FLUIDISED COMBUSTION UNDER PRESSURE

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1. INTRODUCTION

Over the last two decades, fluidisation has become a widely accepted and reasonably well-understood means for bringing about mass and heat transfer in the chemical and petroleum processing industries.

Where uniform temperature, good mixing, high heat transfer rates, large areas of reaction surface, and mobility of reacting species are important, it would be difficult to envisage a more suitable processing tool. It cannot, of course, be inferred that such systems do not have many problems, or that all the potential benefits of fluidised bed processing systems have been successfully realised. The literatures contain many dissertations, (e.g. Squires, 1961) written by those who have encountered difficulties in coming to terms with fluid beds.

The purpose of this paper is to outline the potential benefits of fluidised combustion, mainly in the field of power generation, and particularly when it is carried out under pressure. We also indicate some of the problems that have to be overcome to realise these benefits, and outline some of the investigations being made to solve them.

2. FEATURES OF FLUIDISED COMBUSTION

The fluidised bed for a combustion system can be formed from any inorganic particulate matter, e.g. mineral matter from coal, crushed refractory, limestone or dolomite. The particles should preferably have good resistance to attrition, otherwise excessive quantities of material would need to be fed to make up for elutriation of fines and to maintain bed level.

Coal (or oil) injected into the fluid bed is burned at high rates of heat release and the rates of heat transfer to surfaces immersed in the bed are much higher than the average rates attained in conventional furnaces.

Fluidised combustion is not an entirely new technique. Over the last thirteen years, fluidised combustion systems have been described for burning difficult fuels such as anthracite fines (Stouff, 1957), lignite (Panoiu and Cazacu, 1962; Novotny, 1963) and washery tailings (Fassotte, 1961). Plants described by Godel (1963) and by Okaniwa and Suzuki (1959), which have apparently proved successful, differed from the present concept in that the combustion temperatures were high enough to fuse the ash, and all the heat release was recovered from the gas leaving the bed, using more or less conventional boiler heat exchange surface. Another successful plant (von Friese, 1961) contained cooling tubes in the bed to reduce clinkering, and about half the total steam output was generated in these tubes.

In the present concept of fluidised combustion, most of the heat is extracted from the bed in this way. Though foreshadowed to some extent

by the little-publicised activities of the Badische Anilin und Soda Fabrik (1957) and of Combustion Engineering Inc. (1957), this concept largely stems from investigations started about six years ago in the U.K. at the research laboratories of the Central Electricity Generating Board (Botterill and Elliott 1964), and continued at the Central Research Establishment (CRE) of the National Coal Board and at the British Coal Utilisation Research Association (BCURA). The work at BCURA was originally aimed at developing small packaged industrial boilers (Barker, Roberts and Wright, 1969), whereas the other activities have been concerned with fluidised combustion of coal for large power plant (McLaren and Williams, 1969). For the last two years, BCURA have also been investigating fluidised combustion under pressure, primarily for power production (Hoy and Roberts, 1969).

Fluidised combustion of oil has been pioneered in the U.K. by Esso (Moss, 1968). The system proposed, usually known as the "Chemically Active Fluidised Bed Combustor", involves burning residual oil in a fluidised bed of limestone or dolomite, which absorbs sulphur dioxide. The lime is regenerated, with recovery of the sulphur, by treatment in a separate stage. A similar arrangement has been proposed for burning finely pulverised coal.

2.1. Potential Advantages of Fluidised Combustion

The present concept of fluidised combustion has many advantages over conventional combustion systems. By operating fluidised combustors under high pressure, many additional benefits can be gained. The most important of these are the reduction of plant size and the possibilities for improving thermal efficiency and simplifying some features of fluid bed operation.

All the potential benefits accrue from the following key factors:

a. The large surface available for reaction, long solids residence time, and excellent solids mixing, enable high combustion efficiency and intensity to be achieved at combustion temperatures as low as 1300-1800°F (700-1000°C).

b. The fluid bed provides high rates of heat transfer to immersed surfaces.

Combustion Intensity and Efficiency - The combustion intensity (rate of heat release per unit bed volume) is proportional to the mass velocity of combustion air, and therefore to the fluidising velocity and operating pressure.

Fluidisation velocity depends mainly on the particle size distribution of the material that forms the bed. Unless inorganic material in addition to that associated with the coal is supplied to the bed, the size consist of the bed material will depend upon the size of the ash associated with the coal and its resistance to attrition. Fluidised combustion in its simplest form therefore is better suited for burning uncleaned coals than for burning low-ash clean coals.

The operating range is from the lowest velocity needed to maintain fluidisation to the velocity above which elutriation is excessive. Though the lower limit is relatively insensitive to pressure (Fig. 1), increasing the pressure can increase the quantity of material elutriated from the bed (Fig. 2). With operation under pressure, therefore, rather more carryover material has to be recycled to attain the same level of combustion efficiency.

The fluidisation velocities and heat release rates relevant to the three size ranges of coal that have been used in most of the U.K. investigations are as follows :

Nominal coal size range	in.	1/16 - 0	1/8 - 0	1/4 - 0
Fluidising Velocity range	ft/s	1 - 4	2 - 9	5 - 12
Heat release rate	10^6Btu/ft^{2}h	0.09-0.36	0.18-0.81	0.45-1.08

(Bed temp 800°C; 10% excess air)

Combustion intensity depends upon two further factors, (i) the minimum depth of bed needed to get good dispersion of the fuel and to complete release and combustion of volatile matter; this is the main factor at atmospheric pressure, and (ii) the depth of bed required to accommodate the heat transfer surface needed for attaining the chosen bed temperature; this is the main limiting factor at high pressures.

At atmospheric pressure combustion efficiencies in excess of 99% have been obtained when burning 1/16"-0 coal in beds about 2 ft deep (McLaren and Williams). Combustion intensities in excess of 0.1 million Btu/ft^{3}h, some ten times those allowable in conventional boiler plant, are achieved. Burning 1/4"-0 coal the combustion intensity can be at least five times higher, albeit at some sacrifice of combustion efficiency.

At high pressures the potential reduction in boiler size is dramatic (Fig. 3), a fluidised bed boiler operated at 15-20 atm could be about 1/15th the volume of a conventional boiler operating at atmospheric pressure.

The size of the boiler 'envelope', however, is not solely dictated by combustion intensity attained in the bed and the space needed for the heat transfer surface. Factors such as (a) the amount of 'freeboard' needed above the bed to minimise elutriation, (b) size and location of steam headers and (c) arrangement of hot gas ducting can also have an important effect on the overall size of the plant.

Clearly the minimum size of containment will be obtained with the particle size range that gives the highest fluidising velocity; the conditions as regards heat transfer unfortunately are the converse of this.

Heat Transfer - The total heat transfer coefficient between a fluidised bed and an immersed surface is primarily a function of particle size, but it is also influenced by the temperature of the bed and of the immersed surface, and by the ability of bed material to circulate freely (i.e. on the closeness of tube packing). The total heat transfer coefficient, which comprises radiative and convective components, can be up to 10 times higher than in conventional gas-to-surface heat exchange systems, depending on particle size (Fig. 4). For example, in fluidised combustors burning 1/16"-0 coal, heat transfer coefficients to water cooled tubes of approx. 80 Btu/ft^2 h °F are obtained with tubes 2 in. apart, rising to 100 Btu/ft^2 h °F with tubes 6 in. apart. As Fig. 4 shows, higher heat transfer coefficients are obtained with higher tube temperatures.

A further factor that adds to the saving in heat transfer surface obtained with fluidised combustion is that the whole of the surface of the tubes

immersed in the bed (and these absorb c. 70% of the heat of the fuel) is available for heat transfer, whereas only half of the surface of the tubing of a conventional boiler furnace is exposed to the combustion gases.

Operation under pressure does not affect the heat transfer to tubes immersed in the bed. Nevertheless, further savings in high-alloy tubing are achieved by operation under pressure, because the gas turbine absorbs most of the heat required to reduce the temperature of the gas leaving the bed to 700-750°F (375-400°C). The estimated overall savings in tube surface exposed to temperatures above 750°F (400°C), as compared with conventional p.f. firing for a 120 MW boiler, can be seen in Fig. 5. Although the pressure process requires a larger, more expensive economiser to recover heat below 750°F (400°C), this is a small consideration compared with the savings in cost for the higher alloy tubing achieved with fluidised combustion.

Although the heat exchange surface required in fluidised beds burning 1/16"-0 coal is about half that for a coal feed of 1/4"-0, the tube savings thus obtained have to be set against the higher containment costs for the five-fold increase in bed plan area that would be needed.

For boilers in large central power plant, with advanced steam conditions, particularly those operated under pressure, the choice may be for the finer coal size because of the major savings in high temperature alloys that would accrue. Industrial boilers operated at atmospheric pressure however, would need little or no high alloy tubing since advanced steam conditions would seldom be used; for these it is probable that the savings in space and containment costs would make coarse fuel the logical choice.

In either event, fluid bed combustion can result in big savings in tubing requirements and the compact nature of the tubing and of containment that can be achieved would facilitate a maximum amount of factory prefabrication, with consequent savings in erection costs.

Bed Temperature - At the temperatures currently favoured for fluidised combustion systems in the U.K., the vapour pressures of the alkali components of ash known to play a part in fouling and corrosion of heat transfer surfaces are several orders of magnitude lower than at the temperatures in conventional combustion systems, and as a result sodium concentrations in the gases from fluid bed combustors are about 1 ppm, equivalent to less than 1% of the sodium content of the fuel. This is in contrast to the 10% that has been recorded with p.f.-fired boilers, or 38% for a cyclone-fired boiler (Ounsted, 1958). The potassium contents of gases from fluidised bed combustors are typically less than those of sodium.

Combustion of residual oil in "chemically active beds" can result in a similar dramatic reduction in the concentration of fouling constituents in the combustion gases; deposition compounds of sodium, vanadium, and sulphur on superheaters has led to even greater restrictions on superheat temperatures for oil firing than for coal firing. Fluidised combustion may therefore be the key to the resumption of advances in superheat temperature for both coal and oil firing, and hence to realising the improvements in power generating efficiency predicted in the past (e.g. Downs, 1955).

For fluidised combustion under pressure, the low concentration of fouling constituents in the combustion gases gives hope that the gases can be expanded through gas turbines without loss of performance. In the past, successful operation of solid fuel fired gas turbines has been prevented by blade fouling or, in the extreme, by choking of the passageways through the blade system.

Erosion of coal-fired gas turbines has also been a problem in the past, and from this point of view low bed temperature is also an advantage; ash particles from a bed operating at 1470°F (800°C) show no signs of fusion and are similar in texture, appearance and composition to those produced by ashing in conventional laboratory ashing furnaces. In addition to being less abrasive than normal p.f. combustor ash, fluid-bed ash is coarser and is simpler to separate from the combustion gases; there is therefore good reason to believe that turbine blade erosion will not be a problem.

If, however, the low fouling and erosion propensities of the gases could be sustained to appreciably higher bed temperatures than 1470°F (800°C), additional advantages would accrue, e.g. (i) a further reduction in heat transfer surface, (ii) higher gas turbine efficiency, and (iii) simpler conditions for achieving a high combustion efficiency when burning the coarser grades of coal. Higher bed temperatures may ultimately be feasible for non-pressurised systems, but at the present state of the art it would not be prudent to predict this possibility for pressurised systems, particularly as there is evidence to show that particle temperatures can be appreciably higher than the mean bed temperature.

Bed temperature is also important from the point of view of emission/retention of the oxides of sulphur and nitrogen. At 1470°F (800°C) and thereabouts, the concentration of oxides of nitrogen may be less than 100 ppm.

Emission of sulphur as SO_2 can be reduced to less than 10% of the sulphur content of the coal (McLaren and William) by adding lime to the bed equivalent to rather less than twice the stoichiometric quantity; lime also reduces emission of nitrogen oxides.

There is greater tolerance of bed temperature from the point of view of sulphur retention (Fig. 6) however, than there is for volatilisation of alkalis.

3. SOME APPLICATIONS FOR FLUIDISED COMBUSTION UNDER PRESSURE

The power generation industry is a major consumer of coal and residual oil, and in spite of competition from nuclear power, it would be surprising if throughout the world fossil fuels failed to retain the greater part of the power generating market for at least another 20 years. Most of the work on fluidised combustion has consequently been carried out with this in mind, and almost all of the potential applications of pressurised fluid bed combustion discussed here are concerned with power generation.

3.1. Combined Power Generation Cycles

The thermal efficiency of power generation processes is mainly determined by the practical limitations on the temperature range over which the working fluid converts heat energy to power. The properties of ideal working fluids have been specified by Meyer and Fischer (1962) and by Reti (1965), who concluded that no known fluid possesses all the required properties. Steam, however, has more of the desired properties than any other single fluid.

The problems of increasing the temperature of high pressure steam have already been mentioned. There is little prospect of reducing low-pressure steam turbine exhaust temperatures below their present levels of around 80 - 90°F or 25 - 35°C without resorting to uneconomically large condensers and cooling water flows. The temperature range and efficiency of conventional cycles have therefore reached their limits, particularly for

smaller plant.

Combined power generation cycles increase the working temperature range by using more than one fluid. The literature abounds with proposals for employing "topping" fluids to increase the maximum working temperature, and "bottoming" to reduce the minimum working temperature. Many of these cycles would need a clean fuel as heat source to avoid the unacceptable corrosion, erosion and fouling that would occur with conventional combustion of p.f. or residual oil. There are, however, a number of cycles which, if pressurised fluid bed combustion were successfully developed, would be suitable immediately or in the future for coal or residual oil firing.

Combined Gas-Steam Cycles - There are basically two types:

a. Exhaust-fired boilers, in which the combustion air to a more or less conventional boiler is replaced by the hot but oxygen rich exhaust gas from a gas turbine power plant.

b. Supercharged boilers, in which the boiler furnace operates at high pressure and the combustion gases are expanded through a turbine that provides power to drive the combustion air compressor and an additional alternator.

Both systems have their advocates, and their thermodynamic and economic principles have been discussed by Seippel and Bercuter (1961) and by Sheldon and McKone (1962). The supercharged combined cycle appeared the most likely to provide a worthwhile improvement in efficiency and capital cost in-so-far as combustion of coal was concerned, and experimental work and thermodynamic studies at BCURA have concentrated on this system.

An arrangement of a supercharged boiler cycle, based on a compression ratio of 8:1 and a gas turbine entry temperature of 1380°F (750°C) is shown in Fig. 7. Because the combustion air is heated by compression to over 500°F (approx. 250°C), alternative ways have to be found for recovering heat from the turbine exhaust. In the arrangement shown in Fig. 7, some of the feed heaters of the standard 120 MW steam cycle have been replaced by a low level economiser. Although the reduced extraction of steam for feed heating gives a poorer steam turbine heat rate, the power output is increased by about 5 MW. The calculated heat rate for such an arrangement (8580 Btu/kWh), thermal efficiency 39.8% based on the gross calorific value of the coal) would be about 450 Btu/kWh (about 2 percentage points in thermal efficiency) better than for a conventional steam plant.

Operation over a wide load range should be feasible, a feature of particular advantage for sites not served by power distribution networks.

This system, though not offering dramatic improvements in efficiency, would provide a good starting point for introducing the power industry to advanced cycles, and to fluidised combustion of coal and residual oil. A particular advantage of the combined cycle over pure gas turbine cycles, from the point of view of using these fuels, is that any fall off in turbine power from deposition or erosion has a much smaller effect on the output of the whole plant.

Gas - Potassium - Steam Cycle - In this cycle, potassium would be used for "topping" a conventional steam cycle by combining the functions of a potassium condenser with those of a steam boiler, superheater and reheater. A pressurised fluid bed combustor would provide a favourable heating system for

generating the potassium vapour, since fireside corrosion would be less than with other combustion systems. Heat rates of 6250 Btu/kWh (thermal efficiency 54.6%) have been projected by Fraas (1966) for a system with nuclear heating of potassium vapour to temperatures of 1540°F (838°C) at 29 psia. Taking into account the currently envisaged fluid bed temperatures; together with stack-losses, recalculation of the data gives a heat rate of about 7100 Btu/kWh (thermal efficiency 48%). Though this is a large improvement over conventional plant, it might not compensate for the higher capital costs likely to be incurred, and this challenging system must await the next generation of fluid bed combustors operating at higher temperatures.

Refrigerant Cycles - The use of refrigerants as "bottoming" fluids has been suggested by a number of authors for reducing the capital cost or improving the efficiency of steam cycles (e.g. Aronson, 1961) and gas turbine cycles (Hicks, 1965; Bindon and Carmichael, 1968). Based on an exhaustive analysis, Eaves and Hadrill (1968) concluded that, for U.K. conditions with conventional combustion systems, both capital and operating costs of combined cycles using refrigerants were unattractive. The situation might be changed with pressurised fluid bed combustion; by using lime to remove sulphur, low stack temperatures giving higher efficiencies would be possible without risk of low-temperature corrosion.

3.2. Pure Gas Turbine Cycles

Pressurised fluid bed combustion potentially converts "dirty" fuels to acceptably "clean" fuels. In addition to its application to combined cycle power plant, therefore, it has attractions for coal or residual oil firing of pure gas turbine cycles which at present need clean fuels, nuclear energy or large costly air heaters.

Simple Open Cycles - These are more susceptible to the effects of pressure loss than combined cycle plant. Attempts to develop directly-fired coal-burning gas turbines over the past two decades (Cox, 1951; Rozenberg, 1962; Wisdom, 1964; Nabors, Strimbeck, Cargill and Smith, 1965; Smith, Strimbeck, Coates and McGee, 1966) have been beset with difficulties of blade erosion and fouling by ash; these difficulties should be minimised by fluidised combustion. Simple open cycles are characterised by high air/fuel ratios, and to avoid excessive fluid bed cross sections, most of the excess air would need to be indirectly heated in tubes immersed in the bed (Fig. 8). Although fluidised combustion may successfully overcome the main problems that have prevented successful firing of turbines by coal and residual oil the number of applications where the additional cost of the combustion system would be justified may be limited.

Semi-Closed Cycles - These are characterised by having a high-pressure closed circuit, using relatively small, cheap turbomachinery, with a bleed of air or gas to an open cycle gas turbine operating at lower pressure. They have good start-up and part-load characteristics, and better heat rate (e.g. 10700 Btu/kWh or 32% efficiency) than simple open cycle plant, (Gasparovic, 1967) but their main potentiality is in the field of peak-load power generation. Pressurised fluid bed combustion could be used in semi-closed cycles in a number of ways which can be categorised as :

(a) Cycles with direct firing of the closed circuit (Fig. 9)

(b) Cycles with indirect heating of the closed circuit and direct heating of the open circuit (Fig. 10)

Closed Cycles - Several p.f.-fired closed air cycle plants have been constructed (Keller and Caehler, 1961; Aver, 1961). In some of these, the heat rejected by the air before recompression was used for works or district heating, giving high heat utilisation efficiency. The air heaters were large and costly (Bammert and Nickel, 1966). Major savings should be possible with pressurised fluid bed combustion for heating the air and generating additional power (Fig. 11). Helium is a better closed cycle fluid than air because of its higher specific heat and ratio of specific heats at constant pressure and volume, its lower molecular weight, its higher thermal conductivity and its chemical inertness. A 25 MW nuclear heated helium closed cycle plant is being constructed at Geesthacht, W. Germany (Keller and Schmidt, 1967). Its heat rate of 9220 Btu/kWh (37% thermal efficiency) with a helium turbine entry temperature of 1350°F (730°C), could probably be closely matched if the nuclear heat source were replaced by a pressurised fluid bed combustor.

Air Storage - Fluidised combustion under pressure would be a suitable means for firing air storage power schemes (Stal-Laval) for peak load power production. The arrangement would be as shown in Fig. 12. Air, compressed to approx. 600 psia using off-peak electrical power, would be stored in a subterranean cavern under a constant head provided by a lake, reservoir or sea. Peak power would be generated by an indirectly heated gas turbine followed by a directly fired gas turbine system, with a heat consumption of 4350 Btu/kWh (thermal efficiency 79%)

3.3. Continuous Reforming of Hydrocarbons

Reforming of liquid and gaseous hydrocarbons is a major feature of processes for making ammonia, ethylene and town gas. 'Reforming' is probably a misnomer because, as is well known, the process taking place in the heated tubes of a continuous reforming unit is largely catalysed thermal decomposition of higher hydrocarbons to a mixture of lower hydrocarbons, carbon oxides and hydrogen. The relative proportions of the gases produced depend upon the temperatures and pressures that are used.

The equilibrium temperatures generally range from 1200°F (650°C) for manufacture of town gas to over 1800°F (1000°C) for production of ammonia synthesis gas and hydrogen. Tube wall temperatures required in reformer units, which could be heated by fluidised combustion furnaces, would therefore be in the range 1400°F (750°C) to 2000°F (1100°C).

The reforming equilibria are favoured by operating at high pressure; for example, the yield of methane can be increased. Metallurgical considerations are of major importance in design of the plant, since at the pressures (up to 600 psi) and temperatures used the tube metal creeps. By operating a fluidised combustion furnace under pressure, the pressure difference across the tube walls could be reduced or eliminated. Capital costs could thereby be reduced because thinner-walled tubing could be used, the materials being chosen mainly with regard to resistance to corrosion. Maintenance costs could also be lowered, since the reduction in creep would give a large (e.g. tenfold) increase in tube life.

4. DEVELOPMENT OF THE COMBUSTION SYSTEM

In a system that has so many potential advantages over other combustion systems for coal and residual oil there are inevitably some problems. We do not know of any that are likely to be unsolvable, but an appreciable amount of development work has been done, and more may be needed to ensure that the solutions do not detract significantly from the savings in cost that

the benefits of the system should bring.

A major research effort is in progress at the Leatherhead research laboratories of BCURA, and the Cheltenham research laboratories of the NCB, aimed at proving the 'virtues' and overcoming the potential 'vices'. The pilot-scale equipment includes (a) a pressurised combustor with a bed area of 8 ft^2 capable of burning 500 lb/h of 1/16"-0 coal at 5 atm pressure, (Fig. 13); (b) a boiler with a bed area of 12 ft^2 capable of burning 1200 lb/h of ¼"-0 coal at atmospheric pressure; and (c) three other pilot-scale combustors capable of carrying out long term (e.g. 1000 h) test programmes.

4.1. The Programme

These research programmes include in their objectives:
(a) minimising the number of coal injection points needed to obtain good distribution without the need for excessively deep beds. Deep beds entail high pressure loss, and the larger the number of coal injection points the more expensive is the distribution system;
(b) evolving the optimum means for recycling incompletely burned particles so as to obtain a high combustion efficiency. The design of the space above the bed is also important from this point of view;
(c) exploring means for improving dust collector performance. Two stages of dust collectors are used on the pilot-scale pressurised combustor. The cleaned gases contain only a small proportion of particles larger than 10 μm, and the concentration of dust passing over the cascade downstream of the dust collectors is much lower than for previous solid fuel fired gas turbines. Although the pressure loss over the cleaning system is acceptable, lower pressure loss is desirable;
(d) establishing the best procedures for part load operation. Operating over a wide load range in a system in which the main factor that controls heat absorption, namely bed temperature, can only be varied over a small range presents a certain amount of difficulty. Two main methods have been followed (i) to stop fluidising parts of the bed (i.e. to compartment the bed) and (ii) to expose part of the tubing to gas from the bed by altering bed level (heat transfer coefficients to tubes in the bed are several times those to tubes above the bed).

Operation over a wide load range in the combined cycle will require some care in matching combustion and heat transfer characteristics of the fluid bed to the pressure, temperature and mass flow characteristics of the gas turbine. Fig. 14 shows the part-load characteristics of a typical industrial gas generator and Fig. 15 shows the calculated effects on air-fuel ratios (overall and in the bed) of following one method of load control. Achieving this should not involve an excessively expensive control system.

An expanding part of the programme involves a comprehensive series of investigations to optimise operating conditions with additions of lime (as limestone or dolomite) to the bed to reduce atmospheric pollution by sulphur and nitrogen oxides. An agreement between the NCB and the National Air Pollution Control Association provides for a full exchange of information on these and other aspects of the research programme.

4.2 The State of the Art

The pilot-scale pressure combustor has been operated successfully for several hundred hours. Combustion efficiencies of 99% can be achieved, and few operating difficulties have been experienced with the fluid bed.

Heat transfer rates to tubes in the bed are similar to those expected from tests at atmospheric pressure. The combustion gases at approx. 1400°F (750°C) have been passed over two designs of static turbine blade cascade; that currently in use is a segment from the first stage stator row of a marine version of an aero engine. The approach velocity is about 400 ft/s and the leaving velocity about 1800 ft/s. No erosion of the blades, or of a target tube downstream of them has occurred. Very little ash has deposited on the surfaces, and deposits that have formed can be easily removed by 'on line' cleaning methods commonly used for gas turbine compressors.

There is cause for cautious optimism as to the technical success of the process. The next stage of proving this involves long term running of a gas turbine on gases from a fluidised combustor. This will be an expensive project and one of many pre-requisites is for design studies to show that the process can be justified economically.

The size and the characteristics of the gas turbines likely to be available in the next 5 - 10 years could be a dominant factor, because the cost of developing turbines specially for the process would be prohibitive. High pressure ratios (e.g. 15 : 1), good part load characteristics, and air mass flows of 300 lb/s upwards are amongst the features desired.

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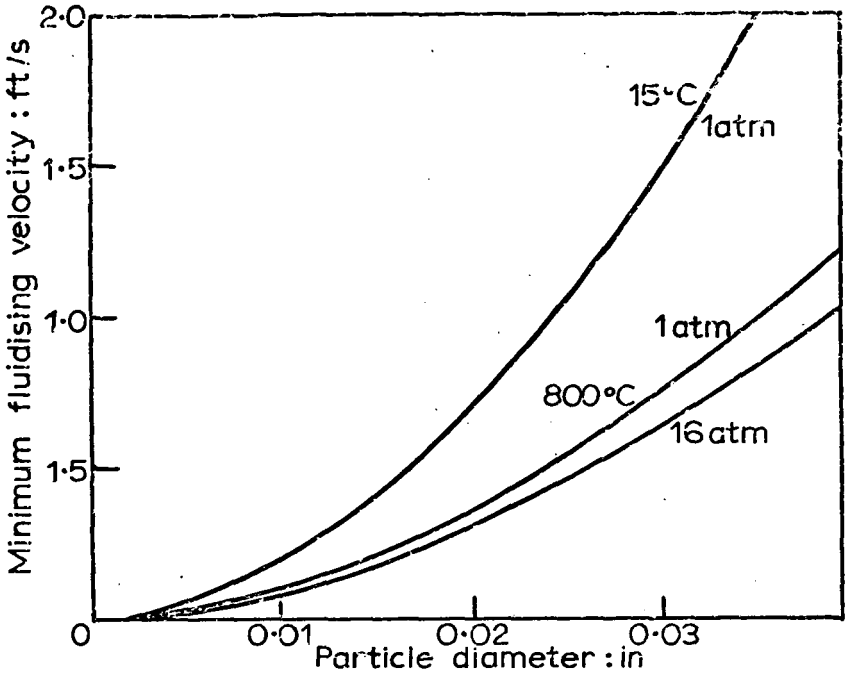

Fig. 1. Minimum fluidising velocity : effect of pressure.

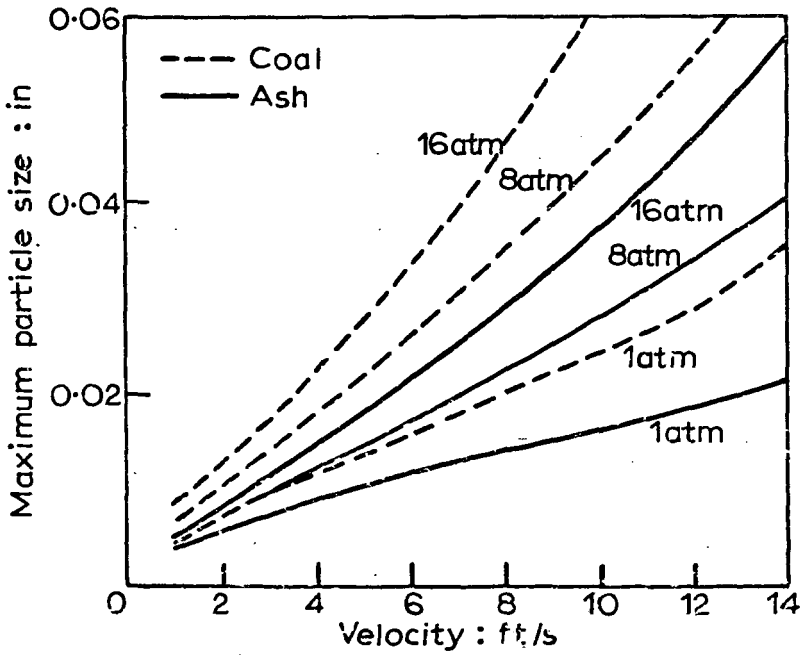

Fig. 2. Size of particle elutriated : effect of pressure

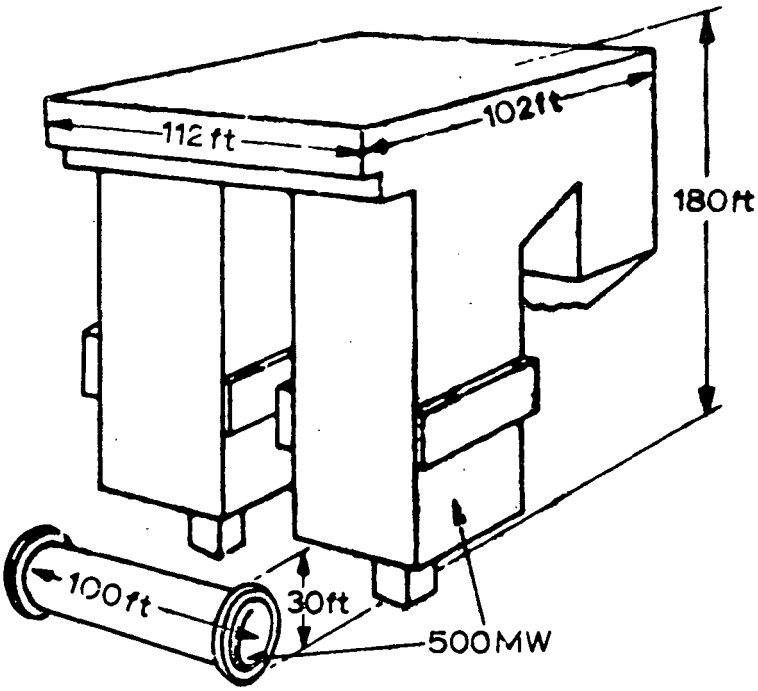

Fig.3. Comparison of boiler size : pressurised fluid bed v. convential p.f.

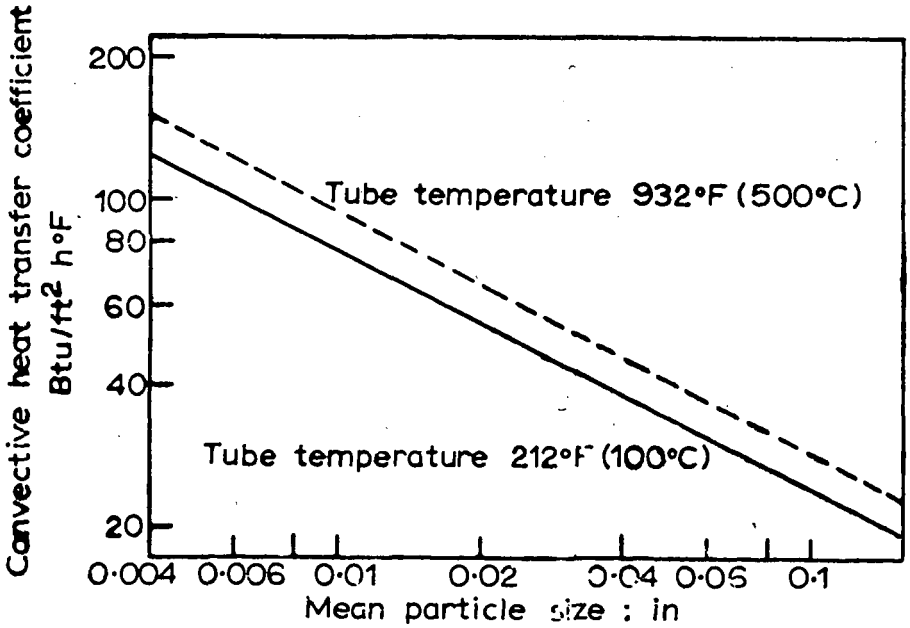

Fig.4. Fluid bed heat transfer coefficients

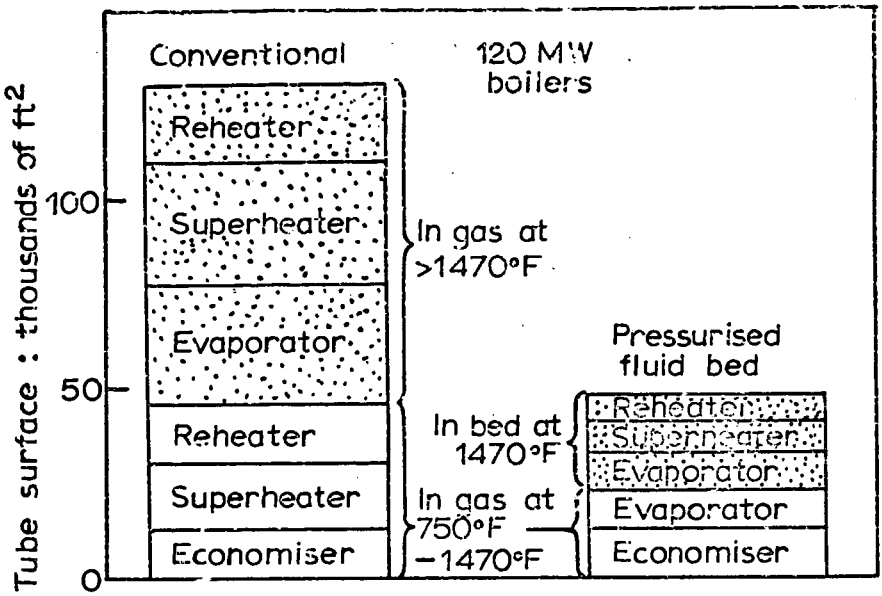

Fig. 5. Comparison of tube surface areas

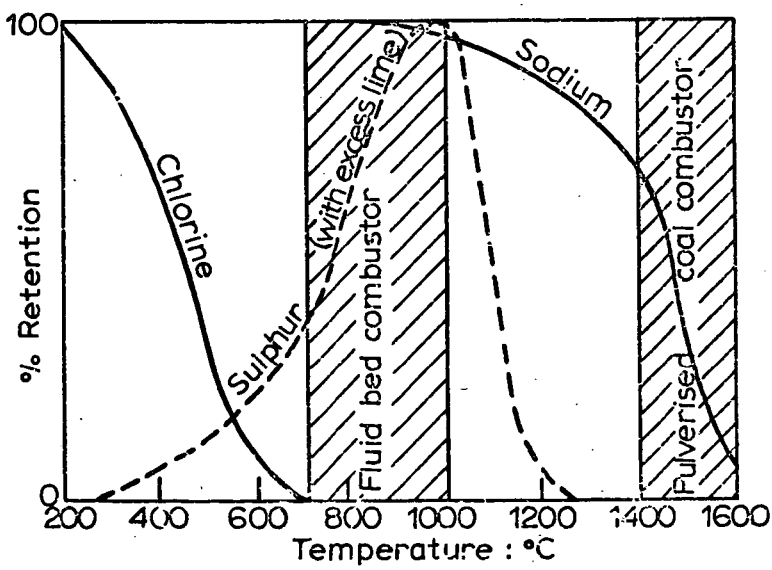

Fig. 6. Retention of ash constituents

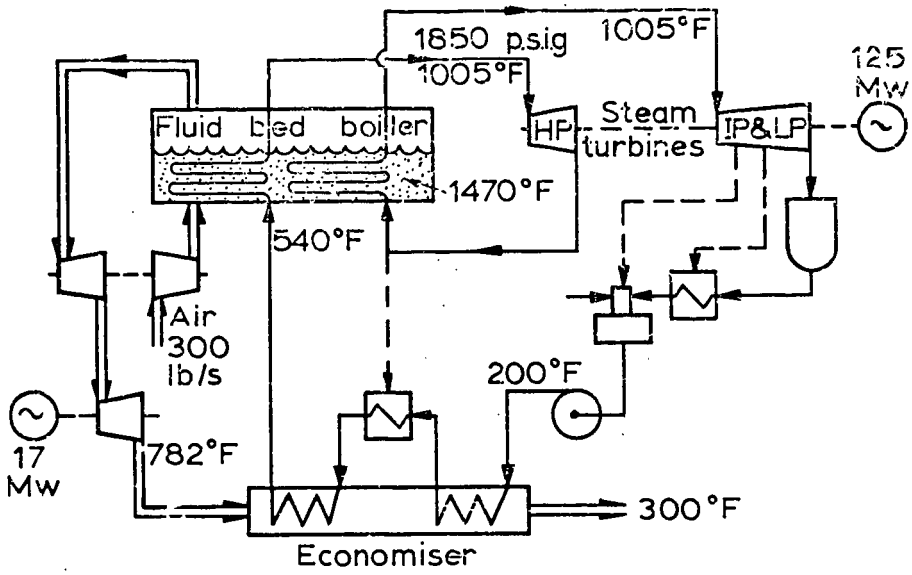

Fig.7. 140 MW Gas-steam turbine system

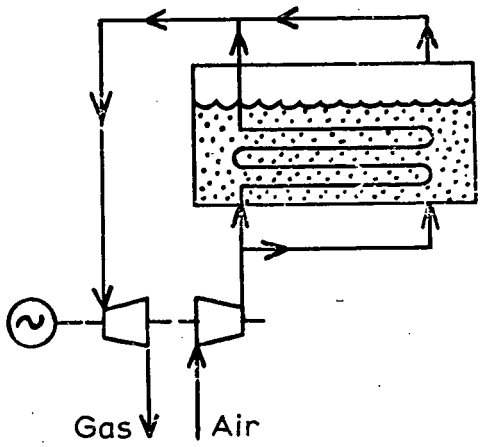

Fig.8. Open cycle plant

120/4mh

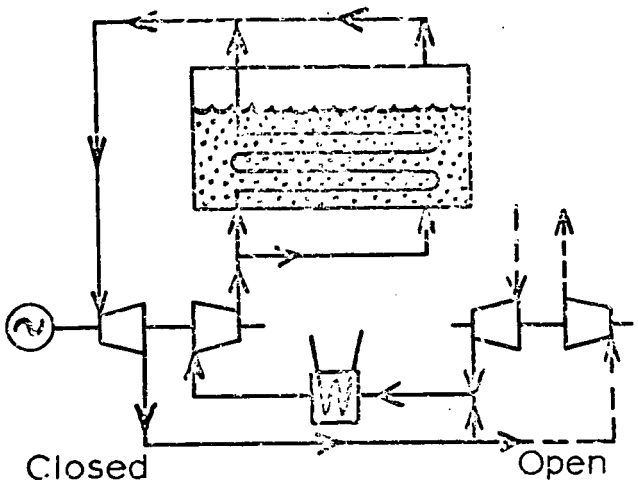

Fig. 9. Semi-closed cycle : combustion in the closed cycle

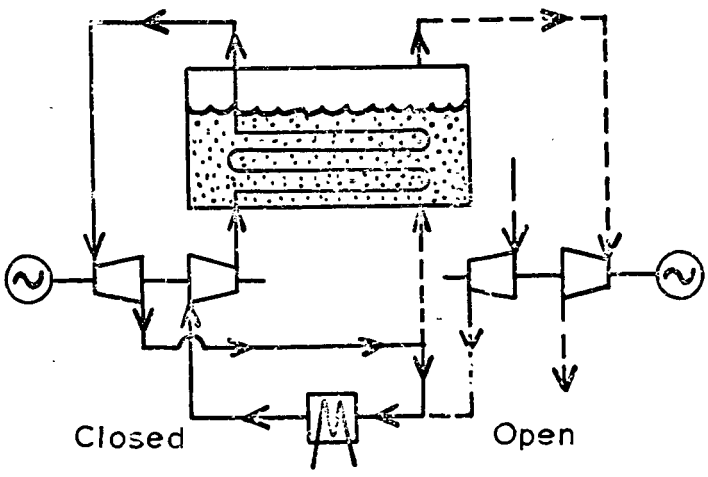

Fig. 10. Semi-closed cycle : combustion in the open cycle

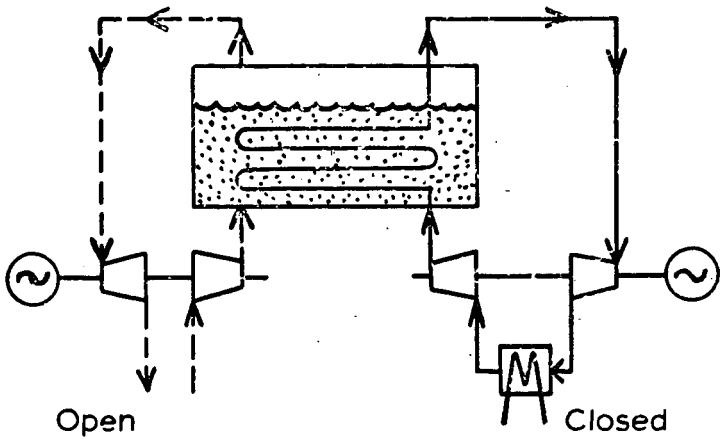

Fig.11. Closed cycle plant

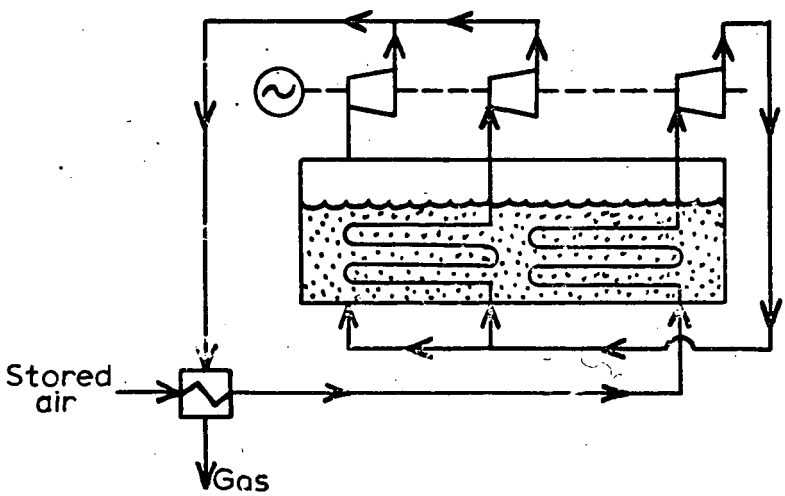

Fig.12. Air storage scheme

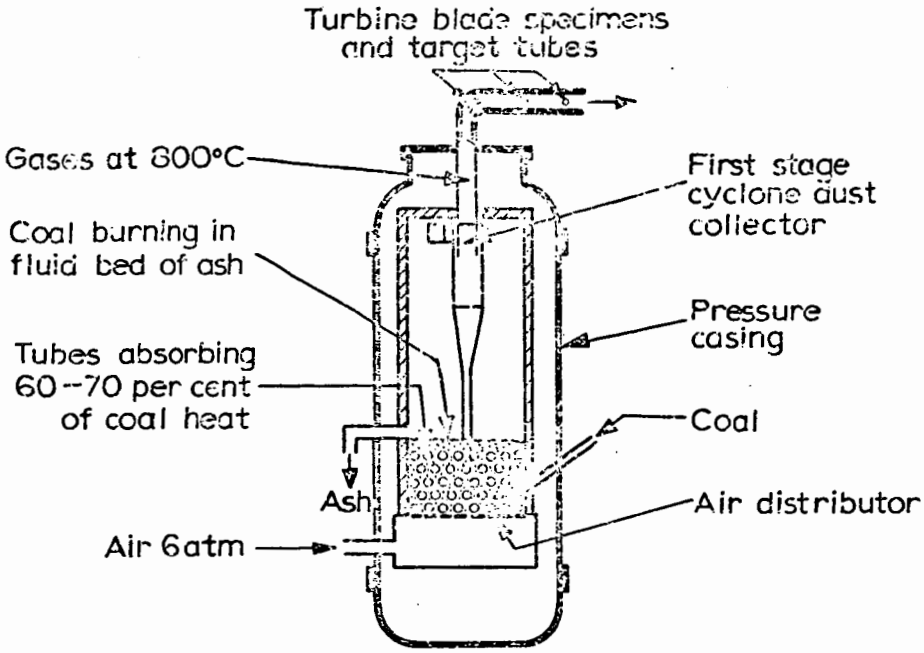

Fig. 13. Experimental pressurised fluid bed combustor

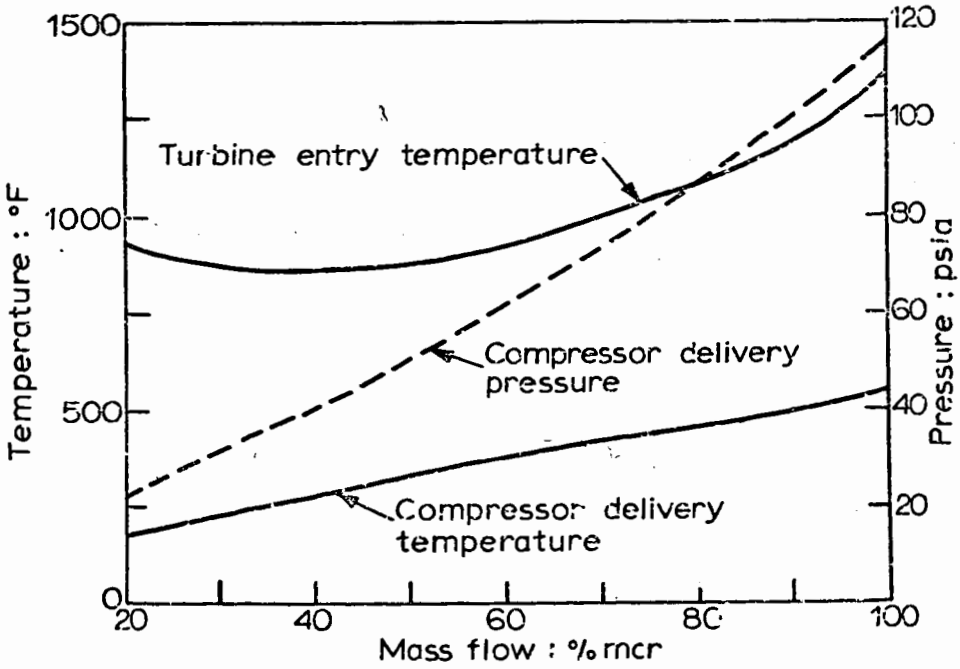

Fig.14. Part load characteristics: industrial gas generator

120/7mh

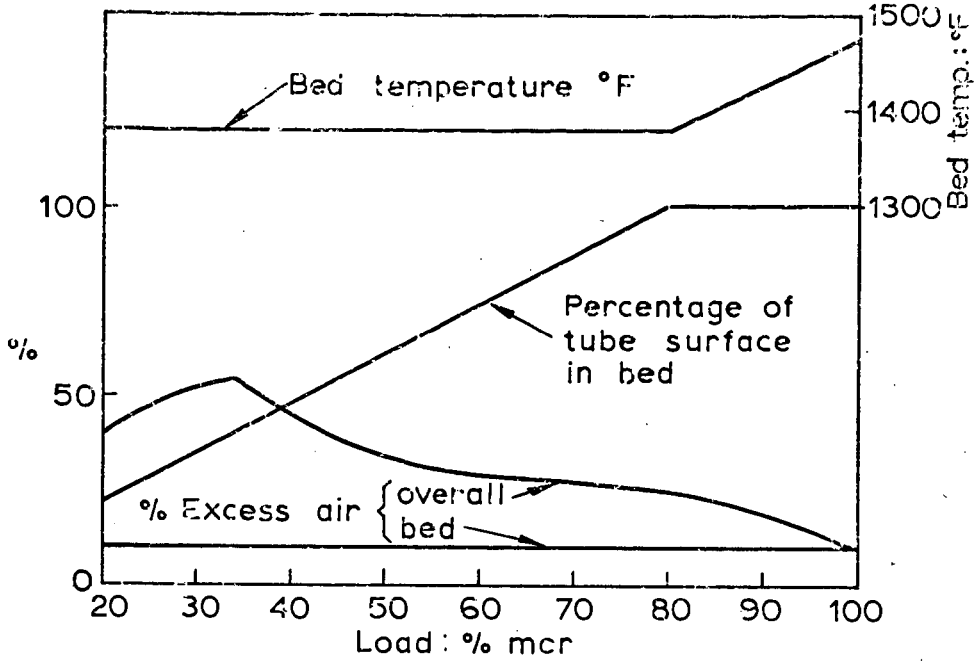

Fig.15. Calculated part-load characteristics : combustor with variable bed level