8.27 Furnace and Reformer Controls

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INTRODUCTION

The discussion that follows covers a wide range of process furnaces, including heaters, cracking furnaces, and reformers. Each type of furnace is described from a mechanical and process standpoint, in enough detail to make the recommended control strategies understandable. Examples are presented so that extrapolation can be made to services not specifically discussed in this section. The recommended control strategies are broken down into the following categories: 1) process controls, 2) fuel firing controls, and 3) safety controls.

In the first part of the section, general information is provided concerning the furnace and fired heater processes, their sensor and analyzer requirements, and their basic control requirements, including air preheat controls. In the second part of this section, specific control systems are described for start-up heaters, process heaters, and reforming and cracking furnaces (Figure 8.27a). The last part of this section discusses some of the more advanced control strategies that can be applied to furnace controls and optimization.

In furnaces and heaters, thermal energy is transferred to a process stream or feed in a controlled manner. The typical furnace, or heater (the terms will be used interchangeably), usually takes the form of a metal housing lined with an insulating refractory. The charge can enter as a liquid, gas, or two-phase mixture and may or may not be transformed to a different state by the energy supplied. In these types of furnaces, the charge can be carried through the furnace or heater continuously through metal tubes or can be batch-heated by leaving it stationary after it enters the furnace.

FIG. 8.27a
Illustration of a multistage reforming process.
The discussion in this section covers the controls of 1) refinery feed heaters and reboilers, 2) pyrolysis furnaces for ethylene production, and 3) steam reformers for hydrogen or synthetic gas production.

As will be seen later, the heat content of the hot flue gases leaving the furnace can be used to preheat process feed in a feed preheater or can preheat the boiler feedwater and generate process steam.

Controls for the more common types of process furnaces will first be described from a process standpoint. Next, the important process variables will be noted and the methods used to measure and control them will be outlined. The various types of firing controls applicable to the particular type of furnace will then be described. Finally, specific safety considerations and instrumentation will be presented.

As will be seen, the common control strategies include a feedback temperature/flow cascade loop, where the furnace outlet temperature adjusts the fuel flow into the fired furnace. The firing controls may use feedforward based on the feed flow rate in order to speed up the control system response to changes in feed flow rate.

Furnaces with long dead times or with highly interacting control loops tend to be unstable (Figure 8.27a). To overcome these problems, the use of mathematical analysis and process simulation may become a necessity. The control systems outlined have been empirically developed, and most of them are tried and reliable designs. In the more advanced control strategies, which are described in the last part of this section, process dynamics are also taken into full consideration.

GENERAL CONSIDERATIONS

The primary functions of furnace control systems are

1. To ensure that the charge receives the heat energy at the proper rate. In feed heater furnaces, the main controlled variable is the exit temperature of the charge.
2. To maintain efficient combustion of the fuel. Proper combustion of the fuel requires the regulation of the air-fuel ratio, and the control of the atomizing steam flow rate when fuel oil is burned. Other important controlled variables are draft and stack emissions of NOx, and of other pollutants.
3. To maintain the safety during all phases of furnace operation so as to prevent explosions or fires.

Standards Applicable to Furnace Controls

The ANSI, API, CFR, IEC, ISA, NFPA, and OSHA standards that are used to regulate furnace controls are listed at the end of this section, before the Bibliography.

In furnace operations, safety is a very important consideration. In the case of refinery furnaces, the potential sources of hazards include 1) fire or explosion caused by tube rupture. Such rupture can occur because of tube overheating due to feed flow loss or because of flame impingement; 2) explosion in the firebox caused by the loss of flame or by improper ignition or purge procedures; and 3) implosion of the furnace or refractory damage caused by high draft.


The required level of reliability must be determined by the analysis of the required Safety Integrity Level (SIL), described in the ISA Standard TR84.02-2002. The SIL level is established using process hazard analysis (PHA), which determines if dual- or triple-redundant PLCs must be used. An international companion standard that is also applicable in making this decision is IEC 61508, “Functional Safety—Safety-Related Systems.” In addition, local codes and industry practices, usually set by the insurers of the plant, should also be consulted before controls are designed and installed.

The Combustion Process

To completely burn the combustible portion of any given fuel, an ideal quantity of oxygen and, therefore, an ideal quantity of air is required. Under real conditions, the inefficiencies in combustion require that some additional air be provided to ensure complete combustion. The quantity over and above the ideal (stoichiometric) amount of air is called the “excess air.”

On a volumetric basis, air contains 0.21 oxygen and 0.79 nitrogen (on a mass basis 0.232 oxygen and 0.768 nitrogen). For example, in the combustion of methane (CH4), the ideal amount of air required per pound is 40.232 lb = 17.24 lb, and in volumetric units, the volume of air required per cubic foot of methane is 2/021 = 9.52 ft3.

The ratio of air supplied per pound of fuel (Wf) to the air theoretically required (W) is

\[W/Wf = \{3.02[N/(CO + CO2)]/\{34.56[C/3 + H – O/8]\}\] 8.27(1)

Combustion Efficiency and Excess Air

If we call “a” the ideal (minimum) amount of air required for complete combustion and we call “x” the actual amount of air admitted, then “x – 1” is the excess coefficient. On a volumetric basis, the excess air requirement (E in %) can be calculated by

\[E = K[21/(21 – %O2) – 1] \cdot 100\] 8.27(2)

where \(K = 0.9\) for gas, 0.94 for oil, and 0.97 for coal.

Using the stack gas composition analyzer readings for carbon monoxide (CO), the air supply to the furnace can be adjusted to maintain the combustion efficiency at the optimum. Figure 8.6ttt in Section 8.6 shows the relationship between measured ppm concentration of CO in the stack gases and furnace efficiency.
The optimum percentage of excess oxygen is some percentage greater than what is theoretically needed for complete combustion. This margin is usually between 2 and 4% for most furnaces. For continuous emission monitoring system (CEMS) purposes, the pollutant concentrations are calculated with a reference basis of 3% \( \text{O}_2 \) on a dry basis.

The amount of carbon monoxide in the stack gases can be measured to determine the optimum set point for excess \( \text{O}_2 \) control. Elevated CO levels indicate that some of the fuel is unburned, which results in the waste of heat and the danger of potential explosion at high CO levels. In some installations, instead of continuously monitoring CO, only a one-time measurement is made to establish the crossover between the presence of excess oxygen and excess unburned fuel.

Combustion efficiency is usually defined in terms of heat input and output. In the case of furnaces, an energy balance around the unit must account for the total heat input and the total useful heat output. The difference is the total heat loss, as illustrated in Figure 8.6 in Section 8.6.

\[
H_I = H_O + H_L
\]

where
\( H_I \) = heat input rate
\( H_O \) = heat output rate
\( H_L \) = heat loss rate

Furnace efficiency can be defined by one of the following three equations:

**Input-output method:**

\[
\text{EFF} = 100 \left( \frac{H_I}{H_O} \right)
\]

**Input-loss method:**

\[
\text{EFF} = 100 \left( 1 - \frac{H_L}{H_I} \right)
\]

**Output-loss method:**

\[
\text{EFF} = 100 \left[ \frac{Q}{(1 + H_O/H_I)} \right]
\]

Now, if these equations are expressed in terms of \( Q \) = heat absorbed by fluid
\( W \) = fuel rate
\( I \) = heating value of fuel
\( L \) = total heat loss

Equations 8.27(4) to 8.27(6) become

\[
\text{EFF} = 100 \left( \frac{W \cdot I}{100} \right)
\]

\[
\text{EFF} = 100 \left( \frac{Q + W \cdot L}{100} \right)
\]

Although, in theory, any of these equations should produce the same results, experience has shown that the input-loss method (Equations 8.27(5) and 8.27(8)) produce the most reliable results, because the other methods are more sensitive to errors in process measurements.

Many furnaces burn gas preferentially and oil only as a standby. Emission compliance for \( \text{NO}_x \) is easier if gas fuel is being burned. However, some of the control systems described in this section are suited for combination firing (i.e., firing both gas and oil simultaneously).

**Combustion Air Preheat** With regard to furnaces, the overall efficiency is the ratio of the amount of heat absorbed by the process to the amount of heat liberated by the fuel. One of the major heat losses in a furnace is the heat lost up the stack in the form of hot flue gases. Therefore, much attention has been devoted to reducing the flue gas exit temperature as much as practical (to approximately 300°F, or 150°C).

A common method of reducing this waste is to add a combustion air preheater to the furnace. This device is a heat exchanger that transfers some of the heat from the hot flue gases to the cold combustion air, before it enters the burners (Figure 8.6 in Section 8.6). Thus, the heat energy re-enters the furnace and is available for transfer to the process stream.

In addition to the combustion air preheater, it is usually necessary to add a forced draft fan to push the combustion air through the preheater (exchanger) instead of relying on natural draft. The instrumentation necessary to control this equipment is relatively simple. Figure 8.27b shows a typical combustion air preheat system.

In this control system, the forced draft fan is driven by a steam turbine drive, equipped with a variable-speed governor. A pressure controller (PIC-1) maintains the discharge pressure (and consequently the airflow) by manipulating the fan speed. A low-pressure alarm (PAL-1) is included to alert the operator of possible fan malfunction.

A trip interlock (FY-1) is provided to trip the forced draft fan to minimum speed in the event of failure of the induced draft fans. This precaution is necessary to prevent positive pressure in the hot combustion chamber, which could cause the hot gas or flames to blow out through the burner openings and other leaks in the furnace.

Temperature indicators TI-1, TI-2, TI-3, and TI-4 are provided on both streams in and out of the combustion air preheater to monitor the operation. Pressure measurements PI-1 and PI-2 are also included to allow the checking for excessive pressure drop across the unit.

**Safety Considerations**

As it is also discussed in the next paragraph, some 70% of furnace explosions occur during start-up or shutdown, where operator involvement is significant, while 21% of accidents were found to be caused by undocumented changes after commissioning.
Fuel Gas Controls

Figure 8.27c shows a typical fuel gas header, which can be branching off to several furnaces after the knockout pot. The relief valve shown should be piped to a relief header. For larger furnaces, the pressure control would be by a continuously throttling controller, rather than by a regulator.

The primary function of the furnace’s safety system is to shut down the fuel supply if unsafe conditions evolve. In earlier furnace designs, the fuel control valve also served as the shut-off valve. This is no longer permissible, and separate, dedicated shut-off valves are required. Figure 8.27c illustrates a typical fuel gas regulating station with the safety shut-off valves left out and only their location being shown in the broken pipe line.

Figure 8.27d shows the safety shutdown valving usually used in the gas feed to a furnace. The top configuration is installed in the main gas line and consists of three on/off, tight shut-off, usually rotary ball valves. The dual shut-off

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**FIG. 8.27b**
Combustion air preheat controls.

**FIG. 8.27c**
Fuel gas regulation station showing both the main gas supply line (top) and the pilot gas line (bottom). The locations of the safety shut-off valves are also shown in the broken pipe, but their actual configuration is separately illustrated in Figure 8.27d.
valves are fail closed (FC), while the vent valve between them is fail open (FO). Therefore, when the shutdown interlocks are actuated, the two FC valves close, while the FO vent valve opens and vents the gas between the two FC valves, plus any leakage that might occur, to a safe location. The ZSCO (closed-open limit switches) provided on all three valves confirm to the controlling PLC that the interlock requirements have been performed.

The pilot gas line is usually provided with only a single shut-off valve with limit switch.

**Safety Instrumented Systems** SIS (formerly known as emergency shutdown system, or ESD) systems in general are discussed in detail in Sections 5.8 and 6.10. When designing a furnace control system, the designer should evaluate the following functional SIS requirements and clearly define the following:

- Define the safe state of the furnace (e.g., fuel shut-off, forced draft dampers open, and so on)
- Define the process variables, their normal operating range, and their limits
- Define the process outputs (conditions) and the actions required in response to them
- Considerations for manual shutdown
- Reset functions
- Actions on loss of power; UPS requirements
- Response time requirements for the SIS to bring the process to a safe state
- Operator interface criteria, including alarms and alarm responses
- Diagnostics; on-line and off-line testing
- Minimize nuisance trips while maintaining safety

As the final control elements in any SIS system are valves and dampers, their requirements should be defined by giving consideration to the following:

- Opening/closing speed
- Leakage
- Fire resistance–body and actuator
- Failure position
• Performance after staying in the same position for long periods
• Use separate shut-off and control valves
• Selection and correct sizing of solenoid valves and protecting them against plugging with bug screens
• Installing the solenoids between the valve positioner and the valve actuator
• Providing all shut-off valves with open-closed position detecting limit switches, which are wired to the SIS

The reliability of PLC-based SIS systems is increased by implementing them in redundant or triple-redundant (voting system) configurations, as far as their processors and power supplies are concerned. Important measurement and status input signals also are configured into 2 out of 3 voting systems, to avoid nuisance shutdowns caused by the failure of a single device or instrument. The shutdown output signals should also be redundant, and these redundant signals should originate on different I/O cards in the DCS or PLC systems.

The SIS safety and shutdown system is usually located on a PLC that is separate from the control equipment that directs the normal operation of the furnace. Such safety systems usually include a flame scanner. It is important to keep the air flowing through the firebox during a shutdown. In case of tube rupture, this may generate a lot of smoke, but it will protect the system from explosions that are caused by fuel-rich mixtures. Shutdowns are usually triggered by the following conditions:

• Low gas pressure: flame may go out and the resumption of gas flow can cause explosion
• High gas pressure: may blow flame away from burner
• Loss of flame, which can be detected by flame scanners
• High draft: may buckle furnace
• Low to zero draft: may push flames out
• Low feed flow: will cause tube overheating, coking, and eventual tube rupture
• Safety system failure: if PLC watchdog timer times out, this triggers hardwired fuel valve closure.

The emergency shutdown system software package within the PLC logic (also called the “problem solver”) will cause the following actions as applicable:

• Fuel gas shutdown, with manual reset
• Pilot gas shutdown (not all furnaces)
• Opening of stack and fan dampers
• Ammonia injection shutdown—NH₃ valve, blowers (if the process includes them)

On furnaces with two induced air fans, dampers may be programmed to close if the fan is not running. The feed is usually shut down later manually when tubes have cooled off.

Guidelines for training can be found in OSHA Regulation 1910.119, which defines the requirements for safety systems-related training.

Procedures for on-line testing must also be established. Manual bypass switches should be available for each input that can initiate a shutdown so that the device can be tested periodically. If a bypass is open, that condition should also be indicated locally and alarmed in the central control room. In connection with testing of ESD systems, the ISA standard (S91.1-1995) should be followed, which lists the “Requirements for Functional Testing.”

Purge Controls

After a shutdown, the pilots must not be turned on and the furnace must not be reignited until all combustible gases are purged out. The purge cycle is initiated by the operator, who must not start the cycle timer in the safety PLC system until after the purge time has elapsed. At that point, the PLC unblocks the shut-off valves. A pilot flame detector is usually also part of the purge logic, and if no flame is detected after a few seconds, the purge will shut down and the cycle has to be restarted.

Large, PLC-controlled furnaces that are provided with emission abatement and monitoring systems are also provided with their own local control panel (Figure 8.27e), which is integrated into the total DCS- or PLC-based control system. Flow and draft indicators, alarms and shutdown bypass/test switches, and purge cycle controls are also often provided on these local panels. The purge-related pilot lights are usually designated as “purge on,” “purge failed,” or purge complete.” After the purge is complete, the pilot burners can be ignited, and later the main gas control valve can also be opened.

Pollution Abatement

Furnace emissions must meet federal (EPA) and local air quality requirements. The applicable standards and guidelines include:

• ANSI/API 536, “NOₓ Control for Fired Equipment in Refineries”
• 40CFR Part 60, “New Source Performance Standard” (section for oil refineries)

Larger furnaces must be fitted with CEMS, which will be discussed in the next paragraph after NOₓ controllers.

Gas- and oil-fired furnaces, operating at over 2800°F in their hot zones, typically produce about 100 ppm NOₓ in their stack gas. EPA standards require that this concentration be reduced to 5 ppm or even 2.5 ppm. This can be achieved by several means:

• Use of cool-burning burners, with optimal air/fuel mixing nozzle design
• Use of flue gas recirculation, where part of the flue gas is returned into the firebox to cool the flame
Installation of catalytic converters between furnace and stack
A combination of all above

Installing new burners and providing recirculation, by means of fans, can reduce NO\textsubscript{x} to around 25 ppm. This still leaves the need for costly catalytic converters, which use vaporized ammonia to convert NO\textsubscript{x} (mostly N\textsubscript{2}O\textsubscript{3}), according to Equation 8.27\textsuperscript{(10)} as:
\[
N\textsubscript{2}O\textsubscript{3} + 2NH\textsubscript{3} = 2N\textsubscript{2} + 3H\textsubscript{2}O
\]

To accomplish this conversion, because of the resistance of the selective catalytic reduction (SCR) catalyst bed, forced draft fans with control dampers are required. They must be installed on elevated platforms, making the installation expensive.

In the SCR process, by using a suitable catalyst, the NO\textsubscript{x} reaction can be carried out at 300–400°C, a temperature normally available in a flue gas system. Figure 8.27f shows a schematic diagram of the SCR process. In this process at least 1% O\textsubscript{2} must be present in the flue gas, which is normally the case in boiler and furnace applications.

Using a movable injection lance is another effective means of reducing NO\textsubscript{x}, CO, and volatile organic carbon (VOC), while improving thermal efficiency by optimizing the combustion process in boilers. The injection lance can be used with or without low NO\textsubscript{x} burners.

These lances reduce NO\textsubscript{x} emissions by 60–90% by injecting air, ammonia, or urea through retractable lances in the upper furnace. This creates turbulence and better mixing in the gas flow in addition to lowering the stoichiometric ratio of O\textsubscript{2}. The lances are automatically retracted from the boiler on a regular basis and cleaned to remove the accumulated layers of soot and other depositions. Their costs are about 75% less than those of SCRs.

### SCR Controls
The controls of the SCR process are shown in Figure 8.27f. Here, from a storage tank, liquid ammonia is metered by a positive displacement pump or by Coriolis flowmeter to the ammonia vaporizer, which is heated by the dilution air. From the vaporizer, an array of small pipes takes the ammonia vapors to the distribution grid for injection at different elevations into the firebox.

Each pipe section in the distribution grid is provided with a balancing throttling valve, which serves to evenly distribute the vapors. The control valves in the major branches are controlled by the ammonia flow controller (FIC-1), which also controls the positive displacement ammonia pump. This controller measures the ammonia flow and in addition receives a feedback signal from a chemiluminescent NO\textsubscript{x} analyzer transmitter and a feedforward signal, FT-1, the fuel gas flow transmitter, which detects the firing rate (gas flow) of the furnace or boiler.

FIC-1 also receives a trimming signal from the oxygen analyzer transmitter. It was found that increasing the amount of excess oxygen initially tends to increase the formation of NO\textsubscript{x}, but further increases tend to decrease it due to flame cooling. The injection of ammonia is stopped by TSHL-1 (high-low temperature switch) when the converter temperature drops under 600°F, to prevent catalyst damage.

### The NO\textsubscript{x} Controller
Figure 8.27g describes the ammonia controller (FIC-1 in Figure 8.27f) that is used as a cascade slave of AIC-1 to control the NO\textsubscript{x} in a crude oil distillation heater furnace, which has a maximum gas firing rate of 8.5 MMSCFD. The figure also shows the various feedforward and trimming adjustments of the total control algorithm.

Feedforward is applied from the fuel gas flow transmitter (FT-1), which is the main determining factor in arriving at the set point of FIC-1. Oxygen content, detected by the transmitter AIT-2, serves to trim the fuel gas flow signal. Therefore,
changes in the output signals of FT-1 and AIT-2 will instantaneously change the set point of the ammonia flow controller, FIC-1. The basis for this relationship is that the NO\textsubscript{x} production is proportional to both fuel flow and to excess oxygen, because the free nitrogen radicals—at over 2800°F—will seek out the extra oxygen and will combine with it.

The cascade master of the feedback portion of this control system is the NO\textsubscript{x} controller, AIC-1. This loop is slow; its dead time can be 10 min, because the time lags from the NH\textsubscript{3} injection points to the stack and then through the sample line to the NO\textsubscript{x} analyzer all add up before a measurement is obtained.
For the control algorithm shown in Figure 8.27g all measurement and control signals are scaled, so that the measurement output ranges of each transmitter or controller are converted to a 0–1 scale. For example, the output of the NO\textsubscript{x} analyzer controller (AIC-1) is also 0–1, and when it is 50% (a value of +0.5), by subtracting −0.5, its influence on the set point of FIC-1 is eliminated. On the other hand, when the feedforward portion of this algorithm cannot correct for the changes in the SCR process, the feedback controller (AIC-1) will start moving its output away from 0.5 and will start correcting the FIC-1 set point.

Such an algorithm can be implemented either by a single-loop programmable controller or by the DCS system.

For a particular set of conditions, the following calculations can serve as an example of the operation of this control scheme:

At an average NO\textsubscript{x} concentration of 110 ppm, the total unabated NO\textsubscript{x} flow rate in the stack has been calculated to be 26.7 lbm/hr. The conversion of 1 mole of NO\textsubscript{x} (Mw = 47) requires about 1 mole of NH\textsubscript{3} (Mw = 17). Thus, the rate at which pure ammonia should be added is 17/46 ⋅ 26.7 = 9.87 lbm/hr NH\textsubscript{3}. Ammonia is received in a 19% solution; consequently, this solution should be injected at a rate of 9.87/0.19 = 52 lbm/hr.

It was found that excess oxygen also contributes to NO\textsubscript{x} formation and that up to 4% more NO\textsubscript{x} is formed for each additional percentage of excess O\textsubscript{2} over the concentration of 2%. Because of draft limitations, the furnace in this example operates at a 5% excess oxygen level (3% over the 2% minimum). Therefore, 3 ⋅ 4% = 12% added NH\textsubscript{3} is required, which comes to 1.12(52) = 58.2 lbm/hr.

To measure the ammonia flow rate, a Coriolis meter with a range of 0–120 lbm/hr can be used, so that the 58.2 lbm/hr rate would approximately correspond to 50% of range.

The “manual ratio” correction factor applied to the set point of FIC-1 is available for the operator to correct for such differences as the calculated 58.2 lbm/hr and the 50% range of the flow meter.

**Continuous Emission Monitoring Systems** In order to comply with the requirements of the federal agencies (see “Standards and Guidelines” at the end of this section) and with local air quality district requirements, microprocessor-based, self-calibrating CEMS analyzers are used. The CEMS microprocessor calculates the pollutant concentrations reduced to 3% O\textsubscript{2} (as a measure of gas dilution) and provides rolling averages, peaks, their duration, and other records as required by the local agency. The CEMS is usually wired directly to the agency’s computer. Emissions are referenced to the firing rate (gas flow) to provide the total mass of pollutants emitted.

For gas-fired heaters, the pollutant that is continuously monitored is only NO\textsubscript{x}. In case of fuel oil-fired boilers and furnaces, SO\textsubscript{2} is also monitored. Other pollutants, such as CO, CO\textsubscript{2}, and particles (opacity) are only checked periodically by portable instruments. EPA 40CFR60 provides specific criteria for CEMS.

Described here is a typical CEMS system used on a refinery furnace with selective catalytic reduction-based NO\textsubscript{x} abatement controls.

The CEMS can utilize a zirconium oxide-based stack oxygen analyzer for firing controls and a chemiluminescent NO\textsubscript{x} analyzer.

The CEMS provides NO\textsubscript{x} readings (corrected to 3% O\textsubscript{2}) and an O\textsubscript{3} signal for the ammonia injection controller (Figure 8.27g). The data collected by the CEMS is also used by the local air quality agency and by the plant monitoring system (PMS), using Equation 8.27(2). The O\textsubscript{2}-corrected NO\textsubscript{x} emission (E) is calculated on the basis of the actual measured concentration O\textsubscript{2} concentration (C).

If sampling-based analyzers are used (and not directly inserted probe-type analyzers), the components of CEMS systems can include:

- Stack sample probe, located usually 3/4 up the stack (Figure 8.27h)
- Heated sample line with thermostat
- Sample conditioning cabinet with sample pump
- O\textsubscript{2} and NO\textsubscript{x} analyzers
- Microprocessor with auto-calibration controller and solenoid valves
- Rack of calibration gas bottles

**Sampling** The stack sample probe is a stainless steel tube that extends into the stack and has a HastelloyC, 0.5-µ-size filter, a test and sample gas connection, and an electric heater with RTD. The sample line is heated to 300°F to keep moisture from condensing. An alternative method is to use a dilution extractive sample probe (Figure 8.27i). This method of sampling has the advantage of not requiring a heated sample line or a chiller/dryer.

In the standard sampling system, a sample conditioning cabinet is provided, where the sample is quickly chilled to knock out water without washing out the gases of interest. These components are usually followed by a gas dryer, then a bypass rotameter, which is used to control the sample gas flow rate to the NO\textsubscript{x} analyzer.

A solenoid manifold is also provided, so that auto-calibration can be performed every 24 hours, by injecting zero and span gases. Sample system alarms are also provided to signal such conditions as high sample gas moisture content, low sample line temperature, and high condensate level.

**NO\textsubscript{x} Analyzer** In the chemiluminescent NO\textsubscript{x} analyzer, the reaction that takes place is described by Equation 8.27(11):

\[
\text{NO} + \text{O}_3 \rightarrow \text{NO}_2 + \text{light} \atop \text{at } 0.6-3 \mu 
\]  

8.27(11)

The intensity of light emission is proportional to the NO concentration in the sample. The chemiluminescence analyzer is usually provided with a catalytic converter to reduce the NO\textsubscript{x} to the NO form and then uses its ozone generator to measure NO\textsubscript{x} in the range of 0–50 ppm NO\textsubscript{x}. The main components of this analyzer are shown in Figure 8.27j.
Analyzers for Furnace Control

In addition to the analyzers discussed above, in connection with pollution abatement-related furnace analyzers, are the analyzers that are used in controlling the furnace’s operation. These include oxygen analyzers, combustibles detectors, and fuel heating value (calorific) analyzers.

Oxygen and Excess Air Analyzers

An oxygen analyzer is commonly used on furnaces to measure the oxygen content of the flue gas. From this information, the amount of excess air being delivered to the furnace can be computed. Keeping the excess air at a minimum results in conservation of heat, because the sensible heat content of the excess air is discharged into the atmosphere and is an outright heat loss.

The efficiency of combustion can be maximized by throttling the air of the furnace to maintain the oxygen content of flue gas at a desirable value. The analyzer is also tied to a low-oxygen alarm, which warns the operator if hazardous furnace atmospheres are developing.

The decision whether to install an oxygen analyzer is based on economic considerations, and energy efficiency usually justifies it. The cost of the analyzer and its upkeep must be balanced against the energy savings and increased safety. If the firing load or the type of fuel to the furnace often changes, the oxygen analyzer is a necessity from a safety standpoint alone.

The O₂ sensor can be a solid-state heated zirconium oxide probe that can be placed directly in the stack (Figure 8.27k). An instrument air purge connection is recommended for periodic blowing. At temperatures of over 600°F, these probes produce an open circuit voltage that is related to the partial pressure of oxygen in accordance with the Nernst Equation shown in Equation 8.27(12):

$$E = \frac{RT}{nF} \ln \left( \frac{O_2 \text{partial pressure in reference gas}}{O_2 \text{partial pressure in sample gas}} \right)$$

where
- $E$ = the open-circuit voltage developed
- $R$ = the universal gas constant
- $T$ = the temperature
- $n$ = the number of electrons transferred per molecule of oxygen
- $F$ = Faraday’s constant

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Paramagnetic oxygen analyzers are less frequently used. They can be installed on the sides of fireboxes, to check for potentially explosive fuel-rich pockets. The sample gas is drawn to these analyzers by an air aspirator provided with a water seal.

**Combustible Analyzers** Combustible analyzers measure the amount of unburned fuel in the furnace flue gas (CH₄, CO); they are mostly used as portable instruments during emissions certification. For an in-depth discussion of combustible analyzers refer to Section 8.16 in Chapter 8 of the first volume of this handbook.

The concentration of one combustible gas component, carbon monoxide, is sometimes used as a constraint variable in a “low select” configuration, in connection with the excess oxygen controller as described in connection with Figure 8.6 in Section 8.6. The CO analyzer can be of the infrared type and can be installed to look “across the stack.”

**FIG. 8.27a**
The components of a dilution-extractive sampling system.

**FIG. 8.27b**
Chemiluminescence nitric oxide analyzer.

*Converter can be omitted if only NO is measured

**FIG. 8.27c**
High-temperature, electrochemical, zirconium oxide-based oxygen analyzer probe.
NH₃ Analyzers  Wet chemical NH₃ analyzers are used to detect the ammonia slip when selective catalytic reduction is applied for emission control. Excess ammonia in the flue gas is referred to as “ammonia slip” and must be avoided. NH₃ is difficult to sample because it is very easily dissolved in water. Experimental laser detectors, beaming across the stack, have been used as ammonia analyzers with some success.

Fuel Gas Heating Value  When the refinery waste gas and utility gas are combined, the mixture resulting from their varying heating values will also have a varying heating value. BTU analyzers are used to measure the heat flow rate (Figure 8.27l) provided by the fuel being fed to the furnace (see Section 2.4 in Chapter 2 in Volume 1 of this handbook).

In order to stabilize furnace firing, the heating value of the fuel should be kept constant. This can be achieved by blending refinery gas with natural gas, propane, or some other supplemental fuel having a high and constant heating value. If the heating value of the total stream drops, more of the supplemental fuel is blended in.

This BTU instrument (calorimeter) can also serve as a safety device by actuating an alarm when the heating value of the fuel drops to the point where it cannot support combustion.

Both the blending of the fuels and the emergency shutdown controls can be automated (Figure 8.27m). In this control configuration, if the BTU analyzer detects a drop in the heating value, the fuel supply is shut down.

If the heating value of the two gases that are blended are known, but their ratio varies, the resulting variation in the total heating value can be compensated for by a gas blending system on the main fuel gas header.

Relatively inexpensive BTU analyzers are available for “sweet” gases. They operate by burning a sample stream of fuel and measure the oxygen concentration of the combustion products. The BTU measurement so obtained can be used in a feedforward manner, to compensate for the varying BTU content of the fuel values.

Figure 8.27n illustrates a fuel gas blending controller. The formula it uses to arrive at the total heating value of the blended stream is

\[
HT = \frac{(F1H1 + F2H2)}{FT}
\]

where:

- HT and FT are the total BTU content and total flow of the mixed fuel
- H1 and F1 are the flow and the BTU content of fuel 1
- H2 and F2 are the flow and the BTU content of fuel 2

Furnace Instrumentation  While the control hardware and software are constantly changing, today’s furnaces in larger plants such as refineries are usually controlled by DCS systems, with independent PLCs used for safety shutdown. In case of some furnaces, PLCs with human-machine interfaces (HMI)s are also used in place of DCS systems, as are graphic software-supported PC displays located in the control room and in management offices. Smaller furnaces can be controlled by single-loop analog or digital PID controllers.

Both the DCS systems or the microprocessor-based unit controllers provide adaptive gain, auto-tuning, feedforward, and the capability of decoupling the interacting loops. Historical trends and temperature profiles can be graphically displayed,
and alarm conditions and status summaries can be shown on graphic displays with event printouts. Nuisance alarms can be eliminated by the use of smart alarm logic, and diagnostic messages can be generated for operating and maintenance information. All of these capabilities contribute to reducing the frequency of furnace shutdowns and increase its safety.

**Transmitters and Valves** Mostly 4–20 mA analog transmitters are used with the digital HART protocol superimposed over the analog signals to the DCS. In order to save on wiring costs, newer installations use Fieldbus networks, but their reliability for critical systems is still under evaluation.

Most field devices and their wiring need to be intrinsically safe or explosionproof, approved for Class 1 Div. 2 Gr. B, C, D. Intrinsically safe units are provided with current-limiting barriers. Most transmitters and I/P or E/P converters are provided with NEMA4X/7 explosionproof enclosures. For analyzers, purged enclosures are also used with proper safeguards (see ISA Standard S12.4).

Field instrumentation should not be located close to potential fire sources, such as on furnace walls. Their wiring should be routed from furnaces to junction boxes or from DCS I/O cabinets that are at a safe distance from potential fire sources, so that in case of a furnace fire, only the wiring to the junction boxes will need to be replaced.

Final control elements, such as control valves or dampers, should be selected so their gain variation will compensate for the variations in the process gain, with the goal being a constant loop gain over the range of the valve openings. Equal-percentage (gain increasing with load) valve characteristics should be used when the process gain drops as the load rises, in order to keep the loop gain at around 0.5.

Control valves should be provided with positioners, in order to overcome packing friction-caused hysteresis, but it is important to make sure that the positioner is faster than the controller that sets it. Newer E/P positioners also provide information on valve diagnostics such as packing problems.

Firing shutdown valves should always be separate from fuel control valves and be of the tight shut-off type with fire-resistant design. Usually, ball valves with steel seat rings are used for shut-off services. One should also consider the use of fireproof insulation of the valve actuators and of the air tanks on air-fail switch valves.

**Flame Scanners** Only some refinery furnaces are provided with flame scanners. Ultraviolet, visible, and infrared designs can be considered. Ultraviolet flame detectors measure the flicker of a flame in the UV band and are not blinded by the hot refractory (Figure 8.27o). Infrared sensors are able to

![FIG. 8.27o](image)

*Pressure- and temperature-compensated fuel gas blending control system used when the BTUs of the blended streams are known, but their ratio varies. This typical controller also handles the safety shutdown interlocks.*

![Applicable ranges of selected flame sensors and the range of hot refractories effect.](image)
penetrate through the flame by-products such as smoke, atomized oil, or steam. Instrument air for purging and sometimes cooling water is also required for these sensors.

**FURNACE TYPES**

**Start-Up Heaters**

Start-up heaters are discussed here first because of their simplicity. These units are required at the start-up of a process unit, and their use lasts from a few hours to a few weeks. They are usually vertical, cylindrical units with vertical process tubes along the inner walls and with a single burner centered in the floor. Draft is normally by natural convection induced by a stack mounted on the top of the heater.

Processes that require start-up heaters include catalytic cracking units to heat up fluidized catalyst beds, ammonia units to heat up the ammonia converter catalysts, and fixed-bed gas-drying units to regenerate the dryer beds.

The start-up heater usually heats an intermediate stream, such as air or natural gas, which in turn heats another fluid or solid, such as a reactor catalyst. For example, the start-up heater for an ammonia unit is used to heat "synthesis gas" (primarily a mixture of hydrogen and nitrogen), which in turn is used to heat the catalyst bed in the ammonia converter to a temperature of 700°F (371°C).

The synthesis gas is recirculated through the catalytic bed, gradually bringing it up to operating temperature. After normal operation has begun, the exothermic nature of the ammonia synthesis reaction keeps the bed at a certain temperature, and the start-up heater can be shut down.

**Process and Firing Controls**  The important variables are the flow and temperature of the "synthesis gas." Figure 8.27p shows the necessary controls for the operation of this unit. The flow of the cold synthesis gas is measured by the flow transmitter (FIT-1) and is indicated on a flow indicator (FI-1). The desired gas flow is manually adjusted by operating the hand valve (HV-1), while observing the local flow indicator (FIT-1). The effluent synthesis gas temperature is maintained by the temperature controller (TIC-1), which uses a thermocouple to measure the gas temperature and controls the flow of fuel gas by modulating the control valve TV-1.

The fuel gas firing rate is set by process temperature controller (TIC-1). The heater draft (i.e., negative pressure in the firebox) is produced by the stack; the operator sets it by observing the draft gauge (PI-1) and by manually adjusting the position of the stack damper. Once initially set, the damper is rarely adjusted again, unless the furnace conditions or loads change drastically.

**Safety Controls**  Start-up heaters are usually controlled by simple PLCs or relay systems. Most start-up heaters have flame scanners. Their SIS system requirements have already been described in a previous paragraph.

**Fired Reboilers**

The fired reboiler provides heat to a distillation tower by heating the tower bottoms and vaporizing a portion of it. Normally, a tower reboiler uses steam or another hot fluid as a source of heat, but where heat duties are great or where tower bottom temperatures must be high, a fired reboiler can be used. Depending upon its size, the reboiler may be of the vertical cylindrical type or the larger, conventional horizontal-type furnace.

The fired reboiler heats and vaporizes the tower bottoms as this liquid circulates by natural convection through the heater tubes. The coils are generously sized to ensure adequate circulation of the bottoms liquid. Temperature of the reboiler return fluid is generally used as the means of controlling the heat input to the tower, provided that the bottoms product material has a wide boiling-point range. Overheating the process fluid is a contingency that must be prevented, because most tower bottoms will coke or polymerize if they are subjected to excessive temperatures for some length of time.

**Process and Firing Controls**  A common control scheme is shown in Figure 8.27q, which depicts the tower bottom along with the fired reboiler. It is usually not practical to measure the flow of tower bottoms to the reboiler, first, because the liquid is near equilibrium (near the flash point), and second, because it is usually of a fouling nature, tending to plug most flow elements.

Proper circulation of the fluid is provided in the careful hydraulic design of the interconnecting piping. An important variable is the reboiler return temperature, which is controlled by TRC-1 throttling the fuel gas control valve. The high-
temperature alarm (TAH-1) is provided to warn the operator if the process fluid reaches an excessive temperature.

The reboiler return temperature is actually an inferred indication of the percentage of vaporization. The sensitivity of TIC-1 depends upon the boiling-point range of tower bottoms. A wide boiling-point range provides adequate sensitivity. However, a narrow range does not control well. Often, for these cases, a differential pressure controller is used in place of the reboiler temperature to infer percentage of vaporization. A differential pressure controller (DPIC, not shown) offers increased sensitivity to firing for narrow-range boiling-point fluids.

The firing controls of fired reboilers are relatively simple and are similar to those of the start-up heater. The process temperature controller (TIC-1), or tower differential pressure controller, sets the set point of the gas pressure or flow controller. The fuel in this case is gas, but it could just as well be fuel oil. The furnace draft can be manually set by means of the operator throttling the stack damper while observing the draft gauge (PI-1). The stack temperature (TI-3) and the tube skin temperatures are monitored as checks for excessive temperatures that may develop during periods of heavy firing.

Safety Controls  The major dangers in this type of furnace are caused by either the interruption of process fluid flow or by the stoppage of fuel. The loss of process fluid can occur if the liquid level in the tower bottom is lost. If this happens, flow will stop in the reboiler tubes, and a dangerous overheating of these tubes may result. To protect against this, the low-level switch (LSL-1) is wired to close the fuel gas valve (TV-1). For a more detailed description of the required shut-off safety system, refer to Figures 8.27c and 8.27d.

Process and Crude Oil Heaters, Vaporizers

The feed heater of a refinery crude unit is representative of this class of furnaces (Figure 8.27r). Crude oil, prior to distillation into the various petroleum fractions (gasoline, naphtha, gas oil, heavy fuel oil, and residual) in the “crude tower,” must be heated to around 750°F and partially vaporized. The heating and vaporization are done in the crude heater furnace, which consists of a firebox with preheat coils and vaporizing coils.

Larger-duty heaters usually have multiple zones encompassing multiple passes, and they heat the oil inside the coils in the convection section of the furnace. This is the portion that does not see the flame but is exposed to the hot flue gases on their way to the stack. The vaporizing takes place at the end of each pass in the radiant section of the furnace (where
the coils are exposed to the flame and the luminous walls of the firebox). The partially vaporized effluent then enters the crude tower, where it is flashed and distilled into the desired “cuts.”

Other process heaters that fall into this category are refinery vacuum tower preheaters, reformer heaters, hydrocracking heaters, FCCU feed heaters, and dewaxing unit furnaces. The control system presented is also applicable to these types of process heaters.

**Process Controls**  
The prime variables of this process that need to be controlled are

1. The flow of the feed flow to the unit
2. The proper splitting of the total flow into the parallel paths through the furnace, in order to prevent overheating of any one of the streams and to protect against its resultant coking
3. The correct amount of heat supplied to the process stream

Figure 8.27s shows the typical process controls for this type of furnace. The crude feed rate to the unit is set by the flow controller (FIC-4). This flow is split into the parallel paths of the furnace by adjustment of the manually set control valve openings by the hand indicating control (HIC) stations (HIC-1 through HIC-3).

The temperature indicators TI-1 through TI-3 (there may be several TIs on each pass) are periodically observed to determine if unbalanced temperatures are developing in any one of the passes. If such a trend develops, the flow through that pass is altered slightly to drive its temperature back toward the desired norm.

The outlet temperature controller (TIC-4) of the combined crude stream sets the firing rate through a cascade fuel flow or pressure controller (not shown).

However, the desired heat input into the feed stream can be more difficult to control, because the effluent of the furnace is partially vaporized and the feedstock varies in composition depending upon its source. If the feed were only heated and no vaporization took place, the control would require only that the effluent temperature be maintained. If complete vaporization and superheating occurred, this too could be handled by straight temperature control.

In the case of partial vaporization, combined with a variable feed composition, effluent temperature control alone is not sufficient for reliable control. The composition and, hence, the boiling-point curve of the feed varies with time, and the required control temperature itself also varies. Therefore, additional information is required, and it is obtained from the distillation process, which is downstream of the furnace. By observing the product distribution from the fractionation, a need for changing the heat input can be determined.

Current practice is to achieve approximate control with a temperature controller (TIC-4) whose set point is periodically changed by the operator to account for feed variations. The operator depends both on experience and on the results in the fractionator (possibly a crude tower optimization strategy) to determine the proper temperature setting.

**FIG. 8.27s**  
The controls of a crude heater-vaporizer, in which the flow distribution between the passes is manually adjusted.

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Firing Controls

Figure 8.27t shows the firing controls for the furnace using fuel gas (or fuel oil as standby). The fuel gas headers serve many burners spaced equally along the floor of the firebox. The burners, being essentially fixed-diameter orifices, will pass more or less fuel depending on the header pressure. In the past, a pressure controller was often used in place of flow control. Because flow through an orifice is a function of the square root of the pressure, nonlinearity is eliminated by the use of pressure control.

Although fuel oil is the make-up fuel (trim medium), it must be available in sufficient quantity to take the whole load in the event of a fuel gas interruption. The temperature controller (TIC-1) varies the set point of the fuel oil header pressure controller (PIC-2) to satisfy process load requirements. All burners have turndown ratio limitations. This is the ratio of minimum to maximum fuel burning capacity, which ratio is usually 3:1. Low pressure in the fuel oil header is indicative of the potential approach of a minimum firing condition. Consequently, the low-pressure switch (PSL-2 on PIC-2) is used to warn the unit operator when this situation arises. The operator then has the option of going out to the furnace and manually turning off some of the individual fuel oil burners or to reduce the fuel gas firing rate by lowering the set point of PIC-1. Either change will increase the fuel oil demand and, thus, bring the system back into a stable operating zone.

Newer installations use flow instead of pressure controllers (as shown in Figure 8.27u) on the fuel oil make-up to better control the heat balances. These controls are designed to meet a percentage of the total firing duty assigned to the hearth or floor burners to prevent furnace damage that can result from uneven firing. The percentage of the total firing duty that is assigned to the floor burners is a percentage that is recommended by the furnace manufacturer to protect metallurgy, reduce maintenance, and extend furnace life.

In Figure 8.27u, the effluent temperature controller (TIC-4 in Figure 8.27s) is the cascade master, and it adjusts the set point of FIC-5 to maintain the furnace effluent temperature. Cascading the TIC-4 to FIC-5 is beneficial in that the flow controller compensates for the disturbances (e.g., changes in fuel supply pressure) without allowing them to upset the effluent temperature, whereas the TIC-4 provides the correction required to correct the process for slower ambient changes.

Draft Control  Furnace draft is normally maintained by free convection in the furnace (i.e., the stack produces a negative pressure in the firebox), and air is drawn in through louvers
along the sides or bottom of the furnace. This is known as natural draft, because it is produced without mechanical means. Draft is controlled by pneumatically or motor-operated dampers in the stack.

Some furnaces use burner louvers with piston actuators for oxygen control (Figure 8.27u). Here, the overall furnace draft pressure is controlled by dampers in the stack, which are throttled by PIC-1, the draft controller, which strongly influences the O₂ content, because an increase in draft increases excess O₂. It is difficult to maintain the optimum (minimum) excess O₂ concentration in the flue gas without reaching dangerous pressure conditions at the furnace vault. Low excess O₂ and safe high arch/draft pressure limits are sometimes implemented in a duty constraint (cut-back) control configuration.

Damper characteristics are usually less than ideal, and linkages may stick. Installing powerful damper actuators will pay off in fuel savings. Newer furnaces with induced draft fans are usually provided with segmented damper blades, which have a near-linear characteristic. The nonlinearity of dampers can be compensated by using error-squared algorithms in their PID controllers.

Draft may violently oscillate, which can cause noise and furnace vibration. Therefore, measurement signal dampening is often required for PIC-1 in Figure 8.27u. The dampening filter should be so designed as to filter out fast pressure oscillations, but allow for the accurate measurement of all major pressure excursions in draft.

Changes in ambient temperatures, wind force and direction, or rain can also upset both the draft and the temperature controls. Draft controls set points should be selected with sufficient safety margins that a major storm will not cause the development of excessively low draft pressures.

If the furnace is large, or is provided with SCR NOₓ abatement controls, forced draft fans that operate at positive pressures will serve the firebox. If the fans are located at the outlet of the combustion zone, they usually operate at below atmospheric pressures and are called induced draft fans. They usually are provided with variable-speed drives (VSDs).

**Excess Oxygen Control** The zirconium oxide stack oxygen analyzer (Figure 8.27k) that is used for combustion control can also be used to display the O₂ concentration next to the draft PIC (Figure 8.27u). This allows the operator to adjust the stack damper draft controller set point to keep the furnace pressure safely “on the negative side” and yet approach the optimum excess air concentration.

Attempts to reduce excess air by maintaining excess O₂ to 2–3% often fail, because of the draft limitations. Most furnace SIS systems are set to shut down if draft is out of limits for over 5 sec. The high-draft or low-pressure limit is usually set at any pressure below −1.0” W.C. (in order to prevent buckling of the steel or damaging the refractory lining). The high-pressure or low-draft limit is usually set at any pressure that is below 0” W.C., because overpressure could force the flames out and cause the burning of the sidings.

The sample tap (Figure 8.27h) serving the O₂ analyzer is often used to also bring a heated sample to the NOₓ analyzer.

**Safety Controls** The primary sources of hazards in the operation of process heaters include the interruption of the charge flow, and the interruption of the fuel flow and resultant loss of flame. The reduction of crude charge rate below a minimum rate will result in overheating and possible tube rupture. Resumption of flow may cause hydrocarbon leakage into the firebox, with catastrophic results. The low-flow alarms (FAL-1, -2, or -3 in Figure 8.27s) alert the operator of this impending condition. If this happens, the operator has the option of correcting the fault or terminating the firing. If the instrument air supply fails, the control valves (FV-1 and HV-1 through HV-3) will fail open, thereby maintaining the flow through the furnace coils.

For the discussion of general safety requirements and the related PLC system design, refer to the earlier discussion on “Safety Instrumented Systems.”

**Reformer Furnaces**

The purpose of a reformer in an ammonia plant is to produce hydrogen, which is used with nitrogen in the synthesis of ammonia (NH₃). Hydrogen is produced by reforming the hydrocarbon feed. This feed (usually methane or naphtha) is reformed with high-pressure steam, as shown in the reaction
described in the equations below:

\[
\begin{align*}
\text{CH}_4 + n\text{H}_2\text{O} & = 3\text{H}_2 + CO + \text{CH}_4
\end{align*}
\]

8.27(14)

General: \[C_nH_{(2n+2)} + n\text{H}_2\text{O} = (2n + 1)\text{H}_2 + n\text{CO}\]

8.27(15)

The carbon monoxide is removed by further reaction later in the process. The reaction is endothermic (absorbs heat) and takes place at pressures of approximately 450 PSIG (3.10 MPa) and at temperatures of around 1500°F (815°C).

The reaction takes place as the feed gas and steam pass through tubes filled with a nickel catalyst, which is heated in the radiant section of the reformer furnace. Steam must be provided in excess of the reaction requirements to prevent the side reaction of coke formation on the catalyst. The coking of the catalyst deactivates it, requiring expensive replacement. To minimize coking, steam is usually supplied in a ratio of 3.5:1 by weight, relative to feed gas. Special precautions must be taken to maintain the excess steam at all times, because even a few seconds of interruption in the steam flow, while feed gas continues, can completely ruin the catalyst charge.

**Process Controls**

The major controlled process variables are the feed gas flow, the reforming steam flow, and the temperature and composition of the effluent. As illustrated in Figure 8.27v, the feed gas flow is maintained by means of a pressure-compensated flow controller (FIC-1). Pressure compensation of flow corrects the measurement for fluctuations in feed gas pressure. The steam rate is maintained by means of FFC-2, and the ratio of steam to feed gas flow is continually monitored.

The ratio controller FFC-2 measures the ratio by dividing the gas flow signal from FT-1 with the steam flow signal from FT-2. If this ratio falls below the limit of approximately 3:1, a low flow ratio alarm (FAL) is sounded. If the ratio continues to fall below approximately 2.7:1, the feed gas is shut off by closing the valve (HV-1).

![Diagram of reforming furnace process controls](image_url)

**FIG. 8.27v**

Reforming furnace process controls by manipulating the steam flow in ratio to the hydrocarbon feed.

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If there is no separate shut-off valve (HV-1), the feed valve (FV-1) must be a quick-closing valve (4–5 sec for full closure) so that the flow of gas can be stopped almost instantly if the flow of reforming steam fails, thus protecting the reformer catalyst. If the shut-off valve HV-1 is used, but it is electric motor operated, FV-1 must also be a single-seated tight shut-off valve, to prevent leakage during the time while the electric-operated shut-off valve is closing.

An alternative to the controls shown in Figure 8.27v is illustrated in Figure 8.27w. Here, the steam flow is on straight flow control, and the hydrocarbon gas feed tracks the steam flow on ratio control. In theory, this appears to be an improvement over the previous control system, but in practice, the dynamics of the measurements and of the process make it less stable. The noise in the steam flow measurement and lags may result in cycling of the gas flow set point. Therefore, the integrated error in the gas flow obtained by the control strategy in Figure 8.27w can be considerably greater than when Figure 8.27v is implemented.

Manipulation of the steam instead of the feed gas is the most common method of alleviating this problem. The effluent analyzer (AT-1 in Figure 8.27v) is used to determine reaction completion by measuring the methane (CH₄) content of the stream. Manipulating the profile of the furnace temperature can serve to achieve the desired degree of conversion.

This analyzer (AR-1) can be either an infrared or a chromatographic analyzer. The analysis is relatively simple, involving the measurement of 0–10% methane in a background of hydrogen and carbon monoxide. The only difficulty is the high water content in the stream, caused by the presence of excess steam used in the reaction. Therefore, water removal devices are required in the analyzer sampling system.

In newer DCS controls, the rates of competing reactions can be predicted so that the firebox and the optimum heat input profiles can be computed and set.

Firing Controls Firing of a reformer furnace, because of its massive design and great heat inertia, is often manually controlled. The furnace has approximately a dozen fuel headers with about 20 individual burners per header. Process temperature indicators TI-1 and TI-2 (on Figure 8.27v) are provided at the exit of the reaction tubes. These are constantly monitored, and periodic adjustment of firing is made by manipulation of the fuel header control valves (HV-1, HV-2, HV-3) in Figure 8.27v. The pressure upstream of the header control valves is controlled, so that once the valve stroke is set, fuel flow remains constant.

The fuel used is usually natural gas, with a small amount of purge gas from the NH₃ synthesis loop blended in.

Draft is usually maintained in these furnaces by a steam turbine-driven induced draft fan. The furnace draft (negative pressure) in the firebox is controlled by adjusting the fan speed. The pressure indicator controller (PIC-2) measures the pressure in the furnace (via PT-2) and controls the speed of the fan by adjusting the fan turbine governor to hold the furnace pressure at the desired setting. The draft points PI-1 through PI-4 are used to manually set the openings of the air inlet louvers, on the side of the furnace, to balance the drafts at various points in the furnace.

Safety Controls SIS controls are essentially the same as for the other furnaces described previously.

Upon instrument air failure, the gas feed valve (HV-1 in Figure 8.27v) closes to prevent coking the reformer catalyst. The fuel valves (HV-1, HV-2, and HV-3) close to stop firing during emergencies. The steam valve (FV-2 in Figure 8.27v) is a fail-open valve to maintain the flow of cooling steam through the furnace coils during such emergencies.

Cracking (Pyrolysis) Furnaces

An example of a cracking furnace is the ethylene pyrolysis furnace. Feedstock, which can vary from heavy gas oil, LPG, propane, to ethane, is preheated and vaporized in a preheat coil in the furnace and is then mixed with steam and cracked.

Steam is added to the feed in a fixed ratio to the hydrocarbon to reduce the partial pressure of the hydrocarbon feed. This tends to maximize the amount of olefins produced and to minimize the coke build-up in the coils.

The feed is heated to 1500°F (815°C) in the pyrolysis coils, which causes the cracking of the long chain hydrocarbons into shorter chain molecules and initiates the forming of such unsaturated (olefin) molecules as ethylene. The severity of cracking is dependent upon the temperature achieved.
and upon the residence time in the pyrolysis coils. Therefore, the distribution of furnace products is dependent upon the degree of firing and upon the temperature profile in the furnace. Effluent from the furnace is quickly quenched to prevent recombination of products into undesirable polymers.

**Process Controls**  The important variables to be controlled in order to obtain the desired effluent product distribution are hydrocarbon feed flow, steam flow, coil temperatures, and firebox temperature. The firing controls discussed in connection with the previously discussed furnaces are also applicable here.

As shown in Figure 8.27x, the charge to the cracking furnace is determined by the flow controls on each of the individual passes rather than by total flow control. It is important to keep the flow through the coils constant, because coking causes a gradual build-up in the pressure drop through the coils and reduces both the flow and the heat transfer.

If the feed distribution were left purely to hydraulic splitting, the coking would start in one coil and reduce the flow through that coil, which in turn would cause overheating of that coil, producing even more coking. Eventually, the flow would be reduced to such a low rate that the overheating of the coil would cause its melting and rupture. The individual flow control valves serve to introduce variable pressure drops, which are adjusted to guarantee that all coils will coke at an almost equal rate.

The steam flow controllers (FIC-7 is shown as typical for all three) regulate the steam flow to match the total flow of hydrocarbon feed, controlled by FIC-4. The temperature controller (TIC-4) sets the firing controls by adjusting the total heat input to the process and brings the effluent temperature to the desired value.

The temperature indicator points (TI-1 through TI-6, as well as the tube skin temperature sensors) are monitored by the process operator to maintain a certain furnace temperature profile and, hence, a certain product distribution in the furnace effluent. The temperature relationships are accomplished by manually trimming burners at the required places in the firebox.

In order to determine whether the desired product specifications are being met, an analyzer is installed in the furnace effluent (AT-1). This analyzer is usually a chromatograph, though mass spectrometers could also be used, if the speed of response of this analysis was critical. This analyzer measures most of those components in the effluent stream that are lighter than butane.

This analysis is a difficult one, primarily because of the sample handling requirements. The sample has a high water content, and the water must be condensed and removed before the sample enters the analyzer. The sample also has a

---

**FIG. 8.27x**

Pyrolysis furnace process controls.
large amount of entrained coke and tars, which likewise must be eliminated (scrubbed out).

**Safety Controls**  The major hazards in operating cracking furnaces are the interruption of the feed flow, the interruption of the fuel flow, coking of the individual coils, and the failure of the instrument air supply. Interruption of feed flow can result in a dangerous situation if firing is maintained at the normal rate, because the tubes are not designed for the excessive temperatures that result if charge is stopped or drastically reduced, and the danger of tube rupture is, therefore, pronounced.

The low-flow alarm (FAL-4, Figure 8.27y) is provided in the feed stream to warn of impending danger. Once it is verified that the danger is real, the vent solenoid valve (HY-1) can be tripped by the operation of the pushbutton (HS-1) that vents the diaphragm of the emergency valve (HV-1), shutting off the fuel gas. This shut-off can be automated, so that on a drop in the feed flow, a low-flow switch (FSL-4) automatically actuates the trip solenoid (HY-1), which cuts off the fuel flow.

Interruption of fuel flow will cause burner flameout, and resumption of fuel flow may result in a dangerous (fuel-rich) fuel/air mixture. To protect against such resumption of fuel flow, the low-pressure switch (PSL-1) is used in Figure 8.27y, which triops the emergency shut-off valve (HV-1) via the solenoid valve (HY-1). The solenoid valve is the manual reset type; therefore, once tripped it will reopen only if manually reset.

Excessive coking of an individual furnace coil can occur as a result of the restriction of the flow through it. This is a self-worsening effect and tends to cause dangerous overheating. The prevention of this situation is of prime concern. Should such a condition occur, it will be detected by the high-temperature alarms (TAH-1 through TAH-3 in Figure 8.27x) to warn the operator.

In response, the operator can increase the set point of the appropriate feed flow controller, thus forcing more fluid through the hot tube, thereby hoping to bring the temperature down. If this does not alleviate the condition, the operator has no alternative but to shut down the firing.

Failure of instrument air will result in failing all the control valves open, as in Figure 8.27x. The feed valves and the steam valves open on air failure to continue the flow through the furnace coils and, thereby, to prevent overheating and possible rupture of the coils.

**ADVANCED CONTROLS**

Advanced furnace controls include feedforward control based on feed rate, cross-limiting firing (Figure 8.6r in Section 8.6), coil balancing (Figure 8.21r in Section 8.21), and optimization. Implementation of these control strategies is normally aided by expert system software, distributed control systems, single or dual loop programmable controllers, or dedicated microprocessor-based devices can also perform this type of control to a limited extent. An example of each type of control is presented in the next paragraphs. Control systems can include any combination of these advanced techniques.

**Feedforward Control**

In feedforward control, a simplified model of the process is used to predict the effect of disturbances before they reach and can upset the controlled variable. In contrast, feedback control must first detect an error in the controlled process variable before it can initiate a corrective action.

A simple example of feedforward control is given in Figure 8.27z. Here the feedback loop consists of the temper-
ature controller (TIC-1) providing the set point for the fuel flow controller (FIC-1). When the feed flow to the furnace changes (this flow is an independent variable in this system), there is a need to change the rate of fuel firing.

The feedforward loop includes the feed flow transmitter (FT-1), which detects the change in feed flow rate, and this rate is multiplied by a constant in FY-1. This constant relates to the heating value of the fuel gas, and if a BTU analyzer (AT-1) is used, the correction can be automatically obtained. This multiplying block sets the relationship between a change in feed flow rate and the required corresponding change in fuel header pressure. This is an empirically determined value and can be field-adjusted.

Dynamics may be included (dead time, lead/lags) if warranted (this topic is discussed in full detail in Section 2.9 in Chapter 2). The response of the furnace to an increase in firing rate is often too slow, and therefore such controls are useful only when responding to step changes in feed flow rate.

The modified signal from FY-1 is then summed (FY-2) with the signal from the temperature controller output, thereby setting a new fuel gas flow rate via FIC-2. In effect, advance information is fed forward through FY-1 to the firing controller (FIC-2), indicating that a change in process load will require a change in firing rate shortly and that the firing rate, therefore, should begin to change.

Without the feedforward leg of the loop (FY-1 and FY-2), the required change in firing rate would take place much later, after the temperature controller (TRC-1) detects an error in the controlled variable (the effluent temperature of the furnace). If a constant ratio existed between feed flow and fuel gas flow, the temperature controller would not even be necessary, but with changing ambient and process conditions, this ratio changes with time. Thus, TRC-1 acts in the feedback path as a slow trim-controller, keeping the controlled variable at a desired value.

**Coil Balancing Control**

One of the main considerations in a multipass furnace control is the proper splitting of feed among the parallel passes through the furnace. In a large ethylene plant, six to eight identical cracking furnaces may be present, each with from 10 to 20 parallel coils. Maintaining proper flow splits in these coils is a formidable task if done manually.

The objective is to maximize furnace energy utilization per unit of feed flow. In general, heat transfer efficiency is highest when the percentage of vaporization measurements in all the coils are equal. However, without a measurement of percentage of vaporization, the best that can be done is equalization of all the individual coil outlet temperatures.

Digital control of the total furnace circulation is implemented by feedback manipulation of all furnace coil flow rates. Figure 8.27bb shows an older computer control system. Here, the total feed flow (A/D-1) and the individual coil flows (A/D-2, -3, -4, etc.) are monitored by the DCS system, which calculates the proper valve settings based on these flows. The proper valve openings are sent by the DCS system (through the digital-to-analog converters (D/A-2, -3, -4, etc.), and the valves divide the total feed flow properly.

The total feed flow rate sets the total charge to the furnace. Each coil flow rate set point is calculated as the total furnace flow (minus the flow of all nonautomated coils), divided by the number of coils that are automatically controlled. This
allows for coil balancing of at least a portion of the furnace, if some of the coils cannot be placed under automatic control due to defective instrumentation.

After start-up, the total flow will be divided equally among the passes, but as time progresses, coke builds up at different rates in the individual coils, causing outlet temperatures to vary from coil to coil. This control system keeps the coil effluent temperatures the same (within some tolerance) by adjusting the flows of the feeds through each coil. The DCS system does this by taking the effluent coil temperature information (A/D-20, -21, -22, etc.), comparing them with the desired temperatures, and modifying the “feed-splitting” computation to correct for deviations. The results of the computation are sent out to reposition the feed valves (FV-2, FV-3, FV-4, etc.).

Changes to the furnace charge rate are normally ramped, and their speed of change is limited to avoid rapid upsets in the furnace. Limit constraints, including a differential flow limit between each coil and the average coil flow, are normally included in the overall control algorithm to maintain safe flow rates in all coils, in order to prevent excessive coking or development of hot spots in the furnace.

Many additional optimization functions can be performed using much of the same input data. Some of these are “off-normal” alarms on feed flow, “off-normal” alarms on effluent temperatures, alarms to signal excessive pressure drops across coils, high coil-metal temperatures, and other scanning functions.

**Cross-Limiting Firing**

A cross-limiting firing control technique ensures that air is always in excess of the amount required to fully combust the fuel. This avoids hazardous (fuel-rich) combustible mixtures in the firebox. When an increase in firing rate is needed, cross-limiting firing controls first increase the airflow, and the fuel flow only after that. When a decrease in firing rate is desired, the strategy reduces fuel flow before reducing the airflow. This is performed through a combination of high- and low-select modules and dynamic exponential lag modules. A control block diagram of the cross-limiting firing circuit is shown in Figure 8.27cc.

The success of the cross-limiting firing is predicated on being able to measure or infer the air and fuel flow rates (see Table 8.6d in Section 8.6 for sensors). If the airflow is controlled only by damper position, this flow rate must be interpolated from the damper position. Also, fuel is often not metered, but only controlled by a pressure controller, so the

![FIG. 8.27cc](image)

Cross-limiting firing control block diagram.
header pressure must be converted into an approximation of flow rate. Such indirect methods of flow approximations are highly inaccurate and should no longer be used.

The cross-limiting firing system described in Figure 8.27cc works in the following manner: When the effluent temperature controller (TIC-1) calls for additional heat to be supplied by the furnace, the output of the controller increases. After feedforward adjustment, this signal goes to both a high- and a low-signal selector (TY-1 and TY-2).

At the high-signal selector, this rising signal will be greater than the signal representing current fuel flow (pressure). The high select (TY-2) will thus call for increased heat by increasing its output, and this increased signal will be multiplied by the current air/fuel ratio in FY-1. The output from this multiplier (FY-1) goes to the set point of the airflow controller (FIC-1). Therefore, the result of an increase in the output of TIC-1 is an immediate increase in the airflow controller set point.

At the low select (TY-1), the increasing TIC-1 output signal will not be chosen because it is greater than the signal supplied by the air/fuel ratio FY-2. The airflow measurement signal is sent through a lag block and is divided by the air/fuel ratio set point in FY-2, which produces the second input to the low selector. The immediate increase in air, which followed the rise in TIC-1 output, is thus lagged with a first-order lag block prior to the low select (TY-1), resulting in a gradual increase in fuel. Therefore, an increase in the firing rate (TIC-1 output) results in a fast increase in air and a slow increase in fuel flow.

When the firing demand drops due to a drop in the feed flow or in the temperature controller output, the reduced signal is sent to both the high and low selector modules (TY-1 and TY-2). The dropping signal is immediately passed through by the low selector (TY-1), resulting in an immediate decrease in the fuel flow set point.

However, at the high selector (TY-2), the decreased signal is blocked, because the lag element keeps the apparent flow of fuel higher. The result is a slow (first-order lagged) reduction in the flow of air. A change in the output of the excess air (or O₂) controller (AIC-1) goes through the high selector (TY-1) in a similar manner. The output of the controller (AIC-1) is the air/fuel ratio setting for the furnace, which is multiplied by the signal from the high selector in FY-1. Therefore, the air/fuel ratio directly affects the airflow set point. This same air/fuel ratio is the divisor at the airflow in FY-2. The output of FY-2 is the second input to the low selector TY-1, which selects the fuel oil flow set point.

Severity Control

Using the ethylene cracking furnace in Figure 8.27bb as an example, an analyzer measuring the effluent stream composition (AT-30) also sends its measurement signal to the computer, where it is compared with the desired composition. Based on the difference between the two, the desired degree of fuel firing in various furnace zones can be computed.

These firing rates may be printed out as instructions to the operator or used to automatically manipulate the fuel valves, or fuel flow controller set points, thereby changing the heat flow pattern throughout the furnace and thus controlling the cracking operation.

Model-Based Control

Process models can relate the control variables of the radiant coil to operational parameters. Information on furnace operation includes hydrocarbon flow rate, steam-to-hydrocarbon ratio, coil outlet temperatures and pressure, severity of cracking, and fouling parameters. These parameters are used to develop interrelationships between independent and dependent variables.

Matrix calculations can be performed to change the manipulated variables so that the controlled variables are held at their set points. General-purpose computing modules are used to run these models and optimizers. For in-depth coverage of a variety of model-based control approaches, refer to Sections 2.13 to 2.18 in Chapter 2.

Two common applications of model-based control will be briefly discussed below.

Coil Outlet Temperature (COT) Matrix

The individual COTs can be simultaneously controlled by solving an interaction matrix that relates the change in each coil temperature to the change in valve openings of the wall burners. The matrix coefficients determine the gains associated with each COT-firing zone pair.

Knowledge of furnace geometry and experimental data is employed to define the matrix. If the matrix accounts for only the steady-state character of the process, the dynamic nature must be handled by feedback trimming of the COT controllers.

It may be necessary to remove the excess degrees of freedom that result from having more wall burners than COT measurements. This can often be accomplished by interpolating the desired wall burner valve positions on the basis of the outputs of adjacent COT controllers.

Provisions should be made to disable controllers whose thermocouples have failed (burned out). The proper installation of tube surface-detecting thermocouples is shown in Figure 8.27dd.

Because of the harsh service, COT thermocouple (T/C) failure is a routine incident that the control strategy must handle. To detect the thermocouple burnout, it is necessary to detect the loop resistance of the installed thermocouple (Figure 8.27ee).

Dual or companion thermocouples can be connected to multiplexers and can be used to validate the COT measurements. When a COT controller is placed in manual, its output is forced to be equal to the average output of the COT controllers that are still controlling the process (the average of those controllers that are not in manual).

In this way, temperature control for the failed coil is still maintained to some extent, and responses are made to
disturbances that are affecting all the coils. This approach has proven to be an effective solution whenever thermocouples are to be replaced on-line.

The use of a matrix algorithm alone does not necessarily guarantee an even firing pattern, because there is no feedback component in this strategy to correct for errors in the matrix model. Over time, as the effects of coking, air register adjustments, and burner fouling are better understood in a particular installation and when they are better quantified, solutions can be implemented by shifting the duty requirements between the firing zones in such a way as to equalize the bias station positions.

**Optimizers** Optimizers are used to calculate the required charge rates and the severity of cracking of ethylene furnaces, based upon financial or contractual criteria. The model-based program then simultaneously manipulates several independent variables to achieve these dependent control points.

The model solves simultaneous polynomial equations relating severity to charge rate, steam-to-hydrocarbon ratio, furnace effluent temperature, excess oxygen, and coil fouling rate in a matrix format. Outputs to local controllers or valves are then adjusted all at once.

**CONCLUSIONS**

The furnaces and control systems discussed in this section are representative of a wide spectrum of furnaces throughout the process industry. The strategies are valid whether implemented by older analog instrumentation or by more sophisticated DCS or PLC systems.

The control systems that were described in this section did not cover the specifics of advanced process control. For the subjects of optimization and modeling, the reader is referred to Sections 2.7 to 2.20, and for relative gain calculations or for decoupling of interactions to Sections 2.25 and 2.37 in Chapter 2. It should also be noted that the sections describing boiler controls (Section 8.6) and distillation controls (Sections 8.19 to 8.21) should also be studied, because there is a fair amount of overlap between these unit operations and furnace controls.

With the expansion of industrial facilities and with the use of larger furnace units on the one hand and with the increased availability of advanced process control (APC) on the other hand, the use of more advanced and model-based controls should be considered, while taking full advantage of the basic controls described in this section, to obtain more efficient and more profitable furnace operation.

**STANDARDS AND GUIDELINES**

ANSI/API 536, “NOx Control for Fired Equipment in Refineries”
API 554/1993, “Process Instrumentation and Control”
API 553/1998, “Control Valves”
API 556/1997, “Instrumentation and Control Systems for Fired Heaters and Steam Generators”
API 557.01/2000, “Guide to Advanced Control Systems”
40CFR Part 60, “New Source Performance Standard” (section for oil refineries)
ISA TR84.02-2002, “Fault Tree Analysis”

Bibliography