Chapter 5

Combustion and draught control

When considering fired boilers and heat-recovery steam generators it is clear that in the areas of their steam and water circuits there are many similarities between them (although the HRSG may have two or more pressure systems). But when the systems for controlling the heat input are examined, the two types of plant take on altogether different characteristics. The reason for this is fundamental: within the HRSG, no actual combustion process is involved, since all the heat input is derived from the gas-turbine exhaust (except where supplementary firing is introduced between the gas turbine and the HRSG). The subject of combustion control, which we shall be examining in this chapter, is therefore only relevant to fired plant.

Naturally, in a fired boiler the control of combustion is extremely critical. In order to maximise operational efficiency combustion must be *accurate*, so that the fuel is consumed at a rate that exactly matches the demand for steam, and it must be executed *safely*, so that the energy is released without risk to plant, personnel or environment. (The amount of energy involved in a power plant is considerable: in each second of its operation a large boiler releases around a billion joules, and in a process of this scale the results of an error can be catastrophic.)

In this chapter we shall see how the combustion process is controlled to meet the two objectives defined in the previous paragraph. We shall also examine the subsidiary systems that maintain the correct operational conditions in the fuel-handling plant of coal-fired boilers.

5.1 The principles of combustion control

In Chapter 3 we saw that the theoretically perfect combustion of a fuel requires the provision of exactly the right amount of air needed for complete combustion of the fuel. For the boiler as a whole this means that the total amount of air being delivered to the combustion chamber at any instant matches the total amount of fuel entering that chamber at that time. For an individual burner it means that the fuel and air being delivered to the burner are always in step with one another.

On the surface, therefore, it would appear that the matter of combustion control merely involves keeping the fuel and air inputs in step with each other, according to the demands of the master, and if this were true this role would be adequately addressed by a straightforward flow ratio controller. Unfortunately, when the realities of practical plant are involved, the situation once again becomes far more complex than this simple analysis would suggest.

When the relationship between the fuel and air flowing at any instant into the furnace is chemically ideal for combustion, the relationship between the two flows is known as the stoichiometric fuel/air ratio. However, as stated earlier, it is usually necessary to operate at a fuel/air ratio that is different from this theoretically optimal value, generally with a certain amount of excess air. All the same, even though more than the theoretical amount of air has to be provided, any overprovision of air reduces the efficiency of the boiler and results in undesirable stack emissions, and must therefore be limited.

The reduction in efficiency is due to losses which are composed of the heat wasted in the exhaust gases and the heat which is theoretically available in the fuel, but which is not burned. As the excess-air level increases, the heat lost in the exhaust gases increases, while the losses in unburned fuel reduce (the shortage of oxygen at the lower levels increasing the degree of incomplete combustion that occurs). The sum of these two losses, plus the heat lost by radiation from hot surfaces in the boiler and its pipework, is identified as the total loss.

Figure 5.1 shows that operation of the plant at the point identified at ‘A’ will correspond with minimum losses, and from this it may be assumed that this is the point to which the operation of the combustion-control system should be targeted. However, in practice air is not evenly distributed within the furnace. For example, operational considerations require that a supply of cooling air is provided for idle burners and flame monitors, to prevent them being damaged by heat from nearby active burners and by general radiation from the furnace. Air also enters the

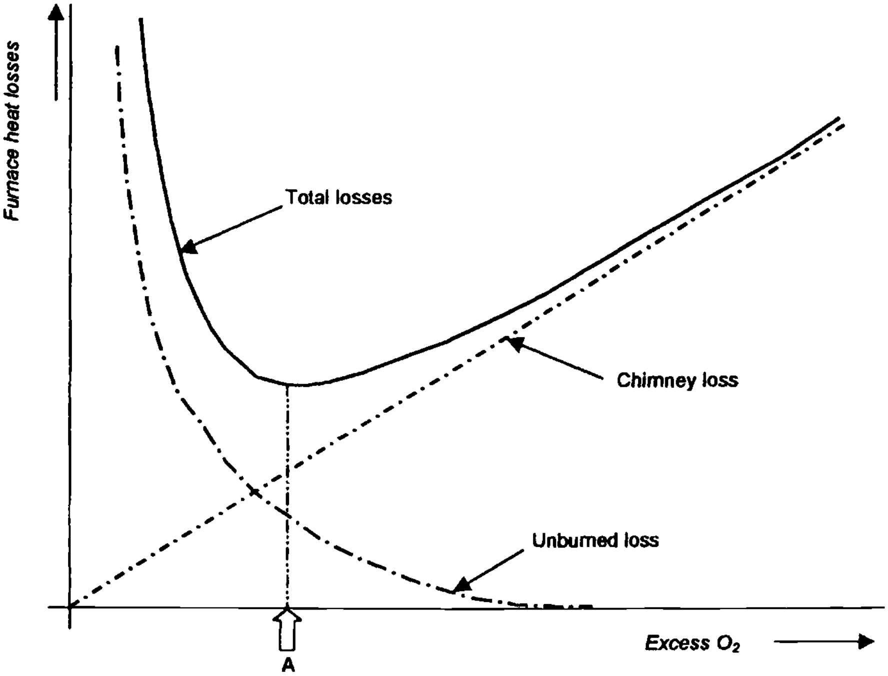

Figure 5.1 *Heat losses in a furnace*

combustion chamber through leaks, observation ports, soot-blower entry points and so on. The sum of all this is referred to as 'tramp air' or 'setting leakage'. If this is included in the total being supplied to the furnace, and if that total is apportioned to the total amount of fuel being fired, the implication is that some burners (at least) will be deprived of the air they need for the combustion of their fuel. In other words, the correct amount of air is being provided in total, but it is going to places where it is not available for the combustion process.

Operation of the firing system must take these factors into account, and from then on the system can apportion the fuel and air flows. If these are maintained in a fixed relationship with each other over the full range of flows, the amount of excess air will be fixed over the entire range.

5.1.1 A simple system: 'parallel control'

The easiest way of maintaining a relationship between fuel flow and air flow is to use a single actuator to position a fuel-control valve and an air-control damper in parallel with each other as shown in Figure 5.2. Here, the opening of an air-control damper is mechanically linked to the opening of a fuel control valve to maintain a defined relationship between

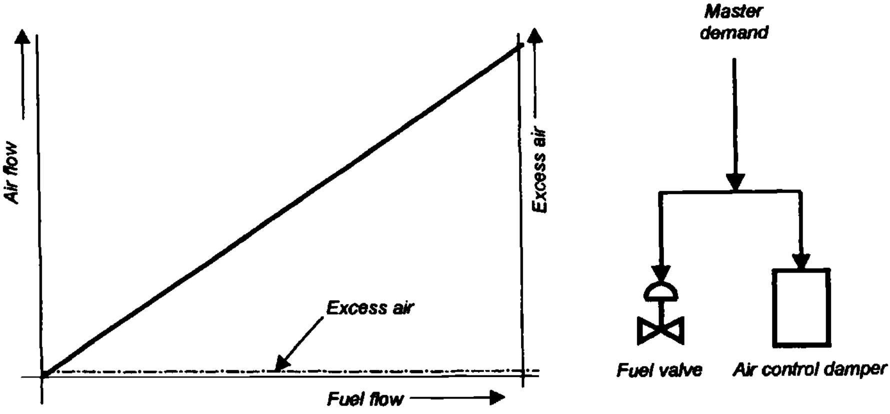

Figure 5.2 Simple 'parallel' control

fuel flow and air flow. This system is employed in very small boilers, and a variant allows a non-linear relationship between valve opening and damper opening to be determined by the shape of a cam, with a range of cams offering a variety of relationships.

Although this simple system may be quite adequate for very small boilers burning fuels such as oil or natural gas, its deficiencies become increasingly apparent as the size of the plant increases.

One limitation of the system is that it assumes that the amount of fuel flowing through the valve and the quantity of air flowing past the damper will remain constant for a given opening of the respective devices. In practice, if a valve or damper is held at a given opening, the flow past it will change as the applied pressure changes. Furthermore, the flow will also be affected by changes in the characteristics of the fuel and air, notably their densities.

Another problem is that the response times of the fuel and air systems are never identical. Therefore, if a sudden load-change occurs and the two controlling devices are moved to predetermined openings, the flows through them will react at different rates. With an oil-fired boiler, a sudden increase in demand will cause the fuel flow to increase quickly, but the air system will be slower to react. As a result, if the fuel/air ratio was correct before the change occurred, the firing conditions after the change will tend to become fuel-rich until the air system has had time to catch up. This causes characteristic puffs of black smoke to be emitted as unburned fuel is ejected to the chimney.

On a load decrease the reverse happens, and the mixture in the combustion chamber becomes air-rich. The resulting high oxygen content could lead to corrosion damage to the metalwork of the boiler, and to unacceptable flue-gas emissions.

5.1.2 Flow ratio control

The first approach to overcoming the limitations of a simple 'parallel' system is to measure the flow of the fuel and the air, and to use closed-loop controllers to keep them in track with each other, as shown by the two configurations of Figure 5.3.

In each of these systems the master demand (not shown) is used to set the quantity of one parameter being admitted to the furnace, while a controller maintains an adjustable relationship between the two flows (fuel and air). Either of the flows can be selected to be the one that responds directly to the master and, in Section 5.1.2.1, we shall see the different effects that result when fuel flow or air flow is used in this way.

In the system shown in Figure 5.3*a* a gain block or amplifier in one of the flow-signal lines is used to adjust the ratio between the two flows. As the gain (g) of this block is changed, it alters the slope of the fuel-flow/air-flow characteristic, changing the amount of excess air that is present at each flow. Note that when the gain is fixed, the amount of excess air is the same for all flows, as shown by the horizontal line.

In practice, this situation would be impossible to achieve, since some air inevitably leaks into the furnace, with the result that the amount of excess air is proportionally greater at low flows than high flows. This causes the excess-air line to curve hyperbolically upwards at low flows (much as is shown in Figure 5.3*b*). Practical burner requirements demand that the quantity of air should always be slightly greater than that which the theoretical stoichiometric ratio would dictate. The characteristic would therefore not pass through the origin of the graph as is shown in Figure 5.3*a*.

Figure 5.3*b* shows a different control arrangement working with the same idealised plant (i.e. one with no air leaking into the combustion chamber). Here, instead of a gain function, a bias is added to one of the signals. The effect of this is that a fixed surfeit of air is always present and this is proportionally larger at the smaller flows, with the result that the amount of excess air is largest at small flows, as shown. Changing the bias signal (b) moves the curve bodily as shown.

Each of these control configurations has been used in practical plant, although the version with bias (Figure 5.3*b*) exacerbates the effects of tramp air and therefore tends to be confined to smaller boilers. The arrangement shown in Figure 5.3*a* therefore forms the basis of most practical fuel/air ratio control systems.

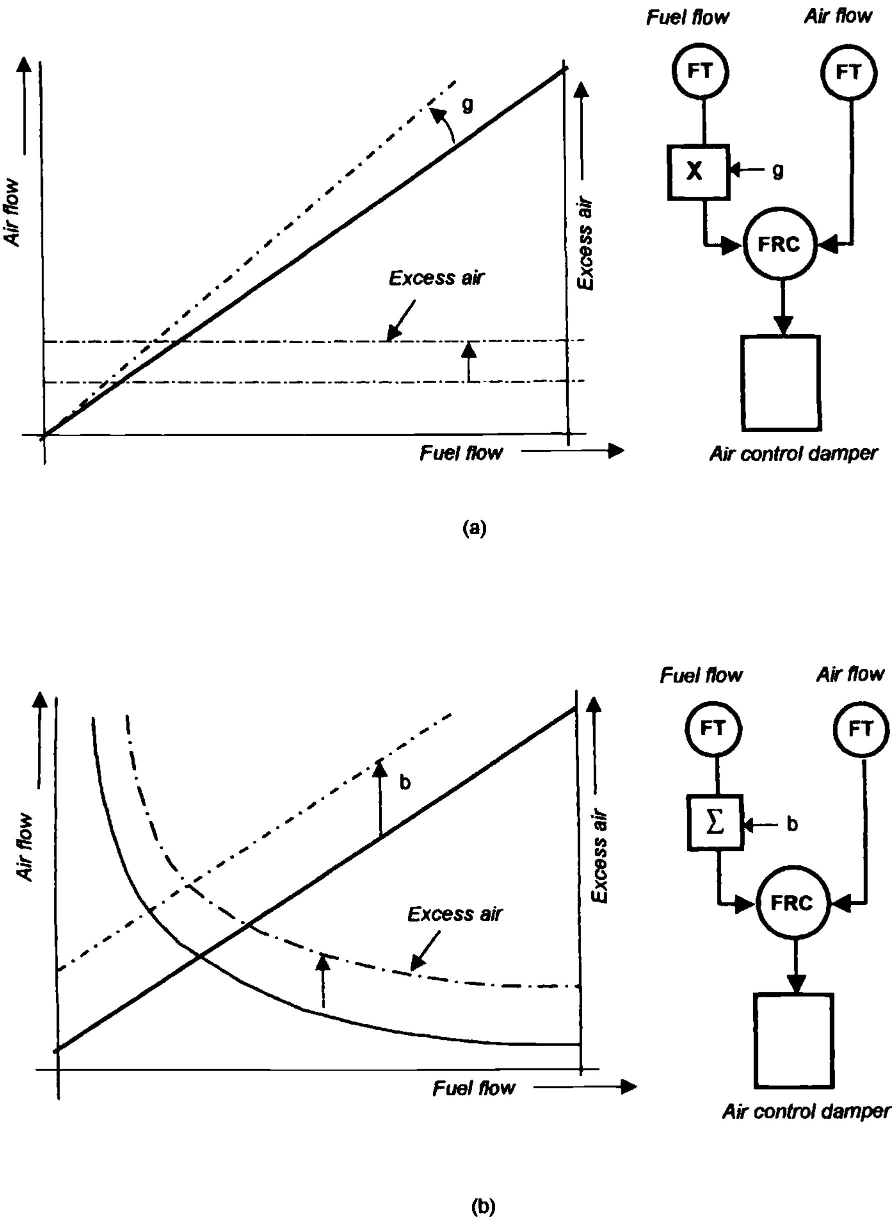

Figure 5.3 *Fuel/air ratio control*
a Gain adjustment of fuel/air ratio
b Bias adjustment of fuel/air ratio

In these illustrations it has been assumed that the master demand is fed to the fuel valve, leaving the air-flow controller to maintain the fuel/air ratio at the correct desired value. When this is done, the configuration is known as a 'fuel lead' system since, when the load demand changes, the fuel flow is adjusted first and the controller then adjusts the air flow to match the fuel flow, after the latter has changed.

It doesn't have to be done this way. Instead, the master demand can be relayed to the air-flow controller, which means that the task of maintaining the fuel/air ratio is then assigned to the fuel controller. For obvious reasons this is known as an 'air-lead' system.

5.1.2.1 Comparing the 'fuel-lead' and 'air-lead' approaches

Of the two alternatives described above, the fuel-lead version will provide better response to load changes, since its action does not depend on the slower-responding plant that supplies combustion air to the furnace. However, because of this, the system suffers from a tendency to produce fuel-rich conditions on load increases and fuel-lean conditions on decreases in the load. Operating in the fuel-rich region raises the risk of unburned fuel being ignited in an uncontrolled manner, possibly causing a furnace explosion. Whereas operating with too much excess air, while not raising the risk of an uncontrolled fire or an explosion, does cause a variety of other problems, including back-end corrosion of the boiler structure, and undesirable stack emissions.

The air-lead system is slow to respond because it requires the draught plant to react before the fuel is increased. Although this avoids the risk of creating fuel-rich conditions as the load increases, it remains prone to such a risk as the load decreases. However, the hazard is less than for the fuel-lead system.

A further limitation of these systems (in either the fuel-lead or air-lead version) is that they offer no protection against equipment failures, since these cannot be detected and corrected without special precautions being taken. For example, in the fuel-lead version, if the fuel-flow transmitter fails in such a way that it signals a lower flow than the amount that is actually being delivered to the furnace, the fuel/air ratio controller will attempt to reduce the supply of combustion air to match the erroneous measurement. This will cause the combustion conditions to become fuel-rich, with the attendant risk of an explosion. Conversely, if the fuel-flow transmitter in the air-lead system fails low, the fuel controller will attempt to compensate for the apparent loss of fuel by injecting more fuel into the furnace, with similar risks.

These are just some of the failure characteristics which the basic system design cannot address. Although the self-diagnostic features incorporated in modern transmitters can be arranged to raise an alarm and trip the burners, or operate the plant in a protected mode, until the fault has been corrected, it would be preferable to employ a system which has greater inherent abilities to deal with failures both in the plant and in its control and instrumentation equipment.

The so-called 'cross-limited' combustion control system addresses these factors in a very comprehensive way, as described in the following section.

5.1.3 Cross-limited control

Figure 5.4 shows the principles of the cross-limited combustion control system. Individual flow-ratio controllers (7, 8) are provided for the fuel and air systems, respectively. Ignoring for the moment the selector units (5, 6) and the fuel/air ratio adjustment block (4), it will be seen that the master demand signal is fed to each of these controllers as the desired-value signal, so that the delivery of fuel and air to the furnace continually matches the load. Because fuel flow and air flow are each measured as part of a closed loop, the system compensates for any changes in either of these flows that may be caused by external factors. For this reason it is sometimes referred to as a 'fully metered' system. The effect of the fuel/air ratio adjustment block (4) is to modify the air-flow signal in accordance with the required fuel/air relationship.

So far, the configuration performs similarly to the basic systems shown in Figure 5.3. The difference becomes apparent when the maximum and minimum selectors are brought into the picture. Remembering the problems of the differing response-rates of the fuel and air supply systems, consider what happens when the master demand signal suddenly requests an increase in firing. Assume that, prior to that instant, the fuel and air controllers have been keeping their respective controlled variable in step with the demand, so that the fuel-flow and modified air-flow signals are each equal to the demand signal. When the master demand signal suddenly increases, it now becomes larger than the fuel-flow signal and it is therefore ignored by the minimum-selector block which instead latches onto the modified air-flow signal (from item 4). The fuel controller now assumes the role of fuel/air ratio controller, maintaining the boiler's fuel input at a value that is consistent with the air being delivered to the furnace. The air flow is meanwhile being increased to meet the new demand, since the maximum-selector block (6) has latched onto the rising master signal.

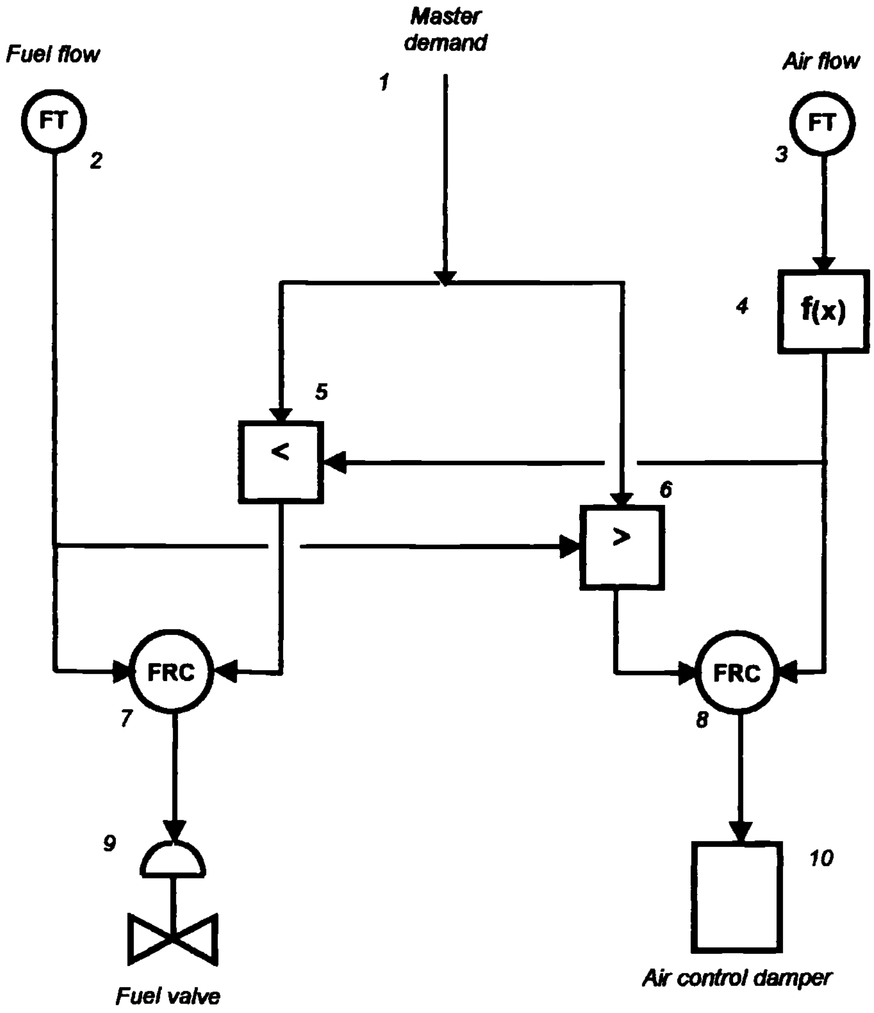

Figure 5.4 Basic cross-limited control system

On a decrease in load, the system operates in the reverse manner. The minimum-selector block locks onto the collapsing master and quickly reduces the fuel flow, while the maximum-selector block chooses the fuel-flow signal as the demand for the air-flow controller (8), which therefore starts to operate as the fuel/air ratio controller, keeping the air flow in step with the fuel flow.

Analysis of the system will show that it is much better able to deal with plant or C&I equipment failures. For example, if the fuel valve fails open, the air controller will maintain adequate combustion air to meet the quantity of fuel being supplied to the combustion chamber. This may result in overfiring but it cannot cause fuel-rich conditions to be created in the furnace. Similarly, if the fuel-flow transmitter fails low, although the fuel controller will still attempt to compensate for the apparent loss of fuel, the air flow controller will ensure that adequate combustion air is supplied.

The system cannot compensate for all possible failures, but it provides a much higher level of protection than any of the simpler systems described earlier, and when coupled with self-checking diagnostics and proper fault-detection techniques it provides a high degree of safety.

5.1.3.1 Using gas analysis to vary the fuel/air ratio

In the systems shown in Figures 5.3 and 5.4, the relationship between the fuel and air quantities is manually adjusted, either the gain or the bias is altered to change the combustion conditions. With such systems, if the adjustment factor is set wrongly, or if changes outside the system dictate that the fuel/air ratio should be altered, no provision exists for automatic correction, and the right combustion conditions can only be restored by manual intervention. To improve performance and safety, some form of automatic recognition and correction of these factors would be preferable.

If the fuel/air ratio is incorrect, combustion of the fuel will be affected and the results will be observable in the flue gases. This indicates that an effective way of optimising the combustion process is to change the fuel/air ratio automatically in response to measurements of the flue-gas content.

For all fossil-fuelled boilers, the oxygen content of the flue gases increases as the excess-air quantity is increased, while the carbon dioxide and water content decreases. The carbon monoxide content of the boiler's flue gases is a direct indication of the completeness of the combustion process and systems based on the measurement of this parameter have long been recognised as an effective mechanism for improving combustion performance in coal and oil-fired boiler plant [1]. However, experience indicates that the use of this gas as a controlling parameter is less advantageous in boilers fired on natural gas [2].

Measurement of the flue-gas oxygen content often provides a good indication of combustion performance, but it must be appreciated that the presence of 'tramp air' due to leakages into the combustion chamber can lead to anomalous readings. In the presence of significant leakage, reducing the air/fuel ratio to minimise the flue-gas oxygen content can result in the burners being starved of air. This is an area where systems based on carbon monoxide measurements provide better results since the carbon monoxide content of the gases is a direct indication of combustion performance and is unaffected by the presence of tramp air.

A system which adjusts the fuel/air ratio in relation to the flue-gas oxygen content is shown in Figure 5.5. The oxygen measurement is fed to a controller (5) whose output adjusts the fuel/air ratio by varying the multiplying factor of a gain block (8).

The transmitters used for measuring flue-gas oxygen are usually based on the use of zirconium probes, whose conductivity is affected by the oxygen content of the atmosphere in which they are installed. True two-wire 4–20 mA analysers are now available (Figures 5.6 and 5.7), and are both accurate and reliable.

The flue gases leave the combustion chamber through ducts of considerable cross-sectional area and it is inevitable that a significant degree of stratification will occur in the gases as they flow to the chimney. Air entering the furnace through the registers of idle burners will tend to produce a higher oxygen content in the gases flowing along one area of the duct than will be present in another area, where fewer burners may be idle.

It is therefore necessary to take considerable care that any gas analysis provides a truly representative sample of the average oxygen content, and this demands that great care should be exercised over the selection of the

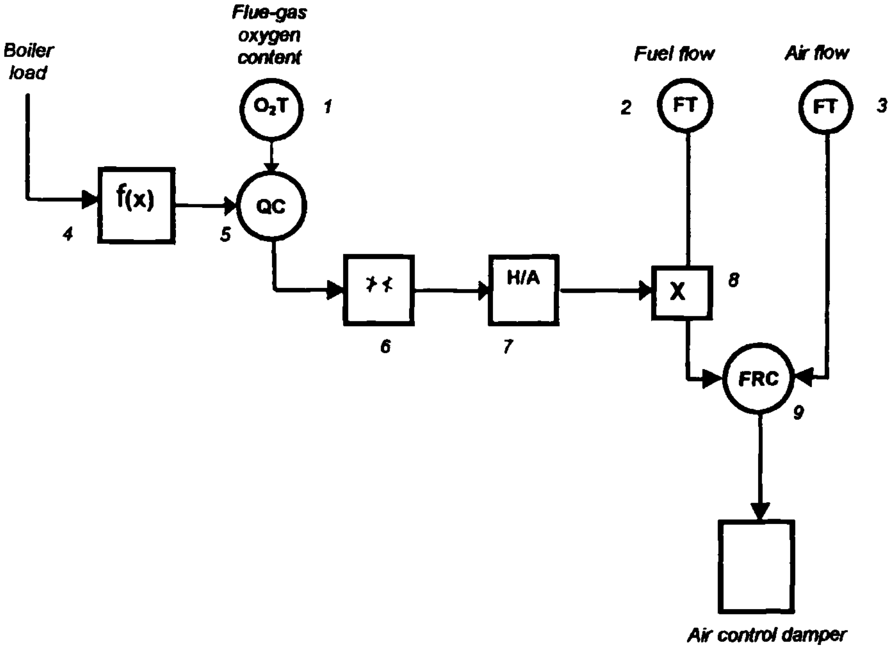

Figure 5.5 Oxygen trimming of fuel/air ratio

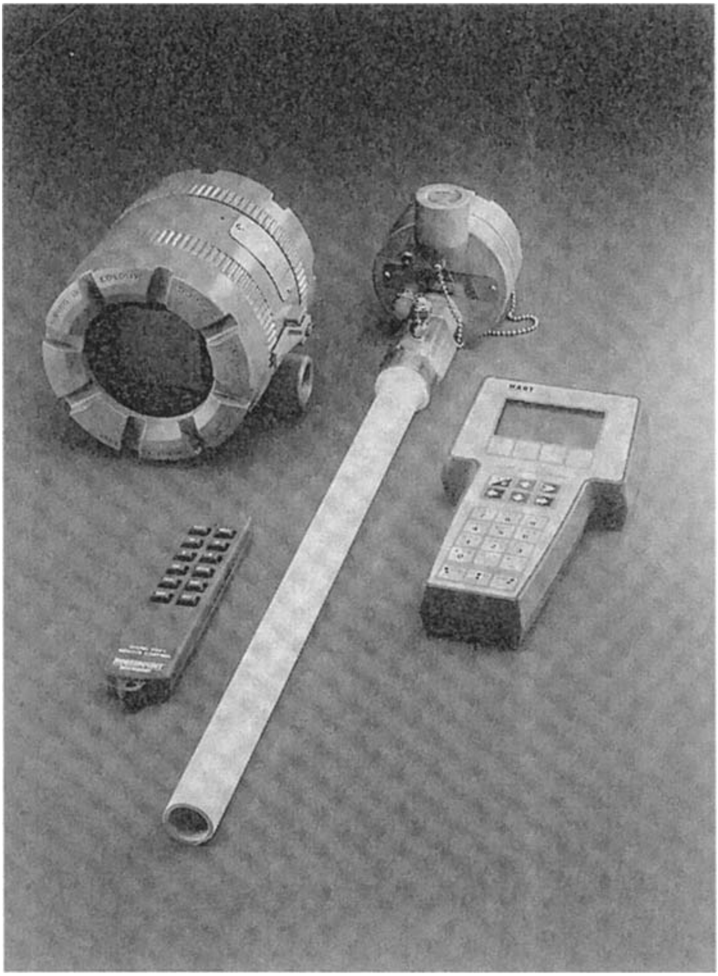

Figure 5.6 An in-situ oxygen analyser
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location of the analyser. With larger ducts it may be necessary to provide several analysers. The signals from these can be combined, or the operator can be given the facility to select one or more of them for use.

A better option is now available. The power and flexibility of modern computer-based control systems allows for truly intelligent sampling to be applied, where the system recognises the dynamic status of the plant, such as which burners are being fired, and automatically selects the analyser signal to be used, or intelligently mixes the analyser signals to optimise performance. The installation of such a system requires careful observation of

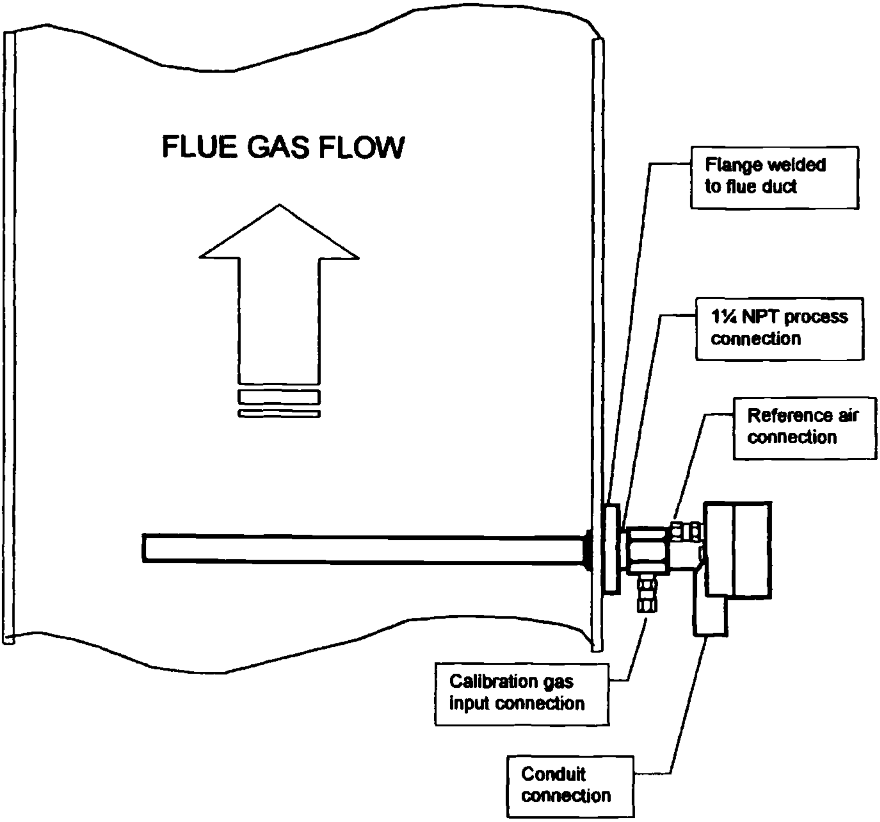

Figure 5.7 Installation of an in-situ oxygen analyser

the plant performance over an extended period and the development and subsequent application of a suitable system based on those observations.

Although such techniques are possible. Despite the considerable advances that have been made in gas-analyser technology over the past few years, fuel/air ratio trimming on the basis of gas analysis is still treated with some reservation. It is generally accepted that the measurements may occasionally fail or be misleading and for this reason it is usual to allow manual intervention in the absence of reliable oxygen control. In Figure 5.5 this facility is provided by the hand/auto station (7). In addition, a maximum/minimum limiter block (6) restricts the amount of adjustment that is permitted, to constrain the effects of anomalous or invalid measurements or incorrect control actions.

This system also characterises the set-value signal for the oxygen controller over the boiler's load range by means of a function block (4), providing for higher excess-air operation at low loads. The indication of boiler load may be obtained from either steam flow or air flow, and the exact shape and parameters of the oxygen versus load characteristic will be defined by the boiler designer or process engineer.

In practice, facilities may also be incorporated to allow the operator to adjust the system by biassing the load signal upwards or downwards at any given point to yield better combustion with reduced stack emissions.

Because the oxygen content of air is 21% by volume (or roughly 23% by weight), a given change in oxygen content represents approximately five times that change in terms of excess air. Since it is indeed *air flow* that is being controlled, the oxygen loop must recognise the presence of this high-gain component, and the gain of the controller (5) should be set at a kick-off low value (typically 0.25, or a proportional band of 400%). The time constants of the fuel/air/flue-gas system are long, and the integral term of the oxygen controller will therefore also tend to be long.

5.1.3.2 Combining oxygen measurement with other parameters

The use of an oxygen-trim signal on its own can be misleading, for the reasons noted earlier, and better performance can be obtained by combining oxygen trim with the opacity of the flue gases, since reducing the air flow eventually results in the production of visible smoke. However, it is usually undesirable to operate a boiler in the region where smoke is being produced, and an improvement is to adjust the air flow on the basis of another parameter, such as carbon monoxide.

Figure 5.8 shows how the carbon monoxide and oxygen measurements can be combined to trim the fuel/air ratio. Basically, the system comprises two gas-analysis controllers (6 and 10) whose set-value signals are determined in relation to the boiler load (via function generators 5 and 7). However, the set value for the oxygen controller is also trimmed by the output of the carbon monoxide controller (the two signals being combined in summator 9). Hand/auto facilities enable the system to operate with both analysers in command, or with only oxygen trim in service (the CO controller being on manual at hand/auto station 8), or with fully manual fuel/air ratio adjustment (hand/auto station 12 being on manual, to isolate both gas-analysis controllers).

In another variant of this system, either of the two flue-gas analysis controllers can be selected for operation, either by manual intervention or automatically by means of a maximum-selection function.

5.1.3.3 Using carbon-in-ash measurements

In boilers burning solid fuels, the carbon content of the ash has traditionally been used to provide an indication of the completeness of combustion,

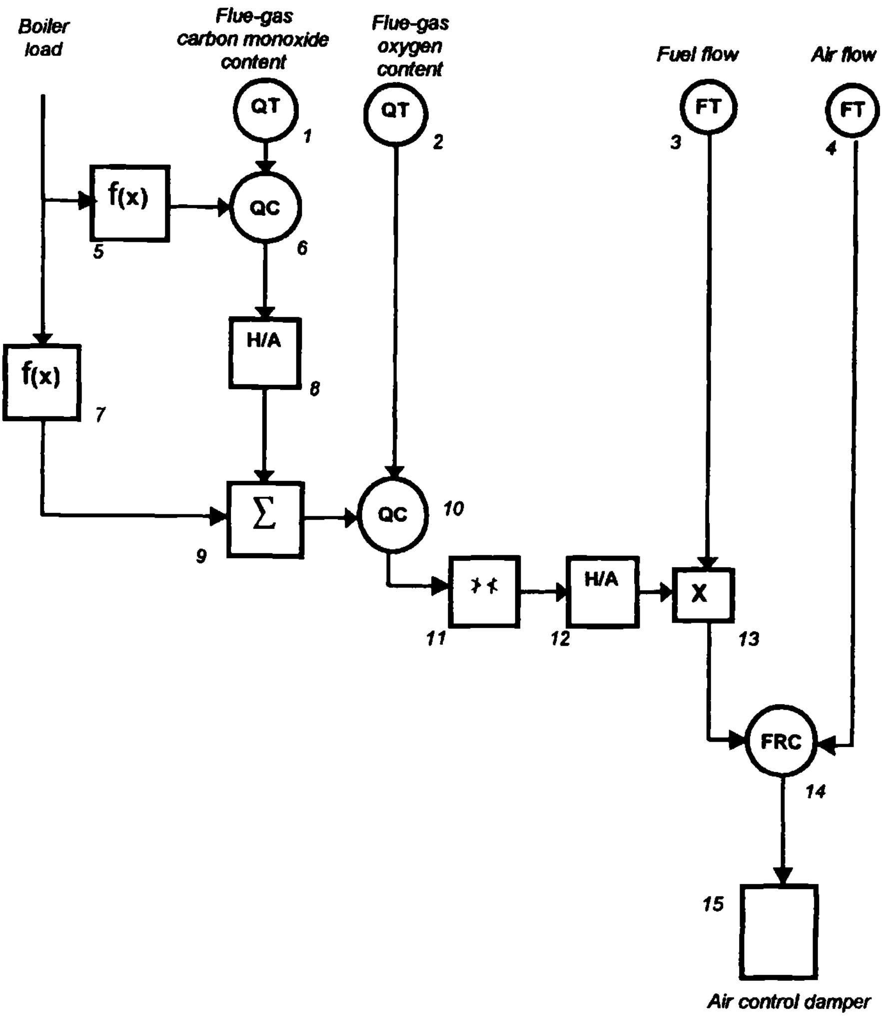

Figure 5.8 Combined CO and O_2 trimming of fuel/air ratio

since any carbon remaining in the ash indicates that incomplete combustion has occurred. Until comparatively recently, accurate online carbon-in-ash sampling was not possible and measurement of this parameter required manual sampling and analysis. With the emergence of online analysers the picture has changed, and tests have indicated that online measurement can play a useful part in optimising the combustion process [3]. In addition, analysis of unburned carbon can indicate whether the coal mills (pulverisers) require adjustment. However, the long transfer-time constants of the combustion process coupled with the comparatively slow response of the instruments and problems of stratification [4] suggest that this technique is only useful for long-term correction of firing, where relatively stable load conditions can be maintained for extended periods.

5.1.4 *Multiple-burner systems*

The systems that have been described so far are based on the adjustment of the total quantity of fuel and air that is admitted to the combustion chamber. This approach may suffice with smaller boilers, where adjustment of a single fuel valve and air damper is reasonable, but larger units will have a multiplicity of burners, fuel systems, fans, dampers and combustion-air supplies. In such cases proper consideration has to be given to the distribution of air and fuel to each burner or, if this is not practical, to small groups of burners. Again, suitable standards have been developed by the NFPA for the design of the plant and control systems of such boilers [5].

The concept of individually controlling air registers to provide the correct fuel/air ratio to each burner of a multiburner boiler has been implemented, but in most practical situations the expense of the instrumentation cannot be justified. Oil and gas burners can be operated by maintaining a defined relationship between the fuel pressure and the differential pressure across the burner air register (rather than proper flow measurements), but even with such economies the capital costs are high and the payback low. The need to provide a modulating actuator for each air register adds further cost.

A more practical option is to control the ratio of fuel and air that flows to groups of burners. Figure 5.9 shows how the principles of a simple cross-limited system are applied to a multiburner oil-fired boiler. The plant in this case comprises several rows of burners, and the flow of fuel oil to each row is controlled by means of a single valve. The combustion air is supplied through a common windbox, and the flow to the firing burners is controlled by a single set of secondary-air dampers.

In most respects the arrangement closely resembles the basic cross-limited system shown in Figure 5.4, with the oil flow inferred from the oil pressure at the row. A function generator is used to convert the pressure signal to a flow-per-burner signal, which is then multiplied by a signal representing the number of burners firing in that row, to yield a signal representing the total amount of oil flowing to the burners in the group.

The system operates in exactly the same way as the basic configuration of Figure 5.4, and it is repeated for each row of burners, so that the ratio of total fuel-oil flow to total air flow entering the boiler is maintained at the desired value. The master demand and the oxygen-trim signals are fed to all the rows to keep the firing rate in step with the load demand and the flue-gas oxygen content at the correct level.

This basic configuration is not restricted to oil-fired boilers. It can also be used with gas-fired plant and it can be applied to systems burning a mixture of fuels, with suitable modifications as will now be described.

5.2 Working with multiple fuels

The control systems of boilers burning several different types of fuel have to recognise the heat-input contribution being made at any time by each of the fuels, and the arrangements become more complicated for every additional fuel that is to be considered.

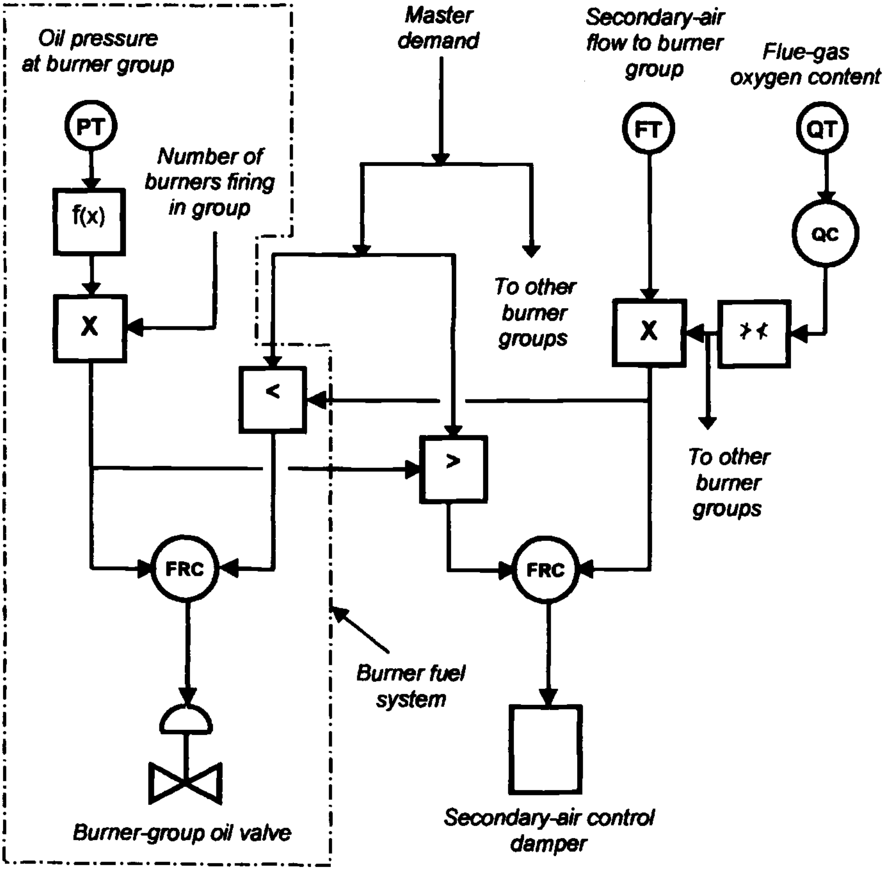

Figure 5.9 A control system for multiple burners (one burner group shown)

Figure 5.10 shows a system for a boiler burning oil and gas. The similarities to the simple cross-limited system are very apparent, as are the commonalities with the fuel-control part of the multiburner system (shown within the chain-dotted area of Figure 5.9).

The cross-limiting function is performed at the minimum-selector block (5) which continuously compares the master demand with the quantity of combustion air flowing to the common windbox of the burner group. The gain block (6) translates the air flow into a signal representing the amount of fuel whose combustion can be supported by the available secondary air.

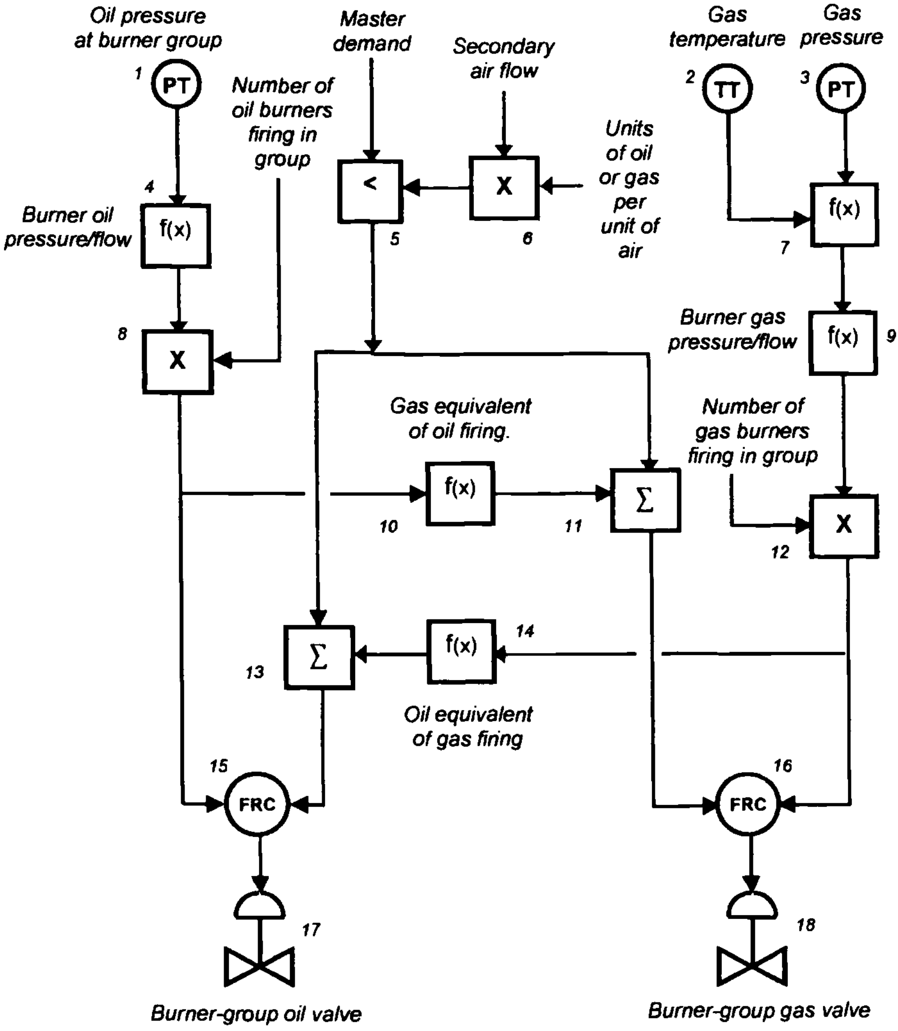

Figure 5.10 Controlling multiple fuels (one burner group shown)

The selected signal (the load demand or the available air) ultimately forms the desired value of both the gas and oil closed-loop controllers. But, before it reaches the relevant controller a value is subtracted from it, which represents the heat contributed by the other fuel (converted to the same heat/m^3 value as the fuel being controlled). The conversion of oil flow to equivalent gas flow is performed in a function generator (10), while the other conversion is performed in another such block (14). Each of the two summator units (11 and 13) algebraically subtracts the 'other-fuel' signal from the demand.

Note that, in the case of this system, the gas pressure signal is compensated against temperature variations, since the pressure/flow relationship of the gas is temperature-dependent.

As before, each fuel-flow signal represents the flow *per burner* and so it has to be multiplied by the number of burners in service in order to represent the total fuel flow.

These diagrams are highly simplified, and in practice it is necessary to incorporate various features such as interlocks to prevent overfiring and to isolate one or other of the pressure signals when no burner is firing that fuel. (This is because a pressure signal will exist even when no firing is taking place.)

5.3 The control of coal mills

So far, we have looked at boilers where the input of fuel can be measured and where its flow can be regulated by means of one or more valves. With boilers burning coal, the mill (or pulveriser) system must be taken into consideration. The mills have already been described in Chapter 3, now we shall look at how they are controlled.

But first it has to be understood that, because the mill has to meet defined performance guarantees, the control strategy to be applied in a given installation must be developed in association with the manufacturer of the mill. Once that strategy has been agreed it must be applied to each of the mills that feed the boiler. The demand is fed in parallel to all the mill sub-systems, with facilities for biassing the signal to any one of them with respect to the others.

5.3.1 The 'load line'

The drop in pressure experienced by air flowing through a mill will be determined by the geometry of the mill, the amount of coal in it and the volume of air flowing through it. Figure 5.11 shows schematically that a

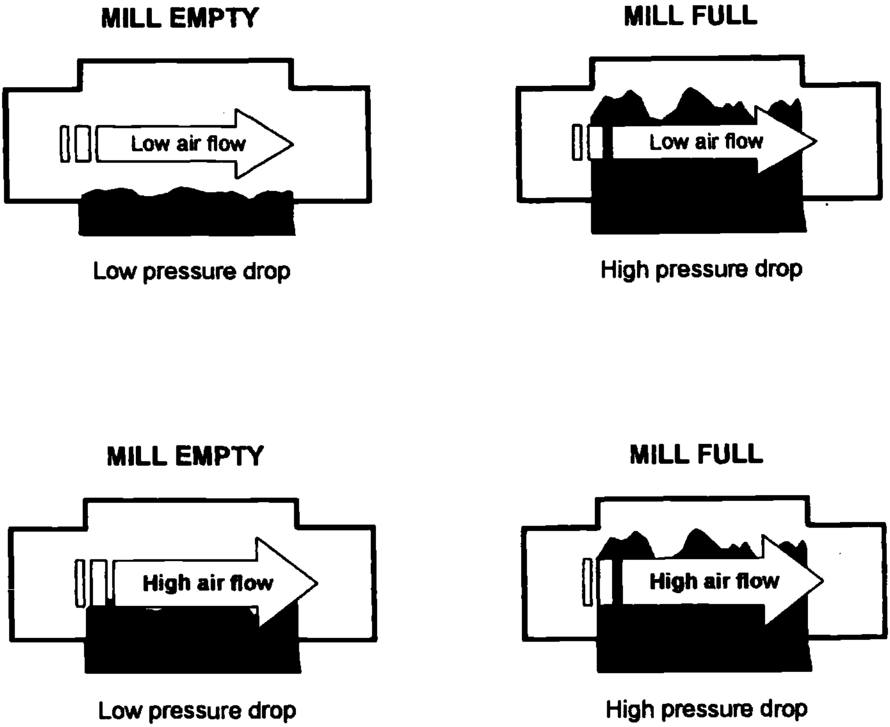

Figure 5.11 Effect of coal load and air flow on cross-mill differential pressure

high pressure-drop across the mill may be the result of a high coal load in the mill or a high air flow through it, or a combination of both. The air-flow rate will bear a square-law relationship to the differential pressure across the mill, and the differential pressure across a restriction such as a flow nozzle or an orifice plate will also have a square-law relationship with the air flow. From this, it can be appreciated that the characteristic curve relating the mill differential pressure and the primary-air differential pressure will be a straight line. This is called the 'load line' and is specific to a given design of mill operating under defined conditions. The manufacturer will define the correct load-line parameters and scales for a given design of mill.

5.3.1.1 Load control strategies for pressurised mills

With pressurised mills, some control systems operate on the principle of comparing the two differential-pressure signals and modulating the feeder speed to keep the relationship between the two in track with the load line, as shown in Figure 5.12. The methods of varying the speed of the feeder include variable-ratio gearboxes or variable-speed motors.

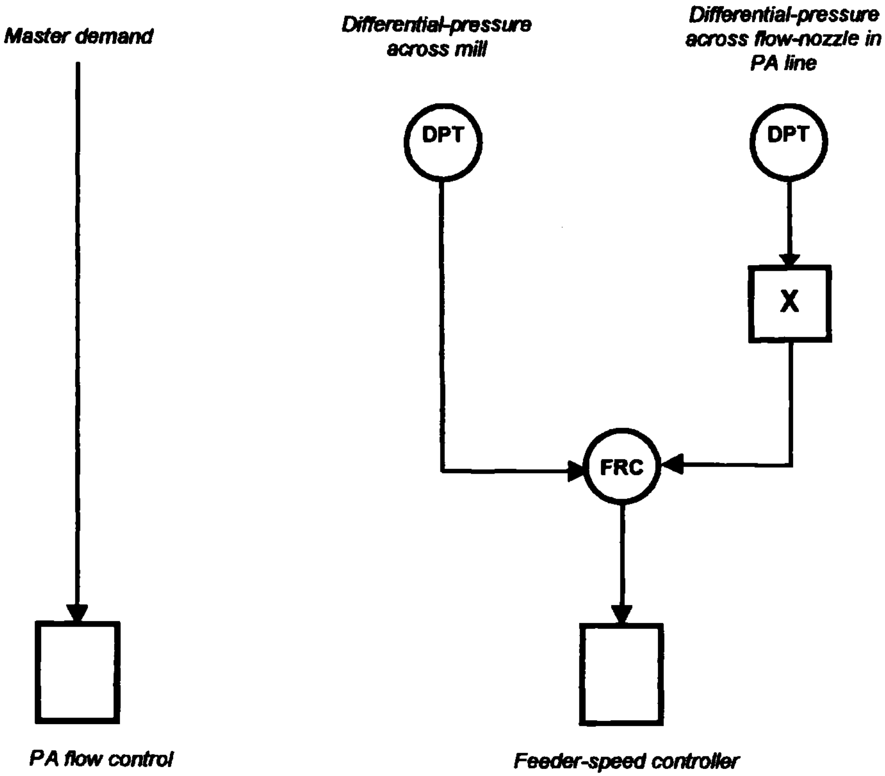

Figure 5.12 *Mill-differential/PA-differential control system*

The speed of the feeder is sometimes fed back to the master system as an indication of coal flow, to provide a degree of closed-loop operation. It is not a perfect solution, since a change in the calorific value of the coal cannot be determined by this system. But, in the absence of reliable and fast systems for measuring the heat input from coal, it is as good as can be achieved.

Although the system described above provides an adequate method of control, it cannot deal with changes in the primary-air (PA) flow caused by external factors. Therefore, if the PA flow changes, the system must wait for the resulting change in steam pressure before a correction can be made.

An approach to overcoming this limitation is to provide closed-loop control of the primary-air flow, as shown in Figure 5.13. Here, because the system detects and immediately reacts to changes in PA flow, and adjusts the flow-control damper to compensate, disturbances to steam production are minimised. Again, a feeder-speed signal, representing fuel flow, is fed

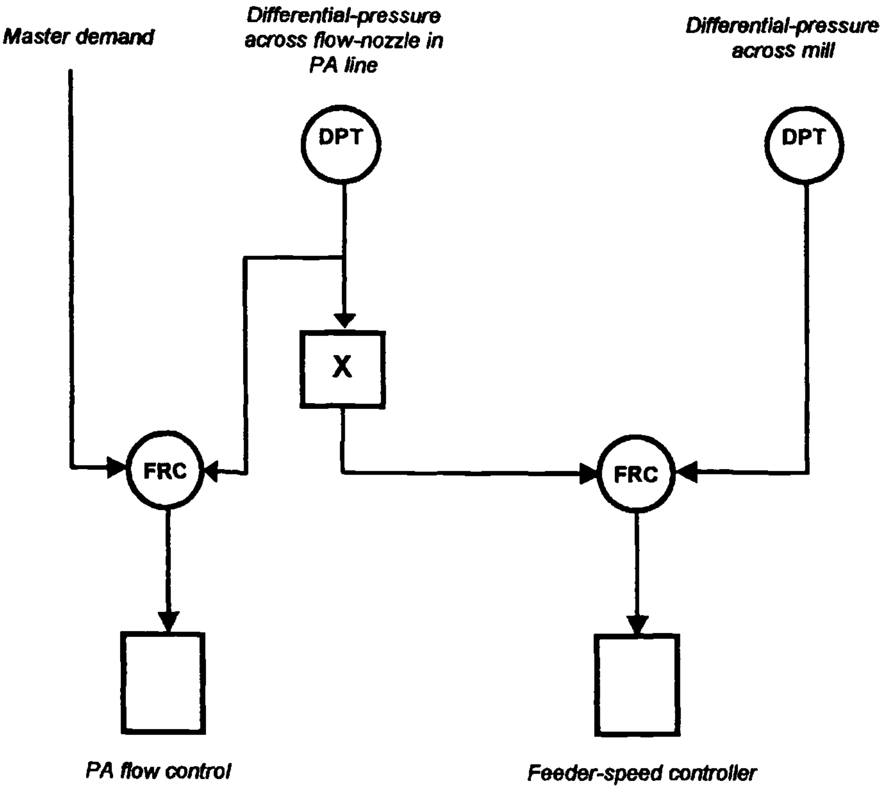

Figure 5.13 Closed-loop control of PA flow

back to the master system to provide closed-loop correction of speed changes, which would otherwise introduce disturbances to the steam pressure.

Both of these systems adjust the feeder speed *after* the PA flow has been changed, and this can lead to delayed response to changes in demand. Figure 5.14 shows a system that adjusts the feeder speed *in parallel with* the PA flow. This also shows some practical refinements: a minimum-limit block that prevents the PA flow from being reduced below a predetermined limit, and a minimum selector block which prevents the coal feed being increased above the availability of primary air (the bias unit sets the margin of air over coal).

5.3.1.2 Load control systems for suction mills

In broad terms, the load-control strategies for suction mills follow similar principles to those of the pressurised mills as described above. A very

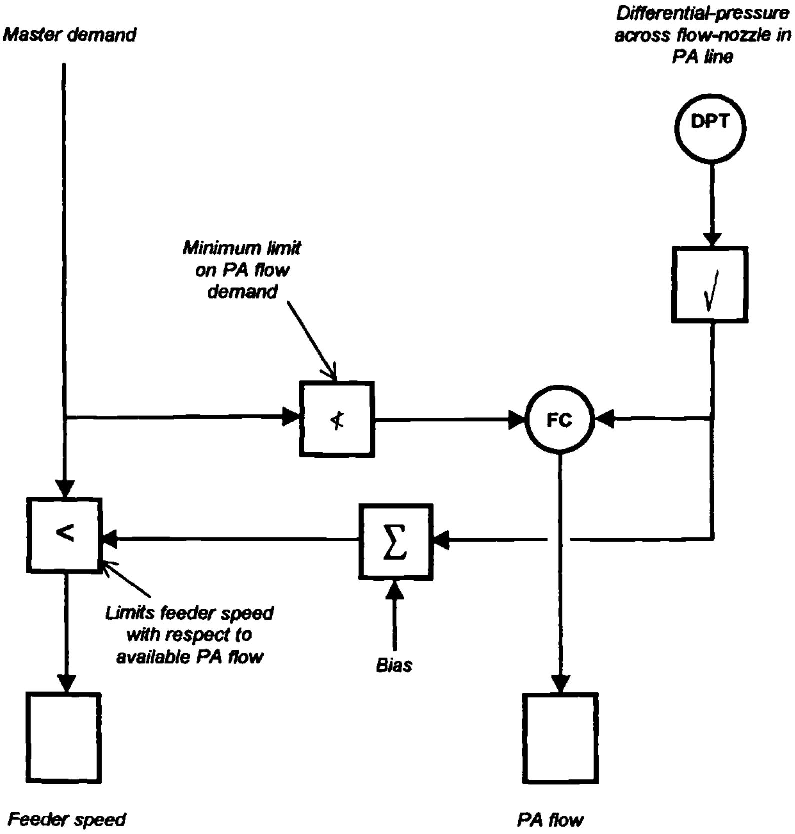

Figure 5.14 *Parallel control of feeder speed and PA flow*

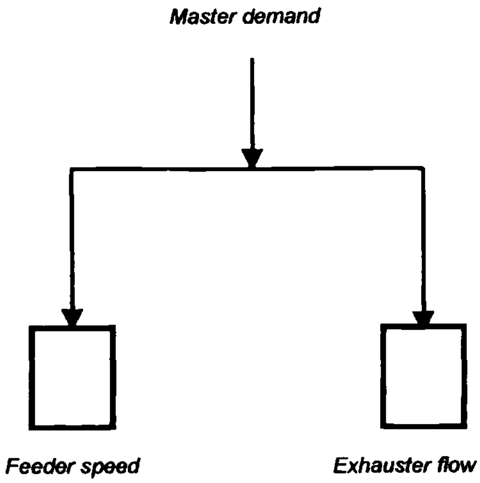

Figure 5.15 *Simple suction-mill control*

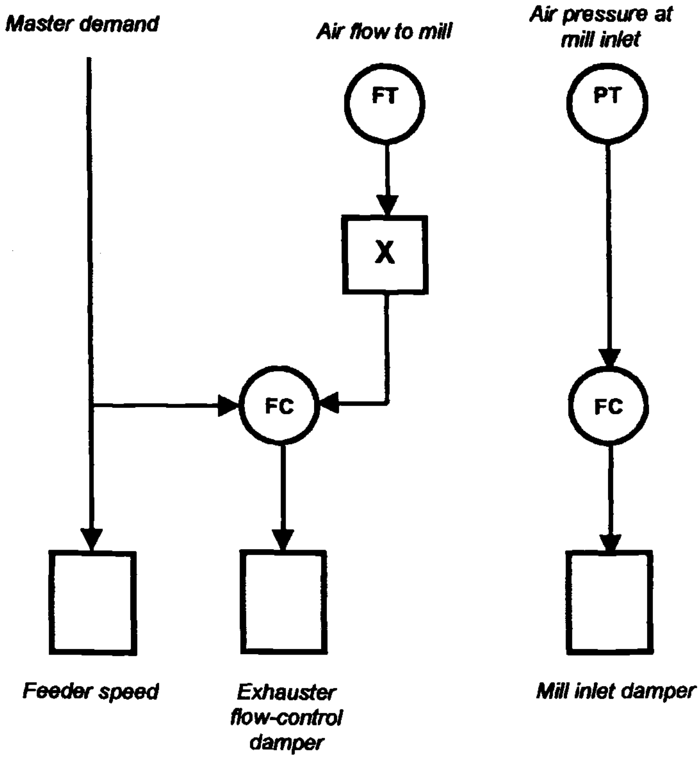

Figure 5.16 Improved control of suction mill

simple technique is to adjust the speed of the coal feeder in parallel with the flow through the exhauster, as shown in Figure 5.15. Here again, the feeder speed is returned to the master system to correct for speed variations that would otherwise disturb the steam pressure.

This system provides open-loop operation of the mill and, once again, improved performance can be achieved by the use of a closed loop around the air flowing through the mill, as shown in Figure 5.16. In this system, an additional control loop maintains a constant air pressure at the mill inlet.

With these systems, it is again necessary to feed back to the master system a signal that represents the input of fuel from the mill to the combustion chamber. Feeder speed provides this function, and thereby minimises steam-pressure disturbances.

5.3.2 *Mill temperature control*

It is very important that the temperature of the air in the mill should be maintained within close limits. For many reasons, including inadequate drying of the coal, combustion efficiency will be reduced if the temperature is too low, while too high a temperature can result in fires or explosions occurring in the mill. The control techniques for both pressurised and suction mills involve mixing hot and cold air streams to achieve the correct temperature. However, whereas pressurised coal mills require the use of two dampers for this purpose (one controlling the flow of hot air, the other the cold air) in a suction mill only one damper needs to be adjusted, to admit more or less cold air into the stream of hot air being drawn into the mill by the exhausters.

Figure 5.17 shows a temperature control system for a pressurised mill, with one actuator provided for the hot-air damper and another for the tempering-air damper.

Sometimes the two dampers are linked mechanically and positioned by a single actuator. The use of two separate actuators adds cost, but allows for a greater degree of operational flexibility since it allows the opening of each damper to be biassed with respect to the other from the central

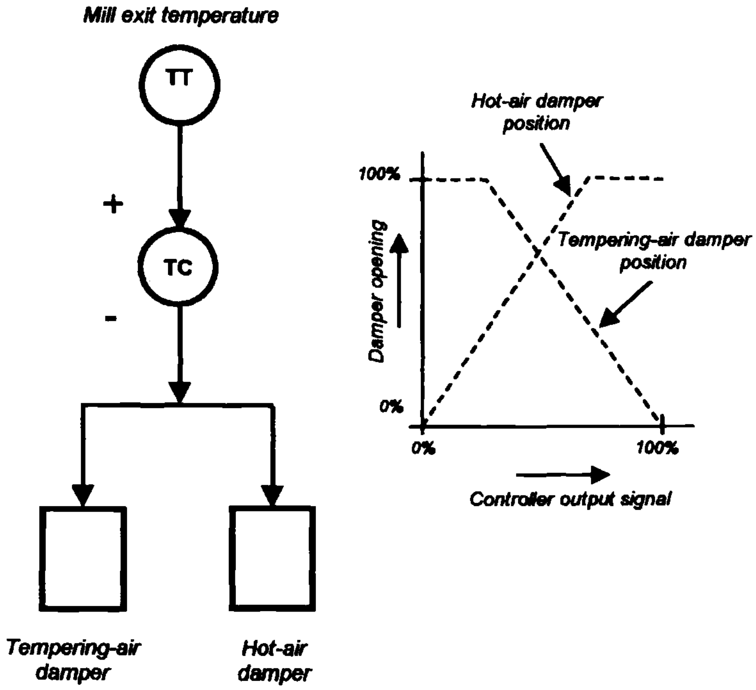

Figure 5.17 Mill temperature control

control room. This enables the operator (or a sophisticated control system) to optimise mill performance whilst still maintaining the mill temperature at the correct value.

5.3.3 Controlling multiple mills and multiple fuels

Large coal-fired boilers are provided with several coal mills, each of which has its own control subsystem as described above, and in addition they invariably burn other fuels as well as coal.

Figure 5.18 shows the mill-control system of such a plant in simplified form. It is presented here to illustrate a requirement that is an integral part of boiler control systems: the need to handle applications where a single controller sends commands to several subloops in parallel, and where any of the subloops may be isolated at will from the controller.

Here, each mill feeds a group of burners (say six), and each of these groups may also fire fuel-oil. Since, at any given time, any mill group may be out of service, operating at a fixed throughput, or otherwise requiring independence from the other groups, the overall loop gain will change, and this is addressed by the gain-compensation block (item 4) in the master-demand signal line. The demand signal from this block is fed to each group via individual hand/auto stations, one for each mill group (item 10).

The output of each of these stations eventually becomes the desired value for the relevant primary-air flow controller (17), but first the heat contribution from any oil burners firing in that group must be taken into consideration. This input is derived from a measurement of the oil pressure at the burners in the group (1), converted to represent the oil flow per burner (by means of function block 2) and then multiplied (4) by the number of oil burners in that group that are firing at the time. The resulting signal is then converted (9) to represent the amount of coal that would equate to that quantity of oil, and this is subtracted from the master demand (block 12) to represent the amount of coal firing that is needed from the group. This firing demand is prevented from falling below a safe predetermined value (minimum-limit block 15).

By accounting for the oil firing, the opening of the primary-air damper is immediately adjusted if an oil burner trips, or if one is brought into service, to compensate for the change, without waiting for the heat-input effects to be detected via the master-pressure controller.

5.3.3.1 The challenge of hand/auto changeover

The heat input from a large coal mill can be as much as 100 MW, but the mechanical design of the mill and its auxiliaries is such that it can vary

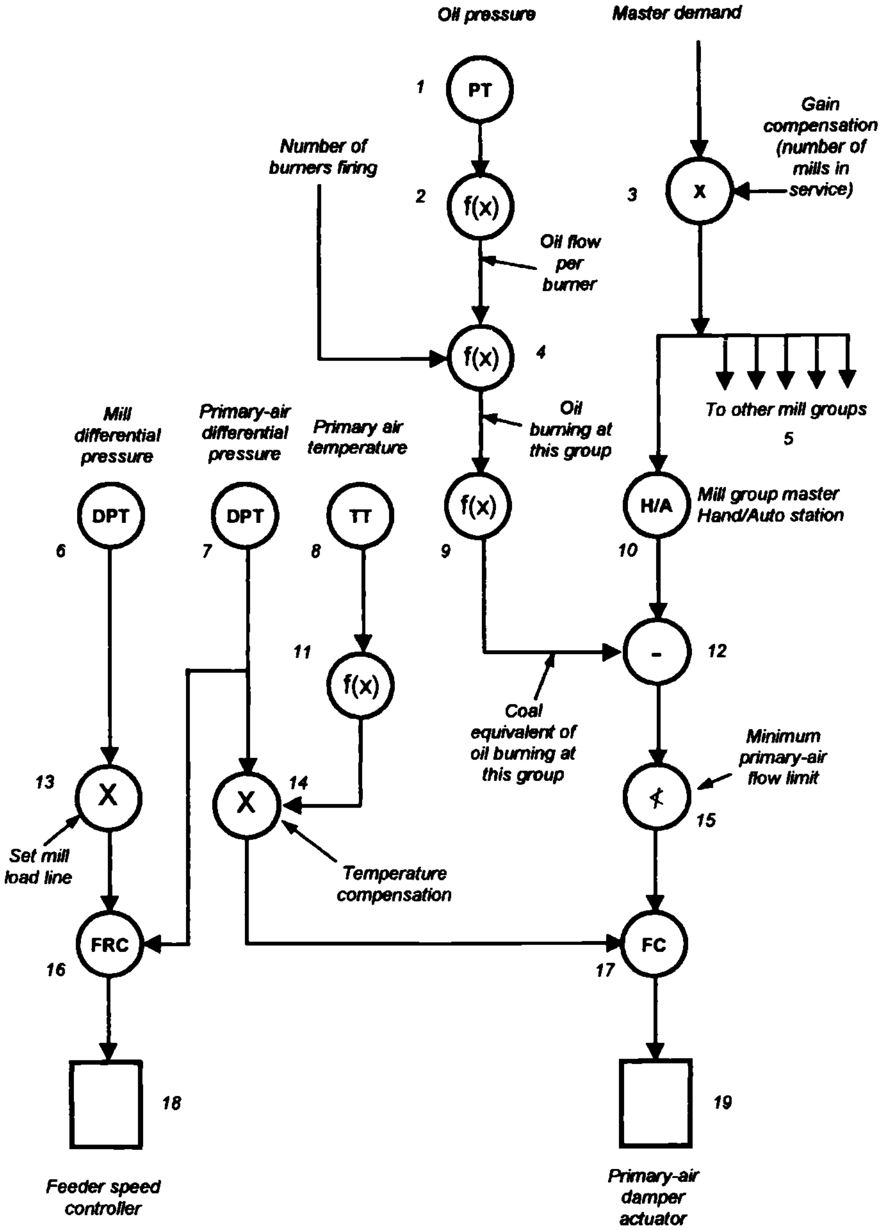

Figure 5.18 *A comprehensive mill control system (one mill group shown, excluding temperature control)*

the throughput by only a comparatively small amount, certainly no more than 50%. Therefore, the introduction of one mill to the heat input of such a boiler amounts to a step change of as much as 50 MW, and the change in throughput that can be smoothly modulated is also 50 MW. Such large step-changes require efficient modulation of any other fuels that are being fired at the same time.

These factors make it impractical to consider starting up more than one mill at a time and require the facility of allowing any mill to be operated under manual or automatic control, independent of the others. This brings about a severe challenge to the DCS software.

The master demand is fed in parallel to several subloops, one for each mill group. On start-up of the plant all of these will be under manual control. When the mill has reached a throughput of roughly 50% of its capacity, or when other conditions determine that automatic control is now possible, the operator will switch the master demand into service. The difficulty is that up to that instant, the system cannot be made aware of which mill group is about to be transferred to respond to the master signal, and each group may be operating at a very different throughput from any other.

While a loop is being transferred from manual to automatic control (or vice versa), it is important that the plant is not subjected to a sudden disturbance. At the moment of changeover, the 'hand' and 'automatic' signals must be equal. This is called 'bumpless transfer', and it can be achieved by providing the operator with indications of both signals so that they can be made equal before changeover is initiated. However, such a system would not be acceptable in most cases, since the process of changing from one mode of control to another should be as quick and simple as possible, and should not require the operator to unduly disturb the operation of the plant.

To achieve what is know as 'procedureless, bumpless transfer' from manual to automatic control, a common technique is to make the controller output follow (or 'track') the manual demand, so that when the system is switched to automatic the signal to the actuator is not subjected to a sudden change.

This is easy enough with a single controller positioning a single actuator, but what happens when one controller commands several subloops as shown in Figure 5.18? It is clearly impossible to force the master controller output to adopt a value that cannot be known ahead of time, or to change the output of the controller if it is already modulating one or more mills.

This problem is frequently not recognised by DCS vendors who have little or no experience of boiler control, and it can be quite difficult to explain it to them. But understanding it and resolving it are absolutely essential if the system is to be expected to operate smoothly and with minimal operator intervention. Various solutions have been developed, such as 'freezing' the master demand while the transfer is effected and gradually ramping one signal up or down to match the other. It is important, however, that the DCS vendor should be able to demonstrate the solution offered within their system, and that they should be able to demonstrate its use on an existing power plant.

5.3.3.2 Complexity of screen displays

In considering the operator displays associated with a system such as that shown in Figure 5.18, attention should be given to the vast amount of information that must be provided. The diagram given here is necessarily simplified, and excludes the many interlocks and other functions that are required in reality. When a practical plant is considered it soon becomes apparent that accommodating the amount of information and control facilities can lead to very cluttered display screens.

Clearly, the mill groups are carbon copies of each other, varying only in respect to the tag numbers of each item and the dynamic information relating to each area of the plant. It is therefore reasonable to display only one group at a time on the screen, allowing it to be started, adjusted or stopped as required. However, to avoid making any mistakes, the operator should be very clearly and unambiguously informed of which group is displayed at any time. Also, a master display should enable the operator to view the status of the entire set of mills feeding the boiler.

The development of these operator displays is therefore unusually demanding and if insufficient time or money is allocated to the performance of this task the results can be at best unwieldy and at worst dangerous.

5.4 Draught control

In Chapter 3 we saw that, in a fired boiler, the air required for combustion is provided by one or more fans and the exhaust gases are drawn out of the combustion chamber by an additional fan or set of fans. On boilers with retro-fitted flue-gas desulphurisation plant, additional booster fans may also be provided. The control of all these fans must ensure that an adequate supply of air is available for the combustion of the fuel and that the combustion chamber operates at the pressure determined by the boiler designer. In a fluidised-bed boiler the air must also provide the pressure required to maintain the bed in a fluid state.

All of the fans also have to contribute to the provision of another important function—purging of the furnace in all conditions when a collection of unburned fuel or combustible gases could otherwise be accidentally ignited. Such operations are required prior to light-off of the first burner when the boiler is being started, or after a trip.

The control systems for the fans have to be designed to meet the requirements of start-up, normal operation and shut-down, and to do so in the most efficient manner possible, because the fans may be physically large and require a large amount of power for their operation (several MW in some cases). In addition, as we saw in Chapter 3, the performance constraints of the fans, such as surge and stall, have to be recognised, if necessary by the provision of special control functions or interlocks.

Chapter 3 also described the methods of controlling the throughput of the fans, i.e. pitch-control, dampers, vanes or speed adjustment. In the present chapter we shall examine how these elements are adjusted to address the operational requirements of the boiler.

5.4.1 Maintaining the furnace draught

Apart from supplying air to support combustion, the FD fans have to operate in concert with the ID fans to maintain the furnace pressure at a certain value. The heavy solid line of Figure 5.19 shows the pressure profile through the various sections of a typical balanced-draught boiler system. It shows the pressure from the point where air is drawn in, to the point where the flue gases are exhausted to the chimney, and demonstrates how the combustion chamber operates at a slightly negative pressure, which is maintained by keeping the FD and ID fans in balance with each other.

If that balance is disturbed the results can be extremely serious. Such an imbalance can be brought about by the accidental closure of a damper or by the sudden loss of all flames. It can also be caused by maloperation of the FD and ID fans. The dashed line on the diagram shows the pressure profile under such a condition, which known as an 'implosion'. The results of an implosion are extremely serious because, even though the pressures involved may be small, the surfaces over which they are applied are very large and the forces exerted become enormous. Such an event would almost certainly result in major structural damage to the plant.

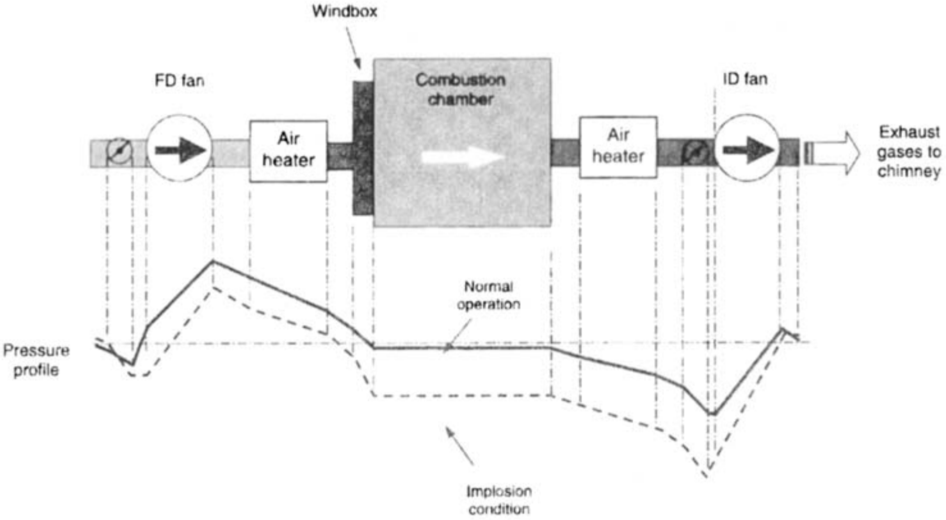

Figure 5.19 Draught profile of a boiler and its auxiliary plant

5.4.2 *Fan control*

The throughput of two fans operating together can be regulated by a common controller or by individual controllers for each fan. Although a single controller cannot ensure that each fan delivers the same flow as its partner, this configuration is much simpler to tune than the alternative, where the two controllers can interact with each other and make optimisation extremely difficult. Whichever option is used, the control system must be designed to provide sufficient air to support combustion.

In the simplest case, the fan or fans will be driven by a cross-limited system (see Figure 5.4), but with multiburner installations the flow must be controlled for each burner or group of burners. The system shown in Figure 5.9 shows how this is arranged by regulating the secondary air flow to each burner group. In such cases this air supply is drawn from a common windbox which is maintained at a pressure which may be fixed or varying with boiler throughput.

Figure 5.20 shows how such a control system can be implemented. The desired-value signal for the pressure controller is derived from steam flow, so that the pressure in the windbox will change over the boiler load range, to a characteristic that will be defined by the process engineer. The

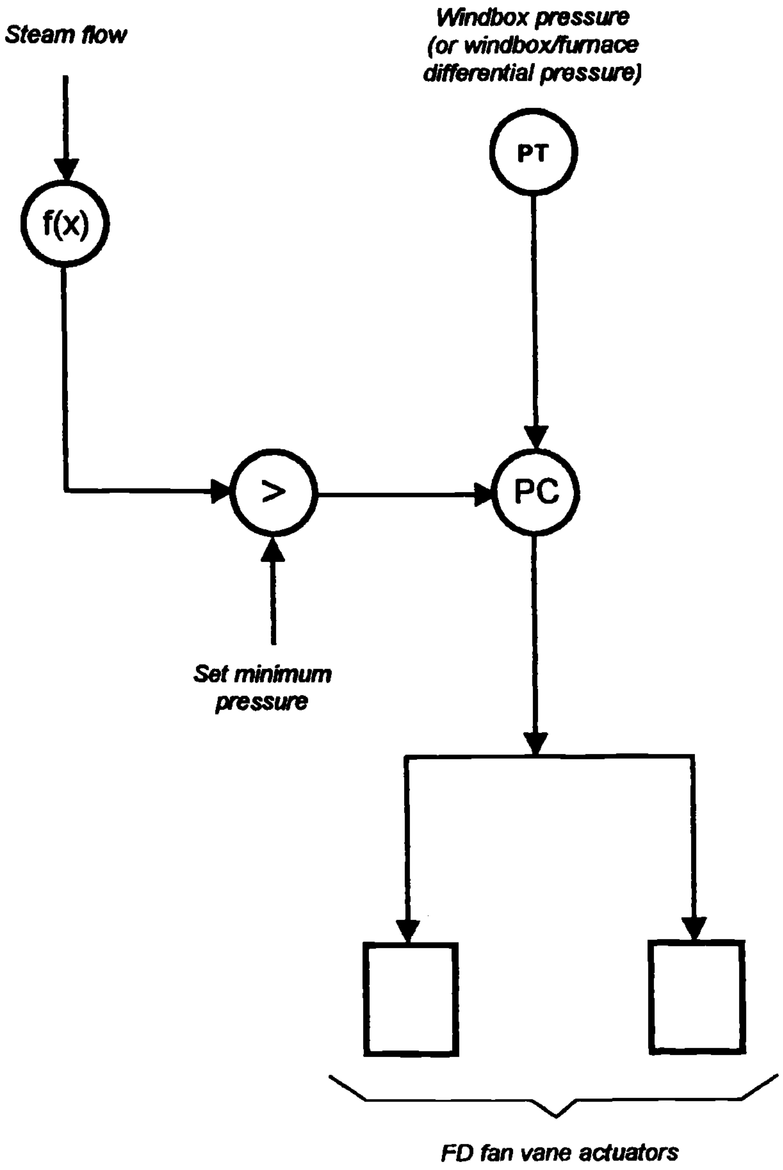

Figure 5.20 *Controlling the windbox pressure*

maximum-selector unit ensures that the pressure-demand signal cannot fall below a predetermined minimum value. The measured value for the controller can be based on a measurement of the windbox pressure or the windbox-to-furnace differential pressure (which is what the boiler designer would probably require).

5.5 Binary control of the combustion system

So far, we have considered only the modulating systems involved with the combustion plant. In practice, these systems have to operate in concert with binary control systems such as interlocks and sequences. The purpose of an interlock is to co-ordinate the operation of different, but interrelated plant items: tripping one set of fans if another set trips, and so on. The purpose of a sequence system is to provide automatic start-up or shutdown of the plant, or of some part of it.

The logic for interlock operations will be defined by the boiler designer and will probably have to comply with some local, national or international standard. The systems are very specific to the particular plant, and no attempt will therefore be made in this book to define these, because the objective here is to provide a general overview of boiler control systems.

However, one topic that we shall look at is burner management since, like modulating loops, this type of system is very dependent on the correct operation of input and output transducers.

5.5.1 *Flame monitoring*

The requirements for a comprehensive burner-management system (BMS) have already been discussed in Chapter 3, and attention was drawn there to the importance of flame monitoring.

Monitoring the status of a flame is not easy. The detector must be able to discriminate between the flame that it is meant to observe and any other in the vicinity, and between that flame and the hot surfaces within the furnace. The detector must also be able to provide reliable detection in the presence of the smoke and steam that may be swirling around the flame. To add to the problems, the detector will be required to operate in the hot and dirty environment of the burner front, and it will be subjected to additional heat radiated from the furnace into which it is looking.

With their attendant BMSs, flame scanners of a boiler are vital to the safety and protection of the plant. If insufficient attention is paid to their selection, or if they are badly installed or commissioned, or if their maintenance is neglected, the results can be, at best, annoying. The problems will include nuisance trips, protracted start-up of the boiler and the creation of hazardous conditions that could have serious safety implications.

Figure 5.21 shows a typical flame detector and the swivel-mounting that enables its sighting angle to be adjusted for optimum performance.

A flame scanner is a complex opto-electronic assembly, and modern scanners incorporate sophisticated technologies to improve flame recognition and discrimination. Although the electronics assembly will be

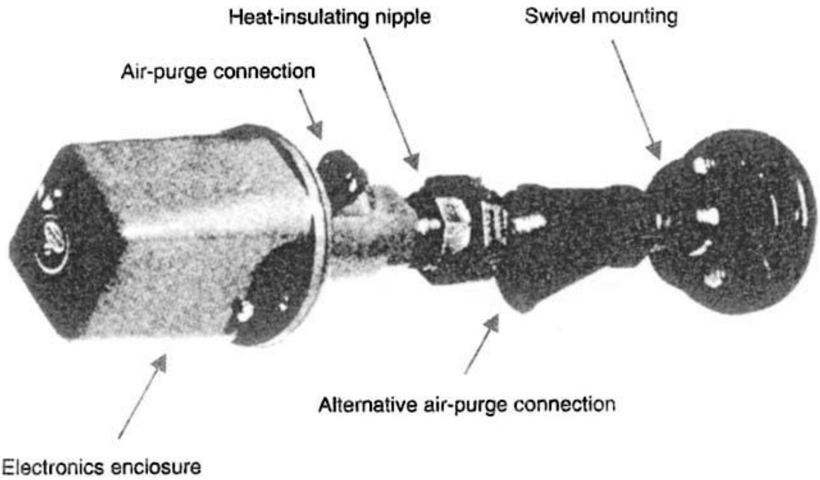

Figure 5.21 *Typical flame scanner*
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designed to operate at a high temperature (typically 65 °C), unless great care is taken this value could easily be exceeded and it is therefore important to take all possible precautions to reduce heat conduction and radiation onto the electronic components. The illustration shows how a heat-insulating nipple is used to prevent undue heat being conducted from the boiler structure to the electronics enclosure. It also shows two purge-air connections that are provided between the electronics enclosure and the swivel mount. Either of these connections may be used, the other being blanked off.

5.5.1.1 The requirements for purge air

The purge air that is supplied to the scanner serves two purposes: it provides a degree of cooling and it prevents dust, oil and soot from being deposited on the optical parts of the unit. The air should be available at each burner, even if the burner itself is not operating.

It should therefore be obvious that the air used for purging should be cool, dry and clean, and that it should be available at all times. But, in many cases these requirements are ignored, and the performance of the instrument is thereby inevitably degraded.

Purge air can be obtained from the instrument-air supply, or it can be provided by dedicated blowers. In some cases it is taken from the FD fan discharge. Each of these is viable, provided the requirements outlined above have been thoroughly considered. It is also important that the presence of the purge-air supply should be monitored and its loss transmitted to the DCS, because failure of the air supply could result in expensive and possibly irreparable damage to the scanners. Modern scanners include self-monitoring circuits that will warn of overheating. The scanner system should be fail-safe, as a failed system represents the loss of a critical link in the plant's safety chain. If it is overridden, the operator can become used to operating without it in place, and such lapses can eventually create a severe hazard.

Figure 5.22 shows an installation which clearly demonstrates examples of neglect, including a broken purge-air connection and a badly misaligned scanner. Unfortunately, in spite of the critical importance of reliable flame monitoring, it is not too difficult to find such examples on operating power plant.

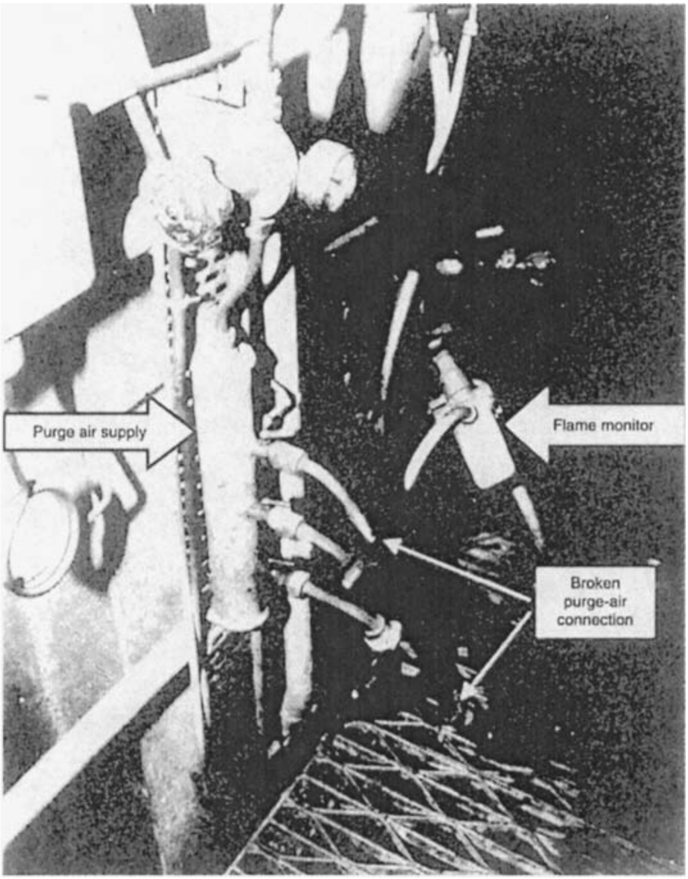

Figure 5.22 Example of a flame-scanner installation

5.5.1.2 *Flame spectra*

The spectrum of radiation from a flame is determined by many factors, including the type of fuel being burned and the design of the burner. The intensity of the flame tends to be low for gas and high for coal and oil. The flame will also flicker and, in general, low-NOx burners will demonstrate a lower flicker frequency than gun-type burners. Oil and coal flames tend to produce a higher degree of infrared radiation, whereas a gas flame is rich in ultraviolet radiation. Radiation in the visible part of the spectrum will also depend on these factors, but these days the tendency is to use detectors whose response is biassed towards either the infrared or the ultraviolet end of the spectrum, since emissions in these ranges provide better indication of a flame than visible radiation, which can be plentiful and misleading.

Each type of fuel also produces by-products of combustion, which affect the transparency of the flame and therefore the blanking effect it has on adjacent flames or on any flames on the opposite side of the furnace. Oil and coal flames tend to obscure infrared radiation, while gas flames produce water vapour which obscures ultraviolet radiation.

Table 5.1 shows one manufacturer's advice on the type of flame scanner to use in various applications. It is not intended that this table should be regarded as being absolute or rigorous. In certain circumstances a given type of flame scanner will provide better or worse performance than would appear to be indicated from the table. Reputable manufacturers will be pleased to provide application-specific guidance. At the design stage this advice will be based on previous experience of similar installations. For a retrofit on an existing plant, the manufacturer should be asked to carry out a comprehensive site survey, using various types of scanner, while the burners are started, operated under various loads, and stopped. Several tests may be required, and a survey may last for several days. The greater the attention that is paid to this study, the better will be the performance of the final installation.

5.5.1.3 *Burner-management systems and plant safety*

The design of the BMS will aim to address critical safety issues, and the sequences for a given type of boiler or burner will be defined in conjunction with the plant designer, bearing in mind the requirements of applicable codes such as NFPA 8502-95. In fact the NFPA standard defines in some detail the exact sequences involved in lighting-off, monitoring and running-down operations of burners, and shows how these are to be linked with the plant interlock systems (for example, ensuring that the furnace has been purged before any attempt can be made to initiate a burner light-

Table 5.1 Flame-scanner application guide
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Boiler type	Fuel type	Discrimination capability	
		Infrared	Ultraviolet
Front-fired	Gas	M	H
	Oil	H	H
	Coal	H	H
	Gas/oil	M	H
	Gas/coal	M	H
	Oil/coal	H	H
	Coal/oil/gas	M	H
Corner-fired	Gas	L	H
	Oil	H	H
	Coal	H	H
	Gas/oil	L	H
	Gas/coal	L	H
	Oil/coal	H	H
	Coal/oil/gas	L	H
Opposed-fired	Gas	L	H
	Oil	M	M
	Coal	M	M
	Gas/oil	L	M
	Gas/coal	L	M
	Oil/coal	L	M
	Coal/oil/gas	L	M

H = high, M = medium, L = low

off sequence). For these reasons, the sequences will not be described here. However, attention will be paid to certain safety-related aspects of BMSs.

Safety requirements are very comprehensively defined in every applicable standard. For example, NFPA 8502-95 describes the events and failures which should be recognised in the design of the system. The UK Health and Safety Executive (HSE) has described [6] in considerable detail the requirements for the safe design of a software-based system (defined as a programmable electronic system (PES)). However, in practice it is very difficult for the nonspecialist to determine whether or not a system is adequately fail-safe. Even using the checklists provided in the HSE document can be inadequate. For example, one item in the checklist asks:

Have adequate precautions been specified to protect against electrical interference in the environment of the PES with regard to:

(i) inherent design of the PES;
(ii) installation practices (e.g.: separation of power and signal cables);
(iii) Electromagnetic compatibility (EMC) test programme, including conducted interference on power supplies, electro-static discharges and radiated interference?

In that it is difficult to say what is or is not *adequate* in this context, this is a subjective assessment. For example, one system surveyed by the author found that the effectiveness of very comprehensive shielding in the DCS of a plant had been negated by the provision of poorly designed access doors.

One solution is to assume that a programmable system will occasionally generate incorrect commands and to therefore ensure that all its operations are continuously shadowed by another, independent, system. If a discrepancy occurs between the actions of the two systems a trip should be initiated or the relevant sequence prevented from being carried out.

5.6 Summary

Having looked at the control systems applying to the combustion and draught plant, in the next chapter we shall turn our attention to the feedwater systems.

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