2. INTRODUCTION

2 INTRODUCTION

2.1 Fluidised Combustion and its Advantages

In fluidised combustion fuel is introduced and burnt in a bed of inert material fluidised with air. The bed temperature is normally maintained in the relatively low range of 750 - 950 ^{o}C (1380 - 1750 ^{o}F) which has the advantage of eliminating the formation of slag or clinker and greatly reduces the volatilisation of alkali salts. Furthermore it is the temperature range within which the reaction of sulphur dioxide with limestone or dolomite is most effective and lower than the temperature at which substantial quantities of oxides of nitrogen are formed.

To maintain the bed at the operating temperature the heat of combustion is removed as sensible heat in the exit gases, by means of heat transfer tubes immersed in the bed, by surfaces surrounding the bed, or by any combination of these methods. In-bed cooling is especially effective as the heat transfer coefficients obtained can be as much as 10 times those in conventional equipment using gas to tube heat transfer. These high coefficients may make reductions in combustor size possible.

Fluidised combustion can be carried out at either ambient or elevated pressure; when the latter, equipment for energy recovery from the combustion gases is needed but further advantages in size reduction are possible compared with ambient pressure operation. Low grade and dirty fuels in any physical form are readily handled and additives may be introduced into the bed to retain a significant portion of the sulphur released by the fuel. In short, therefore, fluidised combustion systems can be more versatile, more environmentally acceptable and more compact than conventional systems.

2.2 Process Design Manual Basis

This Manual is based on research work carried out since 1964 by the National Coal Board, the British Coal Utilisation Research Association (now the National Coal Board Coal Utilisation Research Laboratory), the British Petroleum Company Limited, and on the ongoing development programme and collations of Combustion Systems Limited.

Table 2.1

Main Features of the Principal Fluidised Bed Units Used

Location		CRE				
Bed size	m	0.9 x 0.9	0.9 x 0.45	0.3 x 0.3	0.15 dia	1.5 dia
	ft	3 x 3	3 x 1.5	1 x 1	0.5 dia	5.0 dia
Slumped bed depth	m	0.4 - 0.6	0.8 - 1.4	0.4	0.2 - 0.8	0.3 - 0.6
	ft	1.3 - 2	2.7 - 4.3	1.3	0.7 - 2.7	1 - 2
Operating pressure	kN/m^2	100	100	100	100	100
	abs.atm	1	1	1	1	1
Fluidising velocity	m/s	0.6 - 1.2	up to 2.3	0.9	0.6 - 0.9	0.9 - 1.2
	ft/s	2.0 - 4.0	up to 7.3	3.0	2.0 - 3.0	3.0 - 4.0
Fuel		coal	coal	coal	coal	coal (slurry)
Total run time	hr	9000	400	12000	2000	3000

Location		CRE		
Bed size	m	0.15 dia	0.5 x 0.8	1.2 x 1.8
	ft	0.5 dia	1.7 x 2.7	4 x 6
		22kW combustor	350kW hot water boiler	2 MW hot gas furnace
Slumped bed depth	m	0.10	0.10	0.10
	ft	0.33	0.33	0.33
Operating pressure	kN/m^2	100	100	100
	abs.atm	1	1	1
Fluidising velocity	m/s	2.0	0.6 - 1.5	2.7
	ft/s	6.5	2.0 - 5.0	9.0
Fuel		coal	coal	coal
Total run time	hr	100	400	120

Table 2.1 (continued)

Location		CURL					
Bed size	m ft	1.3 dia 4.0 dia shell	1.2 dia 3.75 dia boiler	0.3 dia 1.0 dia	1.3 x 0.6 4 x 2	0.9 x 0.6 3 x 2	0.82 dia 2.25 dia
Slumped bed depth	m ft	0.7 2	0.7 2	0.5 to 1 1.5 to 3	0.7 2.5	up to 2.1 up to 6.5	0.5 1.6
Operating pressure	kN/m^2 abs.atm	100 1	100 1	up to 600 up to 6	up to 600 up to 6	up to 600 up to 6	100 1
Fluidising velocity	m/s ft/s	2.6 - 4 8 - 12	1.6 - 3.2 5 - 10	up to 1.8 up to 6	0.8 2.5	up to 3 up to 10	1.8 - 3.3 6 - 11
Fuel		coal	oil, gas, coal	coal, oil gas	coal	coal, oil gas	coal
Total run time	hr	4500		1000	1700		3500

Location		Sunbury			Renfrew
Bed size	m ft	0.075 0.25	0.38 dia 1.25 dia	0.3 dia 1.0 dia	3.2 x 2.9 10.5 x 9.5 commercial water tube boiler
Slumped bed depth	m ft	0.1 0.33	0.5 1.5	0.45 - 1.2 1.4 - 3.8	0.5 1.6
Operating pressure	kN/m^2 abs.atm	100 1	100 1	up to 600 up to 6	100 1
Fluidising velocity	m/s ft/s	up to 1.6 up to 5	up to 1.6 up to 5	up to 3 up to 10	up to 2.6 up to 8
Fuel		gas, oil	gas, oil	gas, oil	coal, oil
Total run time	hr	3000	250	in course of commissioning	2000

Reports available on individual aspects of the research programme are listed in a separate CSL document, reference (2.1). *

A variety of experimental equipment has been used, the largest being a converted water tube boiler generating 20 000 kg/h (45 000 lb/hr) steam with a bed area of 9.6 m^2 (100 ft^2). The main features of the initial research combustion rigs used are shown in Table 2.1.

This Manual sets out the basic steps and factors that must be taken into consideration when designing and operating any equipment using fluidised combustion. Methods and recommendations are given for calculating the optimum design parameters for a desired specification. Use of the Manual will give the principal process design parameters and an outline configuration of the required fluidised combustor. Recommendations concerning operating procedure, feed preparation and waste disposal are also covered. It should be noted, however, that details of the mechanical components are included only insofar as they relate to the operation of the fluidised combustor.

2.3 The Phenomenon of Fluidisation

2.3.1. General characteristics

When a gas is passed upwards at an increasing rate through a bed of uniformly sized particles the pressure drop across the bed increases until it equals the weight per unit area of the bed. At this point the drag force exerted by the gas equals the force of gravity acting on the particles and they begin to stir and move relative to each other; this state is called "incipient fluidisation" and the gas velocity is called the "minimum fluidisation velocity". Further increases in the gas flow cause the bed to expand in such a manner that the pressure drop across it remains constant. As the particles are now separated by the gas the bed exhibits many of the properties of a liquid and is said to be "fluidised". At minimum fluidising conditions a fluidised bed appears like a homogenous liquid. When the gas

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* References are given separately at the end of each section of the Manual.

flow is greater than that needed to just fluidise the bed the excess gas passes through the bed as voids or "bubbles" which give the bed the appearance of a vigorously boiling liquid. This analogy with gas-liquid systems has been extended and common terminology in fluidisation is to consider a fluidised bed as a two phase system. The "liquid" phase in fluidisation is described as the "dense phase" and consists of bed particles with the attendant gas for minimum fluidising conditions. The "gas" phase consists of the voids or "bubbles" which rise through the dense phase.

As a bubble rises through a fluidised bed it carries a certain quantity of the dense phase with it in its wake. When the bubble bursts at the surface the particles from its wake are deposited onto the surface and to preserve continuity they move downwards in the dense phase. In a vigorously bubbling bed the particles throughout the bed are rapidly mixed by this mechanism, particularly in the vertical direction. In practice, because of the pressure drop through a bed, fluidisation starts at the top of the bed and extends downwards as the gas flow rate increases, so that incipient fluidisation conditions occur over a small range of flow rates rather than a single value. Furthermore in the general practical situation the particles are not uniform but cover a range of sizes. The general picture remains as described above however, (provided the size range is not too wide) and the bed behaviour may be characterised by using an average particle size. If the gas flow rate to the incipiently fluidised bed is further increased the gas velocity local to the smallest particle will at some point exceed the free fall velocity of that particle so that it can be elutriated. Particles of increasing size will be elutriated as the gas flow rate is further increased until eventually all the bed will be entrained. Additionally, there may be continuous abrasion of particles in most fluidised beds so that, even at a fixed velocity, particles progressively reduce in size until they are elutriated. Chemical reaction also, may lead to particles reducing in size.

From the above description it will be realised that the gas flow rate is a key parameter in fluidisation. The parameter usually used is the superficial fluidising velocity, U_f †, (hereafter called the fluidising velocity for simplicity) which is the velocity that the gases would have at the operating temperature and pressure when based on the gas flow rate and enpty bed cross-section. Normal operation with a given size of particles will be possible over a range of fluidising velocities limited at the lower end by the minimum fluidising velocity and at the higher end by excessive entrainment. Conversely, operation at any given fluidising velocity will be possible with a range of particle sizes forming the bed. This range is wider than first principles would suggest because elutriation of smaller particles is impeded by the larger particles. The minimum fluidising velocity, however, increases with increases in either particle size or particle density and the normal operating range of velocity is therefore also dependant on the bed particle size and range.

Gas fluidised beds possess three characteristics which are important for their application in combustion systems. They are,

(i) The heat and mass transfer between the gas and the particles is better than in fixed beds, which favours the use of fluidised beds for heterogenous or surface-catalysed reactions.

(ii) Good particle mixing, already referred to above, which allows the establishment of an essentially constant temperature throughout the bed.

(iii) High heat transfer coefficients between the bed and any surfaces submerged within it, or containing it. This arises in part because the solid particles penetrate the gas films adjacent to the surfaces which normally impede heat transfer, but a larger effect arises because of the high thermal capacity of the particles relative to that of the gas. Groups of particles approach heat transfer surfaces where they lose or gain heat, then move back into the bulk of the bed where they rapidly regain the bed temperature. Thus the surfaces are always faced by particles at or near the bed average temperature and the effect is to maintain the maximum temperature gradient between the bulk bed and the surfaces.

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† Symbols and abbreviations are listed in a separate section at the beginning of this Manual.

2.3.2 Fluidised combustion

In fluidised combustion fuel is fed into a hot fluidised-bed of inert material where combustion is rapid. The instantaneous carbon content can be as low as 0.1%. When coal is used the ash naturally present in the coal is a possible source of inert material, but any refractory solid having the right density and size distribution can be used, and in practice at the first start-up of any fluidised-bed combustor an artificial bed has to be prepared.

Under steady-state conditions, the burning fuel is rapidly dispersed throughout the hot bed where it transfers the heat of combustion to the inert particles. These in turn rapidly transfer the heat away to the gas stream and heat transfer surfaces and so prevent local high temperatures which might result in sintering of particles in the bed. Because the inert particles of the bed act as a heat transfer medium through which heat is transferred from the burning fuel to the heat transfer surfaces, it becomes possible to stabilise the reaction rate for all fuels at much lower temperatures than in most conventional combustors. The burning fuel particles will always be hotter than the average bed temperature, but in a fluidised-bed carbon particles rarely achieve temperatures more than 200 °C in excess of the bed temperature and it is usually possible to operate the bed at temperatures up to 200 °C below the softening temperature of the ash before ash sintering in the bed begins to occur.

The fuel may be fed as a solid, liquid, gas or slurry, and to obtain high combustion efficiencies it is important that it is rapidly and uniformly mixed through the bed. This is achieved by the use of special distributor designs and by choosing suitable fluidising conditions so that vigorous solids mixing of bed particles is maintained, especially around the distributor region. Effective fuel distribution is particularly important for oil firing to avoid carbonisation and agglomeration of bed particles.

The combustion rates are sufficiently high at the normal bed temperatures that bed depths as low as 0.15m (6 in.) can be sufficient to obtain substantially complete combustion and the depth is often determined from considerations other than those of combustion alone. Fluidisation processes always require a gas space or "freeboard" above the bed. The freeboard is necessary for reducing entrainment of solids by allowing space for the larger bed particles ejected into the gas stream by bursting bubbles to fall back to the bed and it also serves as a part of the combustion zone. Normally with coal firing any fine carbon particles elutriated from the main bed continue to burn in the freeboard and will release some part of the total heat of combustion there. In fact cooling surface may be required there to limit the temperature of the freeboard gases.

2.4 Fluidised Combustion Applications

A fluidised combustor is a part of a complete system for heat and/or power generation which will impose certain constraints on the combustor. This should be appreciated at the outset. Most fluidised combustion applications fall into the groups shown in Table 2.2 where the classification is according to method of heat removal and operating pressure. Whilst at first sight Group 3 might seem unnecessary because any existing equipment could be classified in Groups 1 or 2, it should be remembered that the design constraints for conversion of existing equipment may be quite different from those for new applications. A sketch of each sub-group 1a to 2b is shown in Figure 2.1 and the following comments are made to highlight the different design implications.

Table 2.2
Classification of Fluidised Combustion

Group	Description
1	No in-bed cooling
a	atmospheric pressure operation
b	pressurised operation
2	With in-bed cooling
a	atmospheric pressure operation
b	pressurised operation
3	Use in existing equipment

In Group 1 the fluidised combustor is used to provide only hot gases. Atmospheric pressure applications, Group 1a (Figure 2.1a), might be for crop drying or incineration. For pressurised operation, Group 1b (Figure 2.1b) the combustor would be linked to a gas turbine. The design implication of Group 1 is that the excess air level will be high as all the heat of combustion must be removed as sensible heat. (Section 3.5.7).

In Group 2 (Figures 2.1c, 2.1d) advantage is taken of the high in-bed transfer coefficients to remove a large proportion of the heat of combustion directly from the bed itself. Adwquate bed height must be provided to accommodate the necessary tubing. (Section 10). Recovery of heat from the waste gases must also be considered. In Figure 2.1c a feed water preheater/ waste-gas cooler is shown but many other arrangements are possible. The commonest applications of Group 2 are for steam or power generation.

Some design implications are common to all systems. Attention must always be given to the removal of fine particles entrained in the exit combustion gases to minimise environmental pollution and possible erosion of, or deposition on, heat transfer surfaces or turbine blading (Section 14). The solids removed, including any elutriated carbon, may be processed separately (Figure 2.1a), recycled to a main bed (Figures 2.1b,c,d), or refired in a separate carbon burn-up bed. The choice will depend primarily on the combustion efficiency required (Section 3.5). All fluidised combustion systems can be operated with or without the addition of additives for sulphur retention (Section 11). The need for sulphur retention must be considered at the start of any design (Section 3.5). Freeboard cooling, (Section 4.1 and 10.4), may be required in any system, depending on the proportion of the combustion that occurs there and the allowable temperature rise.

The highest rates of combustion will be given by pressurised operation, Group 2b, because at constant excess air, fluidising velocity and temperature the pressure determines the amount of oxygen and hence fuel that can be fed. Bed depths may have to be increased merely to accommodate the necessary in-bed heat transfer tubing. The resulting increase in pressure drop incurred is of a second order magnitude relative to these higher operating pressures.

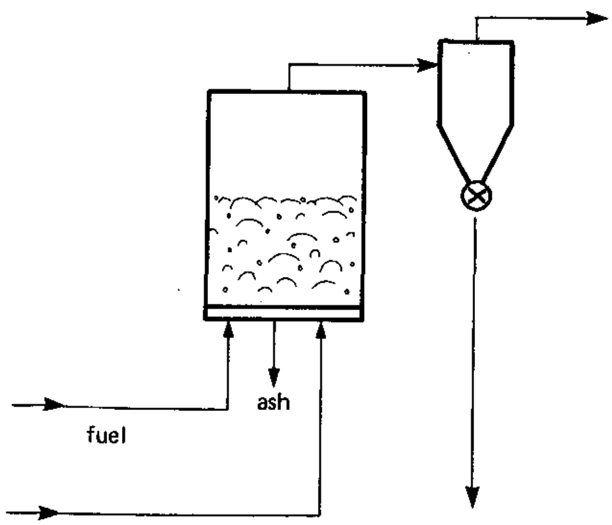

Figure 2.1a (Group 1a)

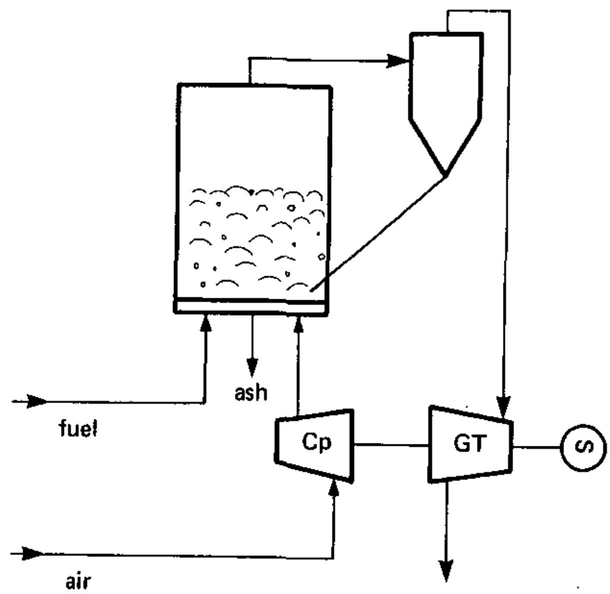

Figure 2.1b (Group 1b)

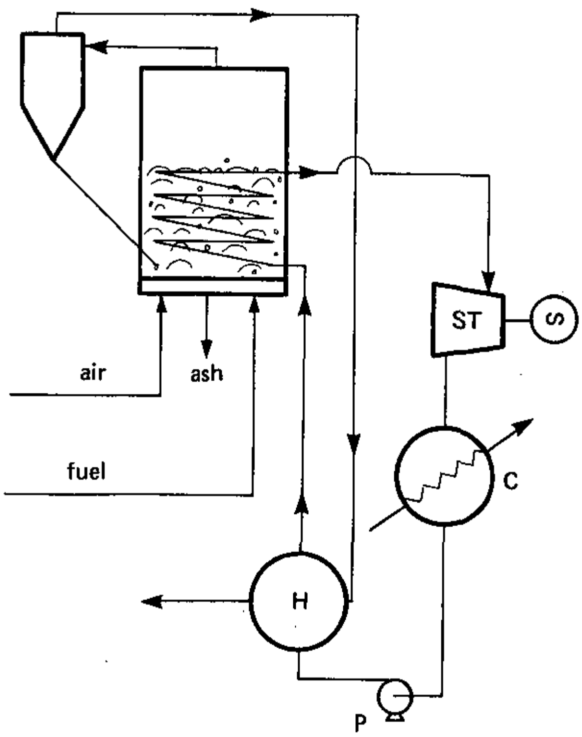

Figure 2.1c (Group 2a)

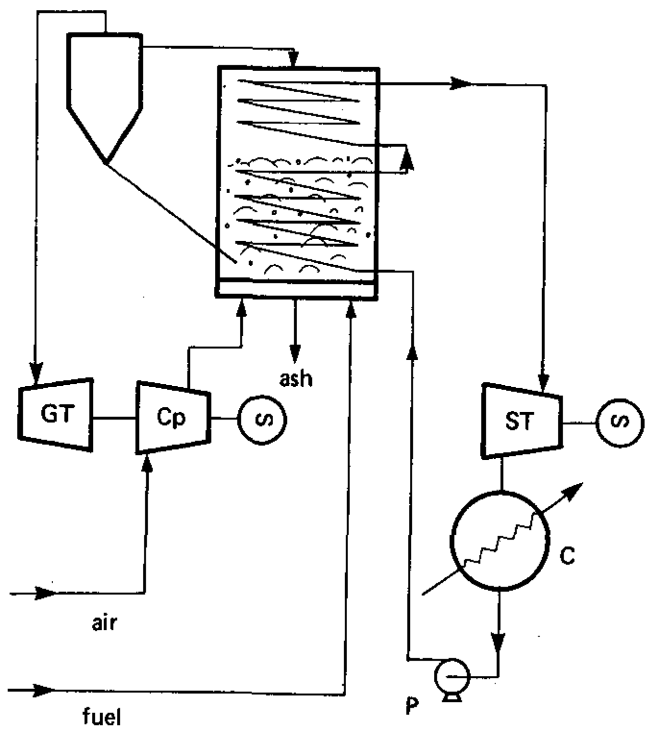

Figure 2.1d (Group 2b)

Figure 2.1
Typical Fluidised Combustion Systems

Cp	air compressor	GT	gas turbine	ST	steam turbine
C	condenser	H	heat exchanger	P	water circulating pump

When a fluidised combustion system is installed in existing equipment, Group 3, some or all of the surface for heat removal from hot combustion gases already exists. In this case the height available for both freeboard and bed depth may be restrictive. Also in order to obtain combustion intensities similar to previous means of firing the fluidising velocity must be high to provide the required oxygen. The design implication is that the bed particle density and the fuel feed size of solid will be relatively large. (Section 4.3). Some in-bed heat transfer surface will probably be necessary, along with a possible reduction of backend heat transfer surface.

When fluidised combustion is used for power generation there are many possible ways (cycles) for arranging heat transfer surface and turbines and of choosing working fluids to recover and convert the heat of combustion as efficiently as possible. Besides thermodynamic considerations, choice of the optimum cycle must take into account the operation and control problems when a fluidised bed combustor is operated in conjunction with the turbine stages. (See sections 8.1 & 13.3). The effects of the combustion exhaust gases on downstream equipment must also be considered. (See section 14).

2.5 References

2.1 CSL. Compendium of Proprietary CSL Technical Information on Fluidised Combustion. Jan. 1977.