

Section 14.3 is the plant. What a learner identifies is a single number, the slope K read from case 1 or 7. The controllers' models are the PI's absence of one, the feedforward's meter balance, and the MPC's three-state integrator with the declared volume, stem lags and the makeup valve's declared capacity, which knows neither the composition nor a supply shortfall. Its numbers are the declared ones, fixed when the application loads, so another header volume or a Parameters edit is model mismatch: at 30 m^3, twice the gain the model assumes, case 4 under the MPC cycles about 0.16 bar from its setpoint, where a model given the true volume held it within 0.015 bar. With the natural gas supply cut to half its capacity before case 8 starts, the header's worst error after the heater lights is 0.215 bar under the PI, 0.110 bar with flow feedforward and 0.015 bar under the MPC, against 0.118, 0.015 and 0.007 bar with full supply. That cost is the honest consequence of a disturbance no instrument measures.

14.5 Nine Cases, Measured

The nine cases appear in Table 14.4. All share one reference configuration (the defaults above, Auto with the plain split range, and the design disturbances), and a row lists only what differs. Every number below was taken headless from the engine of Section 1.6.1 at seed 20261016, advanced step by step as the page advances it, with a row's settings entered before the run. Each case produces the same run when loaded first, when picked after another case and after Reset. Pressure deviations are on the true header against its setpoint.

14.5.1 An Integrator With Nobody at the Valve

In case 1 the split-range output is held in Manual when the coker switches at 3 min. The pressure falls in a straight line and passes 3.0 bar g 45 s after the switch began, which is K times the 3000 Nm^3/h shortfall over the 0.5 min ramp and the quarter minute after it. Nothing stops it until H-1's fuel valve opens wide at 4.47 min. Then the heaters starve, burn less, and close the balance themselves, and the header settles at 1.74 bar g with H-1's outlet 27.6 K low at 15 min. Auto at 3.8 min, with the header at 2.94 bar g, brings it back within 0.1 bar from 8.0 min. Pressing *Balance the header* at 3.8 min only stops part of the fall, because the gas the coker stopped sending is the richest in the header. The Wobbe index falls from 54.69 to 53.67 MJ/Nm^3 by 7 min, the lumped heaters' meters rise from 20,634 to 21 178 Nm^3/h as their loops burn more of the leaner gas, and the heaters starve at 8.12 min. Case 7 repeats the switch with a 240 m^3 header, which passes 3.0 bar g after 133.5 s instead of 45 s and starves the heaters at 7.89 instead of 4.47 min, while both end near 1.75 bar g. In Auto with the same tuning the larger header dips 0.204 bar against 0.280 bar. Four times the volume quarters the rate of fall and buys time, but it does not change where the balance ends.

> **TRY IT IN THE APP** **1 · A coker drum switch, by hand (Manual)**
>
> Load the case and press Run. The split-range output stays in Manual, and at 3 min the coker sends 3000 Nm^3/h less gas. Watch the header pressure trend: it falls in a straight line and passes 3.0 bar g 45 s after the switch began. Nothing stops it until the fuel valve of H-1 opens wide at 4.47 min and the starved heaters burn less.

14.5.2 The Overlap and the Dead Band

Case 2 ships the −4 % overlap. When the other heaters fire 4 % less at 5 min, the makeup the header needs falls to a few hundred Nm^3/h and the output rises into the overlap, where both valves open. At 12 min the output is 48.5 %, the makeup stem 6.8 % open passing a metered 533 Nm^3/h, and the flare stem 1.2 % open passing 198 Nm^3/h, as shown in Figure 14.1b. Over the 30 min case the refinery imports and flares for 14.38 min, flares 49.8 Nm^3 and buys 362 Nm^3, while the header never leaves 0.025 bar of its setpoint. With any dead band from 0 to 20 % the import and flare is zero, nothing is flared, the makeup falls to 310 Nm^3, and the worst error is 0.020 to 0.026 bar, as shown in Figure 14.2b. Wider overlaps do worse, 30 min at $\delta = -8$ % with 210 Nm^3 flared, and a 1 % overlap happened to give none. The application's tests repeat the overlapped case at twelve tunings, gains of 30 to 240 % per bar and integral times of 0.5 to 10 min, and every one imports and flares for 14.2 to 15.3 min. On this integrating header with a PI loop, a positive dead band costs nothing measurable, because the integral carries the output across it once and does not return. In the challenge, with the other three suggested changes in place, a dead band of exactly zero still imports and flares for 4.5 s in 8 h, because a closing stem lags its command by seconds at each crossing, while 2 and 12 % give none.

14.5.3 A Balance No Tuning Can Close

In case 3 the FCC, the largest source at 8000 Nm^3/h and 48.9 % of the header's heat, trips at 5 min. The makeup valve, already passing about 1000 Nm^3/h, reaches its 8000 Nm^3/h 1.35 min after the trip began, and natural gas at 42.53 MJ/Nm^3 replaces only part of FCC gas at 55.00 MJ/Nm^3. The header keeps falling, the heaters starve at 6.82 min, and it settles at 1.838 bar g with H-1 23.8 K low. The tests sweep the gain from 30 to 240 % per bar and the integral time from 0.5 to 10 min, and every tuning lets the header fall below 3.0 bar g. By hand, the wide-open makeup supports 210.4 MW with the FCC gone, so the lumped heaters must fall to 82.8 % of their firing. Shed at 10 min to 84 % they change nothing, because starved they already burn less. At 82 % the header reaches only 2.83 bar g by 50 min, at 81 it is back within 0.1 bar at 38.8 min, and at 80 % at 30.9 min.

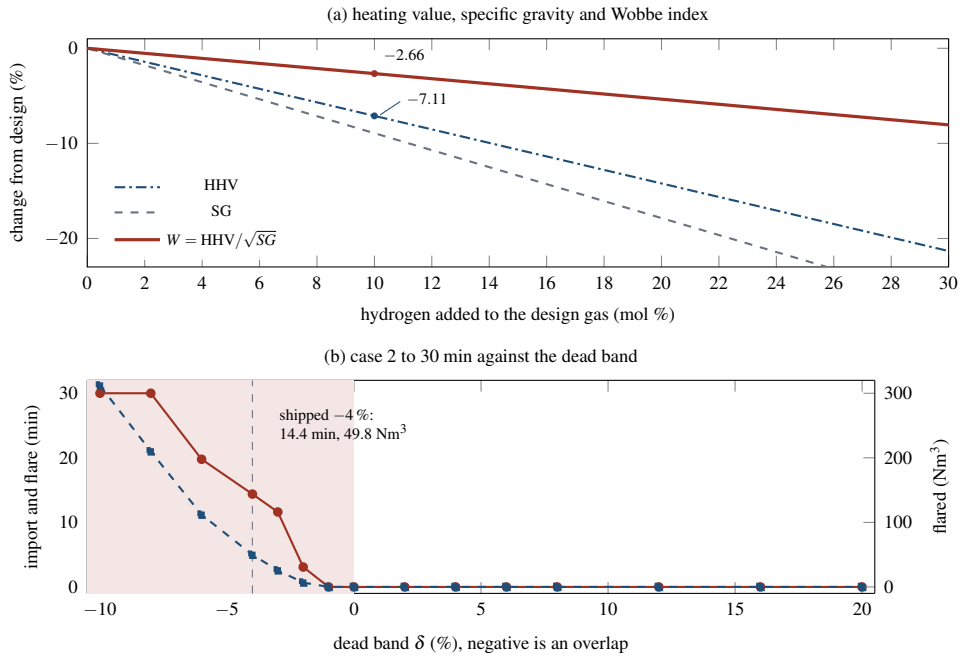


Figure 14.2 Two characteristics computed from the application. (a) Heating value, specific gravity and Wobbe index of the design gas as pure hydrogen is added: heating value dash-dotted, specific gravity dashed, Wobbe index solid. At 10 % the heating value falls 7.11 % and the Wobbe index 2.66 %. (b) Case 2 run to 30 min at each dead band, the import-and-flare time (solid with circles, left) and the volume flared (dashed with squares, right). Overlaps are shaded. Every $\delta \geq -1$ % gives zero.

14.5.4 Hydrogen, the Wobbe Index and the Feedforward

In case 4 the purge rises by half at 5 min with H-1's loop on Man. The header's hydrogen rises from 32.09 to 38.33 %, the heating value falls 5.33 % from 44.097 to 41.746 MJ/Nm^3, the specific gravity falls from 0.6501 to 0.6085, and the burners pass 3.37 % more gas at the same pressure, so the Wobbe index falls only 2.14 %, from 54.69 to 53.517 MJ/Nm^3. H-1 drops from 20.00 to 19.57 MW and its outlet settles 3.22 K low, below 368 °C at 8.49 min. The meter's 53.48 MJ/Nm^3 at 30 min is 2.21 % below W_{ref}, which is what the Quality view prints. With the loop in Auto the demand rises 2.19 % and the outlet returns. In case 5, the same step with the loop in Auto and back at 30 min, the outlet strays 1.23 °C 3.3 min after the step without the feedforward and 0.36 °C with it, and 1.23 against 0.33 °C on the way back. Across five seeds the two are 1.22 to 1.25 and 0.33 to 0.38 °C. What the feedforward leaves is the 20 s to 30 s by which the meter's report trails the gas at the burners.

14.5.5 Staging Against the Seal

Case 6 raises the relief load from 900 to 1600 Nm^3/h for 45 min, more than one 1200 Nm^3/h stage takes, and ships stage 2 unloading below 40 mbar g. Two loaded stages hold the flare header at 15.0 mbar g, well under that threshold, so stage 2 unloads as soon as its 2 min minimum run ends and loads again when one stage lets the header climb back to 45 mbar g. It starts 11 times, and the recovered gas, returned to a fuel gas header that is already nearly balanced, leaves through the header's flare valve, 51.3 Nm^3 in all. With the unload threshold at 12 mbar g, below where two stages hold the suction, stage 2 starts once and 3.0 Nm^3 are flared. Stage 1 loading above 70 mbar g, above the seal, never loads, and $900 \cdot 15/60 + 1600 \cdot 45/60 = 1425$ Nm^3 goes over the seal in the hour, exactly what the engine counts.

Table 14.5 Measured Cases. Ranges Cover Seed 20261016 and Seeds 0, 1, 2 and 3 Where Those Were Run

Case	Configuration	Result
1	Manual, 60 m^3	3.0 bar g after 45 s, starved 4.47 min
7	Manual, 240 m^3	3.0 bar g after 133.5 s, starved 7.89 min
7	Auto, 60 / 240 m^3	dip 0.280 / 0.204 bar
2	$\delta = -4\,\%$	$t_{I\&F}$ 14.38 min, 49.8 Nm^3 flared
2	$\delta = 0$ to 20 %	$t_{I\&F}$ 0, 0 Nm^3 flared
3	any of 12 tunings	below 3.0 bar g, settles 1.838 bar g
4	H-1 on Man	W −2.14 %, outlet −3.22 K
5	feedforward off / on	outlet 1.22–1.25 / 0.33–0.38 °C
6	U_2 40 / 12 mbar g	11 / 1 starts, 51.3 / 3.0 Nm^3 flared
8	PI / flow FF / MPC	dip 0.118–0.119 / 0.013–0.016 / 0.006–0.008 bar

Table 14.6 The Eight-Hour Challenge. Ranges Cover Five Seeds (20261016, 0, 1, 2, 3), Each at Δt and $\Delta t/2$

Settings	$\lvert p - p_{SP}\rvert$ (bar)	Flared (Nm^3)	$t_{I\&F}$ (min)	$\lvert T - T_{SP}\rvert$ (°C)	Verdict
shipped	0.303–0.305	7203	480	1.22–1.23	fails
suggested	0.153–0.156	6.1–6.3	0	0.32–0.35	passes
with $\delta = -4\,\%$	0.162–0.165	958–959	179.6–179.7	0.32–0.35	fails
with stages 65 / 80	0.153–0.156	7200	480	0.33–0.36	fails
with feedforward off	0.153–0.155	15.6–15.8	0	1.21–1.23	fails
with 60 %/bar	0.292–0.294	5.6–5.8	0	0.32–0.35	fails
flow FF, 60 %/bar	0.060–0.063	8.2–8.6	0–0.07	0.32–0.35	passes
MPC, preview	0.009–0.019	6.1–6.5	0	0.32–0.35	passes
MPC, no preview[a]	0.013–0.019	6.1–6.5	0	0.32–0.35	passes

[a] At Δt only, five runs.

TRY IT IN THE APP 6 · Recovery compressor staging and hysteresis

Load the case and press Run. At 5 min the relief load rises to 1600 Nm^3/h, more than one stage takes. Two stages hold the flare header at 15.0 mbar g, below the 40 mbar g at which stage 2 unloads, so it starts 11 times. Set Stage 2 unloads below to 12 mbar g, press Reset and run again: it starts once, and 3.0 Nm^3 are flared instead of 51.3.

14.5.6 A Heater Lights

Case 8 lights H-20 over a minute at 5 min, 1473 Nm^3/h more gas. The PI alone lets the header dip 0.118 bar, 1.26 min after the burners begin to light, and 0.118 to 0.119 bar at seeds 1 to 3. Flow feedforward sees the new heater's meter and opens the makeup at once, and the dip is 0.015 bar (0.013 to 0.016). The MPC, reading the same meters with its model of the stems, holds 0.007 bar (0.006 to 0.008). The panel's *Heater start-up* button is different, because it ramps the lumped bank's demand 8 % over 2 min, and their loops draw the extra gas over about ten minutes, 1473 Nm^3/h at 10 min and 1556 Nm^3/h at 20 min, so the header dips only 0.044 bar.

14.5.7 The Challenge

The challenge runs 8 h: a published coker switch at 1 h, the FCC gas 40 % down from 3 h for half an hour, and the purge up by half from 5 h. Its target, judged on the truth every physics step, is the header within ±0.2 bar of setpoint after the first minute, at most 500 Nm^3 flared, at most 1 min of import and flare, H-1's outlet within ±1 °C and no heater starved. It ships with the −4 % overlap, stages that load at 65 and 80 mbar g, above the seal, the Wobbe feedforward off and 60 % per bar. The outcomes over five seeds and two steps, 85 runs in all, are in Table 14.6, and Figure 14.3 sets them against the four targets.

As shipped, the stages never load because the seal holds the flare header at 61.8 mbar g, below the 65 mbar g at which stage 1 would, so the whole 900 Nm^3/h relief load burns while the header buys natural gas. The flare budget is gone in 33.3 min, 7203 Nm^3 are flared by 8 h, and the import-and-flare

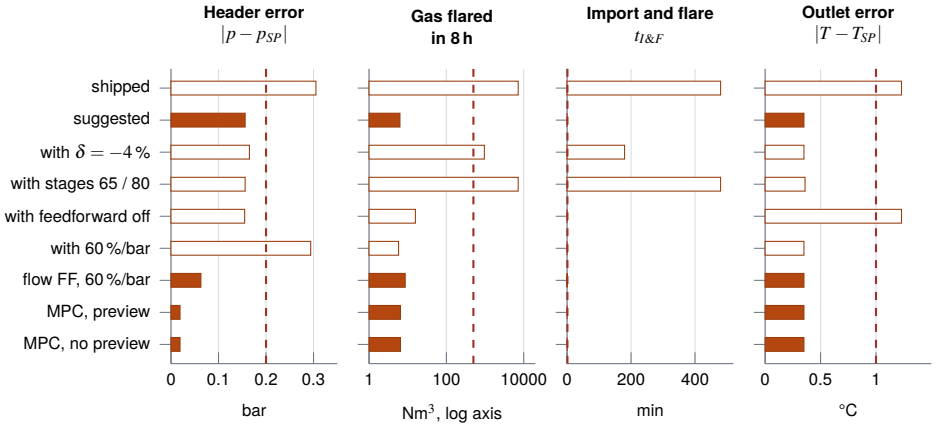


Figure 14.3 The eight-hour challenge of Table 14.6 against its four targets, one panel each: the header's worst pressure error, the gas flared (logarithmic axis), the import-and-flare time and H-1's worst outlet error. Solid bars pass the challenge and white bars fail it. Where the table gives a range the bar reaches its upper end, and a dashed line marks each target. Notice that dropping the dead band or the staging leaves the pressure error almost unchanged while the flaring and the import-and-flare time rise, and that dropping the feedforward or the higher gain fails only the outlet or only the pressure.

count runs the full 480 min. The coker switch takes the header 0.294 bar below setpoint at 60.95 min, the FCC upset 0.303 bar at 181.3 min, and the outlet strays as far as 1.23 °C. The suggested settings make four changes, a 6 % dead band, stages that load at 30 and 45 mbar g, the Wobbe feedforward on and 120 % per bar, and pass with the header within 0.154 bar, 6.1 Nm^3 flared, no import and flare and the outlet within 0.34 °C. Each change is necessary. Dropping any one fails at all ten of its runs, the overlap with 179.7 min of import and flare once the purge brings the header near balance, the staging with 7200 Nm^3 flared, the feedforward with the outlet 1.23 °C off, and the gain with the FCC upset taking the header 0.292 bar off. The 1 °C band is tighter than the 3 °C first planned for the application, for a measured reason. The worst outlet error without feedforward is 1.23 °C, so a 3 °C band would be met by any loop and the feedforward would teach nothing.

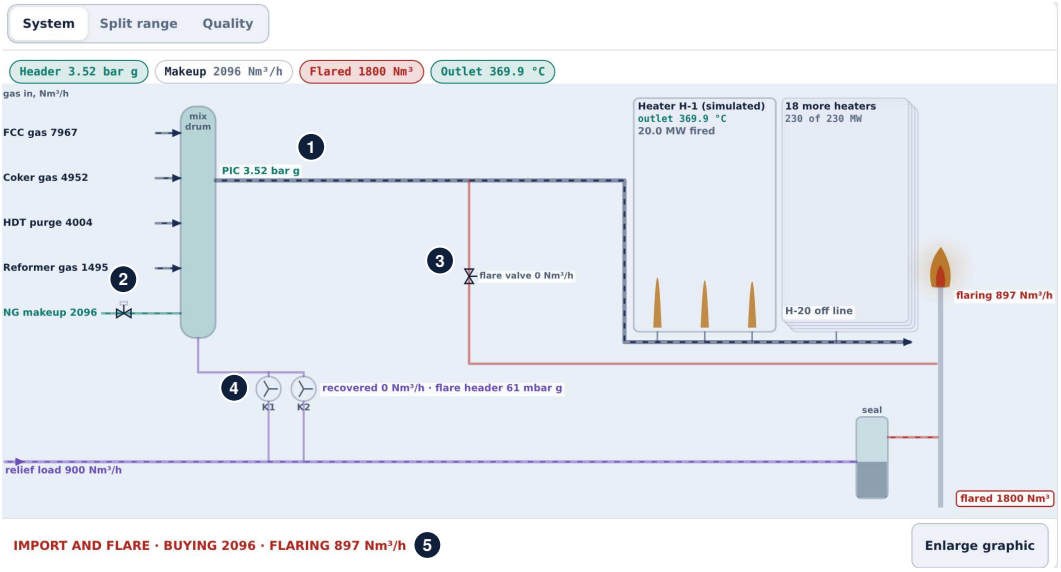


Figure 14.4 The challenge as shipped at $t = 2$ h on the System view, light theme, cropped to the plant. (1) The header reads 3.52 bar g on its 3.50 bar g setpoint. (2) The natural gas makeup passes a metered 2096 Nm^3/h. (3) The header's flare valve is shut. (4) The stages sit idle with the flare header at 61 mbar g, so the flame is lit at 897 Nm^3/h over the seal and the counter reads 1800 Nm^3. (5) The status strip reads IMPORT AND FLARE.

> **DID YOU KNOW? Stages Above the Seal Never Start**
>
> From the simulator (Table 14.6). With every suggested setting in place except the recovery stages, which load at 65 and 80 mbar g, above the 60 mbar g water seal, the challenge flares 7200 Nm^3 in 8 h against 6.1 to 6.3 Nm^3, and imports and flares for all 480 min. The header pressure error is the same, 0.153 to 0.156 bar.

Flow feedforward at the default 60 % per bar also passes, within 0.060 to 0.063 bar, but its deadband crossings import and flare for 0.5, 3, 0.5, 4 and 0.5 s at the five seeds and 0, 3, 0.25, 4 and 0.25 s at half the step, at most 4 s against the 1 min limit. The MPC with the coker preview holds the header within 0.009 bar at the default seed and 0.013 to 0.019 bar at the others, and without the preview within 0.013 to 0.019 bar. At the top speed of 120 min/s the 8 h play in 4.0 s in a browser (4.02 s measured in Chrome at both 1366×768 and 390×844, 120 min of simulated time per second of wall time). The shipped challenge at 2 h is shown in Figure 14.4.

14.6 Technology in Practice

Figure 14.5 draws the header pressure loop, the heater loop with its Wobbe feedforward and the recovery staging of Section 14.4 with the hardware a refinery installs.

What Measures It

The pressure loop reads one transmitter on the header, the feedforwards read the flow meters and the Wobbe meter, and the staging reads the flare header. The federal rule for refinery flares asks for the same pair of gas quality instruments that the chapter's Wobbe meter combines: a calorimeter that continuously records the heating value of the vent gas and, if the owner chooses, a hydrogen monitor, whose reading corrects the calorimeter's [18]. The flow to a flare is hard to meter, because the quiet

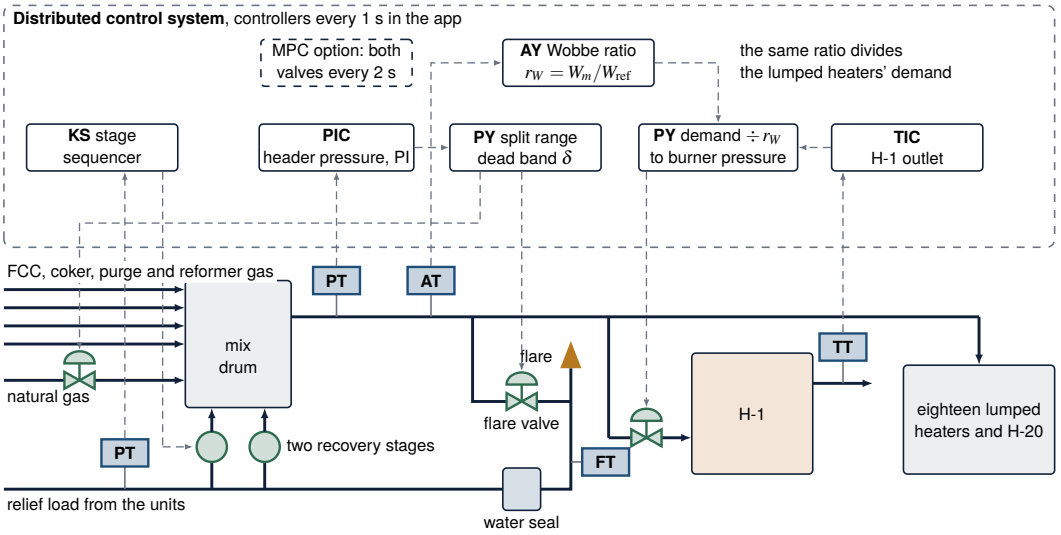


Figure 14.5 The loops of the fuel gas header with their hardware. Lettered boxes are sensing devices: the header pressure transmitter (PT), the Wobbe meter (AT), the H-1 outlet thermocouple (TT), the flare header pressure transmitter (PT) and the flare flow meter (FT). Valve symbols and the two compressor stages are final elements, and dashed arrows are signals. Notice that one controller output reaches two valves through one split-range block, and that the recovery stages answer the flare header, not the fuel gas header. The positioners' stem readings, the burner pressure transmitter and the MPC's signals are left out. Not to scale, and not a piping diagram.

flow of leaking relief valves and the full flow of an emergency call for a very large turndown, and the gas changes in composition. Velocity meters such as ultrasonic ones are less affected by composition than pressure-based or thermal meters, and multi-path transit-time ultrasonic meters show promise, at a high cost on large flare pipes [19]. The chapter's flare tip meter is ultrasonic with 2 % of noise.

> **TECHNOLOGY** **Sensor: The Header Pressure Transmitter**
>
> A common electronic pressure sensor is a taut metal diaphragm between two fixed plates, so that a pressure difference flexes the diaphragm and changes the two capacitances [19]. A needle valve between the process and the instrument damps pulsation, because the restriction and the instrument together form a low-pass filter. In gas service the transmitter is mounted above its tap, so that liquid drops cannot collect in the impulse line and add a false pressure [19]. A controller acts on such an error as on a true pressure, because it sees only the instrument, as the controllers of this chapter do. The chapter's transmitter has a 1 s lag and 0.003 bar of noise.

What Moves It

The pressure loop moves the makeup and flare valves, the heater loop moves the burner pressure, and the sequencer starts and stops the two compressor stages. A common way to split-range two valves is to give each its own 4–20 mA output from the same controller, which also leaves each smart positioner on its own circuit [19]. That positioner is the readback the chapter's MPC interlock waits for.

TECHNOLOGY Final Element: Two Valves on One Output

Valves that follow one controller output are split-ranged. In exclusive sequencing both are shut at an output of 50 % and one opens toward each end, so that the fluid passes one valve or the other but never both, which suits two valves whose effects cancel [19]. The ranges can be set in each valve's positioner or transducer, or in the controller, which then sends each valve its own signal. Where the sequencing sits decides the fail-safe state: sequencing after the controller makes the two valves fail in opposite states, and two controller outputs let both fail closed [19]. The chapter's makeup and flare stems lag their commands by 5 and 3 s and stroke at most 10 %/s.

Where the Controller Runs

A refinery runs such loops in a distributed control system, in which a supervisory level oversees local controllers and cycle times range from milliseconds to minutes [20]. The app executes its controllers every 1 s and its MPC every 2 s, inside that range. The pressure controller is a PI block whose output feeds a split-range block. One fieldbus standard has a function block for exactly this, which takes one control signal and drives a separate signal to each of two valves [19]. The Wobbe division is a calculation block ahead of each burner pressure loop, and the stage sequencer is logic with its own thresholds and timers.

IN PRACTICE A Written Plan for Every Flare

A United States refinery flare under Subpart Ja of 40 CFR Part 60 needs a written flare management plan. It lists the fuel gas systems connected to the flare, weighs a flare gas recovery system among the ways to cut flaring, and sets procedures to reduce flaring when the refinery has more fuel gas than it needs. For staged recovery compressors it states the longest time the next compressor takes to begin recovering gas [21]. Where the flare is watched by its line pressure against the liquid depth of its water seal, every period above that depth outside compressor staging calls for a root cause analysis [21]. The chapter's stages load below its seal for that reason.

What Is Modernizing It

Three developments touch this header. The first is continuous flare monitoring. Since January 30, 2019, a refinery flare under the federal rule has measured the flow in the flare header continuously, kept a pilot flame lit at all times and held the heating value of the gas in the combustion zone at or above a limit in each 15 minute block [18]. The second is the flare management plan of the in practice box above, which puts flare gas recovery and the staging of its compressors on paper. The third is predictive control, with more than 4600 applications reported and refining the largest share [17], which can move both valves of a header at once, as the chapter's MPC does.

14.7 Limitations

The sizes, compositions, prices and thresholds are generic teaching values chosen for a consistent design point, a 250 MW heater population on about 20 400 Nm^3/h of gas, and none was fitted to a refinery. The header is one isothermal volume with no transport delay, the gas is four lumps whose heating values are not computed by ISO 6976, and the C_{2+} lump's heating value is somewhat high for its molar mass. Only one heater is simulated in full, the eighteen others share one integral loop, and H-20 has no starvation check. The header's flare valve bypasses the seal and the compressor by construction, the coker's switch is a teaching shape, and the flare's carbon dioxide assumes complete combustion that measured flares do not achieve [11]. Combustion effects of hydrogen beyond the Wobbe index, such as flame speed and flashback, are outside the model.

The controllers carry the declared volume (the header as built), the declared valve capacities and the meters, so model error reaches them only through what a case changes, and a supply shortfall no instrument measures shows up only in the pressure. The MPC's model is linear in the valve positions, rebuilt every 2 s, and carries no guarantee beyond its horizon. There is no Wobbe blending loop and

no Wobbe band in the MPC or the challenge, and the equality of the natural gas and header indices that makes blending pointless here is a coincidence of the compositions. Every number is from one model at one default seed, with four more seeds and a halved step checked for the challenge and the switching cases.

OPEN CHALLENGE A Burner Measure Beyond the Wobbe Index

A 2026 review calls the Wobbe index one of the most important indicators of whether one gas can replace another, because it follows the heat a burner delivers. Hydrogen lowers the index but raises the burning speed sharply. Its laminar flame speed is about six times that of methane, and flashback becomes a critical factor limiting burner operation as its fraction rises [22]. The 1977 utility study had already found the interchangeability indexes of its day unable to predict hydrogen blends [15], and the review still lists combustion stability control among the breakthroughs required [22]. Progress would be a measured quantity, beside the Wobbe meter, that tells a controller how close a burner is to flashback.

14.8 Conclusion

A refinery fuel gas header is an integrator between sources and heaters that nobody schedules for it, and this simulator logs its pressure, its makeup, its flaring and its gas quality side by side from an ideal-gas balance on four lumps. A coker switch takes the 60 m^3 header from 3.5 to 3.0 bar g in 45 s, at the rate the declared volume predicts. A 4 % overlap in the split range imports and flares for 14.38 min of a 30 min case while the pressure stays within 0.025 bar, and any dead band of zero or more removes it. Ten percent hydrogen lowers the heating value 7.11 % and the Wobbe index 2.66 %, and the Wobbe feedforward holds the heater within 0.36 °C where feedback alone lets it stray 1.23 °C. Recovery stages placed above the seal never load, and the challenge needs all four suggested changes at every seed. An MPC whose plans never open both valves still imports and flares for minutes unless it waits for the positioners. The model is lumped and its compositions are teaching values. Further work would add transport delay along the header, a distributed heater population, a burner model that responds to flame speed as well as the Wobbe index, and destruction efficiency at the flare. The simulator shows that a split range is a statement about money as well as about pressure.

KEY POINTS

- The header holds well under a minute of its gas, so a coker drum switch takes it from 3.5 to 3.0 bar g in 45 s.
- A 4 % overlap in the split range imports and flares for 14.38 min of a 30 min case while the pressure stays within 0.025 bar, and any dead band of zero or more removes it.
- The Wobbe feedforward holds the heater within 0.36 °C where feedback alone lets it stray 1.23 °C.
- Recovery stages placed above the seal never load, and an MPC whose plans never open both valves still imports and flares for minutes unless it waits for the positioners.

Where else this applies. Volume 4, Chapter 5 splits one output between the heating and cooling of a barrel zone, and Volume 4, Chapter 9 uses valve-position control on a site with an import limit.

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14.9 Exercises

14.1 Concept check · 2 min

In case 1 the split-range output is held in Manual when the coker switches drums and sends 3000 Nm^3/h less gas. What stops the header pressure from falling?

(a) Nothing answers the pressure until the heaters' fuel valves open wide, and the starved heaters then burn less

(b) The makeup valve passes more natural gas as the header falls, so the header settles a little below its setpoint

(c) The four sources send more gas as the header falls, because their units see a lower back pressure

(d) The recovery compressor returns more relief gas, because its stages load as the header pressure falls

14.2 Concept check · 1 min

In case 4 the hydrotreater purge rises by half while H-1's outlet loop is on Man, so its burner pressure stays where it was. The heating value of the header gas falls 5.33 %. How does the heat that H-1 releases change?

(a) It falls by about the same 5.3 %, because a fixed burner pressure passes a fixed volume of gas

(b) It falls by less, about 2.1 %, because the lighter gas passes more volume at the same burner pressure

(c) It falls by more than the heating value, because the lighter gas passes less volume at the same burner pressure

(d) It does not change, because the burner-pressure loop opens the fuel valve until the heat is restored

14.3 Concept check · 2 min

The MPC of Equation (14.10) charges for the gas of both valves, so none of its plans opens the makeup and the flare valve together. Without the interlock on the positioners, the challenge still counts 7.88 to 9.33 min of import and flare in 8 h. Why?

(a) The model's header volume differs from the plant's, so the plan opens the wrong valve after each disturbance

(b) A solve fails at each hand-over, and the split-range PI with the shipped overlap takes the valves

(c) The stems lag their commands, so at a hand-over the closing valve still passes gas while the other opens

(d) The import-and-flare count reads the valve commands, and the plan sets both commands at each hand-over

14.4 Theory and calculation · 7 min

The header is one ideal-gas volume at 40 °C. Use Equation (14.2) with $R = 8.314\,\mathrm{J/(mol\,K)}$.

(a) Compute the integrating gain K of the 60 $\mathrm{m^3}$ header in bar per minute per $\mathrm{Nm^3/h}$, and the rate at which a 3000 $\mathrm{Nm^3/h}$ shortfall lowers it. *Checkpoint:* $K = 3.227 \times 10^{-4}$ and 0.968 bar a minute.

(b) The coker's gas falls by 3000 $\mathrm{Nm^3/h}$ along a straight ramp of 0.5 min and then holds. With nothing else changing, show that once past the ramp the header has fallen Δp at $t = T_r/2 + \Delta p/(K\,\Delta F)$ after the switch began, with T_r the ramp time, and find when the header passes 3.0 bar g from 3.5 bar g at 60 and at 240 $\mathrm{m^3}$. *Checkpoint:* 46.0 s and 139.0 s.

(c) The application measures 45.0 and 133.5 s. Subtract the half ramp from each measured time, compare their ratio with the ratio of the volumes, and name the flow that makes the real header fall slightly faster than the calculation. *Checkpoint:* 30 and 118.5 s, a ratio of 3.95. The heaters pass more volume of the lighter gas.

14.5 Theory and calculation · 6 min

The design gas of the header has a specific gravity $SG = 0.6501$ and a heating value HHV $= 44.097\,\mathrm{MJ/Nm^3}$. Pure hydrogen has a heating value $H = 12.75\,\mathrm{MJ/Nm^3}$ and a molar mass $M = 2.016\,\mathrm{kg/kmol}$, and air has a molar mass of 28.96 kg/kmol.

(a) Compute the Wobbe index of the design gas. *Checkpoint:* 54.69 MJ/Nm^3.

(b) A tenth of the gas is replaced by pure hydrogen, so the mixture is 0.9 design gas and 0.1 hydrogen by mole. Compute its heating value, specific gravity and Wobbe index, and the percentage change of the heating value and of the Wobbe index. *Checkpoint:* 40.96 MJ/Nm^3, 0.5921 and 53.24 MJ/Nm^3, then -7.11 and -2.66 %.

(c) Evaluate $\mathrm{d}\ln W/\mathrm{d}a$ at $a = 0$ for a fraction a of hydrogen added, and use it to estimate the change at $a = 0.1$. *Checkpoint:* $-0.711 + 0.447 = -0.264$, so about -2.64 %.

14.6 Theory and calculation · 6 min

A loaded recovery stage takes up to 1200 Nm^3/h, its spillback holds its suction above 5 mbar g, and it delivers its full flow 15 mbar above that, so N loaded stages with enough capacity settle the flare header at $p_{\min} + \Delta p_{sb} F_{rel}/(N F_{st})$. The water seal lifts at 60 mbar g and passes 500 Nm^3/h per mbar above it.

(a) Find where one stage holds the flare header with the design relief load of 900 Nm^3/h, and where two stages hold it with the 1600 Nm^3/h of case 6. *Checkpoint:* 16.25 mbar g and 15.0 mbar g.

(b) Case 6 ships stage 2 unloading below 40 mbar g and loading above 45 mbar g. Explain why it short cycles, and state the condition its unload threshold must meet. *Checkpoint:* Two stages hold 15.0 mbar g, below 40 mbar g, so the threshold must lie below 15.0 mbar g.

(c) With no stage loaded, where does the seal hold the flare header at 900 Nm^3/h, and what does that mean for the challenge's shipped load thresholds of 65 and 80 mbar g? *Checkpoint:* 61.8 mbar g, below 65, so no stage ever loads.

14.7 App challenge · 7 min

Load scenario 2, *Split range and its dead band*, which ships with Dead band at -4 %, an overlap. Run to 30 min at 1 min/s with the default seed.

(a) Read the Import and flare, Flared and Makeup tiles at 30 min. *Checkpoint:* 14.38 min, 50 Nm^3 and 362 Nm^3.

(b) Set Dead band to 6 %, press Reset and run to 30 min again. Read the same three tiles. *Checkpoint:* 0.00 min, 0 Nm^3 and 310 Nm^3.

(c) Compare the extra makeup bought in the first run with the volume it flared, and say what the pressure trend showed in each run. *Checkpoint:* 52 Nm^3 more makeup against 50 Nm^3 flared, and the pressure stayed near setpoint both times.

14.8 App challenge · 6 min

Load scenario 8, *A heater lights: a consumer surge*, with the default seed. H-20 lights at 5 min. Before pressing Run, choose Header control on the PIC card, and make three runs to 15 min at 1 min/s, one with each choice: Split range (PI), Split range + flow feedforward, and MPC on both valves. Export the CSV file after each run and read the largest $|\texttt{truth_p_barg} - 3.5|$ from 4 to 15 min, each within 0.0005 bar.

14.9 App challenge · 8 min

Load scenario 9, the challenge, with the default seed. Before pressing Run, make the four suggested changes: Dead band 6 %, the stages loading lower (Stage 1 loads above 30 mbar g and Stage 2 loads above 45 mbar g), Wobbe feedforward On, and Pressure gain 120 % per bar. Run the 8 h at 120 min/s.

(a) Read the verdict in the note at 8 h: the pressure band, the volume flared, the import-and-flare time and the outlet band. *Checkpoint:* Met: 0.154 bar, 6 Nm^3, 0.00 min and 0.34 °C.

(b) Set Pressure gain back to 60 % per bar, press Reset and run the 8 h again. Which target fails, by how much, and what upset causes it? *Checkpoint:* The pressure, 0.292 bar against 0.2 bar, in the FCC upset.

14.10 Application area · 4 min

In case 3 the FCC trips. Use the heating values and flows of Table 14.2 and a wide-open makeup of 8000 Nm^3/h. H-1 keeps its 20 MW, and the lumped heaters fire 230 MW at 100 %.

(a) Compute the heat the header can deliver with the FCC gone, on the higher heating value. *Checkpoint:* 210.4 MW.

(b) Find the firing to which the lumped heaters must be shed, and say why a shed to 84 % changes nothing once the heaters have starved. *Checkpoint:* 82.8 %. Starved, they already burn less.

14.11 Application area · 3 min

The simulated header's flare valve discharges past the water seal straight to the stack, and the Flare CO_2 tile assumes that the flared gas burns completely. Name what each simplification hides from a plant engineer.

14.12 Review the agent · 5 min

An AI assistant reviews case 2 and writes: "The header holds within 0.025 bar of setpoint, but the output keeps drifting into the 4 % overlap and the Import and flare tile counts minutes. The loop is too sluggish to keep the output out of the overlap. Raise the Pressure gain from 60 to 240 % per bar, and keep the overlap, since it ensures that no stretch of output leaves both valves shut." Find the flaw and say how you would check it in the app.