6. GAS FIRING

6. GAS FIRING

6.1 Introduction

Gas-firing of fluidised combustors for start-up has been used by CSL and its Partners on a routine basis for many of the research rigs listed in Table 2.1 of Section 2. In industrial boiler applications gas fired start-up has similarly been used successfully by CSL Licensees and Partners for start-up of equipment up to 20 MW (70 x 10^6 Btu/h) in size (6.1, 6.2). Fluidised combustors up to this size designed to operate with gas as an alternative main fuel have operated successfully (6.1) and a 30 MW (1 x 10^8 Btu/h) unit fired on coke oven gas is currently being commissioned (6.3).

In all the above, and similar applications, it is desirable that the heat of combustion should be released as far as possible within the fluidised bed so that start-up times may be minimised and so that advantage may be taken of the high heat transfer rates to in-bed surfaces. It has been found that the combustion of gaseous fuels will occur mainly within the bed only when such fuels are fed pre-mixed with air, or at such a large number of ditribution points situated very close to the combustion air inlet nozzles that the fuel and air may be regarded as "pseudo pre-mixed".

In this Section the principles of the combustion of gases in fluidised beds are briefly outlined to explain the need for pre-mixing of the fuel and air and the optimum conditions for gas-fired start-up are discussed. Suitable designs of distributor for gas-firing are also described.

All the information given in this Section is concerned with atmospheric pressure operation. No information is available on pressurised operation of gas-fired fluidised combustors.

6.2 Combustion of Gases in Fluidised Beds

6.2.1 Combustion at operating temperatures

6.2.1.1 Division of gas between phases

The bed of a fluidised combustor consists of a dense phase made up of bed particles fluidised at the minimum fluidising velocity and a bubble phase comprising gas bubbles dispersed through the dense phase. Gas fed to the distributor to fluidise the bed is apportioned between the dense phase and the bubble phase as soon as it enters the bed. Gas in excess of that needed to just fluidise the bed enters the bubble phase. For the usual operating conditions of fluidised combustors the bubble phase will contain 60 - 90 % of the total gas fed. In the short time the bubbles are being formed just above the distributor there may be significant heat and mass transfer between the bubble and the dense phases. Once the bubbles are formed they rise rapidly through the bed and grow through coalescence but, in fluidised combustors, their size is such that there is little interchange of components between the gas in the bubbles and the gas in the dense phase. As a result considerable by-passing of unreacted fuel gas may occur. Gas by-passing can be minimised by increasing the flow through the dense phase. This can be achieved by increasing bed particle size, reducing bubble size or by reducing the operating fluidising velocity.

The usual operating bed temperatures of fluidised combustors are in the range 750 - 950 °C (1380 - 1740 °F) which are above the ignition temperatures of most gaseous fuel/air mixtures. Combustion occurs, therefore, in either or both of the phases. The presence of bed solids in the dense phase and in the bottom portion or wake of each bubble may, however, affect the reaction kinetics of the combustion process.

When conditions are such that bubble formation is complete before ignition occurs the combustion of gas in the bubbles is often characterised by a popping sound as the bubbles burn explosively. This sound is especially evident at low bed temperatures during start-up; its intensity is influenced by the kind of fuel, the mixture strength and the bed temperature and may be much reduced, or eliminated, for fast burning mixtures at full operating temperatures. If the bed temperature is sufficiently high for ignition to occur before bubble formation then a process similar to "incandescent" combustion occurs at the surface of bed particles, two or three particle layers deep, at the bottom of the bed.

6.2.1.2 Significance of pre-mixed gas feeding

If a mixture of fuel gas and air in the correct proportions for complete combustion is fed to the bed via a single distributor then complete combustion may be obtained in the gas in both the bubble and dense phases during its passage through the bed. However, if the fuel gas and air enter through separate distributors there may be insufficient time for complete mixing of the gaseous components during bubble formation and the possibility exists that some bubbles may be either too rich or too lean in fuel to burn completely during their passage through the bed. Combustion would then be completed in the freeboard as it is there that the next opportunity occurs for significant gas mixing.

The above picture suggests that the in-bed combustion efficiency will be dependent on the spacing of the fuel and air entry points when separate distributors are used for each. Confirmation of such a dependence is provided by experimental results for a combustor with separate sparge pipe distributors for the fuel and air (6.4) and by computer model studies of the action of sieve tray distributors using adjacent holes for fuel and air (6.5). It is, however, possible to achieve high in-bed combustion efficiencies when the fuel and air are fed separately provided the distribution system for each is designed to feed the two components in the proper proportions at points very close to each other at the base of the bed. Such a system is termed here "pseudo pre-mixed".

From the foregoing it is clear, therefore, that a pre-mixed or "pseudo pre-mixed" feeding system is to be preferred for those applications where it is desired that the heat of combustion should be released as far as possible within the bed of the combustor.

6.2.1.3 Bed depth for complete combustion

The bed depth needed merely to complete the combustion of pre-mixed gases is quite low. Experimental studies have shown that a combustion efficiency of 99% can be obtained with propane/air mixtures in a 100 mm (4 in.) diameter fluidised combustor within a bed depth of 30 mm (1.2 in.). (6.6). It is also reported that complete combustion of natural gas/air mixtures can be obtained in beds only 25 mm (1 in.) in depth (6.9). Depths of a similar order have been calculated for the complete combustion of methane/air mixtures at 850 °C (1520 °F), (6.7).

The operating bed depths will normally be greater than these low values required to ensure complete in-bed combustion and will be determined by other considerations, such as in-bed heat transfer requirements.

When the fuel and air are fed to the combustor separately the necessary bed depth to complete the combustion depends mainly on the distribution system. If "pseudo pre-mixed" conditions are not provided then combustion may not be complete in beds 1 m (3 ft) or more in depth because of the low rates of gas mixing between ascending bubbles and the dense phase gas.

6.2.1.4 Combustion rates and bed particle effects

It has been shown that the rate controlling step in the high temperature oxidation of gaseous hydrocarbons is the oxidation of carbon monoxide. By assuming,

(i) that the combustion is a homogeneous gas phase reaction, and
(ii) that the reaction temperature is the same as the bed temperature,

and using a correlation for the rate of CO oxidation developed by Hottel (6.8) it has been shown that the combustion of pre-mixed methane/air mixtures at 850 °C (1520 °F) should be completed in a bed depth of 20 mm (0.8 in.) (6.7). The further assumption that the average gas velocity is the same as a typical fluidising velocity of 1.2 m/s (4 ft/s) shows that an average reaction time of 16 milliseconds is needed. This time agrees well with estimates in the range 6 - 22 milliseconds calculated from experimental results for the time to complete 90% of the combustion of natural gas in a fluidised combustor operated at 1020 °C (1865 °F).

The combustion of hydrocarbons is known to be a chain process and the presence of the bed particles could alter the reaction kinetics. It is possible that they could either,

(a) speed up the combustion reactions or,
(b) slow them down by providing surfaces for heterogeneous chain termination reactions.

Currently, experimental evidence is conflicting (6.4, 6.7) and it is not possible to decide between these alternatives. The agreement between calculated and experimental reaction times and bed depths for complete combustion quoted above suggests that the overall effects of the presence of the particles may be small. If the combustion process were speeded up the combustion zone at the base of the bed would be greatly reduced and the combustion intensity greatly increased so that some sintering of bed solids might be anticipated. These conditions are most likely to occur when operating under pressure. In pressurised applications there will be some limiting pressure above which the gas flow required to maintain a given bed temperature results in unacceptably high combustion intensities at the base of the bed.

The presence of hot bed particles provides a continuing supply of ignition sources during combustion. One result of this is that the lower limit of flammability of gas mixtures is decreased so that mixtures which are otherwise too weak to ignite can be burnt readily in a fluidised combustor. It was observed during the combustion of natural gas/air mixtures (6.9) that mixtures as weak as 3.7% v/v natural gas could be burnt. The usual lower flammability limit is 4.7% v/v. In general, provided sufficient heat is available to maintain a high enough bed temperature either as preheat or through the combustion of an alternative fuel, it is possible to burn any combustible gas or vapour, irrespective of its concentration, in a fluidised combustor.

6.2.1.5 Effect of bed temperature on combustion efficiency

The overall combustion efficiency for the combustion of pre-mixed gases is normally high (> 99%). Provided that some excess air (of the order of 10%) is present the combustion efficiency is mainly influenced by the bed temperature. An illustration of the effects is given in Figure 6.1 which shows the variation of combustion efficiency with bed temperature found for the combustion of pre-mixed propane/air mixtures. The data of Figure 6.1 was obtained from a 0.3 m (12 inch) diameter rig with a cooled freeboard (6.10) so the absolute values of combustion efficiency are likely to be low. The loss in combustion efficiency is mainly due to unburnt carbon monoxide in the waste gases.

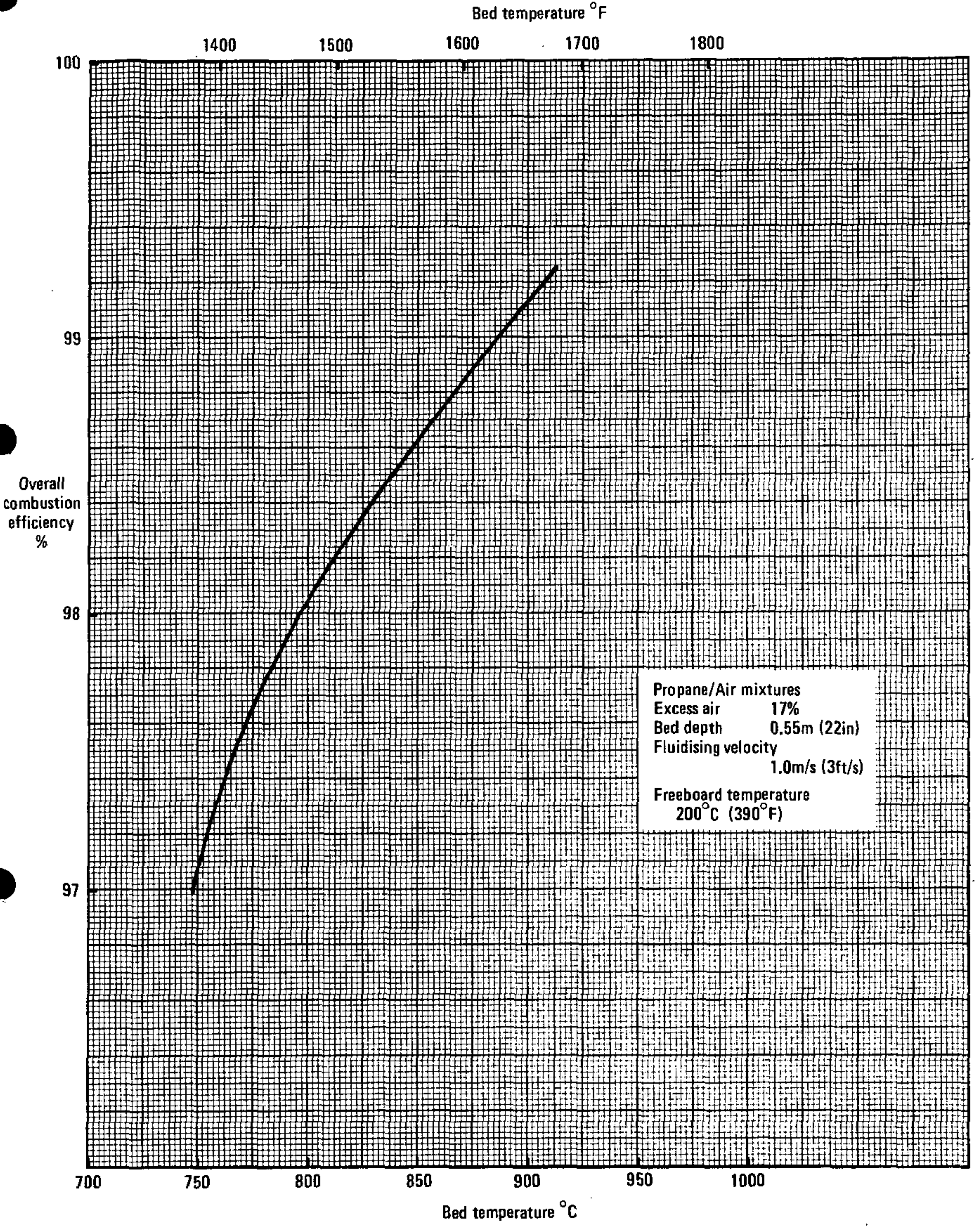

Figure 6.1
Effect of Bed Temperature on Overall Combustion Efficiency

6.2.2 Start-up from cold

6.2.2.1 Sequence of events

The sequence of events when pre-mixed gas is introduced to the base of a bed of cold particles with an ignition source above the bed surface is as follows. The mixture will first ignite above the bed irrespective of whether the bed is static or fluidised by the incoming gas. Once ignition has been achieved the pre-mixed flame may stabilise at, or at some distance above, the bed surface. The precise location of the flame depends on the temperature, the mixture strength and the velocity profile of the gases above the bed surface. Radiation from the flame will then heat the bed surface. As a fluidised bed is raised in temperature from cold to normal operating values there is, approximately, a 4-fold increase in the gas volume. The cold gas supply, therefore, may or may not be sufficient to fluidise the bed. Assuming that the gas supply is sufficient to fluidise the bed when hot, the uppermost layer of the bed is either already fluidised or will begin to fluidise on heating. When fluidised the heat transfer rates will be increased through the action of bed solids splashing through the flame and transporting heat back to the bed. Provided a flame stabilises close to the bed surface, then the gradual heating up of the bed provides pre-heat to the mixture approaching the flame, and ensures that the flame actually settles onto the bed surface. The bed then heats up quickly as the combustion zone (a recognisable "flame" no longer being present) traverses down through the bed. Eventually as all the bed material heats up to 100 - 200 ^{o}C (180 - 360 ^{o}F) above the auto-ignition temperature the combustion zone occupies only a shallow region [about 20 - 30 mm (0.8 - 1.2 in.) see Section 6.2.1.3] above the distributor. Combustion then proceeds as described in Section 6.2.1 above.

6.2.2.2 Conditions for optimum start-up

The start-up time can be minimised if three conditions are met

(i) The start-up gas mixture flow is such that the bed is initially static but becomes fluidised at the operating bed temperature.

(ii) Only a minimum of in-bed heat transfer surface is covered by the expanded bed when fluidised by the start-up gas flow.

(iii) The initial flame in the freeboard becomes stabilised at, or close to, the bed surface.

A UK Patent No. 1 159 310 (6.11) covers a gas-fired start-up process operated according to condition (i).

The importance of condition (ii) should not be overlooked by the designer. At start-up it is necessary to provide a flow of coolant to protect any in-bed cooling surfaces from over-heating. If the bed which is being raised to operating temperature expands to cover these in-bed cooling surfaces then much of the heat provided for start-up will not serve to raise the bed temperature but will leave via the in-bed surfaces. In extreme cases the start-up time may be unduly prolonged, or an unduly high consumption of fuel may be needed for start-up, or it may be impossible to raise the bed temperature to the ignition temperature of the main fuel.

The attainment of a stable flame at the bed surface as required by condition (iii) is discussed below.

6.2.2.3 Flame stability at the bed surface

For a given gaseous fuel the location of a stable flame depends on the velocity of gases through the combustor, the mixture strength and the bed temperature. In practice the distinction between the flame stabilising at the bed surface and the flame "blowing off" is very clear. A reduction of fuel flow (i.e. reducing mixture strength) to a stable flame can cause it to "blow-off" the bed surface.

Experiments have been carried out at CURL using a 100 mm (4 in.) diameter quartz combustor to determine the conditions for obtaining a stable flame using pre-mixed propane/air mixtures (6.12). A bed depth of only 50 mm (2 in.) was used so the bed was essentially isothermal. The results obtained are summarised in Figures 6.2 and 6.3.

In Figure 6.2 operating conditions represented by a point below any line will lead to a stable flame at the bed surface while conditions represented by a point above any line will cause "flame blow-off". The Figure shows that increasingly lean mixtures, at a given mixture velocity, can be tolerated as the bed temperature increases before "blow-off" occurs. The data should not be extrapolated to higher temperatures as the experimental excess air levels causing

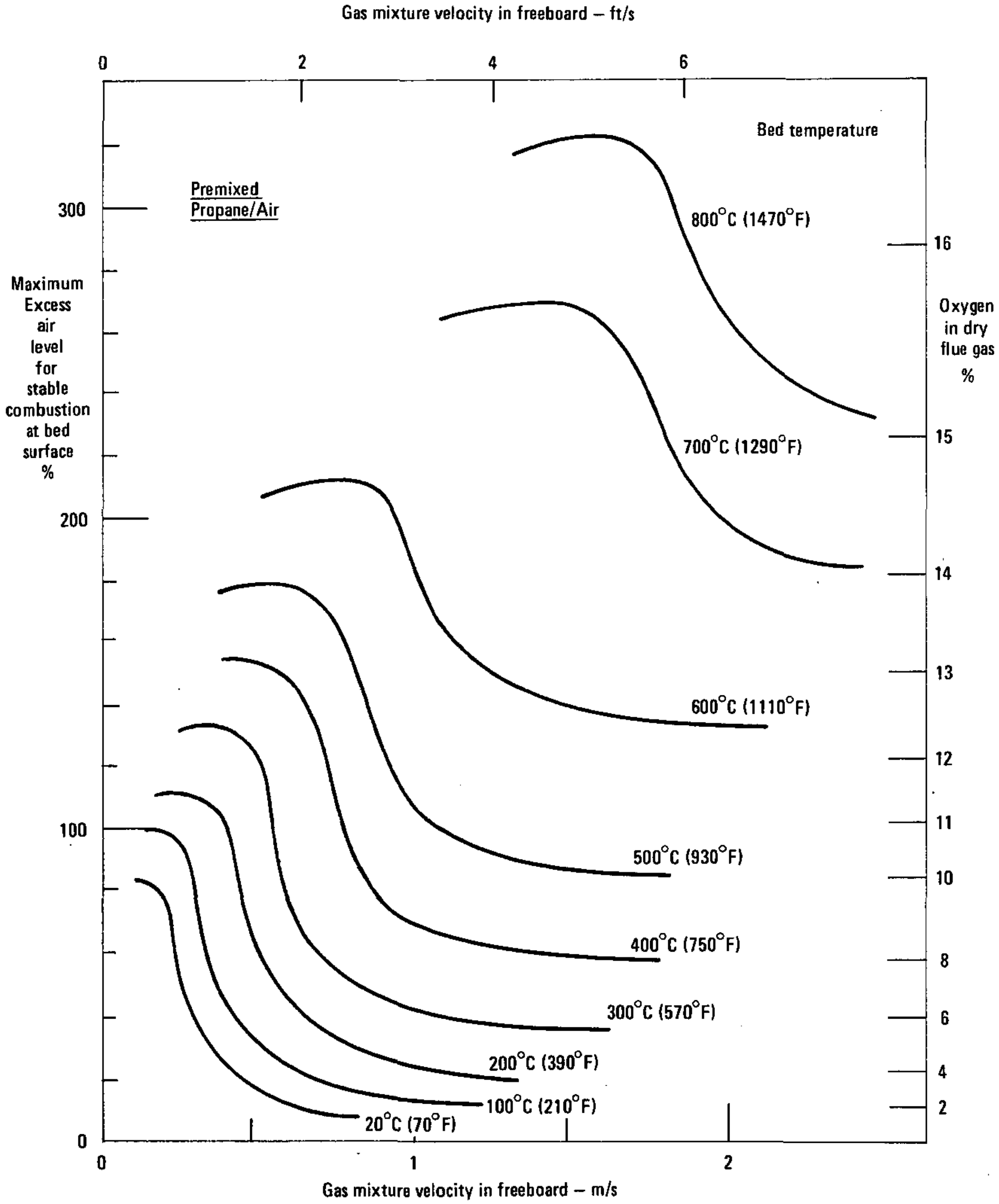

Figure 6.2
Effect of Combustion Parameters on Flame "Blow-off" Limits

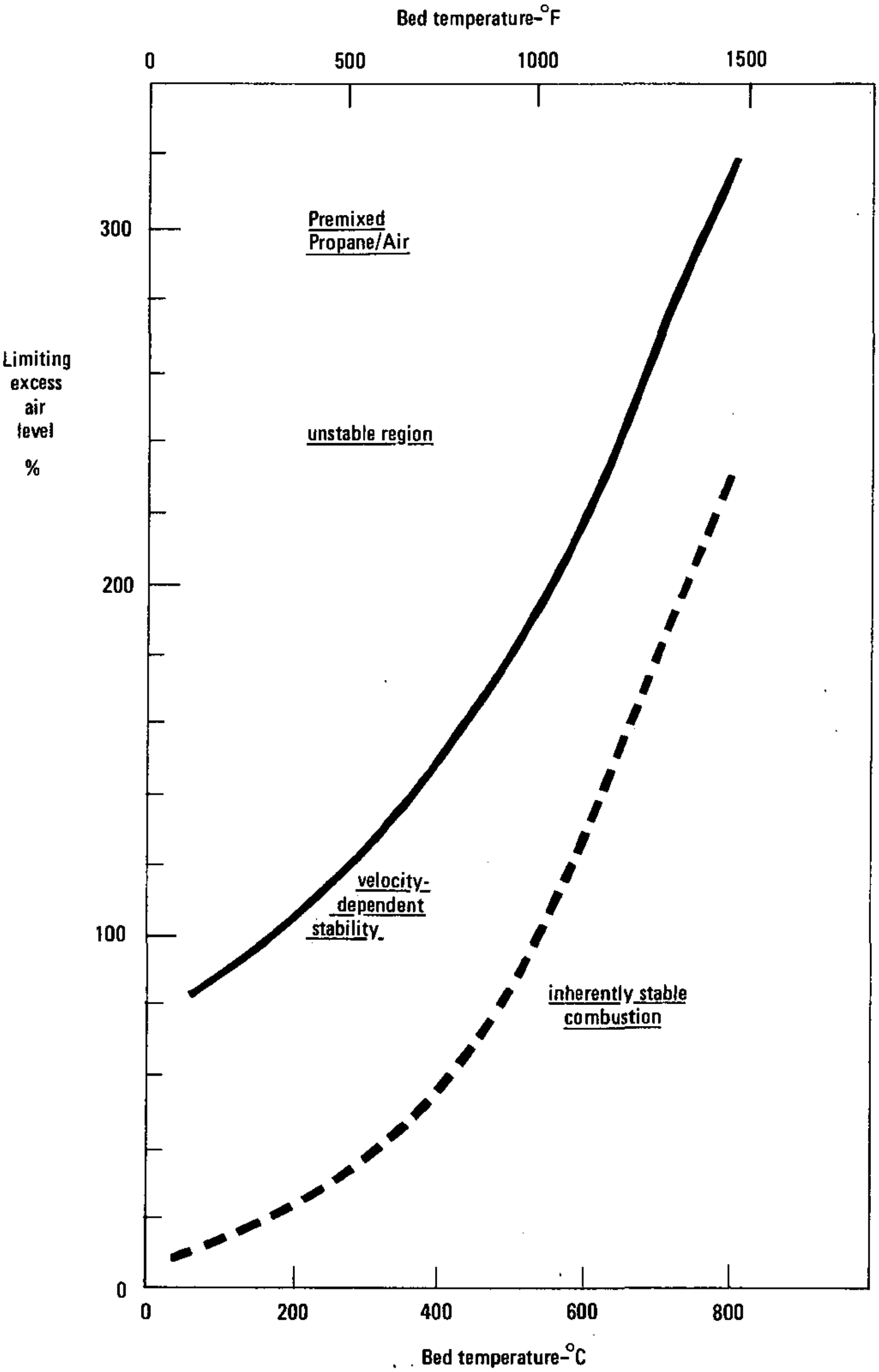

Figure 6.3
Flame Stability Limits

flame "blow-off" appeared to be approaching an asymptotic value at bed temperatures over 800 °C (1470 °F). Increases in the mixture velocity (which is the same as the fluidising velocity in the bed) should be matched by an increase in the mixture strength to avoid "blow-off" but for each temperature there is a value of excess air below which flame stability is always assured for the full range of velocities investigated [0.2 - 2.5 m/s (0.6 - 8 ft/s)]. Also for each temperature there is a value of excess air above which a stable flame cannot be supported. These regions of flame stability are shown on the graph of excess air versus bed temperature plotted in Figure 6.3.

In any particular combustor the internal components located in the bed might either help or hinder flame stability. It is recommended, therefore, that operation should be in the "inherently stable region" shown in Figure 6.3 to obtain a stable flame at the bed surface. Operation in the "inherently stable region" implies initial operation at relatively low excess air levels which will also be desirable to minimise sensible heat losses during start-up.

It is probable that the combustion of air with fuel gases other than propane would give flame stability limits that are similar, qualitatively, to those of Figure 6.3. Currently, quantitative data is only available for propane/air mixtures.

6.3 Gas Feeding Equipment

6.3.1 Distributor designs

Figures 6.4 and 6.5 show two designs of gas and air distributors that have been used successfully for gas-fired fluidised combustors (6.1 - 6.3). In Figure 6.4 the design shown is fitted with a gas plenum and a small hole is drilled in each air nozzle to produce a pre-mixed gas/air flow from the nozzle exit holes. A suitable diameter for the hole which admits fuel gas to the air nozzle is often about 3 mm ($\frac{1}{8}$ in.). The diameter should be chosen so that the gas velocity through the hole is considerably in excess of the flame speeds of any possible air - fuel gas mixtures. Flame speeds are often of the order of 1 m/s (3 ft/s). This design can with advantage be used with oil-firing nozzles incorporated with some of the air nozzles (see Figures 15.6 to 15.8 on pages 17 to 19 of Section 15) so that the distributor becomes suitable for multi-fuel applications.

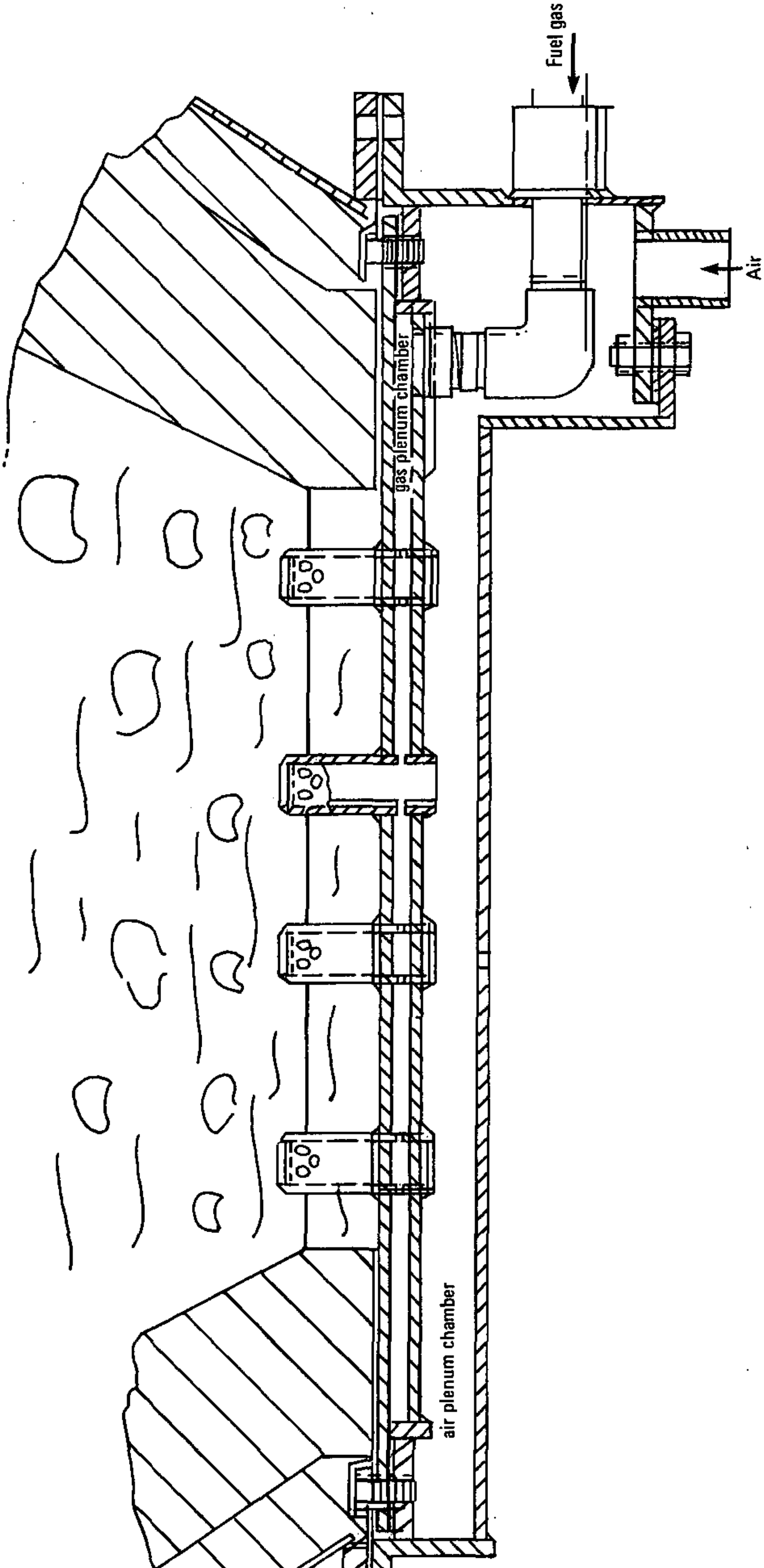

Figure 6.4
Pre-mixed Gas Distributor: Design with Gas Plenum

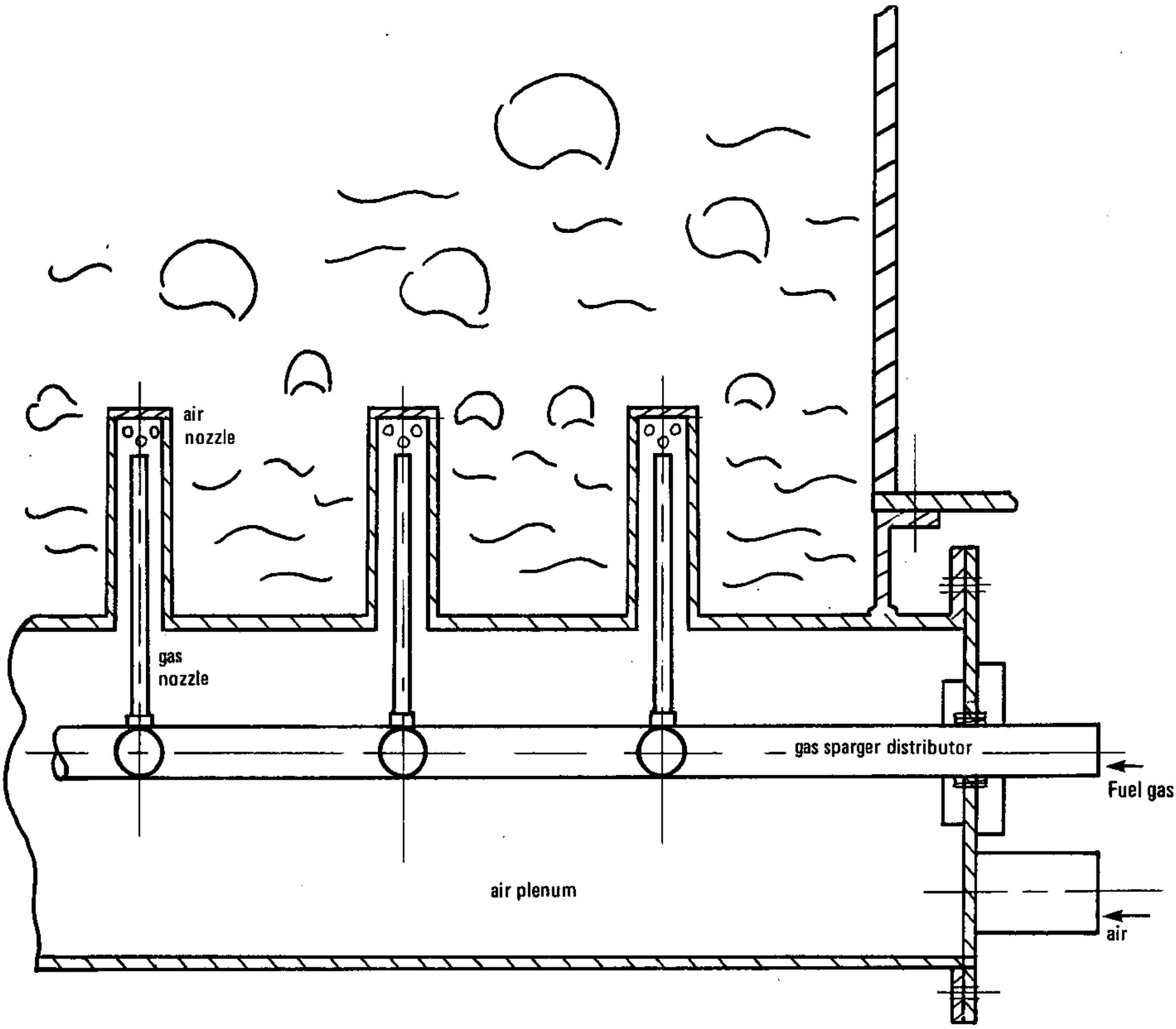

Figure 6.5
Pre-mixed Gas Distributor:
Design with Individual Supplies to Air Nozzles

Figure 6.5 shows a design with individual gas supply tubes to each air nozzle and is suitable for use with sparge pipe distributors.

It should be noted that the use of distributor designs as shown in Figures 6.4 and 6.5 for fluidised beds offers several advantageous features. The plenum chambers and the distributor plate itself operate at a relatively low temperature as they are covered by an insulating layer of static bed particles and are cooled by the incoming combustion air. The gas plenum volumes are kept to a minimum and the velocity of the gas/air mixture entering the bed through the final holes of the nozzles is high compared with the speed of any flame front. All these features, together with the cooling action of the bed particles in lowering the combustion temperature, make for safe stable operation of gas-fired fluidised combustors.

6.3.2 Ancillary equipment

Additional equipment and operating procedures are required in all gas firing applications to ensure safe operation at all times. These additional features include,

(a) an above bed ignition source complete with its own flame proving facilities, safety interlocks, etc. which should remain in operation during any gas-firing period.
(b) the need to purge all lines with an inert gas before any fuel gas supply is turned on.
(c) initial start-up using a low gas flow for a restricted bed area
(d) additional above bed flame detectors
(e) equipment for the detection of fuel gas in the distributor air plenum
(f) automatic operation of the start-up routine
(g) provision of non-return valves, flame traps, shut-off valves, etc. in each gas supply line.
(h) equipment for the detection of combustibles in the off-gas.

The extent to which an individual application requires all the above features will depend primarily on its scale of operation and on the requirements of any safety standards. In considering suitable ancillary equipment it should be borne in mind that gas-firing may sometimes cause appreciable vibration, particularly during start-up, because of the explosive combustion that occurs in the gas bubbles. The explosive combustion in the bubbles can also bring about bed particle degradation and initially high particle elutriation rates.

6.4 Combustion of Dilute Gases and Vapours

In some processes it is desirable to burn mixtures that are so dilute that they are not only below the lower limit of flammability but also have such a low calorific value that their combustion on their own would be unable to maintain the bed at the operating temperature. Typical examples of such materials are refinery tail gases and waste gases from oil shale treating plants.

A fluidised combustor is ideally suited for the combustion of such materials. The presence of the hot bed solids provides continuing ignition sources and an auxiliary fuel can be fed to maintain the heat balance.

In such applications it will be necessary to feed the dilute fuel gas to the bed pre-mixed with air to ensure complete combustion. However, as such a mixture cannot ignite outside the bed some simplifications may be possible in the additional features normally necessary for gas-firing.

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