
8 Combustion Controls

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8.1 FUNDAMENTALS

This chapter discusses various control system components, concepts, and philosophies necessary for understanding how control systems work, what the systems are designed to accomplish, and what criteria the controls engineer uses to design and implement a system. The interested reader can find further information on controls in numerous references.¹⁻¹⁰ The American Petroleum Institute has issued a recommended practice concerning instrumentation and control for fired heaters and steam generators.^{11,12}

The purpose of the control system is to start, operate, and shut down the combustion process and any related auxiliary processes safely, reliably, and efficiently. The control system consists of various physical and logical components chosen and assembled according to a control philosophy and arranged to provide the user with an informative, consistent, and easy-to-use interface.

A combustion system typically includes a fuel supply, a combustion air supply, and an ignition system, all of which come together at one or more burners. During system start-up and at various times during normal operation, the control system will need to verify or change the status of these systems. During system operation, the control system will need various items of process information to optimize system efficiency. Additionally, the control system monitors all safety parameters at all times and will shut down the combustion system if any of the safety limits are not satisfied.

8.1.1 CONTROL PLATFORMS

The control platform is the set of devices that monitors and optimizes the process conditions, executes the control logic, and controls the status of the combustion system. There are several different types of platforms and several different ways that the tasks mentioned above are divided among the types of platforms. Following is a list and a brief description of the most commonly used platforms.

8.1.1.1 Relay System

A relay consists of an electromagnetic coil and several attached switch contacts that open or close when the coil is energized or de-energized. A relay system consists of a number of relays wired together in such a way that they execute a logical sequence. For example, a relay system may define a series of steps to start up the combustion process. Relays can tell only if something is on or off and have no analog capability. They are generally located in a local control panel.

Relays have several advantages. They are simple, easily tested, reliable, and well-understood devices that can be wired together to make surprisingly complex systems. They are modular, easily replaced, and inexpensive. They can be configured in fail-safe mode so that if the relay itself fails, combustion system safety is not compromised.

There are also a few disadvantages of relays. Once a certain complexity level is reached, relay systems can quickly become massive. Although individual relays are very reliable, a large control system with hundreds of relays can be very unreliable. Relays also take up a lot of expensive control panel space. Because relays must be physically rewired to change the operating sequence, system flexibility is poor.

8.1.1.2 Burner Controller

A variety of burner controllers is available from several different vendors. They are prepackaged, hardwired devices in different configurations to operate different types of systems. A burner controller will execute a defined sequence and monitor defined safety parameters. They are generally located in a local control panel. Like relays, they generally have no analog capability.

Advantages of burner controllers include the fact that they are generally inexpensive, compact, simple to hook up, require no programming, and are fail-safe and very reliable. They are often approved for combustion service by various safety agencies and insurance companies.

There are also some disadvantages. Burner controllers cannot control combustion systems of much complexity. System flexibility is nonexistent. If it becomes necessary to change the operating sequence, the controller must be rewired or replaced with a different unit. Controllers also require the use of attached peripherals from the same vendor, so some design flexibility is lost.

8.1.1.3 Programmable Logic Controller (PLC)

A programmable logic controller (PLC) is a small, modular computer system that consists of a processing unit and a number of input and output modules that provide the interface to the combustion components. PLCs are usually rack-mounted, and modules can be added or changed (see Figure 8.1). There are many types of modules available. Unlike the relays and burner controllers above, they have analog control capability. They are generally located in a local control panel.

PLCs have the advantage of being a mature technology. They have been available for more than 20 years. Simple PLCs are inexpensive and PLC prices are generally very competitive. They are compact, relatively easy to hook up, and, because they are programmable, they are supremely flexible. They can operate systems of almost any complexity level. PLC reliability has improved over the years and is now very good.

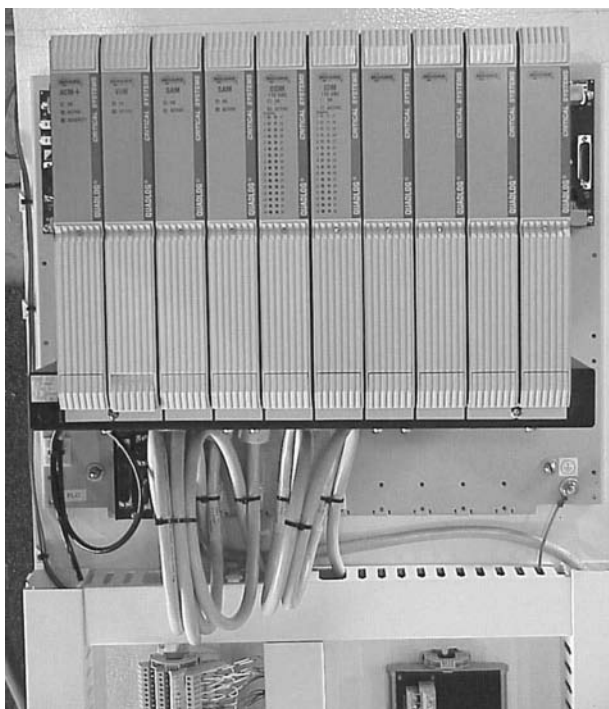


FIGURE 8.1 Programmable logic controller.

Disadvantages of PLCs include having to write software for the controller. Coding can be complex and creates the possibility of making a programming mistake, which can compromise system safety. The PLC can also freeze up, much like a desktop computer freezes up, where all inputs and outputs are ignored and the system must be reset in order to execute logic again. Because of this possibility, standard PLCs should never be used as a primary safety device. Special types of redundant or fault-tolerant PLCs are available that are more robust and generally accepted for this service, but they are very expensive and generally difficult to implement.

8.1.1.4 Distributed Control System (DCS)

A distributed control system (DCS) is a larger computer system that can consist of a number of processing units and a wide variety of input and output interface devices. Unlike the other systems described above, when properly sized, a DCS can also control multiple systems and even entire plants. The DCS is generally located in a remote control room, but peripheral elements can be located almost anywhere.

DCSs have been around long enough to be a mature technology and are generally well-understood. They are highly flexible and are used for both analog and discrete (on-off) control. They can operate systems of almost any level of complexity and their reliability is excellent.

However, DCSs are often difficult to program. Each DCS vendor has a proprietary system architecture, so the hardware is expensive and the software is often different from any other vendor's software. Once a commitment is made to a particular DCS vendor, it is extremely difficult to change to a different one.

8.1.1.5 Hybrid Systems

If you could combine several of the systems listed above and build a hybrid control system, the advantages of each system could be exploited. In practice, that is what is usually done. A typical system uses relays to perform the safety monitoring, a PLC to do the sequencing, and either dedicated controllers or an existing DCS for the analog systems control. Sometimes, the DCS does both the sequencing and the analog systems control, and the safety monitoring is done by a fault-tolerant logic system. Most approval agencies and insurers require the safety monitoring function to be separate from either of the other functions.

8.1.1.6 Future Systems

Over the next decade or so, it is expected that embedded industrial microprocessors using touch-screen video interfaces (see [Figure 8.2](#)) will start to appear in combustion control. The interfaces will communicate with field devices such as valves and switches via a single communications cable. They will use a digital bus protocol such as Profibus or Fieldbus. These systems are becoming common on factory floors around the world. Because establishment of a single standard has not yet happened and combustion standards are slow to change, these systems have not yet achieved widespread acceptance in the combustion world.

8.1.2 DISCRETE CONTROL SYSTEMS

The world of discrete controls is black and white. Is the valve open or shut? Is the switch on or off? Is the button pressed or not pressed? Is the blower running or not running? There are two basic types of discrete devices: (1) input devices (sensors) that have electrical contacts that open or close, depending on the status of what is being monitored; and (2) output devices, or final elements, that are turned on or off by the control system.

In a typical control system, sensors such as pressure switches, valve position switches, flame scanners, and temperature switches do all of the safety and sequence monitoring. These devices

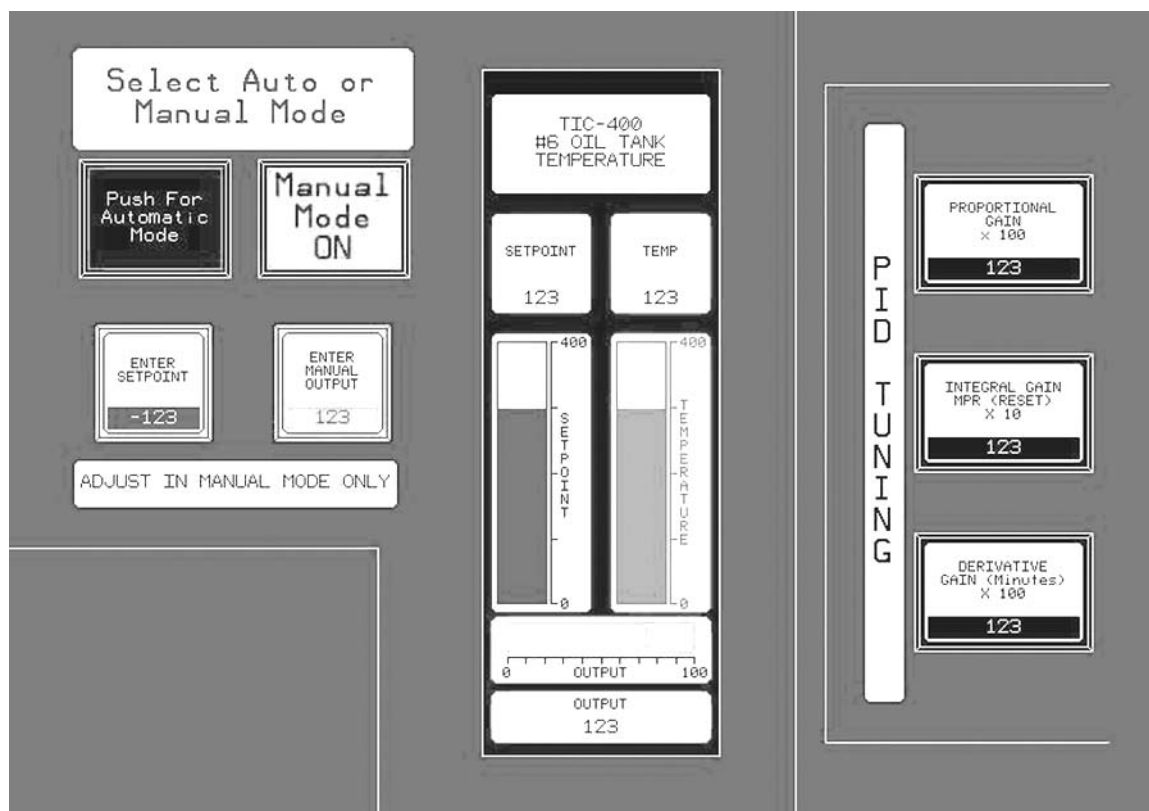


FIGURE 8.2 Touchscreen.

tell the control system what is happening out in the real world. They are described in more detail in the next section.

The final elements carry out the on/off instructions that come from the control system. These are devices such as solenoid valves, relays, indicating lights, and motor starters. These devices allow the control system to make things happen in the real world. They are described in more detail in the next section.

The discrete control system does safety monitoring and sequencing. Typically, the system monitors all the discrete inputs; and if they are all satisfactory, allows combustion system start-up. If a monitored parameter is on when it should be off or vice versa, the start-up process is aborted and the system must be reset before another start-up is permitted. The system also controls such things as which valves are opened in what order, if and when the pilot is ignited, and if and when main burner operation is allowed. Once the system starts, the discrete system has little to do other than monitor safety parameters. If any of the defined safety parameters are not satisfactory, the system immediately shuts down. [Figure 8.3](#) is a simplified flow diagram showing a standard burner light-off sequence.

8.1.3 ANALOG CONTROL SYSTEMS

The world of analog controls is not black and white — it is all gray. How far open is that valve? What is the system temperature? How much fuel gas is flowing?

There are two categories of analog devices with familiar names: (1) sensors, which measure some process variable, such as flow or temperature, and generate a signal proportional to the measured value; and (2) final elements, such as pumps or valves, that change their status (speed or position, for example) in response to a proportional signal from the control system.

In contrast to the discrete control system, the analog control system usually has few tasks to perform until the system completes the start-up sequence and is ready to maintain normal operation. Most analog devices are part of a control loop. A simple loop consists of a sensor, a final element, and a controller. The controller reads the sensor, compares the measured value to its setpoint, set by the operator, and then positions the final element to make the measured value equal the setpoint. [Figure 8.4](#) illustrates a simple analog loop.

In this case, the thermocouple transmits the temperature to the controller. If the temperature is higher than the setpoint, the controller will decrease its signal to the control valve. This will decrease the fuel flow to the burner, thus lowering the temperature. In this way, the loop works to maintain the desired temperature — also known as the setpoint.

The previous illustration is a good example of a simple feedback system. After the controller adjusts the control valve, the resulting change in temperature is fed back to the controller. In this way, the controller “knows” the result of the adjustment and can make a further adjustment if it is required. Another good example of feedback takes place whenever you drive your car. If you get on the expressway and decide to drive at 60 mph, you press your foot on the accelerator and watch the speedometer. When you get near 60 mph, you begin to ease off the accelerator so that you do not overshoot. From then on, you glance at the speedometer every now and then and adjust your foot position as necessary.

Feedback alone is not enough, however. What if there is traffic congestion? You begin to slow down in anticipation. This is called feedforward, which occurs when you change your operating point because some future event is about to happen and you need to prepare for it. Feedforward is commonly used in combustion control systems. A good example from the world of combustion is waste flow. In a combustible waste destruction system, what happens if the waste flow suddenly doubles? There will no longer be enough combustion air in the system to allow destruction of all of the waste. Unburned waste will burn at the tip of the smokestack and clouds of smoke will billow from the stack. Phone calls from irate neighbors will soon begin to accumulate. Using feedforward, as shown in [Figure 8.5](#), the waste flow is measured. When it doubles, the combustion airflow immediately increases by a similar amount, avoiding all the unpleasant consequences listed above.

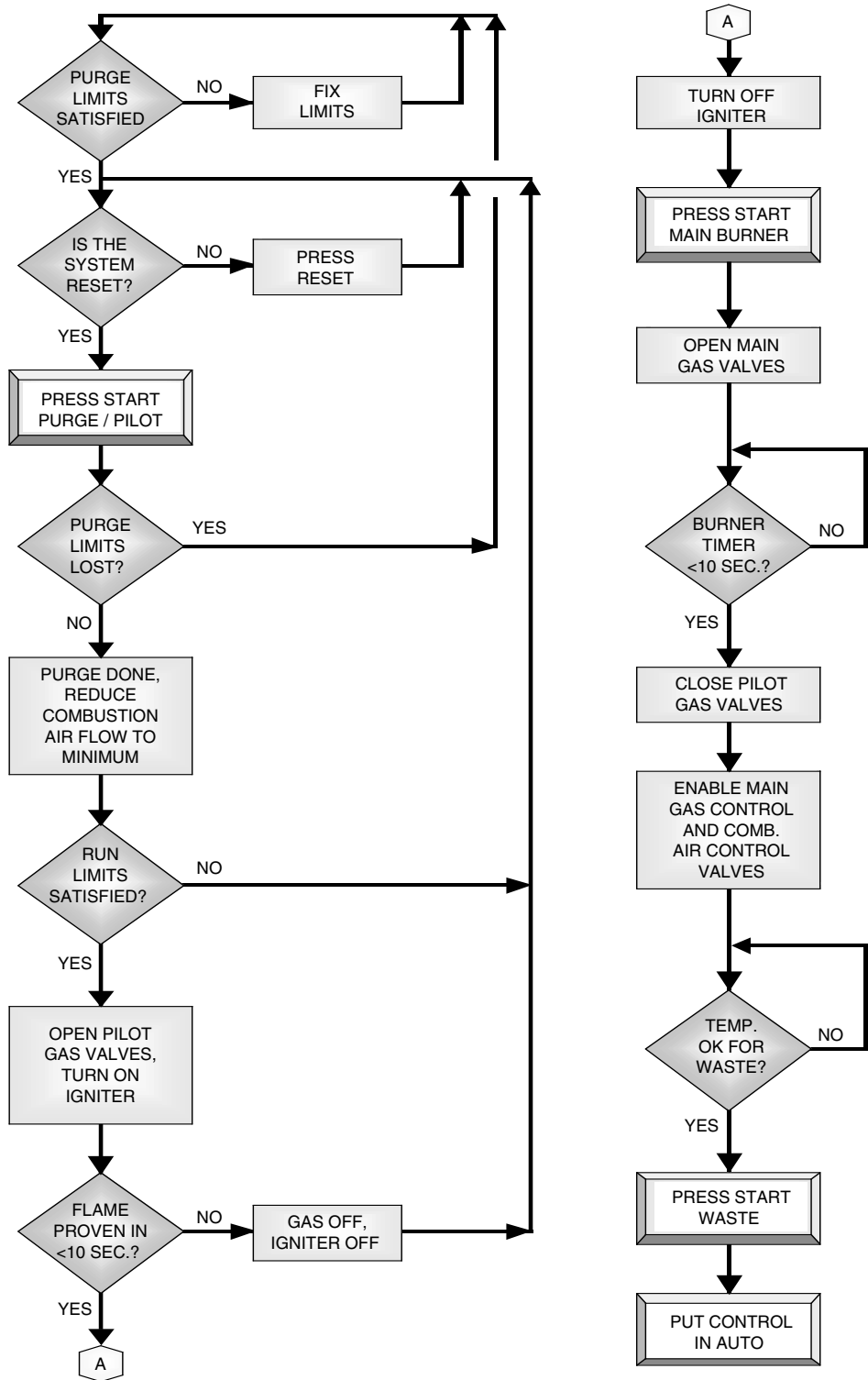


FIGURE 8.3 Simplified flow diagram of a standard burner lightoff sequence.

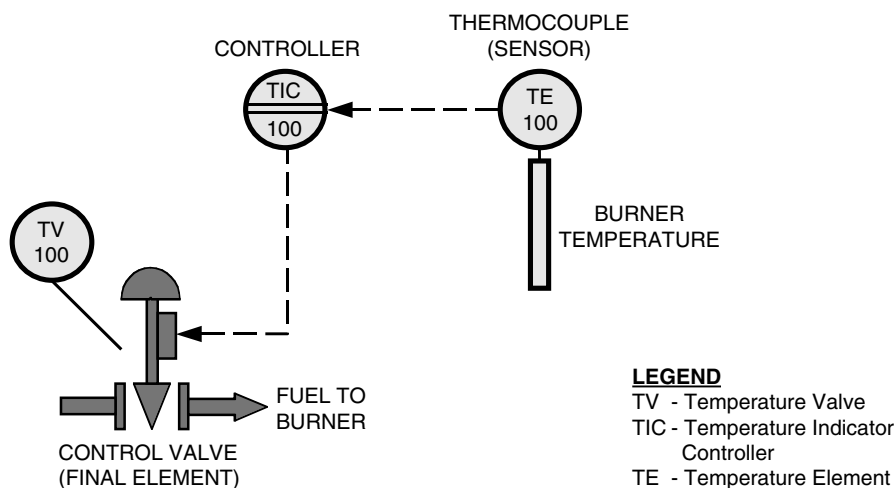


FIGURE 8.4 Simple analog loop.

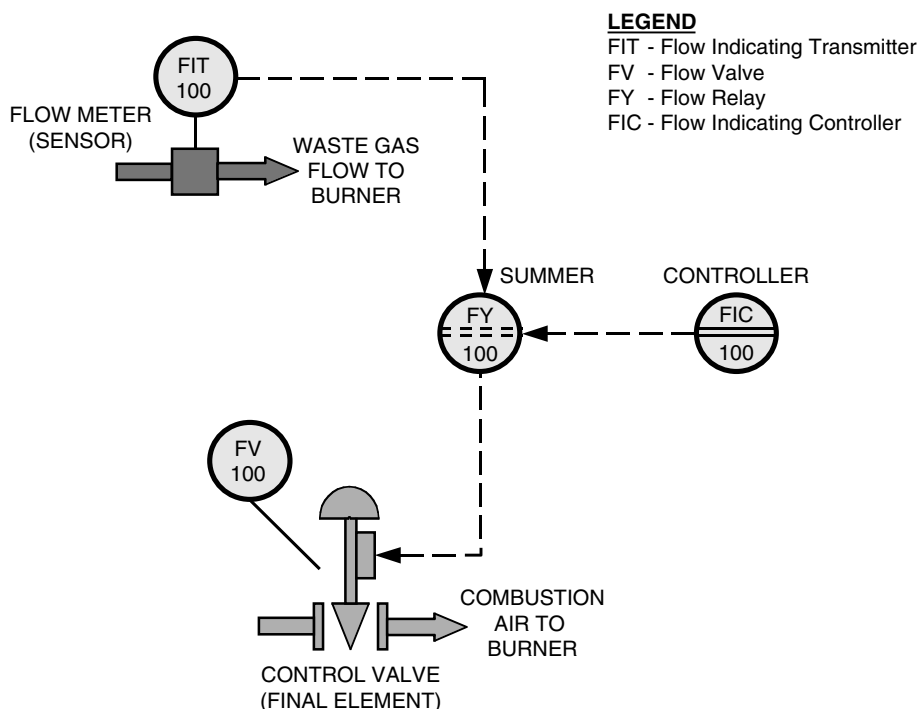


FIGURE 8.5 Feedforward loop.

8.1.4 FAILURE MODES

Almost everything fails eventually. No matter how well the components of a control system are designed and built, some of them will fail from time to time. One of the primary tasks of the controls engineer is to design the controls system so that failure of one or even several components will not cause a safety problem with the combustion system.

All components used in a control system have one or more defined failure modes. For example, if a discrete sensor fails, it will most likely cause the built-in switch contacts to fail open. To design a safe system, the controls engineer will choose and install the sensor so that when an alarm condition is present, the switch contacts will open. Thus, the alarm condition coincides with the failure mode. If it did not, the sensor could fail and the control system would still think everything was normal and attempt to keep operating as before, a condition that could be catastrophic.

In addition to sensors, final control elements also have failure modes. The controls engineer can usually select the desired failure mode. If a burner has an actuated valve that turns the fuel gas supply on and off, the actuator is installed so that the valve will spring closed (fail shut) on loss of air. In addition, assume there is a solenoid valve that turns air to the actuator on and off. The solenoid valve should be selected and installed to rapidly dump air from the actuator on loss of electrical power, thus closing the valve shut. These designs assure that the two most likely circumstances of component failure enhance system safety.

Construction of a well-designed system ensures that every component that can fail is installed so that component failures do not compromise system safety. At its core, that is what controls engineering is all about.

8.1.5 AGENCY APPROVALS AND SAFETY

Worldwide, there are hundreds of private, governmental, and semi-governmental safety organizations. Each ostensibly has the proper implementation of safety at the top of its agenda. Some agencies are concerned with the electrical safety and reliability of the components used in a control system. Other agencies are concerned about preventing explosions caused by sparking equipment in a gaseous atmosphere. Still other agencies are concerned with the proper design of control systems to ensure safe operation of various combustion processes. No single organization does all the things listed above.

The design of combustion systems in the U.S. should include specifications that meet National Fire Protection Association (NFPA) and National Electrical Code (NEC) standards. In accordance with the applicable standards and years of experience in the field, systems should be designed with some or all of the following safety features.

8.1.5.1 Double-Block-and-Bleed for Fuel Supply

This means that there are two fail-shut safety shutoff block valves with a fail-open safety shutoff vent valve located between them, as shown in [Figure 8.6](#). Each of the three safety shutoff valves (SSOVs) in the double block and bleed system has a position switch not shown here. For a system purge to be valid, the block valves must be shut and verified. For burner lightoff, the vent valve is shut. After the vent valve position switch confirms that the valve is shut, the two block valves are opened. If there is a system failure, all three of the valves de-energize and return to their failure positions. Note that if the upstream block valve ever leaks, the leakage will preferentially go through the open vent valve and vent to a safe location rather than into the burner.

8.1.5.2 Unsatisfactory Parameter System Shutdown

An unsatisfactory parameter for any critical input immediately shuts down the system. The control system typically receives critical input information as shown in [Figure 8.7](#). The pressure switch PSL-100 is wired so that if it fails, the voltage is interrupted to the relay and the programmable logic controller (PLC). The PLC will then shut down the system. If either the switch or the relay fails, the system shuts down.

In addition, the relay has another contact in series with all of the other critical contacts. If any of these contacts open, the power cuts off to all ignition sources (all fuel valves, igniters, etc.), immediately shutting down the combustion system.

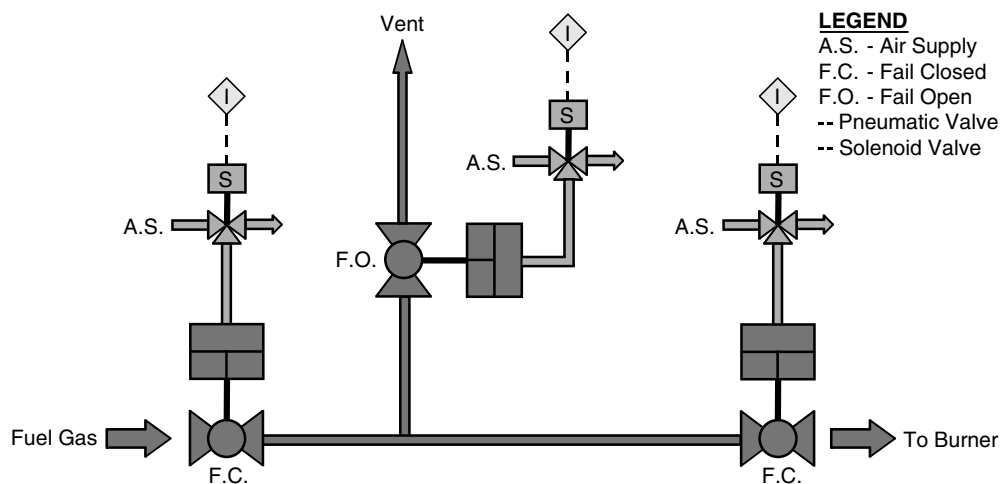


FIGURE 8.6 Double-block-and-bleed system.

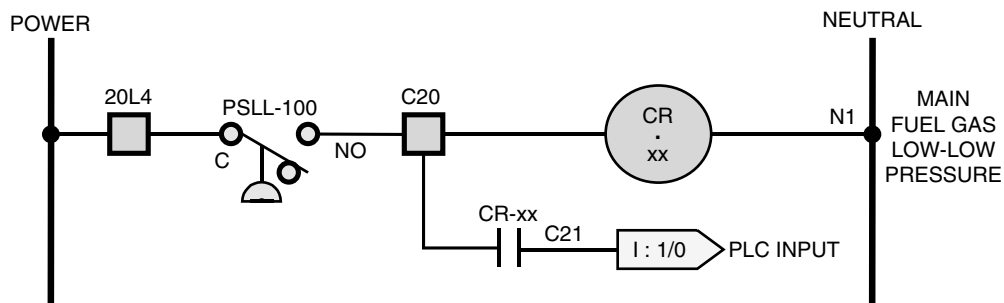


FIGURE 8.7 Failsafe input to PLC.

In [Figure 8.8](#), if there is a failure anywhere in the circuitry, the system shuts down. Even if damage to the PLC occurs, the relays will shut down the system. This is an excellent example of redundancy, fail-safe design principles, and effective design philosophy.

8.1.5.3 Local Reset Required after System Shutdown

After a system shutdown caused by an alarm condition, the system allows a remote restart only after an operator has pressed a reset button located at the combustion system. The operator should perform a visual inspection of the system and verify the correction of the condition that caused the shutdown.

8.1.5.4 Watchdog Timer to Verify PLC Operation

If the PLC logic freezes, a separate timer fails to receive an expected reset pulse from the PLC and shuts down the system.

8.1.6 PIPE RACKS AND CONTROL PANELS

For most combustion control systems, two major assemblies make up the bulk of the system: the pipe rack and the control panel. A pipe rack is shown in [Figure 8.9](#). Sometimes called a skid, the pipe rack is a steel framework that has a number of pipes and associated components attached to it. Usually, most combustion process feeds, such as air, fuel, and waste, have their shutoff and control

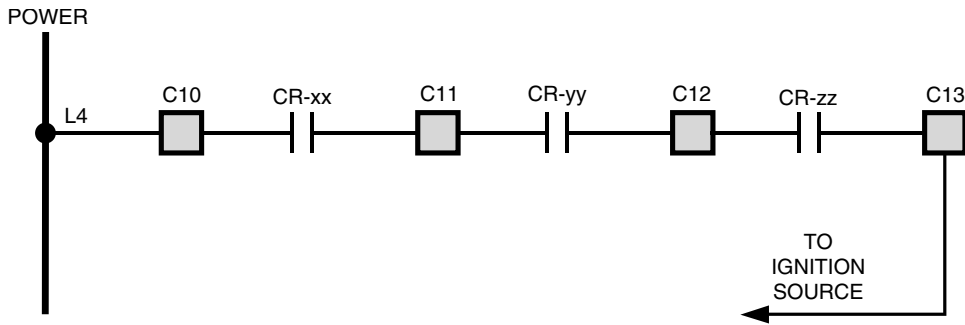


FIGURE 8.8 Shutdown string.

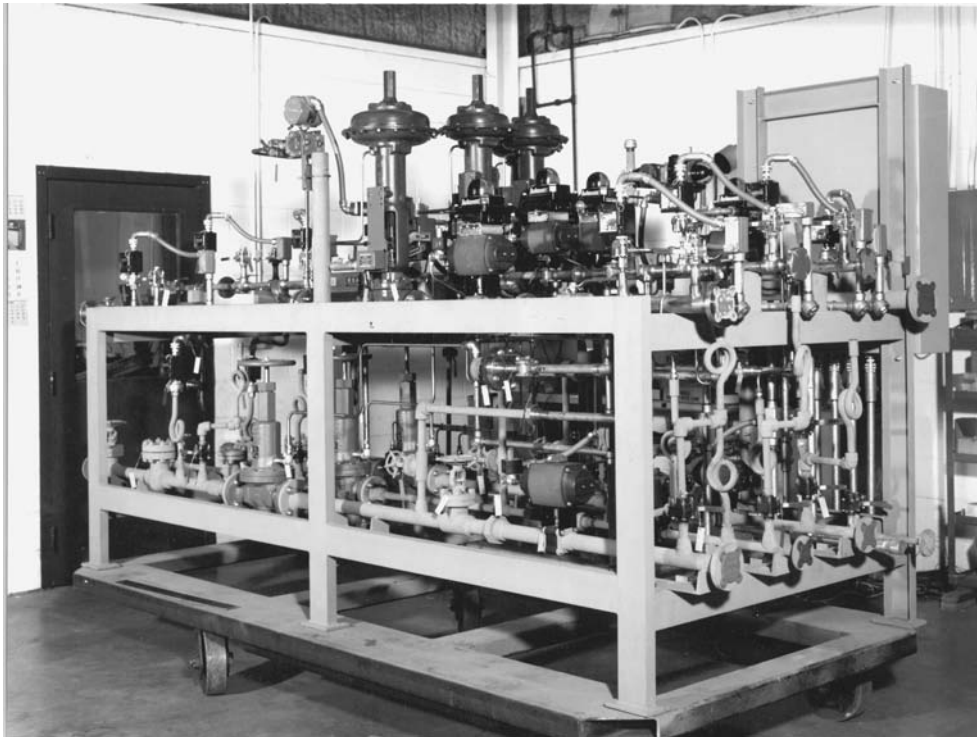


FIGURE 8.9 Typical pipe rack.

elements located on the pipe rack. This makes maintenance and troubleshooting more convenient and reduces the amount and complexity of wiring systems required to connect all of the components.

A typical control panel is shown in [Figure 8.10](#). [Figure 8.11](#) shows the inside of the control panel. The control panel is usually attached to the pipe rack. All of the devices on the pipe rack, as well as the field devices, are electrically connected to the control panel. The control system usually resides inside the control panel. In addition to the wiring, maintenance, and troubleshooting benefits mentioned above, another benefit to packaging the control system is far more important — that the people who designed and built the system can test and adjust it at the factory. When the control system arrives at the job site, installation consists mostly of hooking up utilities and the interconnecting piping, thus minimizing the amount of expensive on-site troubleshooting and tuning.



(a)



(b)

FIGURE 8.10 Control panels: (a) large and (b) small.

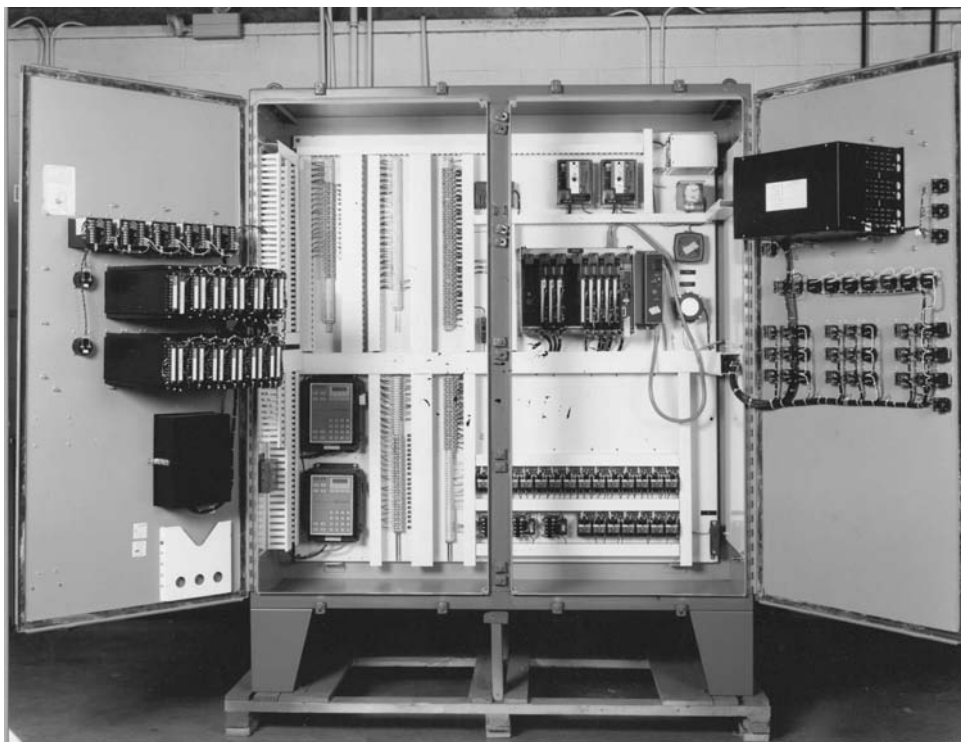


FIGURE 8.11 Inside the control panel.

8.2 PRIMARY MEASUREMENT

This section describes a number of different analog and discrete devices used to provide the interface between combustion systems and control systems. All of these devices are available from numerous suppliers around the world. There are vast differences in price, quality, and functionality among the different devices and suppliers.

8.2.1 DISCRETE DEVICES

8.2.1.1 Annunciators

An annunciator is a centralized alarm broadcasting and memory device. Typically, all the alarms in a control system are routed to the annunciator. When any alarm is triggered, the light associated with that alarm will flash and the annunciator horn will sound. If the annunciator is a “first-out” type, any subsequent alarms that occur will trigger their associated lights to come on solidly — rather than flashing, as the first alarm does. This is very useful for diagnosing system problems. When a safety shutdown occurs, other alarms are usually triggered while the system is shutting down. With a first-out capability, the original cause of the shutdown can be easily determined.

8.2.1.2 Pressure Switches

Pressure switches (see [Figure 8.12](#)) are sensors that attach directly to a process being measured. They can be used to detect absolute, gage, or differential pressure. The switches generally have a pressure element such as a diaphragm, tube, or bellows that expands or contracts against an adjustable spring as the pressure changes. The element attaches to one or more sets of contacts



(a)



(b)

FIGURE 8.12 Pressure switch.

that open or close upon reaching the setpoint. The devices are used in a number of ways, but in combustion systems they are usually used to test for high and low fuel gas pressure. They are normally set so the contacts are open when in the alarm condition.

8.2.1.3 Position Switches

Also called limit switches, these sensors attach to or are built into valves, insertable igniters, and other devices. Position switches usually employ a mechanical linkage, but proximity sensors are also quite common. They are adjustable, and can tell the control system if a valve is open, closed, or in some defined intermediate position. Position switches are not usually used for alarms. In combustion systems, they are generally used to check valve positions during purges and burner lightoff sequences. Position switches are often used with integrated beacons and other visual devices. They are normally installed so that their contacts are closed only when the valve is in the desired safety position.

8.2.1.4 Temperature Switches

Temperature switches are usually attached to auxiliary equipment such as tanks or flame arresters. These sensors generally do not have the range to test for combustion system temperatures, so those applications use other devices. The switches usually use a bimetallic element, where the differential expansion of two different metals generates physical movement. The movement opens or closes one or more sets of contacts. The failure mode of temperature switches is not always predictable. Generally, installation requires open contacts when the switch is in the alarm condition.

8.2.1.5 Flow Switches

Flow switches are sensors that generally insert into the pipe or duct in which flow is measured. Because of the lack of a quantitative readout and the improved reliability of analog transmitters in this service, these devices are becoming less common. Their failure mode is not always predictable. Usual installation requires open contacts when the switch is in the alarm condition.

8.2.1.6 Run Indicators

A run indication sensor shows whether a pump or fan is running. The sensor is especially important when outlet pressure indication of the device may not be definitive. It is usually possible to order a motor starter with a built-in set of signal contacts that close when the starter motor contacts are closed. However, that does not always ensure that the pump is running and pumping fluid. A magnetic shaft encoder rotates a magnetic slug past a pickup sensor every revolution and provides positive indication of shaft revolution, but that too does not always ensure that the pump is pumping fluid. It is usually preferable to have a pressure or flow indicator that shows that the system is functioning normally and moving fluid.

8.2.1.7 Flame Scanners

Flame scanners are crucial to the safe operation of a combustion system. If the flame is out, the fuel flow into the combustion enclosure is stopped and the area is purged before a re-light can be attempted. Flame scanners come in two main varieties: infrared and ultraviolet. The name tells which section of the electromagnetic spectrum it is designed to see. Generally, ultraviolet scanners are preferred because they are more sensitive and quicker to respond. The detector is a gas-filled tube that scintillates in the presence of flame and gives off bursts of current, called an avalanche, several hundred times per second as long as the flame continues. When the flame stops, the current stops. There is a 2- to 4-second delay, to minimize spurious shutdowns, and then the contacts open

to designate the alarm condition. Most systems have two flame scanners. To achieve system shutdown, both scanners must fail. Use of infrared scanners is desirable if there is a waste stream, such as sulfur, which absorbs ultraviolet light and makes operation of ultraviolet scanners unreliable. Self-checking scanners are usually used. They have output contacts that open on either loss of flame or failure of the self-check. Usually, the contacts are part of an amplifier/relay unit located in the control panel, but some newer systems have everything located in the scanner housing, which mounts on the burner endplate. One limitation with flame scanners is the possibility of the power wire to the scanner inducing false flame indications in the signal wire from the scanner. If there are separate wires for scanner power and scanner signal, they must run in separate conduit or shielding to prevent false signals caused by induction.

8.2.1.8 Solenoid Valves

Solenoid valves are turned on or off by the presence or absence of voltage from the control system. A solenoid valve has a relay coil that links mechanically to a valve disc mechanism. Energizing the solenoid causes the linkage to push against a spring to reposition the valve disc. De-energizing the solenoid allows the spring to force the valve to the failure position. The most common types of solenoid valves are two-way and three-way valves. Two-way valves have two positions; they allow flow or they do not. They are often used to turn pilot gas on and off. Three-way solenoid valves have three ports but still only two positions. If ports are labeled A, B, and C, energizing the valve may allow flow between ports A and B, while de-energizing the valve may allow flow between ports A and C. It is very important to carefully select, install, and test three-way solenoid valves. Three-way solenoid valves typically attach to control valves and safety shutoff valves (SSOVs). In the case of control valves, when the solenoid valve is energized, the control valve is enabled for normal use. When the solenoid valve is de-energized, the instrument air is dumped from the control valve actuator diaphragm, causing the control valve to go to its spring-loaded failure position. For safety shutoff valve (SSOV) service, the solenoid valve is hooked up so that when energized, instrument air is allowed to reposition the SSOV actuator away from its spring-loaded failure position. When the solenoid valve is de-energized, the air is dumped from the SSOV actuator, causing the control valve to go to its spring-loaded failure position. The failure modes of the solenoid valve, control valve, and SSOV are coordinated to maximize system safety no matter what component fails.

8.2.1.9 Ignition Transformers

Ignition transformers supply the high voltage necessary to generate the spark used to ignite the pilot flame during system lightoff. The type of transformer usually used converts standard AC power to a continuous 6000 VDC. This voltage then continuously jumps the spark gap at the igniter, which is located at the head of the pilot burner. High-energy igniters provide a more intense spark. A high-energy igniter is similar to the transformer mentioned above except that capacitors are included to store up energy and release it in spurts, resulting in a more intense spark. Both types of transformers are usually located close to the burner in a separate enclosure and hooked to the igniter using coaxial cable similar to the sparkplug wire used in cars.

8.2.2 ANALOG DEVICES

8.2.2.1 Control Valves

Control valves are among the most complex and expensive components in any combustion control system. Numerous extensive books document the nearly infinite variety of valves. Misapplication or misuse of valves compromises system efficiency and safety. Controls engineers cannot simply pick control valves from a catalog because they are the right size for the line where they will be used. Control valves must be engineered for their specific application. A typical pneumatic control valve is shown in [Figure 8.13](#).

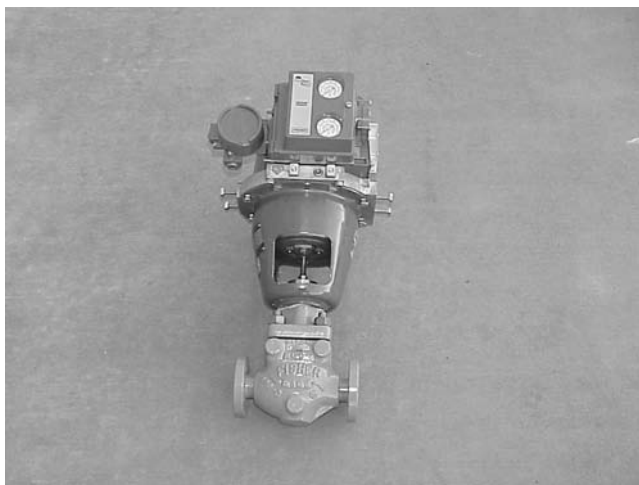


FIGURE 8.13 Pneumatic control valve.

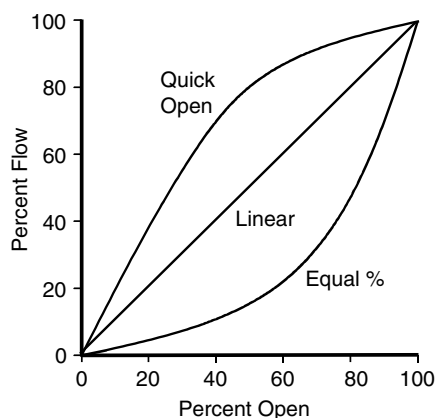


FIGURE 8.14 Control valve characteristics.

As shown in Figure 8.14, the type of service and control desired determines the selection of different flow characteristics and valve sizes. Controls engineers use a series of calculations to help with this selection process. A typical control valve consists of several components that are mated together before installation in the piping system:

8.2.2.1.1 Control Valve Body

The control valve body can be a globe valve, a butterfly valve, or any other type of adjustable control valve. Usually, special globe valves of the equal percent type are used for fuel gas control service or liquid service. Control of combustion air and waste gas flows generally require the use of butterfly valves — often the quick-opening type. Because the combustion air or waste line usually has a large diameter, and the cost of globe valves quickly becomes astronomical after the line size exceeds 3 or 4 inches, butterfly valves are usually the most economical choice. In Chapter 8.3, a discussion of parallel positioning describes how controls engineers use a globe valve and a butterfly valve to work smoothly together for system control.

8.2.2.1.2 Actuator

The actuator supplies the mechanical force to position the valve for the desired flow rate. For control applications, a diaphragm actuator is preferred because, compared to a piston-type actuator,

it has a relatively large pressure-sensitive area and a relatively small frictional area where the stem is touching the packing. This ensures smooth operation, precision, and good repeatability. Proper selection of the actuator must take into account valve size, air pressure, desired failure mode, process pressure, and other factors. Actuators are usually spring-loaded and single-acting, with control air used on one side of the diaphragm and the spring on the other. The air pressure forces the actuator to move against the spring. If air pressure is lost, the valve fails to the spring position thus, the actuator is chosen carefully to fail to a safe position (i.e., closed for fuel valves, open for combustion air valves).

8.2.2.1.3 Current-to-Pressure Transducer

The current-to-pressure transducer, usually called the I/P converter, takes the 24 VDC (4 to 20 milliamps) signal from the controller and converts it into a pneumatic signal. The signal causes the diaphragm of the actuator to move to properly position the control valve.

8.2.2.1.4 Positioner

The positioner is a mechanical feedback device that senses the actual position of the valve as well as the desired position of the valve. It makes small adjustments to the pneumatic output to the actuator to ensure that the desired and the actual position are the same. Current conventional wisdom states that positioners should be used only on “slow” systems and not on “fast” systems, where they can actually degrade performance. There is not a defined border between “fast” and “slow,” but virtually all combustion control applications are considered “slow,” so positioners are almost always used in these systems.

8.2.2.1.5 Three-Way Solenoid Valve

When energized, the three-way solenoid valve admits air to the actuator. When de-energized, it dumps the air from the actuator. Because single-acting actuators are generally used, the spring in the actuator forces the valve either fully open or fully closed, depending on the engineer’s choice of failure modes when specifying the valve. Obviously, a control valve that supplies fuel gas to a combustion system should fail closed, while the control valve that supplies combustion air to the same system should fail open. In an application in which the failure mode of the valve is irrelevant, and there are some, solenoid valves are not used.

8.2.2.1.6 Mechanical Stops

Mechanical stops are used to limit how far open or shut a control valve can travel. If it is vital that no more than a certain amount of fluid ever enters a downstream system, an “up” stop is set. If it is necessary to ensure a certain minimum flow, for cooling purposes for example, a “down” stop is set. In the case of a fuel supply control valve, the “down” stop is set so that during system lightoff, an amount of fuel ideal for smooth and reliable burner lighting is supplied. After a defined settling interval, usually 10 seconds, the three-way solenoid valve is energized and normal control valve operation is enabled.

8.2.2.2 Thermocouples

Whenever two dissimilar metals come into contact, current flows between the metals and the magnitude of that current flow and the voltage driving it, vary with temperature. This phenomenon is called the Seebeck effect. If both of the metals are carefully chosen and are of certain known alloy compositions, the voltage will vary in a nearly linear manner with temperature over some known temperature range. Because the temperature and voltage ranges vary depending on the materials employed, engineers use different types of thermocouples for different situations. In combustion applications, the “K” type thermocouple (0 to 2400°F or –18 to 1300°C) is usually used. When connecting a thermocouple (see [Figure 8.15](#)) to a transmitter, the transmitter should



FIGURE 8.15 Thermocouple.



FIGURE 8.16 Thermowell.

be set up for the type of thermocouple employed. Installing thermocouples in a protective sheath known as a thermowell (see Figure 8.16) prevents the sensing element from suffering the corrosive or erosive effects of the process being measured. However, a thermowell also slows the response of the instrument to changing temperature and should be used with care.

8.2.2.3 Velocity Thermocouples

Also known as suction pyrometers, the design of velocity thermocouples attempts to minimize the inaccuracies in temperature measurement caused by radiant heat. Inside a combustor, the thermocouple measures the gas temperature. However, the large amount of heat radiated from the hot surroundings significantly affects the measurement. A velocity thermocouple (see Figure 8.17) shields the thermocouple from radiant heat by placing it in one or more concentric hollow pipes. Hot gas is induced to flow across the thermocouple, producing a gas temperature reading without a radiant component.

8.2.2.4 Resistance Temperature Detectors (RTDs)

Resistance of any conductor increases with temperature. For a specific material of known resistance, it is possible to infer the temperature. Similar to the thermocouples described above, the linearity of the result depends on the materials chosen for the detector and their alloy composition. Engineers sometimes use RTDs instead of thermocouples when higher precision is desired. Platinum is a

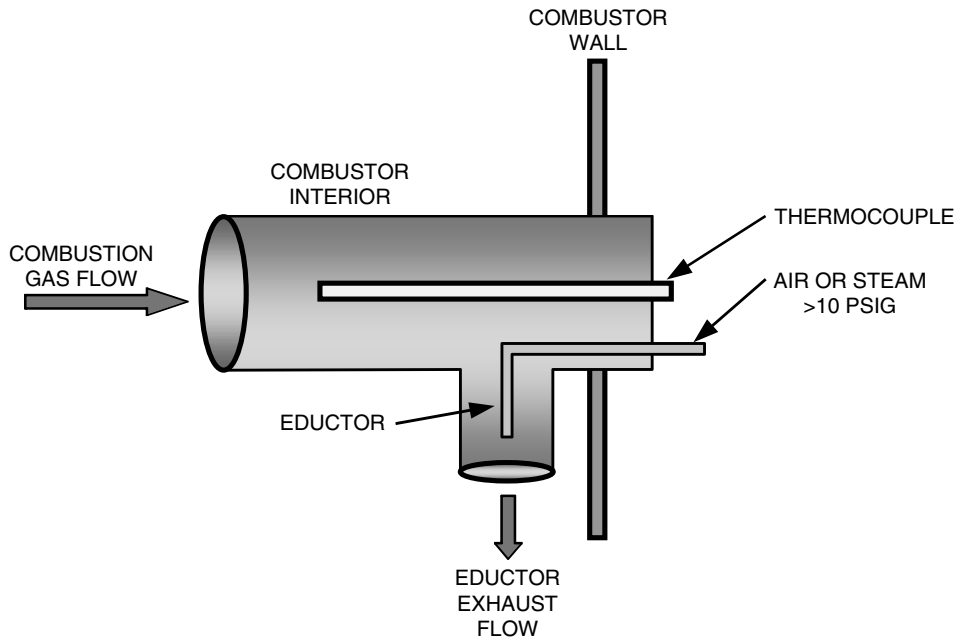


FIGURE 8.17 Velocity thermocouple.

popular material for RTDs because it has good linearity over a wide temperature range. Like thermocouples, installation of RTDs in thermowells is common.

8.2.2.5 Pressure Transmitters

A pressure transmitter (see [Figure 8.18](#)) is usually used to provide an analog pressure signal. These devices use a diaphragm coupled to a variable resistance, which modifies the 24 VDC loop current (4 to 20 milliamps) in proportion to the range in which it is calibrated. In recent years, these devices have become enormously more accurate and sophisticated, with onboard intelligence and self-calibration capabilities. They are available in a wide variety of configurations and materials and can be used in almost any service. It is possible to check and reconfigure these “smart” pressure transmitters remotely with the use of a handheld communicator.

8.2.2.6 Flow Meters

There are many different types of flow meters and many reasons to use one or another for a given application. The following is a list of several of the more common types of flow meters, how they work, and where they are used.

8.2.2.6.1 Vortex Shedder Flow Meter

A vortex shedder places a bar in the path of the fluid. As the fluid goes by, vortexes (whirlpools) form and break off constantly. An observation of the water swirling on the downstream side of bridge pilings in a moving stream reveals this effect. Each time a vortex breaks away from the bar, it causes a small vibration in the bar. The frequency of the vibration is proportional to the flow. Vortex shedders have a wide range, are highly accurate, reasonably priced, highly reliable, and useful in liquid, steam, or gas service.



FIGURE 8.18 Pressure transmitter (left) and pressure gauge (right).

8.2.2.6.2 Magnetic Flow Meter

A magnetic field, a current carrying conductor, and relative motion between the two creates an electrical generator. In the case of a magnetic flow meter, the meter generates the magnetic field and the flowing liquid supplies the motion and the conductor. The voltage produced is proportional to the flow. These meters are highly accurate, very reliable, have a wide range, but are somewhat expensive. They are useful with highly corrosive or even gummy fluids as long as the fluids are conductive. Only liquid flow is measured.

8.2.2.6.3 Orifice Flow Meter

Historically, almost all flows were measured using this method and it is still quite popular. Placing the orifice in the fluid flow causes a pressure drop across the orifice. A pressure transmitter mounted across the orifice calculates the flow from the amount of the pressure drop. Orifice meters are very accurate but have a narrow range. They are reasonably priced, highly reliable, and are useful in liquid, steam, or gas service.

8.2.2.6.4 Coriolis Flow Meter

The Coriolis flow meter is easily the most complex type of meter to understand. The fluid runs through a U-shaped tube that is being vibrated by an attached transducer. The flow of the fluid will cause the tube to try to twist because of the Coriolis force. The magnitude of the twisting force is proportional to flow. These meters are highly accurate and have a wide range. They are generally more expensive than some other types.

8.2.2.6.5 Ultrasonic Flow Meter

When waves travel in a medium (fluid), their frequency shifts if the medium is in motion relative to the wave source. The magnitude of the shift, called the Doppler effect, is proportional to the relative velocity of the source and the medium. The ultrasonic meter generates ultrasonic sound

waves, sends them diagonally across the pipe, and computes the amount of frequency shift. These meters are reasonably accurate, have a fairly wide range, are reasonably priced, and are highly reliable. Ultrasonic meters work best when there are bubbles or particulates in the fluid.

8.2.2.6.6 Turbine Flow Meters

A turbine meter is a wheel that is spun by the flow of fluid past the blades. A magnetic pickup senses the speed of the rotation, which is proportional to the flow. These meters can be very accurate but have a fairly narrow range. They must be very carefully selected and sized for specific applications. They are reasonably priced and fairly reliable. They are used in liquid, steam, or gas service.

8.2.2.6.7 Positive Displacement Flow Meters

Positive displacement flow meters generally consist of a set of meshed gears or lobes that are closely machined and matched to each other. When fluid is forced through the gears, a fixed amount of the fluid is allowed past for each revolution. Counting the revolutions reveals the exact amount of flow. These meters are extremely accurate and have a wide range. Because there are moving parts, the meters must be maintained or they can break down or jam. They also cause a large pressure drop, which can be important for certain applications.

8.2.2.7 Analytical Instruments

There are many different types of analytical instruments used for very specific applications. Unlike the sensors described previously, these devices are usually systems. They are a combination of several different sensors linked together by a processor of some sort that calculates the quantity in question. Unlike a pressure transmitter, most analytical instruments sample and chemically test the process in question. Because the process takes time, the engineer, when designing the system, must plan for a delayed response from the analytical instrument. A detailed discussion of the design and operation of analytical instruments is beyond the scope of this book. Below is a list of several of the more common types and their uses.

8.2.2.7.1 pH Analyzer

Almost any combustion system occasionally requires the scrubbing of effluent or other similar processes. pH monitoring is needed to assure that the water going into the scrubber is the correct pH to neutralize the acidity or alkalinity of the effluent. The analyzer sends information to a controller that is responsible for opening or closing valves that add alkaline chemicals to the water to raise pH.

8.2.2.7.2 Conductivity Analyzer

Conductivity analyzers are often used in conjunction with pH analyzers. Where the pH analyzer system functions to raise pH, the output from the conductivity analyzer is usually sent to a controller responsible for opening or closing valves that dilute salt concentration in the water.

8.2.2.7.3 O₂ Analyzer

O₂ or combustibles analyzers monitor the amount of oxygen or combustibles in the exhaust of a combustion system. The analyzer sends data back to the control system that uses it to tightly control the amount of combustion air coming into the system. This has the dual result of making the system more efficient and reducing the amount of pollutants that result from the combustion process. Different models have varying methodologies, accuracies, and sample times, but there are two major types: (1) *in situ* analyzers carry out the analysis at the probe; and (2) extractive analyzers remove the sample from the process and cool it before analysis.

8.2.2.7.4 Nitrogen Oxides (NO_x) Analyzer

Nitrogen oxides (NO, NO₂, etc.; see Chapter 6) are one of the main components of smog and the result of high-temperature combustion. Noxidizers are combustion systems that use an extended low-temperature combustion process designed to minimize the formation of nitrous oxide compounds. Noxidizers use NO_x analyzers. To properly control the process, the NO_x analyzer output goes to a controller that controls airflow into the system, minimizing NO_x formation.

8.2.2.7.5 Carbon Monoxide (CO) Analyzer

CO is also an undesirable pollutant and is a product of incomplete combustion. The output of the CO analyzer is often used in the analysis of system efficiency or to control airflow to the combustion system.

8.3 CONTROL SCHEMES

Other chapters of this book present the combustion process and the definition of the terms used to describe it. This section describes methods used to control the process. Generally, controlling the process means controlling the flow of fuels and combustion air.

8.3.1 PARALLEL POSITIONING

Designers use analog control schemes to modulate valve position and control fan and pump speeds to achieve the required mix of fuel and oxygen in a combustion system. Simple systems often use parallel positioning of fuel and air valves from a single analog signal.

8.3.1.1 Mechanical Linkage

A common method of parallel positioning is to mechanically link the fuel and air valves to a single actuator. Adjustment of a cam located on the fuel valve supplies the proper amount of fuel throughout the air valve operating range. Figure 8.19 shows the arrangement.

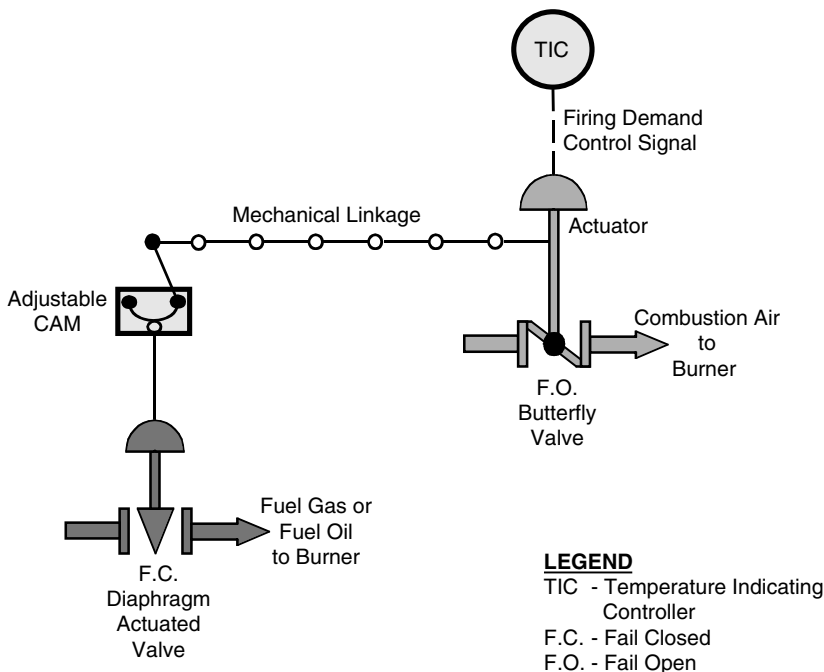


FIGURE 8.19 Mechanically linked parallel positioning.

In the figure, the temperature indicating controller (TIC) operates an actuator attached to the air valve. A mechanical linkage and an adjustable cam operates the fuel valve in parallel with the air valve. Springs or weights attached to the air valve shaft force a full open position of the air valve if the mechanical connection to the air valve fails. The system uses a fail-closed actuator to ensure that a low fire failure mode results from loss of signal or loss of actuator power.

Mechanical linkage is simple in operation but requires considerable adjustment at start-up to obtain the correct fuel/air ratio over the entire operating range. Predictable flow rates of fuel and air throughout valve position require a fixed supply pressure to the valves and constant load geometry downstream of the valves. Analytical feedback to control fuel gas or combustion air supply pressure can make dynamic corrections for fuel variations, temperature changes, and system errors. Dynamic adjustments should be small trimming adjustments rather than primary control parameters.

8.3.1.2 Electronically Linked

Electronically linked fuel and combustion air valves for parallel positioning have many advantages over mechanically linked valves. Figure 8.20 illustrates the scheme.

In the example, a TIC generates a firing rate demand. The controller applies an output of 4 to 20 milliamps to the fuel valve and to a characterizer in the air valve circuit. Electronic shaping of the characterizer output positions the air valve for correct airflow. Predictable and repeatable valve positions require the use of positioners at each valve. Without positioners, valve hysteresis causes large errors in flow rate.

Signal inversion ($1 - \text{the value being measured}$) is sometimes integral to the characterizer. Signal inversion is necessary because the air valve fails open and the fuel valve fails closed. Safety concerns dictate failure modes. Fuel should always fail to minimum and air should fail to maximum.

Electronically linked parallel positioning works well if properly designed. Good design requires valves with known coefficients throughout valve position and use of high-performance positioners. Supply pressure of fuel and air to each valve must be constant or repeatable. System load

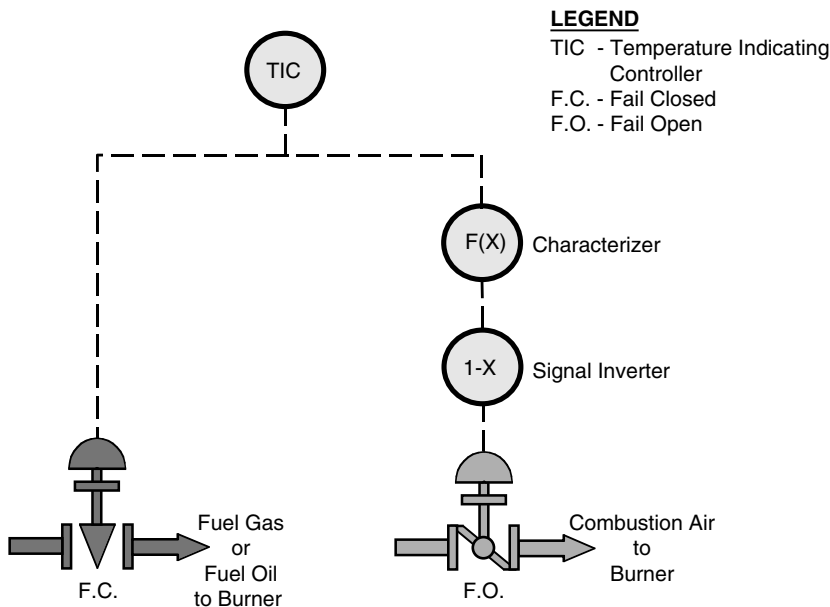


FIGURE 8.20 Electronically linked parallel positioning.

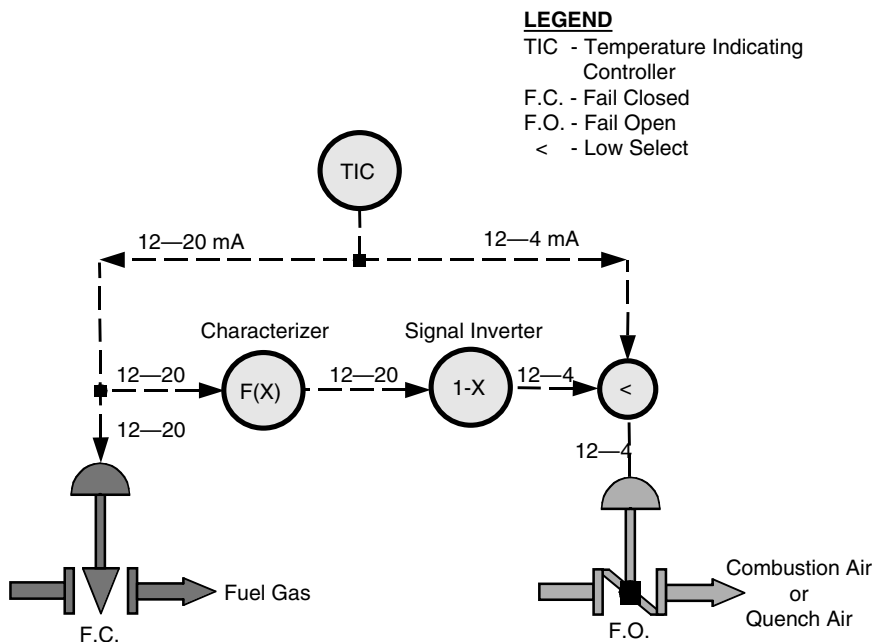


FIGURE 8.21 A variation of parallel positioning.

downstream of the valves must be of fixed geometry. Chapter 8.3.1.3 shows an example of how to calculate and configure a characterizer for the air valve.

Figure 8.21 shows a variation of parallel positioning that permits use of the combustion air valve for the multiple purposes of (1) supplying combustion air during normal operation, (2) supplying quench air when burning exothermic waste, or (3) using another heat source requiring quench air. When showing a range of milliamp signals, the first value is the minimum valve position and the second value is the maximum valve position. This convention aids system analysis and is especially useful for complex systems. The TIC output is split-ranged. The top half, 12 to 20 mA, is used for firing fuel gas. When burning exothermic waste requiring quench air, the temperature controller output decreases, providing low fire fuel at 12 mA, then quench air below 12 mA.

The TIC output is actually 4 to 20 mA. The description of the action of the receivers uses the term “split-ranged.” For example, the TIC applies the entire 4- to 20-mA range to the fuel gas valve but the valve is configured to respond only to the partial range of 12 to 20 mA.

8.3.1.3 Characterizer Calculations

Parallel positioning of a globe-type fuel gas valve and a butterfly type combustion air valve requires characterizer calculations as described below. Figure 8.20 shows the control scheme.

Three general steps are required to define the characterizer:

Step 1: Calculate and graph fuel flow rate vs. control signal.

Step 2: Calculate and graph combustion air flow rate vs. control signal.

Step 3: Tabulate and graph air valve characterizer.

8.3.1.3.1 Step 1: Fuel Flow Rate vs. Control Signal

Predictable and repeatable calculations of fuel gas flow rate vs. control valve position require:

Pressure regulator upstream of control valve to provide constant inlet pressure. Varying inlet pressure can be used only if it is repeatable with flow rate.

1. Constant temperature and composition of fuel gas
2. High-quality positioner on the control valve to eliminate hysteresis and to ensure that valve percent open equals percent control signal
3. Knowledge of valve coefficient vs. valve position throughout the control valve range, including the pressure recovery factor
4. Fixed and known pressure drop geometry downstream of the control valve
5. Subsonic regime throughout the flow range

Results of Step 1 are shown in Figure 8.22 for a typical fuel gas valve with equal percent trim. Low fire position of the valve is approximately 25% open for many applications. Maximum firing rate occurs between 70 and 80% open, resulting in a near linear function of flow rate vs. valve position throughout the firing range. The linear function is not necessary for configuring a combustion air characterizer but is useful for the application of a dynamic fuel/air ratio correction to the control circuit.

Use of a positioner on the fuel gas valve establishes equality between percent control signal and percent valve opening. Columns 1 and 2 of Table 8.1 show gas valve data.

8.3.1.3.2 Step 2: Air Flow Rate vs. Air Valve Position

Calculation of air flow rate vs. valve position that is predictable and repeatable requires:

1. Known and repeatable valve inlet pressure vs. flow rate
2. Near-constant temperature
3. High-quality positioner on the valve

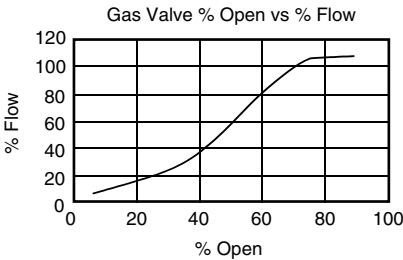


FIGURE 8.22 Fuel flow rate vs. control signal.

TABLE 8.1
Gas Valve Data

Control Signal TIC Output%	Gas Valve % Open	Fuel Gas Flow Rate%
10	10	10
20	20	16
30	30	25
40	40	39
50	50	58
60	60	83
70	70	100
80	80	107
90	90	109
100	100	110

- 4. Knowledge of valve coefficient and pressure recovery factor of the air valve at all valve positions
- 5. Fixed and known flow (pressure drop) geometry downstream of the control valve

Figure 8.23 shows the results of a typical butterfly type valve calculation for Step 2. The low fire mechanical stop is normally set at approximately 20% open.

8.3.1.3.3 Step 3: Air Valve Characterizer

Table 8.2 combines data from Figure 8.23 with data from Table 8.1. Air valve graph data are tabulated in columns 3 and 4. Figure 8.24 is a plot of the data from columns 1 and 4 and represents the required shape of the air valve characterizer. The TIC output signal is the characterizer input and is plotted on the x-axis. The characterizer output is the percent open of the air valve and is shown on the y-axis. Many characterizer instruments are available that will model a curved response using straight line segments. This characterizer is sufficiently defined using three segments.

TABLE 8.2
Data for Characterizer

Control Signal TIC Output%	Fuel Gas Flow Rate%	Combustion Air Flow Rate%	Air Valve% Open
10	10	10	5
20	16	16	13
30	25	25	22
40	39	39	29
50	58	58	33
60	83	83	41
70	100	100	46
80	107	107	48
90	109	109	49
100	110	110	50

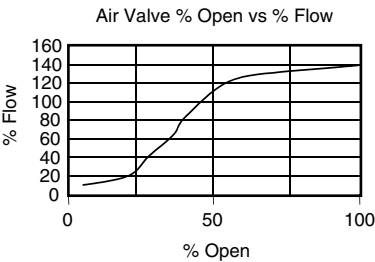


FIGURE 8.23 Typical butterfly type valve calculation.

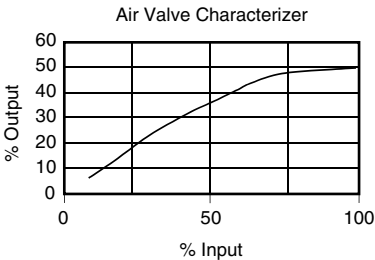


FIGURE 8.24 The required shape of the air valve characterizer.

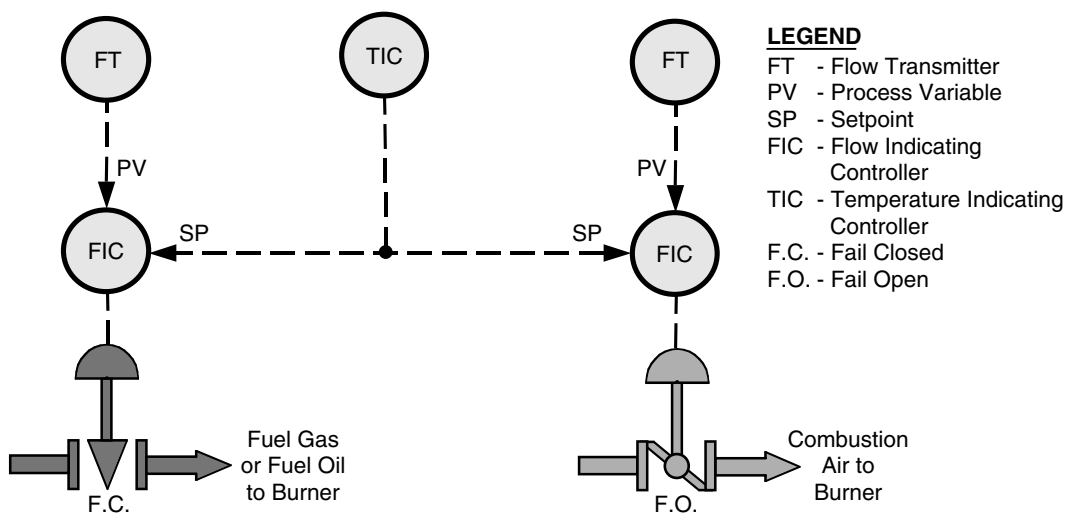


FIGURE 8.25 Fully metered control.

8.3.2 FULLY METERED CROSS LIMITING

Development of a fully metered control scheme for modulating fuel and air to a burner begins with the parallel positioning electronically linked scheme as previously shown in [Figure 8.20](#). [Figure 8.25](#) adds flow meters and flow controllers.

Flow meters are linear with flow rate. Meter output signal scaling provides the firing rate and air/fuel ratio required for the application. The combustion air characterizer used for parallel positioning is not required because the transmitters are linear with flow rate.

In the illustration, temperature controller TIC output sets the firing rate by serving as the setpoint to each flow controller. Signal inversion, shown as $(1 - \text{parameter value})$ in the parallel positioning scheme, is not required. Instead, the controller output mode is configured to match the valve failure mode.

Controller output mode, reverse or direct acting, defines the change in output signal direction with respect to process variable changes. For example, if the controller output increases as the process variable increases, the controller mode is direct-acting. In combustion control schemes, fail-closed fuel valves require a reverse-acting flow controller, while fail-open combustion air valves require direct-acting flow controllers. From controller mode definitions, it is clear that the temperature controller TIC should be reverse-acting. That is, the TIC output should decrease, reducing the firing rate, in response to an increase in temperature, the process variable.

Addition of high and low signal selectors provides cross limiting of the fully metered control scheme as shown in [Figure 8.26](#). The low signal selector ($<$) compares demanded firing rate from the TIC to the actual combustion air flow rate and applies the lower of the two signals as setpoint to the fuel flow controller. The low signal selector ensures that the fuel setpoint cannot exceed the amount of air available for combustion.

The high signal selector compares the demanded firing rate from the TIC to the actual fuel flow rate and applies the higher of the two signals as the setpoint to the airflow controller. This ensures that the air setpoint is never lower than required for combustion of actual fuel flow rate.

Together, the high and low signal selectors ensure that unburned fuel does not occur in the combustion system. Unburned fuel accumulations can cause explosions. Cross limiting by the signal selectors causes air flow to lead fuel flow during load increases and air flow lags fuel flow during fuel decreases. This lead-lag action explains why the fully metered cross-limiting control system is often called “Lead-Lag” control. Whatever the name, the system performs the function of maintaining

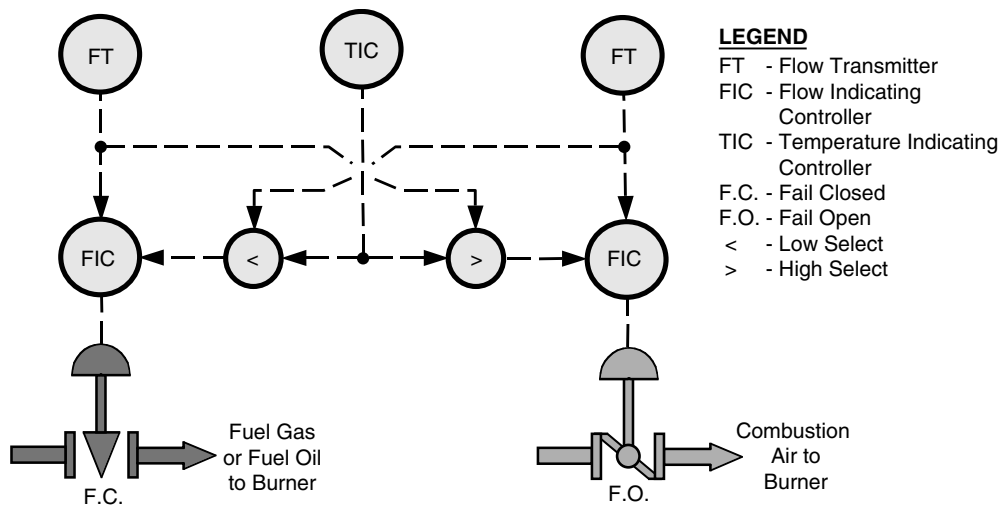


FIGURE 8.26 Fully metered with cross limiting.

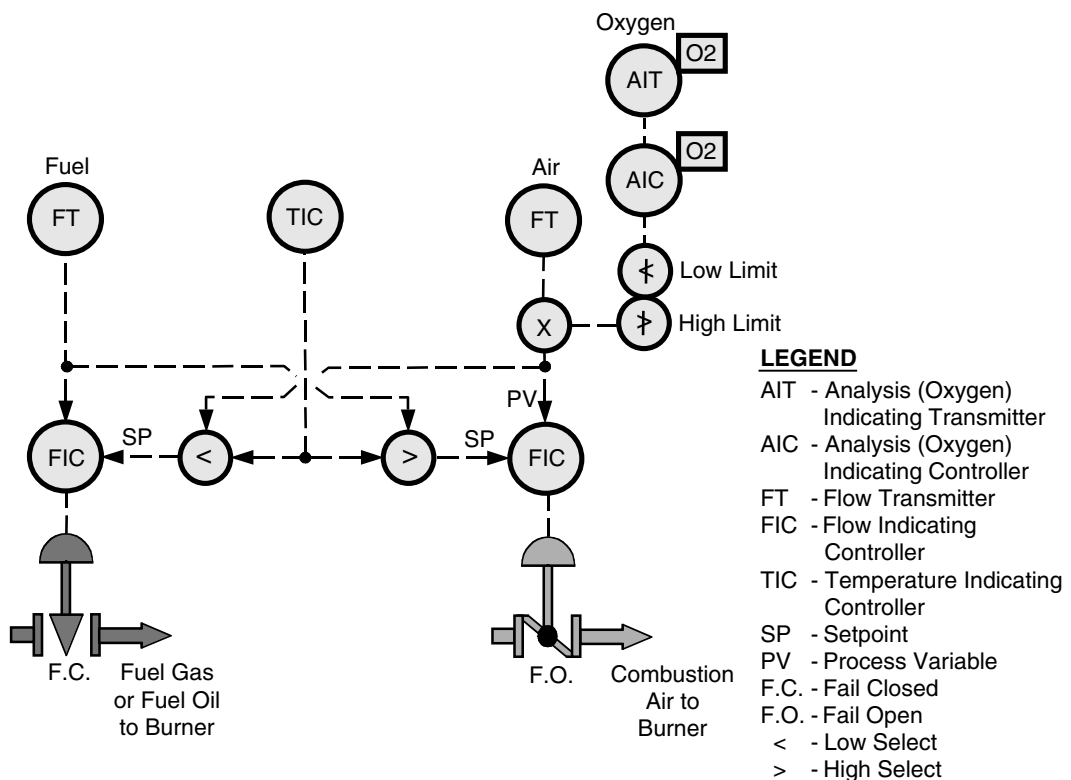


FIGURE 8.27 O₂ trim of air flow rate.

the desired air/fuel mixture during load changes. The system also provides fuel flow rate reduction in the event airflow is lost or decreased.

It is possible to trim the control scheme by measuring the flue gas oxygen content, as in Figure 8.27. For most systems, the oxygen signal should be used to “trim” and not be a primary control. Many oxygen analyzers are high maintenance and/or too slow in response to be used as

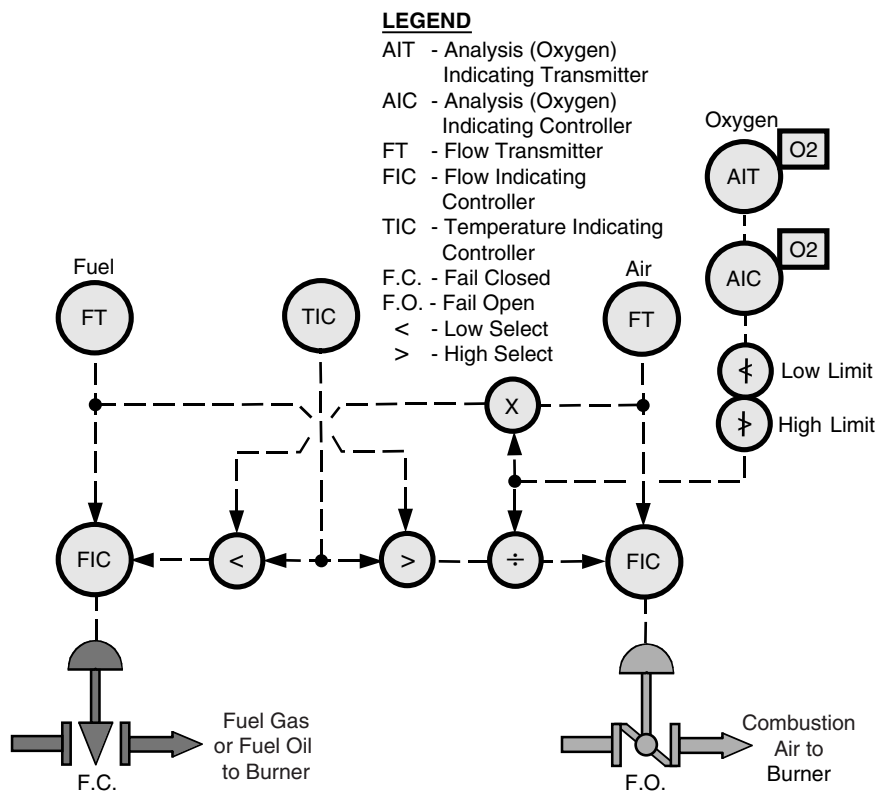


FIGURE 8.28 O₂ trim of air setpoint.

primary control in the combustion process. As shown, the oxygen controller is utilized for setpoint injection and provides tuning parameters to help process customization. High and low signal limiters restrict the oxygen controller output to a trimming function, normally 5 to 10% of the normal combustion air flow rate.

A multiplication function (X) in the combustion airflow transmitter signal makes the oxygen trim adjustment. The multiplier gives a fixed trim gain. Substituting a summing function for the multiplier would result in high trim gain at low flow rates and could produce a combustion air deficiency.

Oxygen trim can be applied to the combustion airflow controller setpoint rather than the flow transmitter signal. If this technique is used, the airflow signal to the low signal selector must retain trim modification. See [Figure 8.28](#) for the scheme.

Multiple fuels and oxygen sources are accommodated by the cross-limiting scheme as shown in [Figure 8.29](#). When multiple fuels are used, heating values must be normalized by adjusting flow transmitter spans or by addition of heating value multipliers. Similar methods are used to normalize oxygen content for multiple air sources.

8.4 CONTROLLERS

Controllers have historically been called analog controllers because the process and I/O signals are usually analog. Controller internal functions performed within a computer or microprocessor by algorithm are sometimes called digital controllers although the I/O largely remains analog. Some digital controllers communicate with other devices via digital communication, but for the most part, controllers connect other devices by analog signals. The analog signal is usually 4 to 20 milliamps, DC.

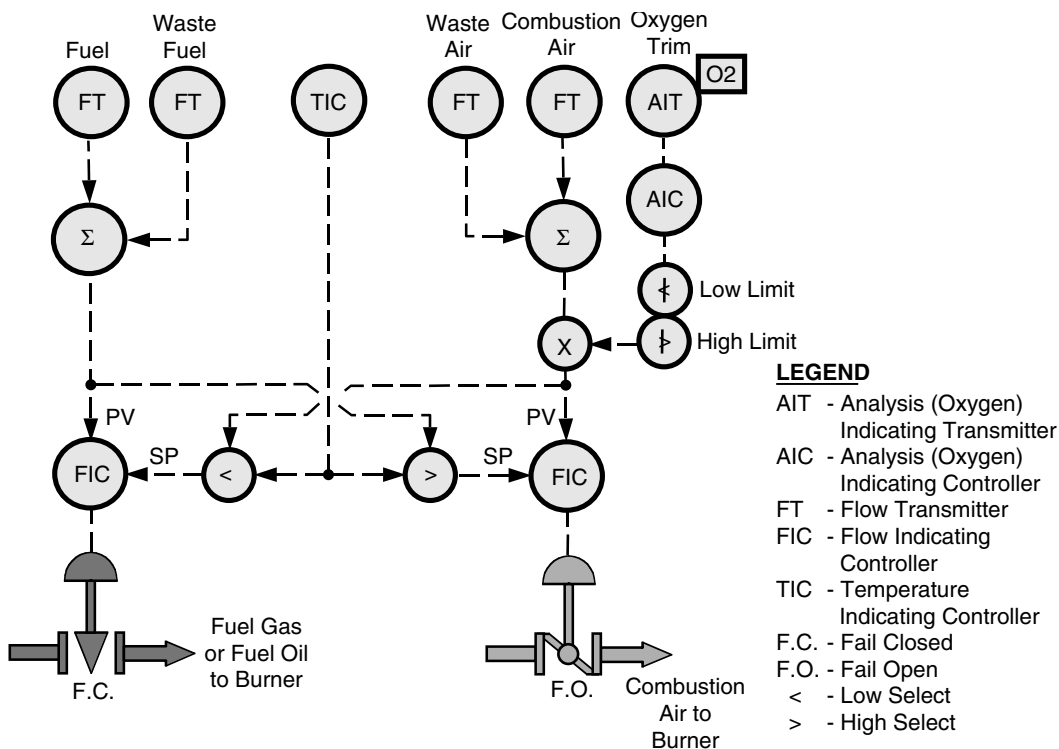


FIGURE 8.29 Multiple fuels and O₂ sources.

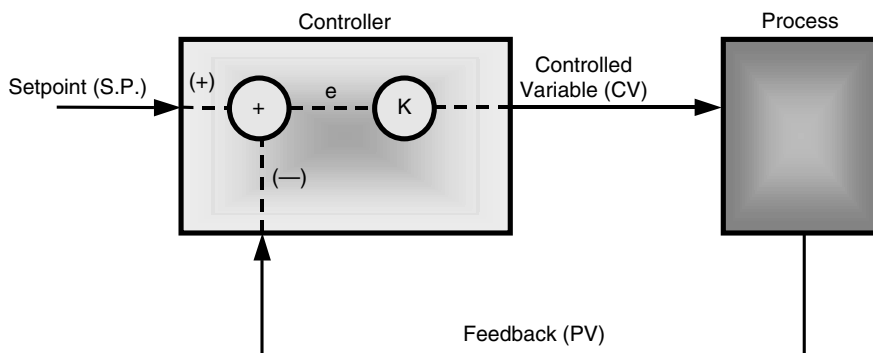


FIGURE 8.30 Controller.

In Figure 8.30, the setpoint is a signal representing the desired value of a process. If the process is flow rate, setpoint is the desired flow rate. Setpoint signals can be generated internally within the controller, called the local setpoint, or can be an external signal, called the remote setpoint.

Controller output, called the controlled variable (CV) or the manipulated variable (MV), connects to a final element in the process. In our example of flow control, the final element is probably a control valve. Feedback from the process, called the process variable (PV) in our example, could be the signal from a flow meter.

The CV is generated within the controller by subtracting the feedback (PV) from the setpoint (SP), generating an error signal “ e ,” which is multiplied by a gain “ K .” The product eK is the controller output (CV).

$$\text{Output (CV)} = (\text{SP} - \text{PV})(K) = eK \quad (8.1)$$

This simple controller is an example of the first controller built early in the 20th century and is called a proportional controller. The output is proportional to the error signal. The proportional factor is the gain K . Proportional controllers require an error (e) to produce an output. If the error is zero, controller output is zero. To obtain an output that produces the correct value of the process variable, the operator is required to adjust the setpoint higher than the desired process variable in order to create the requisite error signal. Reduction of error by increasing controller gain is limited by controller instability at high gain.

Offset is the term given to the difference between the setpoint and process variable. Correction of offset was the first improvement made to the original controller. Offset correction was accomplished by adding bias to the controller output.

$$\text{Output (CV)} = eK + \text{Bias} \quad (8.2)$$

Bias adjustment required operator manipulation of a knob or lever on the controller, which added bias until setpoint and process variables were equal. The operator considered the controller “reset” when equality occurred. Each setpoint change or process gain change required a “manual reset” of the controller. Figure 8.31 illustrates the proportional controller with manual reset.

Many operators prefer the term “proportional band” when describing controller gain. Proportional band is defined as:

$$\text{Proportional band (PB)} = \frac{100}{\text{Gain}} = \frac{100\%}{K} \quad (8.3)$$

Proportional band (PB) represents the percent change in the process variable (PV) required to change the controller output 100%. For example, a controller gain of 1 ($K = 1.0$) requires a PV change of 100% to obtain a 100% change in controller output. Proportional bands for combustion process variables are generally in the range of 1000% to 20% (Gain = 0.1 to 5.0). Flow controller gains are always less than unity. Temperature controller gains vary from 0.1 to 3.0, depending on the process gain. Pressure controllers generally have gains higher than those of flow or temperature controllers. Controller output becomes unstable (oscillatory) when gain is too high. When instability occurs, the controller operating mode must be changed from automatic to manual to stabilize the

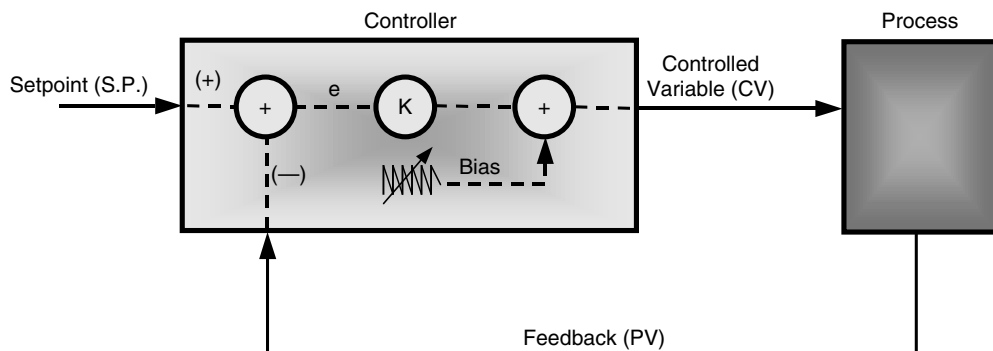


FIGURE 8.31 Analog controller with manual reset.

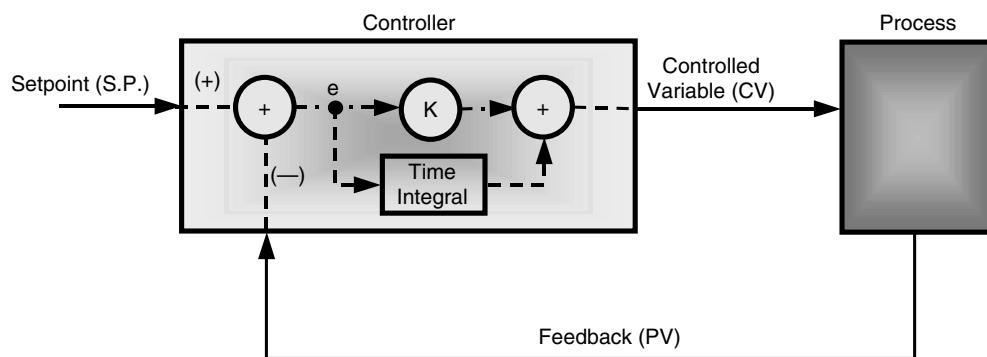


FIGURE 8.32 Analog controller with automatic reset.

process and prevent equipment damage. A reduction of controller gain must occur before a return to automatic mode.

Automatic reset was the next improvement to the process controller. This was a most welcome addition that eliminated the need for manual reset. Automatic reset is a time integral of the error signal, summed with the proportional gain signal, to produce the controller output. Integral gain (controller reset) is highest with large errors and continues until the error is reduced to zero. [Figure 8.32](#) illustrates automatic reset.

Automatic reset is the “I” component of a PID (three-mode) controller. P is proportional gain and D is derivative (rate) gain. I is expressed as repeats per minute (RPM), or as minutes per repeat (MPR), depending on the controller manufacturer’s choice of terms. Some controllers permit user selection of the term. Controller output is the same regardless of terminology, but the operator must know and apply proper tuning constants. For example, if tuning requires an I of 2 RPM, the operator must enter 0.5 MPR into the controller if MPR is the terminology in use. An integral gain of 0.5 minutes per repeat means that automatic reset equal to the proportional gain will be applied at the controller output each 30 seconds. Integral gain is a smooth continuous process that contributes phase lag to the system. Additional phase lag contributes to system instability (oscillation), which prohibits high values of integral gain.

Derivative gain is a function of how fast the process variable is changing. For slow-changing processes, derivative gain is of little use. Derivative gain is not used on flow control loops with head meters or on other loops with noisy process variable signals. High noise levels will drive derivative gain to instability. Derivative gain contributes phase lead that can sometimes be beneficial.

Controllers have many modes of operation. P, I, D, automatic, and manual modes have been discussed. Reverse or direct mode is another choice that must be configured to match the process. Reverse or direct describes the change in direction of controller output when the process variable changes. Reverse-acting means the controller output decreases if the process variable increases. An example illustrates how to select reverse or direct.

In our example of flow control, the process variable (flow rate) increases when the final element (control valve) opens. In addition, the flow meter output or process variable (PV) increases with increased flow rate. If the control valve fails closed and opens on increasing signal (increasing controller output), the controller mode must be reverse-acting. That is, if PV increases, the controller output must decrease to close the valve and restore the flow rate to the correct value. If the control valve fails open (closes on increasing signal), the controller mode must be direct-acting. This example illustrates the need to know if each element in a control loop is reverse- or direct-acting, including transmitters, isolators, transducers (such as I/Ps), positioners, and actuators. Proper selection and configuration of loop elements provide not only proper operation, but also proper failure mode. Reversal of any two elements within a loop will not affect loop response, but failure modes will change.

8.5 TUNING

Many modern controllers have automatic tuning routines built in. Tuning parameters calculated automatically require a loop upset to enable calculation. Parameters are normally de-tuned considerably from optimum because process gains are often nonlinear. Variable loop gain can also be a problem for manual tuning. A controller tuned at low flow rates or low temperature could become unstable at high flow rates or high temperatures. Control of most process loops benefit from addition of feed forward components that relieve the feedback controller of primary control. Operation improves if the feedback controller functions as set point injection and error trimming of the feedforward system.

Many processes controlled by a current proportional controller successfully use the tuning procedure below. The process must be upset to produce oscillations of the process variable. A graphic recorder should be used to determine when the oscillations are constant and to ascertain the time for one cycle (oscillation).

1. In manual mode, adjust the output to bring the process variable (PV) near the desired value.
2. Set the Rate time to 0 minutes and set the Reset time to the maximum value (50.00 minutes), or set repeats per minute to the minimum value to minimize reset action.
3. Increase gain (decrease proportional band PB) significantly. Try a factor of 10.
4. Adjust the local setpoint to equal PV and switch to automatic mode.
5. Increase the setpoint by 5 or 10% and observe PV response.
6. If the process variable oscillates, determine the time for one oscillation. If it does not oscillate, return to the original setpoint, increase the gain again by a factor of two, and repeat Step 5.
7. If the oscillation of Step 6 dampens before the cycle time is measured, increase the gain slightly and try again. If the oscillation amplitude becomes excessive, decrease the gain slightly and try again.
8. Record the current value of gain, and record the value for one completed oscillation of PV.
9. Calculate Gain, Reset, and Rate:
 - a. For PI (two-mode controller):
 $\text{Gain} = \text{Measured gain} \times 0.5$
 $\text{Reset Time} = \text{Measured time}/1.2 \text{ (MPR)}$
 - b. For PID (three-mode controller)
 $\text{Gain} = \text{Measured gain} \times 0.6$
 $\text{Reset Time} = \text{Measured time}/2.0 \text{ (MPR)}$
 $\text{Rate} = \text{Measured time}/8.0 \text{ (minutes)}$
10. Enter the values of Gain, Reset, and Rate into the controller.
11. Make additional trimming adjustments, if necessary, to fine-tune the controller.
12. To reduce overshoot: less gain, perhaps a longer rate time.
13. To increase overshoot or increase speed of response: more gain, perhaps shorter rate time.

The above method is known as a closed-loop method because the controller is dynamically affecting the process. Another method that can be used is an open-loop method in which the controller is taken out of automatic operation and placed in manual mode. A data logger should be utilized to record the process variable and the controller output. Care should be taken prior to using this method to ensure that the operator can maintain control of the process while the controller is in manual mode.

1. Place the controller in manual mode.
2. When the process is stable, make a step change in the controller output.

3. The information obtained from this step change includes apparent dead time and slope. The apparent dead time is the time from when the controller output step change is executed to when the process variable begins to react. The slope is the initial slope of the process variable once it begins to react. The slope is the change per minute of the process variable (expressed as a percentage of the transmitter span) divided by the step change (expressed as a percentage of the controller output span).
4. Calculate Gain, Reset, and Rate:
 - a. $\text{Gain} = 1/(\text{Rate} \times \text{Dead time})$, aggressive
 - b. $\text{Gain} = 1/(2 \times \text{Rate} \times \text{Dead time})$, conservative
 - c. $\text{Reset time} = 5 \times \text{Dead time}$
 - d. $\text{Rate} = \text{Dead time}/2$
5. Enter the Gain, Reset, and Rate values into the controller and place it into automatic mode.
6. Make small setpoint changes and observe the response.
7. Make additional trimming adjustments, if necessary, to fine-tune the controller.
8. To reduce overshoot: less gain, perhaps a longer rate time.
9. To increase overshoot or increase speed of response: more gain, perhaps shorter rate time.

REFERENCES

1. Joel O. Hougén, *Measurement and Control Applications for Practicing Engineers*, CAHNERS Books, Barnes & Noble Series for Professional Development, 1972.
2. *Combustion Control*, 9ATM1, Fisher Controls, Marshalltown, IA, 1976.
3. Boiler Control, Application Data Sheet 3028, Rosemount Inc., Minneapolis, MN, 1980.
4. Instrumentation Symbols and Identification, ANSI/ISA – S5.1 – 1984, Instrument Society of America, Research Triangle Park, NC, 1984.
5. Temperature Measurement Thermocouples, ANSI – MC96.1 – 1984, Instrument Society of America, Research Triangle Park, NC, 1984.
6. F.G. Shinskey, *Process Control Systems, Application, Design, and Tuning*, 3rd edition, McGraw-Hill, New York, 1988.
7. Michael J. Gilbert Polonyi, PID controller tuning using standard form optimization, *Control Engineering Magazine*, March, 1989, 102–106.
8. David W. St.Clair, Improving control loop performance, *Control Engineering Magazine*, Oct., 141–143, 1991.
9. Controller Tuning, Section 11, UDC 3300 Digital Controller Product Manual, Honeywell Industrial Automation, Fort Washington, PA, 1992.
10. Fred Y. Thomasson, Five steps to better PID control, *CONTROL Magazine*, April, 65–67, 1995.
11. API Recommended Practice 556: Instrumentation and Control Systems for Fired Heaters and Steam Generators, First Edition, American Petroleum Institute, Washington, D.C., May 1997.
12. David W. St.Clair, PID Tuning: it's the method, not the rules, *INTECH*, Dec., 26–30, 1994.