CHAPTER 4
AIR/FUEL CONTROL - GETTING THERE AND STAYING THERE

Air/Fuel Control – Safety plus Efficiency

As explained in the previous chapter, stationary combustion systems almost always operate with more air than is theoretically required to burn all the fuel. Having an excess over the stoichiometric, or theoretical, requirement permits fuel/air mixing to be less than perfect, speeds up the combustion process, and reduces the furnace volume requirement. It also provides a margin of safety; as the air and fuel flow controllers adjust to changing load conditions, having some excess air protects against the possibility of unburned fuel reaching explosive concentrations. So burner controls are always set up to provide some amount of excess air over all operating scenarios, typically 2% to 5% oxygen (O_2) in the flue gas.

However, as was also pointed out in the previous chapter, excess air incurs a heat loss; it enters the combustion system at ambient temperature and leaves at stack temperature. Reducing the oxygen level in the flue gas from 5% to 4% would mean an efficiency gain of about 2.5%.[1] Often the most immediate way to reduce fuel costs and atmospheric emissions is to ensure that excess air levels are optimized. This is done through tuning of the air and fuel controls as described in this chapter.

Understanding Air/Fuel Control

The air/fuel ratio is a mass ratio; controlling it involves controlling the pounds or kilograms of air per pound or kilogram of fuel. Control is complicated by the fact that air and some fuels are gases; their mass per unit volume changes with temperature and pressure. If pressure is fixed, the mass of air flowing in a duct will decrease when the temperature increases, for example, from winter conditions to summer conditions. If the controls do not compensate for this, the effect on combustion excess air can be dramatic, as shown in Table 4-1.

Table 4-1 Effects of Air Temperature on Excess Air Level (constant air/fuel control settings)[1]

Air Temp., °C (°F)	Excess Air, %
4.5 °C (40 °F)	25.5
10 °C (50 °F)	20.2
26.7 °C (80 °F)	15.0
37.8 °C (100 °F)	9.6
48.9 °C (120 °F)	1.1

[1] United States Department of Energy, Energy Efficiency Handbook.

Similarly, the mass of natural gas flowing through a pipe will decrease if the pressure in the supply pipe falls, as may happen when the fuel flow increases. Flow of liquid fuels is less sensitive to temperature changes, but constant flow still depends on a constant supply pressure to a valve maintaining a constant position. For a given valve position, oil flow will increase if supply pressure increases, such as when a second fuel pump is started.

Sophisticated air and fuel control systems are designed to correct for variations in temperature and pressure. These advanced systems are expensive; often simpler systems of lower precision are employed, which are then set up with larger margins of excess air to ensure that conditions of insufficient air are avoided. It follows that high-quality controls are an important factor in minimizing losses associated with excess air, and an economic evaluation with this in mind may show them to be a good investment.

For existing combustion equipment, measuring and minimizing excess air is the primary means of optimizing boiler or heater efficiency. Optimizing excess air (also referred to as O_2 control) is a matter of adjusting burner air flow to match fuel flow. The burner adjustment procedure is essentially the same regardless of size or type. The burner is set up with nominal fuel and air flowrates in incremental steps from minimum fire to full load. At each step the air flow is reduced to the minimum safe operating level as determined by a number of parameters, including oxygen, carbon monoxide and smoke in the flue gas, flame colour and shape, flame impingement, and general boiler performance. Carbon monoxide level in the flue gas is a useful, sensitive indicator of incomplete combustion; under conditions of satisfactory mixing and combustion, it should be at concentrations of zero to a few dozen parts per million (ppm). A sudden jump to a few hundred ppm indicates that excess air has been reduced below optimum (see Figure 4-4).

This burner adjustment procedure is part of the initial burner commissioning, and should be repeated at least annually. In fact, every boilerhouse, regardless of boiler size, should have a program to regularly monitor burner settings as just described. The requisite equipment is accurately calibrated analyzers for oxygen (O_2) and carbon monoxide (CO). For plants which do not have on-line flue gas monitoring, a portable analyzer that measures O_2, CO and nitrogen oxides (NO_x) can be purchased for as little as $1500, with an additional expense of about $200 for calibration gases.

Types of Air/Fuel Control

<u>On–Off and High–Low Controls</u>

Techniques for controlling the ratio of air flow to fuel flow vary with the size of equipment controlled. Small boilers employ simple, inexpensive equipment that cannot control precisely and therefore cannot ensure optimum continuous operation. The simplest technique is on-off operation, where the burner operates at a specific setting, and shuts off when the demand, as defined by temperature or pressure, is met.

A slightly more sophisticated version is a high-low system in which the burner operates at a specific high firing rate until temperature or pressure demand is satisfied, then drops back to a specific low-fire condition until high fire is again required. Both these systems are limited to processes such as space heating applications that can tolerate the cycling in temperature or pressure.

Mechanical Jackshaft Controls

Processes that need more precise control require burners that adjust firing rate over their operating range. The simplest type of modulating burner control uses a jackshaft arrangement in which a single actuator motor adjusts its jackshaft arm according to a master load (demand) signal. As shown in Figure 4-1, the air and fuel control devices are connected to the jackshaft by a series of mechanical linkages and cams. As the actuator motor moves the jackshaft arm, the arms connected to the fuel valve and fan damper move with it. The relative movement can be varied by means of the cam adjustments, thereby determining the air/fuel ratio. For multiple-fuel burners, a second cam adjusts the standby fuel valve.

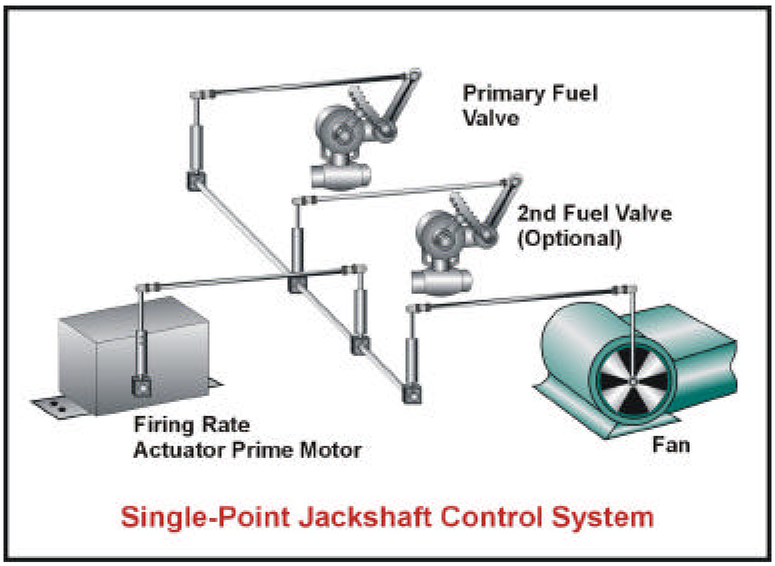

Figure 4-1 Jackshaft/Linkage Control

Usually the cams have a number of setscrews that can be adjusted to control fuel valve position relative to the jackshaft arm position. Calibrating the system involves combustion tests in which the actuator is positioned to various settings, usually at least ten, and at each setting the setscrews are adjusted to achieve the desired level of oxygen in the flue gas. It is important that, once the adjustments are complete, all the jackshaft arms are pinned and that all the setscrews are locked in their final position.

Oxygen trim control is possible by using a signal from an oxygen analyzer to adjust the linkage between the jackshaft and the fan damper arm. However, the range of oxygen trim is usually very limited and the control response must be very slow to ensure that the burner reaches steady state before the oxygen trim control acts.

A mechanical jackshaft system does not include measurement of air flow or fuel flow, nor does it sense changing air temperature or fuel condition. It does not detect any play in the jackshaft and linkages. As a result it must be set up with sufficient air for safe operation under all conditions, which is usually more than the optimum for efficiency. Common applications are small burners where the cost of more complex controls cannot be justified.

Parallel Control

Parallel control systems provide separate controllers and drives to adjust fuel and air flow, each controller taking its signal from a master control, as shown in Figure 4-2. Its main advantage over jackshaft control is that the operator can adjust the air and fuel individually, and can override the automatic control settings, if desired.

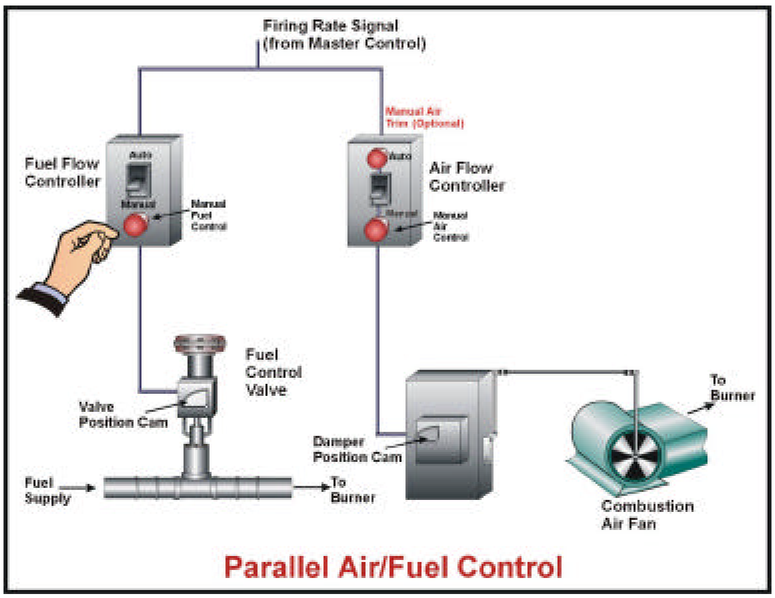

Figure 4-2 Parallel Control

Parallel control has traditionally been applied to older, medium-sized boilers equipped with pneumatic controls. It can also be applied to newer, electronic controllers, but with little additional cost these can be designed as more advanced, cross-limiting controllers, discussed later. Like jackshaft control, parallel control does not measure fuel or air flow, does not sense changing air temperature or fuel conditions, and must take into account any hysterisis or play in the control drives and linkages. Therefore, to provide a margin of safety, the system must be set up with more than the optimum excess air.

The system can be enhanced with respect to safety by mounting position transmitters on the actuators, so that an alarm sounds if the actuator position does not match the control signal. This advises the operator if an actuator has failed or if calibration has been lost, for example, if a shaft or linkage has slipped. To provide some improvement in efficiency by reducing excess air, oxygen trim can be provided via an additional controller which modifies the signal to the fan damper positioner. But, as with jackshaft controls, range of oxygen trim is limited and response must be slow.

Calibration of a parallel control system is carried out similarly as for a jackshaft control system. Combustion tests are done in which the primary fuel valve is set to ten positions, spanning the full operating range, and at each position, the air dampers are adjusted to provide an appropriate level of excess air, providing a safety margin as already discussed. The resulting data are then used to set up the controllers. With pneumatic control systems the cams in the fuel valve and fan damper actuators are cut to provide the correct air and fuel flows for the same output signal from the air and fuel controllers. With programmable controllers it is a simple matter of entering the appropriate data. When the controls have been calibrated for the primary fuel the procedure is repeated to create a second data curve or cam for the standby fuel.

Finally, to ensure safe operation, oxygen in the flue gas should be measured at various firing rates, approached from both higher and lower firing rates. It is also important to check for any spikes in oxygen or carbon monoxide during rapid load changes. If the fuel valve actuator and the fan damper actuator react at significantly different speeds, the air/fuel ratio may become dangerously low during load swings. Where oxygen trim control is employed, care must be taken to ensure that it does not respond quicker than the primary controls.

Cross-Limiting Control

Cross-limiting control is a more sophisticated system that addresses some of the shortcomings of the parallel system. It provides separate fuel and air control devices, measurement of air and fuel flow, and more powerful controllers, all of which make it more expensive. But for larger boilers, at least, it can provide operating savings because it can sense and compensate for some of the factors that affect optimum air/fuel ratio.

Cross-limiting control is shown schematically in Figure 4-3. It takes its name from the important safety feature that does not allow either air flow to be reduced below what is required for the existing fuel flow, or fuel flow to be increased above what is required for the existing air flow. It also monitors air and fuel flow, and adjusts air flow to maintain the optimum value as determined during the calibration tests. Further improvement is possible by continuously measuring oxygen and carbon monoxide in the flue gas, and using this information as a further factor in air control.

Calibration tests are carried out in much the same manner as with other control systems. The primary fuel valve is set for various fuel flows, perhaps ten, at each setting the air flow is adjusted to the minimum acceptable level of oxygen in the flue gas, and a curve of the air/fuel relationship is generated. With pneumatic control systems, the cam in the fuel valve and in the fan damper actuators are cut so that the air and fuel flow meter readings (usually in percent) have a constant relationship over the burner operating range. With programmable controllers, the curve points can be easily programmed into controllers, with the flow measurements in the actual flow units (kg/h, SCFM, etc.)

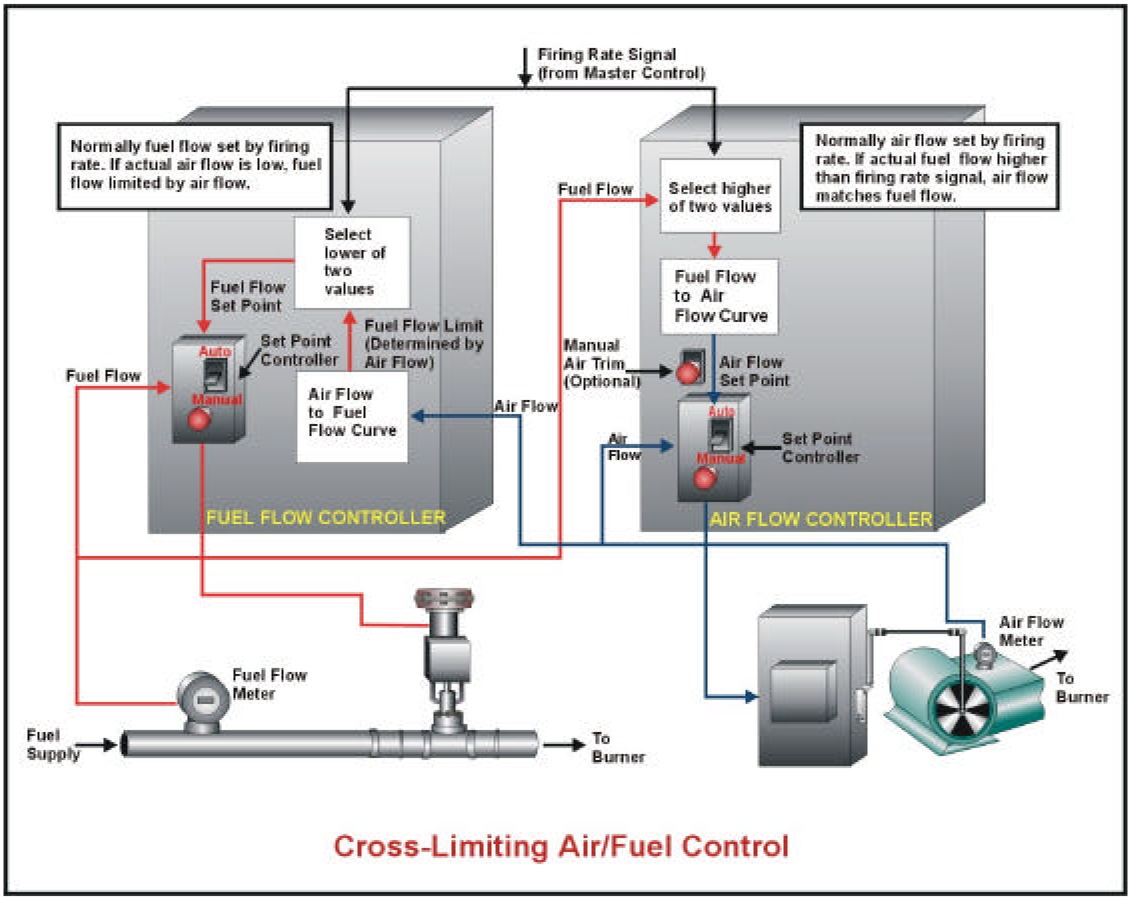

Figure 4-3 Cross-Limiting Control

For multiple-fuel burners with pneumatic controls, settings for the standby fuel are determined for the same air settings that were obtained when calibrating for the primary fuel. With programmable controls an independent fuel/air curve is developed for the standby fuel; the controller selects the applicable curve based on the fuel selected.

Oxygen trim is possible, but again has a limited range of adjustment, and must respond slowly enough to allow the primary controls to reach equilibrium. Since cross-limiting control systems can – and should – be set up to operate with minimum excess air, it is doubly important to run the burner up and down its operating range to check for spikes in oxygen and carbon monoxide. If any are found, due to the fuel and air actuators reacting at different speeds, the controllers can be tuned to make their responses match.

Because the air and fuel flows are measured, cross-limiting systems correct for some variations. For example, they will respond to changes in fuel flow caused by changes in supply pressure. However attention must be paid to how the flows are measured. Most techniques for measuring air and natural gas flow: pitot tube, orifice plate, vortex shedding, etc., actually measure volumetric flow as opposed to mass flow. These volumetric flow measurements, of themselves, do not compensate for temperature and pressure variations. While fuel/air control is better with cross limiting based on volumetric flows (as opposed to no flow measurement), the most precise control can only be achieved with mass flow measurement, usually by temperature and pressure compensation on the volumetric flow measurement. Many flow meters have optional pressure and temperature compensation directly within the transmitter. Fortunately, liquid flowmeters are not affected by minor changes in temperature, but when large temperature variations may occur, as when No. 2 oil is stored outside without any temperature control, the effect on the flow measurement should be checked.

The safety feature of cross-limiting control can be provided without the cost of air and fuel flowmeters by using position transmitters on the fuel valve and fan dampers. However, this arrangement does not compensate for flow variations and cannot provide tight control of fuel/air ratio.

Multiple Burners

Any of the control systems described above can be applied to multiple burner installations. However, the control of air flow through the burner, air/fuel ratio, and oxygen trim become more complicated. If the boiler were to operate only with all burners in service the controls could then treat them as essentially one large burner, but the purpose of most multiple burner designs is to give the plant the flexibility of various burner combinations.

With multiple burners the most common control problems arise from air leakage through the burners that are out of service. The leakage affects flame patterns, and distorts measurement of air flow and flue gas oxygen level. In calibrating the controls extra effort is required to ensure proper combustion occurs for all burner combinations.

Oxygen Trim Control

Typically oxygen trim, or automatic control of excess air, is only installed on large boilers. The cost of the oxygen analyzer, together with installing it and implementing the trim control system, can be $20,000 or more. To this should be added the expense of a continuous maintenance and calibration program to ensure that it continues to function correctly.

The typical efficiency gain from adding oxygen trim to a well-tuned and well-operated boiler will be 1 to 2%. To justify its expense, the boiler must consume at least $100,000 to $1,000,000 of fuel per year, depending on the owner's payback criteria. For very large boilers, where efficiency gains of 0.1% mean significant annual savings, it is usual to measure carbon monoxide as well as oxygen. With this signal the controls are programmed to reduce air to the point where carbon monoxide starts to increase, indicating that air flow has been reduced to the safe lower limit.

Test Procedure for Adjusting Air/Fuel Ratio

Burners should only be adjusted by qualified personnel knowledgeable in the combustion process and the specific equipment. This procedure is provided for the information of boiler owners and operators as a standard procedure for qualified burner technicians to follow when adjusting burners.

A properly adjusted burner will have its air flow set to the minimum, relative to fuel flow, that is safe over the normal range of the various parameters affecting the air and fuel flows. The general procedure for testing and adjusting the air and fuel settings is the same for most burners and air/fuel control systems. It is presented in the following, complete with the steps to determine the proper adjustment and some practical tips. The operating staff must be involved to ensure they are comfortable with the resulting flame and the air/fuel settings.

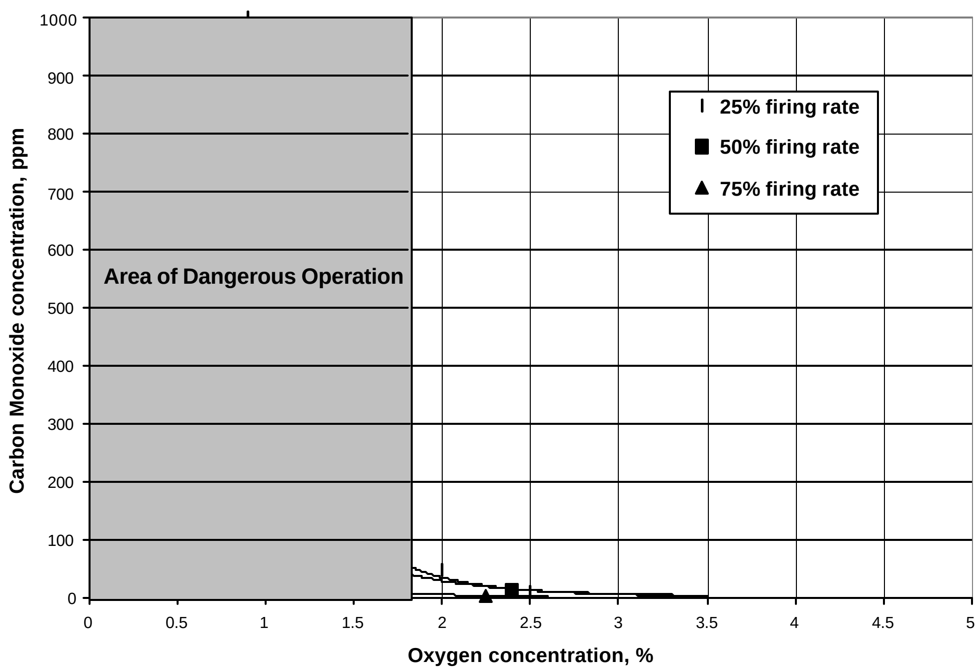

Figure 4-4 Trend of CO versus O_2 for Incomplete Combustion

The flue gas O_2 and CO measurements are critical parameters when adjusting the air for any given firing rate. As discussed earlier, for complete combustion all the carbon in the fuel converts to CO_2. When the reaction does not go to completion, CO is produced instead of CO_2. Therefore, high CO concentrations indicate incomplete combustion and the cause must be determined. When reducing the air flow, increasing CO points to insufficient air for the fuel flow. It is also important to understand that CO increases faster as the air is adjusted further below the point of exactly correct air/fuel ratio and, as shown in Figure 4-4, this phenomenon is accentuated at higher firing rates. (For this reason, when adjusting a burner the operating point for CO should be zero to a few dozen parts per million, rather than the environmental CO limit, typically 400 ppm.) This means that it is important for the technician to understand the capabilities of the burner and its air/fuel control and adjust the burner operating point with enough margin to operate safely in all possible steady state and changing load conditions.

Before starting the test procedure some preparatory steps are necessary. Draw up a chart of all the boiler/heater measurements: flows, pressures, and temperatures. This will provide useful data about performance over the entire operating range and becomes a good reference for comparing future or past operating variations. Also, ensure there is sufficient load for the burner to get to full fire. For steam boilers, this can be done by blowing steam through a muffler. Closed heating loops are more difficult. If demand is insufficient, letting the system cool and firing at a high rate to bring the system up to temperature can simulate higher loads, at least for a short time. However, this technique does not give fully representative results because the equipment is not operating at the normal steady-state temperatures.

Test Procedure for Adjusting Air/Fuel Ratio

Note: Burners should only be adjusted by qualified personnel knowledgeable in the combustion process and the specific equipment. This procedure is provided for the information of boiler owners and operators as a standard procedure for qualified burner technicians to follow when adjusting burners.

1. Calibrate the analyzer with calibration gases.
   Calibration gases containing no oxygen (O_2) and specific concentrations of carbon dioxide (CO_2) and carbon monoxide (CO) in nitrogen are available. If the analyzer also measures nitrogen oxides (NO and/or NO_2) and/or sulphur dioxide (SO_2), calibration gases with a mixture of all these compounds are also available. When the analyzer is exposed to the calibration gases, zero the O_2 measurement and span the other values. When the analyzer is exposed to air, the O_2 span can be set (20.9%) and the other measurements zeroed. (Where accuracy is critical, all components can be set to zero using a calibration gas of 100% nitrogen.)

2. Ensure the boiler/heater/burner is set to its normal operating conditions.
   For, example, check that the windbox burner vanes are in the proper position for the selected fuel, the furnace pressure and economizer controls are in automatic mode, and the appropriate fuel pump is operating.

3. Insert the gas analyzer probe into the flue gas stream.
   The probe should be located as close as possible to the furnace outlet, in an unobstructed flue gas flow. If the boiler experiences a major upset, e.g., a boiler trip, the probe should be removed to ensure that the analyzer is not exposed to high concentrations that will require a long purge time or even recalibration.

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4. Set the burner fuel flow to minimum fire and adjust air flow to minimum setting.

   Often minimum fire is determined by the air flow, rather than the fuel flow. On most combustion air fans the dampers have significant air leakage which allows more air than necessary at minimum fire. If this is the case, the fuel is adjusted to provide a stable flame at a reasonable (as opposed to minimum) O_2 value. At minimum fire air velocity through the burner is lowest, so it is important to ensure that the flame has not anchored so far back in the burner throat that components are being overheated. Also check that the flame is not impinging on any surfaces. Record the various readings.

5. Increase the air first and then the fuel to the next test point. Reduce the air to the minimum setting.

   During the adjustment, monitor the flue gas O_2 and CO and the actual flame. When reducing the air flow, pay close attention to the CO. When it starts to increase, the burner has reached the point of insufficient air and air flow has to be increased slightly. Determine the best settings from the flue gas O_2 and CO, the flame colour and pattern and the general equipment performance. (For low NO_x burners, also adjust any equipment for NO_x control, such as a flue gas recirculation damper.) Once the equipment has reached steady state, record all the settings and process measurements.

Note: Properly adjusted burners should have CO emissions of zero to a few dozen, rather than a few hundred, parts per million, although emissions limits are often allow these levels. The CCME Guideline, for example, allows 125 ng/J of CO, which, depending on the fuel, is about 400 ppm at 3% O_2 in the flue gas. Often, if CO emissions are in the range of a few hundred parts per million, they can increase to significant, even dangerous, concentrations with only minor changes in the burner air/fuel ratio.

6. Repeat the procedure for each test point until full fire is reached.

   As the firing rate increases, the flame usually becomes more stable and complete combustion can be achieved at a lower level of O_2 in the flue gas.

7. Reduce fuel and air flows back to each of the test points. Reduce fuel before air.

   Verify that the flue gas O_2 and CO and the other parameters are approximately the same as for the tests done on increasing firing rate. If they are not, investigate the cause. Often this is due to the hysterisis of the control drives, linkages, and valves, which cannot be completely eliminated. Where significant discrepancies persist the settings will have to be selected to ensure safe combustion on both increasing and decreasing firing rate. (When moving to the lower settings, be sure not to go past the settings and then increase to the desired setting; this will defeat the purpose of this test.)

Note: Burners should only be adjusted by qualified personnel knowledgeable in the combustion process and the specific equipment. This procedure is provided for the information of boiler owners and operators as a standard procedure for qualified burner technicians to follow when adjusting burners.

8. When all fuel/air settings have been determined, build the resulting curves into the control system.

   If controls are the jackshaft type, the setscrews will be adjusted during the test procedure. For other control systems, either the cams will be cut for a pneumatic system or the curves will be programmed into the programmable controller.

9. Place the system under automatic control and monitor flame and flue gas over load swings.

   Often the air/fuel ratio will change during the firing rate transitions. Particular attention should be paid to low O_2 or high CO; although too much air is also a concern due to the possibility of "blowing out" the flame. If any problems occur the control system and/or air and fuel settings must be readjusted. If no problems are found, pin and lock the jackshaft linkage and setscrews.

10. Consider, and test where possible, the effect other system variations may cause.

    Some things will be fairly easy to test: start and stop a second boiler, start and stop another fuel pump, open all the doors and windows in the building. For other variations, like ambient air temperature changes from summer to winter, consider their significance and perform a theoretical calculation if necessary.

Specifying High Performance, Low-NO_x Burners

Often no performance criteria are specified when new burners and boilers are purchased. Some suggested specifications are given below to ensure maximum performance and efficiency. Requirements for NO_x emissions are also given. The descriptions refer to a natural gas fired burner, between 10 million and 100 million Btu/h. Additional requirements, specific to the particular equipment, will be required as determined by the purchaser.

Performance Requirements

1. The burner shall not operate with excess air greater than 15% over the entire operating range, except at minimum fire. At minimum fire excess air shall not exceed 20%.
2. During commissioning the burner and automatic controls shall be adjusted to provide the best possible operating conditions, i.e. lowest excess air.
3. The burner shall not operate with carbon monoxide (CO) in excess of 100 ppm (corrected to 3% O_2, dry basis) over the entire operating range.
4. The burner shall not operate with nitrogen oxides (NO_x) in excess of 29 g/GJ (49.6 ppm, corrected to 3% O_2, dry basis) over the entire operating range.

Acceptance Criteria

1. Acceptance tests shall be conducted after burner commissioning is complete. For the acceptance tests, the burner and boiler controllers shall be in automatic mode.
2. The flue gas analyzer shall be calibrated the day of acceptance tests and after tests have been completed. A calibration report shall be issued before and after tests are conducted.
3. Flue gas measurements shall be taken after boiler operation has stabilized at minimum fire and at 25%, 50%, 75%, 100% of the full firing rate. Tests at 50% and 75% firing rate shall be done for both increasing and decreasing load.
4. Flue gas measurements shall be monitored while firing rate and boiler load transitions are simulated.
5. All excess air (O_2), CO, and NO_x readings are to meet or exceed performance requirements.