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FLUIDIZED-BED COMBUSTION — AN EMERGING TECHNOLOGY

F.D. FRIEDRICH

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FLUIDIZED-BED COMBUSTION - AN EMERGING TECHNOLOGY

by

F.D. Friedrich*

ABSTRACT

New combustion technology is required to meet the twofold challenge of utilizing increasingly low-grade fuels and simultaneously reducing emissions harmful to the environment. In this respect, the paper identifies fluidized-bed combustion as one of the most promising new technologies, which furthermore has reached commercial demonstration in small sizes.

The fluidized combustion process is described together with its advantages, disadvantages and potential applications. The current state of the art is summarized. Also, the objectives and status of the federal fluidized-combustion demonstration program is reviewed.

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*Research scientist, Canadian Combustion Research Laboratory, Energy Research Laboratories, CANMET, Energy, Mines and Resources Canada, Ottawa.

COMBUSTION SUR LIT FLUIDISE-TECHNOLOGIE EN PLEIN ESSOR

par

F.D. Friedrich*

RESUME

Une nouvelle technologie est requise pour affronter le double défi qui consiste à employer des combustibles à plus faible teneur tout en réduisant les émanations nocives pour l'environnement. A cette fin, ce rapport décrit la combustion sur lit fluidisé comme l'une des nouvelles technologies les plus prometteuses qui, de plus, a fait son apparition sur les marchés à dimension réduite.

Ce procédé est décrit ainsi que ses avantages, ses inconvénients et les applications possibles. On résume l'état actuel de cette technologie. De plus, les objectifs et la structure du programme de démonstration fédéral de la combustion sur lit fluidisé sont énoncés.

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*Chercheur scientifique, Laboratoire canadien de recherche sur la combustion, Laboratoires de recherche énergétique, CANMET, Energie, Mines et Ressources Canada, Ottawa.

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Diminishing supplies and rising costs of high-quality petroleum fuels dictate greater use of inferior fuels such as low-grade coal, wood waste and municipal garbage. At the same time, increasing evidence of environmental deterioration demonstrates the need for stringent control of pollution from fuel utilization. One result is that combustion technologies which have served well for decades are inadequate when required to burn low-grade fuel with minimal emissions of SO_2, NO_x and particulates. New technologies must be found and existing technologies improved if increasing energy needs are to be met from poorer resources without environmental deterioration.

Of the new technologies now under development, one of the most promising in the medium and long term is fluidized-bed combustion. It offers greater efficiency of energy utilization than gasification, liquefaction, or conventional combustion with flue gas scrubbing, and furthermore, is on the brink of commercial application at least in the small and medium size ranges. It readily makes possible a reduction in SO_2 emissions of up to 90% and is inherently a low producer of NO_x as well. Thus, it can make a significant contribution to solving the problem of acid rain.

The present report summarizes the state of the art of fluidized-bed combustion, identifies some of the major demonstration programs under way, and describes the present EMR program for implementing this technology in Canada as quickly as possible.

THE FLUIDIZED-BED PRINCIPLE

The fluidized bed is simple in concept, as shown in Fig. 1. If a vertical cylinder of any cross section is closed off at the bottom with a perforated plate, the cylinder partly filled with a granular solid material, and sufficient air or gas blown up through the perforated plate, then the bed of granular material is vigorously tumbled by the rising bubbles and is said to be fluidized. In addition to having the appearance of a boiling liquid, a fluidized bed exhibits several properties associated with liquids. It seeks its own level, it flows through pipes, and it generates a static pressure proportional to its depth.

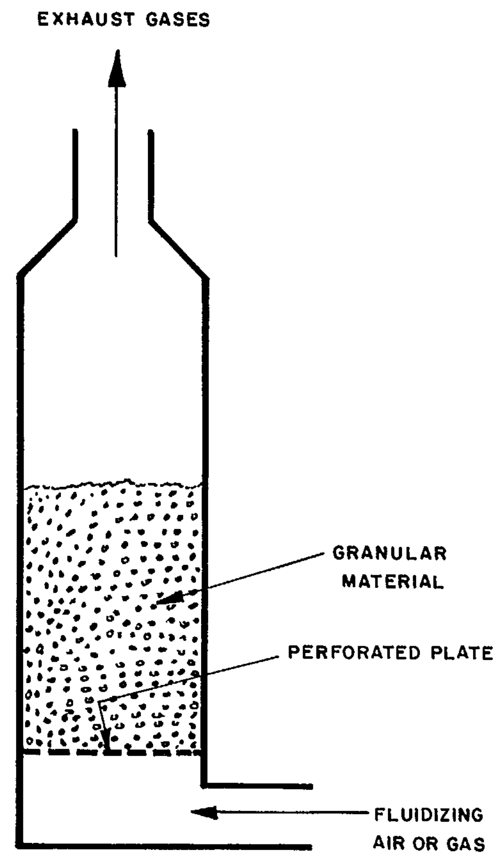

Fig. 1 - An elementary fluidized bed

Additional properties of a fluidized bed are very good mixing of solids, good mixing of gases and solids, and if a thermal gradient exists, very good heat transfer. For these reasons, simple fluidized beds have been used for decades in industry where intimate mixing of gases and solids is required. Examples are catalytic crackers in refineries and some types of ore roasters.

The principles of fluidization are fairly well defined, particularly for the isothermal case. There are several good text books on the subject, several conferences and seminars are devoted to it each year, and work is progressing on more exotic forms such as three-phase fluidized beds involving solids, liquids and gases. However, knowledge of combustion in a fluidized bed is largely empirical. Like its more conventional counterparts, fluidized-bed combustion is as much an art as a science.

COMBUSTION IN A FLUIDIZED BED

In its simplest form, a fluidized-bed combustor (FBC) consists of a refractory cylinder and the perforated plate commonly called the grid or distributor plate designed to withstand high temperatures. Air is usually used as the fluidizing medium because it can also serve as the oxidant. The granular bed material must have adequate refractory properties, silica frequently being used.

If such a bed is fluidized and heated to the ignition temperature of the fuel by some means such as preheating the fluidizing air, then all the conditions required for combustion are met: air and fuel are present, the temperature is high enough for ignition, and mixing is very good. Thus, any fuel introduced will burn, even though it may be very dilute relative to the bed material. However, the heat sink provided by the large mass of inert bed material serves to moderate the temperature at which combustion proceeds which is one of the most significant advantages of fluidized-bed combustion. By appropriately extracting heat from the bed, combustion can be carried out at temperatures in the range of 750 to 1000°C, much lower than in conventional flames.

ADVANTAGES AND DISADVANTAGES

The ability of a fluidized-bed combustor to operate at relatively low temperatures is advantageous from an operational as well as an environmental viewpoint. First, all the problems associated with slagging and sintering of ash are avoided. Second, the emissions of nitrogen oxides and heavy metals are low compared with conventional combustion systems because the formation of these pollutants is temperature-dependent.

Although a fluidized-bed combustor is capable of burning solid, liquid or gaseous fuels, its advantages are most apparent with "difficult" solid fuels that are relatively unreactive or have a high proportion of ash and moisture. The circulating action of the bed provides such fuels with all the residence time necessary to dry and burn, provided the fuel particles are heavy enough not to be elutriated from the bed.

In the eyes of most combustion engineers the chief advantage of FBC is its ability to minimize SO_2 emissions from high-sulphur fuels. This is accomplished by feeding limestone or dolomite into the bed with the fuel. At bed temperatures of approximately 850°C, the $CaCO_3$ readily calcines to form CaO which then reacts with the SO_2 to produce $CaSO_4$ which is a solid and therefore remains in the bed or is trapped in the dust collectors. With a moderately reactive limestone, a Ca:S ratio of 3:1 typically eliminates 90% of the theoretically possible SO_2 emissions. For a coal containing 5% S, close to half a tonne of limestone would have to be fed with each tonne of coal, but economic analyses have indicated that this is still cheaper than building and operating flue gas scrubbers, particularly in small sizes.

There are still further advantages to FBC. Little fuel preparation is required; crushed coal, or coal sized at 25 mm x 0 can be burnt, avoiding the expense of pulverizing, and making it economic to build small fluidized-bed boilers as well as large ones. Heat transfer rates to water-cooled tubes immersed in the bed are very high, making FBC boilers competitive in capital cost with other equipment. Finally, fluidized beds are amenable to pressurized combustion, making possible compact equipment, substantial cost savings on large-scale equipment, and a variety of more efficient fuel-to-electricity cycles.

The chief disadvantage of FBC is the

high power requirement for providing combustion air at pressures of 12 to 25 kPa (50 to 100 in. wg). For a boiler producing 18 t/h of steam, an FBC system would require approximately 225 kW at the forced draft fan, compared with perhaps 75 kW for a stoker-fired system.

Other disadvantages are 1) substantial elutriation of particles from the bed, which can lead to high carbon loss and requires high-performance dust collectors, and 2) inability to operate at low loads as well as at full load, unless special provisions are incorporated into the design, at additional expense.

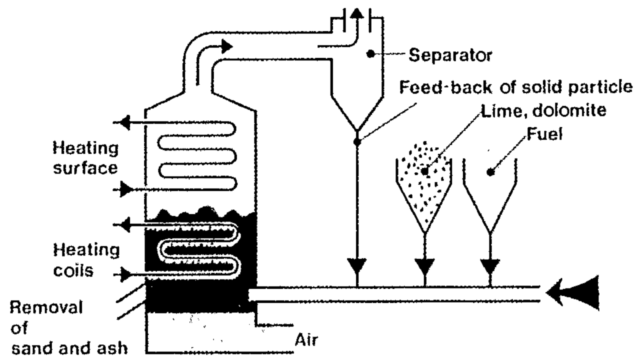

Fig. 2 - Schematic of a fluidized-bed boiler

TYPES OF FLUIDIZED-BED COMBUSTORS

Fluidized-bed combustors are classified into two main types, atmospheric and pressurized, according to the pressure maintained in the freeboard space above the bed. These are commonly referred to in the literature as AFBC and PFBC. AFBC's are in turn subclassified as adiabatic or cooled, depending on whether or not heat is extracted from the bed.

The adiabatic AFBC is the simplest form of FBC. The combustor and freeboard are lined with refractory and the heat must be carried away by the products of combustion. It is therefore suitable for fuels having a low heating value or a high moisture content such as wood waste, bagasse, and sewage sludge. The heat in the exhaust gases may be used directly in certain drying applications, or heat exchangers may be employed to generate hot air, hot water or steam.

A cooled AFBC is required where the heat in the fuel exceeds that which can be carried away by the products of combustion at the desired bed temperature. Heat is then absorbed from the bed by water-cooled, air-cooled or steam-cooled tubes enclosing or passing through the bed. A coal-fired steam boiler would be a typical application of a cooled AFBC. Figure 2 shows a schematic arrangement.

PFBC systems operating at about 1000 kPa offer several advantages, at least in theory. High pressure permits high rates of combustion and heat transfer. This is why PFBC's usually require cooling, but it also makes possible compact, economical systems having a high energy output. PFBC systems produce less NO_x and require lower Ca:S ratios than AFBC systems; in addition they are inherently more amenable to the addition of sorbent regeneration systems which drastically cut the limestone required for sulphur neutralization. Still more important, PFBC offers the potential for high-efficiency combined-cycle power generation using gas turbines together with steam turbines.

Disadvantages of PFBC stem from the fact that the combustor becomes a pressure vessel, and feeding air, fuel and sorbent into it requires complex, expensive equipment. Cleaning the pressurized combustion gases well enough to avoid erosion of a gas turbine also presents a formidable challenge.

STATE OF THE ART

ADIABATIC AFBC

Because of their simplicity, adiabatic AFBC systems were the first to achieve commercial development. They have been marketed by several suppliers over the past ten or fifteen years, priimarily as incinerators for high-moisture waste materials including bark, sawdust, sewage sludge, cereal husks and certain industrial wastes. There are about one hundred such systems presently installed in North America, with beds ranging up to 10 m in diameter. Some generate steam via waste heat boilers. Figure 3 shows one configuration.

There have been experimental attempts to burn municipal garbage in adiabatic FB combustors. Raw garbage presents special problems in feeding and in maintaining the desired bed material size consist. These difficulties can be avoided by shredding the garbage, but once shredded it can then be burned in more conventional equipment. One logical application of the fluidized bed is combined firing of shredded garbage and sewage sludge.

In Great Britain, small adiabatic AFBC systems burning coal and producing hot gases for drying cattle feed have been developed to commercial success over the past five years.

<u>COOLED AFBC</u>

Cooled AFBC units are still in the demonstration stage. Although some manufacturers are offering coal-fired AFBC boilers, with or without sulphur neutralization on a guaranteed performance basis, industrial customers have been reluctant to invest in a relatively unproven technology. Consequently some form of government

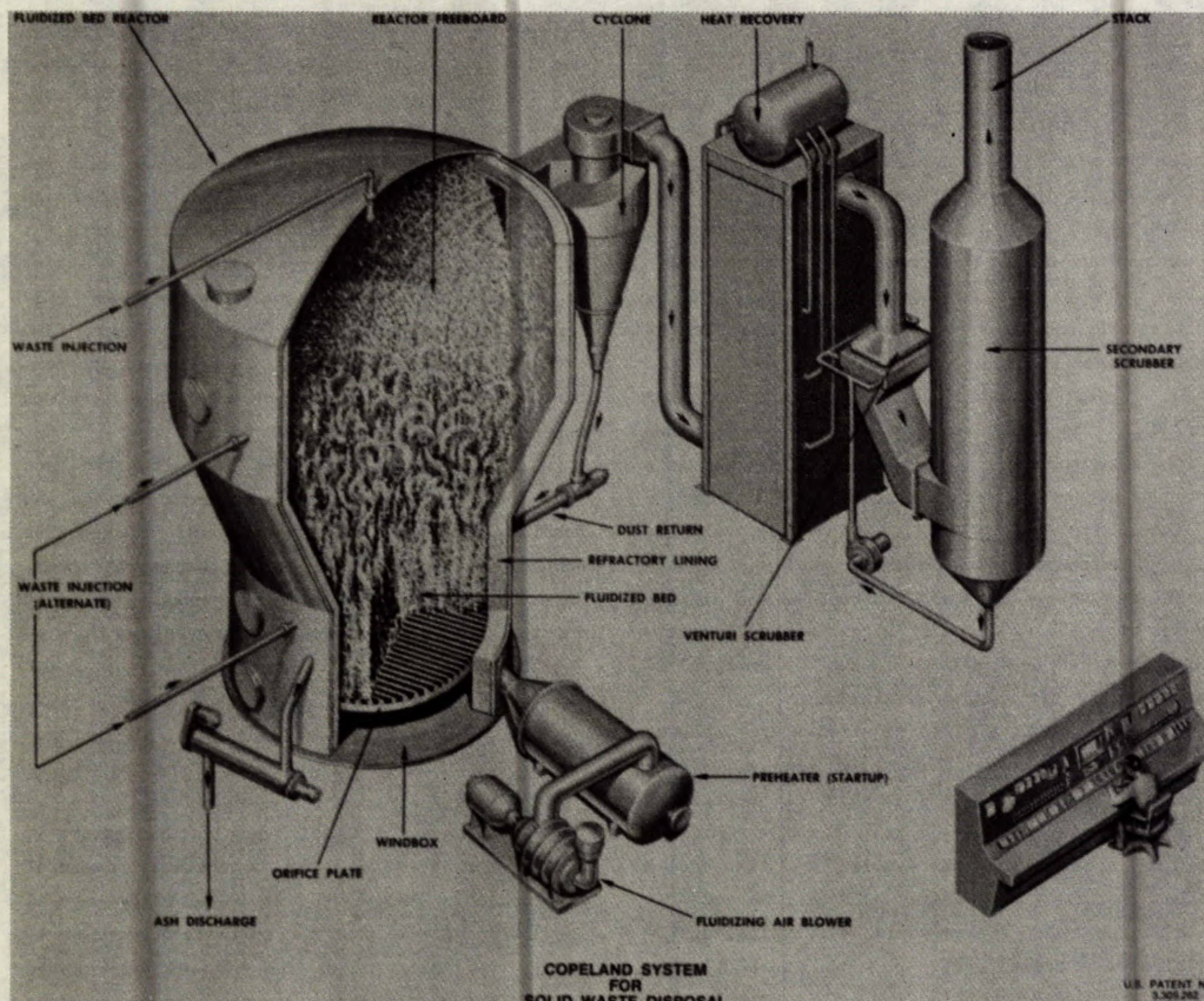

Fig. 3 - An adiabatic fluidized-bed combustor for waste materials

sponsorship supports most of the prototype installations presently in use or under construction.

Most of the development work is taking place in Great Britain and the U.S.A. In the U.K. emphasis is on preserving coal's share of the industrial market, hence small simple systems burning low-sulphur coal are being demonstrated by the National Coal Board at several industrial sites. A design of coal-burning FBC which can be retrofitted into existing oil-fired shell boilers is also being developed. In the U.S.A., FBC technology is seen mainly as a route to pollution-free utilization of high-sulphur coal, and the large demonstration program funded by the U.S. Department of Energy (DOE) concentrates on industrial and utility boilers.

Details of some major cooled FBC demonstrations in the U.K. and U.S.A. follow:

GREAT BRITAIN

- 18-t/h watertube boiler retrofit; B & W Works, Renfrew; pneumatic, underbed feed; operated several years as a test bed;
- 4-t/h vertical firetube boiler; Antler Luggage, Bury; overbed screw feed, double-screened low-sulphur coal; in operation about two years, NCB demonstration;
- 2- to 9-t/h horizontal firetube boilers; several retrofitted with FB combustors; overbed feed, double-screened low-sulphur coal; some in operation about two years, NCB demonstration;
- 13.5-t/h locomotive-type firetube boiler; Rist Wire and Cable, Newcastle under Lyme; overbed chute feed, double-screened low-sulphur coal; in operation about two years, NCB demonstration.

U.S.A.

- 136-t/h package watertube boiler; Rivesville, W. Virginia; pneumatic underbed feed, partial retrofit to overbed feed, spreader stoker; high-S coal, limestone neutralization; in operation about two years as a test facility;
- 45-t/h watertube boiler; Georgetown University, Washington; overbed feed, spreader stokers, double-screened coal; 3.5% S coal, limestone neutralization; commissioning underway (Fig. 4);
- 23-t/h watertube boiler; Great Lakes Naval Training Center; underbed feed of crushed coal and sorbent; high-S coal, limestone neutralization; scheduled completion end of 1979;
- 27-t/h watertube boiler retrofit; Central Ohio Psychiatric Hospital; underbed feed of crushed coal and sorbent; 3.8% S coal, limestone neutralization; scheduled completion Feb 1980;
- 8.2-MW(th) air heater and water heater; Owatonna Tool Co., Owatonna, Minn; underbed feed of crushed coal and sorbent; 4.8% S coal, dolomite neutralization; scheduled completion 1979.

A key feature of FBC technology is the method of coal feed. The first systems to be built utilized pneumatic injection directly into the bed. This method requires that the coal be nearly bone dry and crushed to -6 mm. Systems which feed the coal over the bed, utilizing chutes, screw feeders or spreader stokers can be much simpler and less expensive. They can also feed wet, stoker-size coal. However, fines may be entrained before they reach the bed, increasing carbon carry-over and reducing the effectiveness of sulphur neutralization by limestone. Demonstration plants presently under construction should clarify the relative merits of each system within two or three years.

Officials from the U.S.A. Department of Energy estimate that engineering demonstration of conventional AFBC in industrial applications will be achieved by 1983 and that they will be fully accepted technology by 1990.

Utility boilers utilizing AFBC technology are not likely to be available until the smaller industrial boilers have been adequately demonstrated. A great deal of engineering work has been carried out, particularly in the U.S.A. and several major suppliers have prepared conceptual designs of boilers up to 570 MW_e. Several pilot-scale projects are under way to test and demonstrate critical components such as feeders and boiler materials.

The Tennessee Valley Authority (TVA) is perhaps the utility most active in promoting AFBC technology for power generation. With DOE support, TVA sponsored conceptual boiler designs and

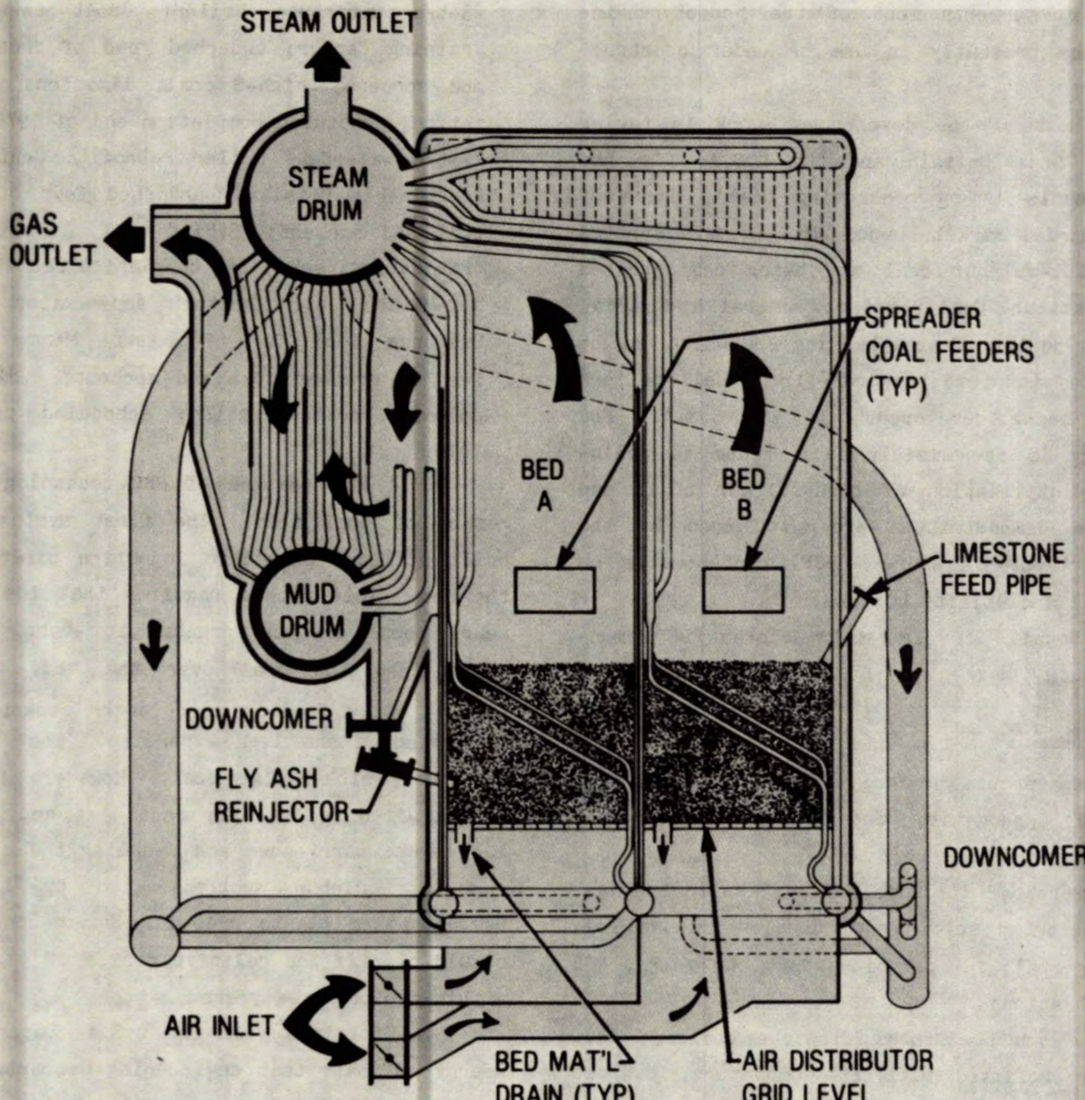

Fig. 4 - Sectional view of the 45-t/h fluidized-bed steam boiler installed at Georgetown University, (Courtesy Foster Wheeler Ltd.)

economic analyses which concluded that AFBC boilers with sulphur retention should have a capital cost advantage of about 15% over conventional boilers with flue gas scrubbers. Savings in operating and maintenance costs are also expected from AFBC. TVA is presently planning to build a 20-MW_e pilot plant which will be used to test various feed systems, develop techniques for improved load following, study a variety of NO_x control techniques, and investigate additional parameters. The pilot plant is expected to be operational by 1982. Further plans by TVA call for a 200-MW_e demonstration plant by 1985 and an 800- to 1000-MW_e commercial plant before the end of the century.

PFBC

The interest in PFBC stems from its potential 10% savings in fuel cost through combined cycles giving a coal-to-electricity efficiency of perhaps 39%, compared with 35% for conventional systems. It is expected that the capital cost of

PFBC combined cycles will be justifiable only in utility-scale units of several hundred megawatt capacity, and these are unlikely to be commercially available until the 1990's.

In the meantime, research, development and demonstration is proceeding in several countries, notably the U.S.A., West Germany, and Great Britain on problems related to feed systems, hot gas clean-up, and erosion and fouling of turbine blades. Adequate hot gas clean-up is crucial to the success of combined cycles.

One approach, shown in Fig. 5, uses compressed air as the cooling medium for the combustor. The hot compressed air is then mixed with the pressurized products of combustion, which have passed through multiple stages of cyclones or a high-temperature precipitator. The mixture of gases and air expands through a gas turbine and then generates steam in a waste heat boiler. This cycle produces about 60% of its power from the gas turbine, the remainder from the steam turbine. A demonstration plant utilizing an air-cooled combustor is presently planned by an industrial consortium in West Germany. The combustion gases will be cleaned in a hot precipitator and will then drive a 4-MW gas turbine. Commissioning is scheduled for early 1980.

An alternative cycle uses the PFB combustor to generate steam, and only the pressurized products of combustion are available to drive the gas turbine. This approach requires highly efficient hot gas clean-up, and produces about 40% of the net power output from the gas turbine.

A large-scale demonstration is planned

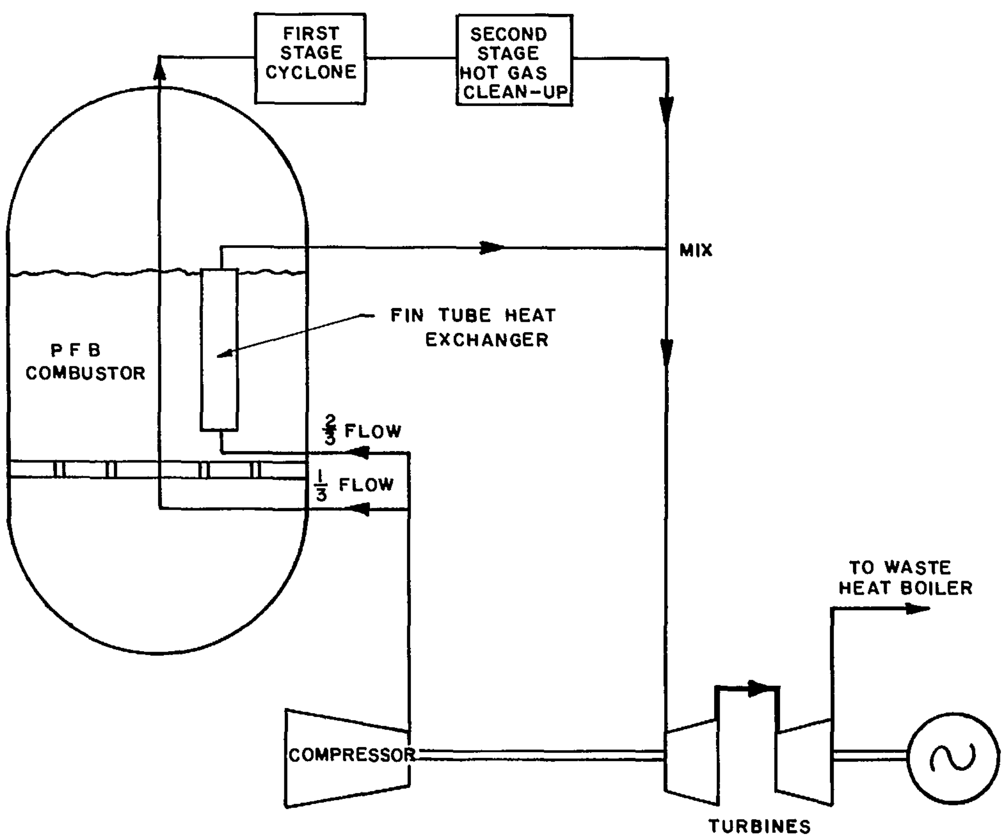

Fig. 5 - Schematic of PFBC combined cycle utilizing an air heater (ASME Paper No. 78-GT-135 S. Moskowitz and G. Weth "Design of a pressurized fluid bed coal fired combined cycle electric power generation plant")

by American Electric Power, which proposes to build a steam-cooled PFBC-gas turbine combination which will generate 67 MW from the gas turbine and 110 MW from the steam turbine. The plant is to be installed at a mothballed power station in Ohio; completion is scheduled for 1983.

FBC TECHNOLOGY IN CANADA

Commercial application of FBC received an early start in this country; one of the first companies to market adiabatic FBC incinerators was formed by George Copeland, a Canadian. Energy, Mines and Resources Canada, currently supports a demonstration program intended to:

a. demonstrate FBC technology at an increasing scale in commercial applications specifically suited to exploit its advantages, and,
b. reduce the technology risk to a level at which private sector funding can be rationalized.

Specific objectives of the EMR demonstration program are:

- provide the industrial market with an alternative to oil and natural gas,
- provide a means to burn high sulphur coal with control of SO_2 emissions,
- provide a technology for utilizing low grade fuels which have some combination of high moisture, high ash, and low reactivity,
- provide more efficient coal-to-electricity cycles.

The main elements of the program are:

- new design of heating plant boiler (Summerside, P.E.I.),
- retrofit or new design of industrial boiler,
- new design of small utility boiler,
- FB combustor burning coal washery rejects,
- combined cycle PFBC (B.C. Hydro),
- back-up R & D program.

The current status of the main elements follows.

HEATING PLANT BOILER

The Summerside project was launched in 1977 when EMR and the Department of National Defence (DND) agreed to cosponsor the demonstration of an AFBC boiler in the heating plant at Canadian Forces Base (CFB) Summerside. Proposals were invited to prepare a conceptual design of an 18-t/h heating boiler. The design fuel was specified as a 5% S coal from Cape Breton, with wood chips as supplementary fuel supplying up to 30% of the heat input at any load. To minimize capital cost, overbed coal feeding was specified. Federal guidelines on the emission of SO_2 and particulates were also to be met, i.e., 2.96 kg/10^6 kcal and 0.36 kg/kcal respectively.

From the proposals received, two were selected - one based on British, the other on American technology. The successful contractors were Foster Wheeler Ltd., which offered the technology of their American parent, and Integ, a Vancouver-based consulting firm which had established a working relationship with Coal Processing Consultants (CPC) of Great Britain, which in turn is jointly owned by Babcock and Wilcox, U.K., and the U.K. National Coal Board.

The contractors completed the conceptual boiler designs in late 1978. The British design features four independent bed sections, each fed by a water-cooled screw conveyor with forced circulation heat exchange surface in each section. The U.S.A. design is similar to the boiler at Georgetown University, Washington, D.C. It has two bed sections, one being the "preferential" bed, which is always in service and provides up to 40% of the capacity. The other "secondary" bed is brought into service for higher loads and contains natural circulation heat exchange surface. Both beds are fed by means of spreader stokers.

The same contractors have now completed conceptual plant designs. Negotiations are well under way on two identical contracts for detail design and firm price proposal for a plant containing one FBC boiler with space for a second. In this phase, the Integ-CPC team will be replaced by Dominion Bridge Co. Ltd. which has a licence to build the British design in Canada.

The rationale for carrying two parallel sets of contracts through to the point of detail design and firm price proposal is threefold:

1. a strong element of competition is maintained, which should influence both design and price;

2. two Canadian companies are supported to the point of being able to offer AFBC boilers; and
3. technology transfer into Canada of both American and British AFBC expertise is accomplished.

The tendering phase should be complete by the end of 1980, at which time it is intended to award a contract for construction, basing the selection on a combination of price and design criteria. Allowing 20 to 24 months for construction, Canada's first FBC boiler may be commissioned in mid-1982. It will then be subjected to a testing and demonstration program expected to last more than a year.

INDUSTRIAL FLUIDIZED-BED BOILER

Substantial quantities of oil could be saved if industrial steam-generating capacity could be switched to alternative fuels. Conversion of existing oil-fired boilers to coal or wood waste is usually impossible with conventional technology, but may be feasible with fluidized-bed technology. It may also develop that it is equally cost-effective to replace existing equipment with new fluidized-bed boilers designed to burn several fuels. EMR plans to initiate a "Request for Proposal" in 1980 to carry out conceptual design and economic analysis of an industrial fluidized-bed boiler, producing about 120 t/h of steam, to burn low-grade coal and wood waste. Such a design would find many applications in the pulp and paper industry and might include provision for cogeneration of electricity.

SMALL UTILITY BOILER

A need has been perceived to demonstrate the suitability of AFBC for power generation with high-sulphur coal. A boiler of about 50-MW_e output is viewed as a suitable size for such a demonstration - first because it is a reasonable step toward the 150- to 500-MW_e boilers usually purchased by Canadian utilities, and second because it is representative of large industrial boilers where FBC technology is also expected to play a significant role. Alternatively, there are sound arguments for proceeding immediately with the demonstration of a 150-MW_e boiler, although the technical risk is greater.

No firm plans for such a demonstration have been made as yet, but a review of suitable sites is presently being sponsored by the Nova Scotia Power Commission, with financial support from the federal government. Identification of a suitable site will hopefully be followed by a conceptual design study.

FBC BURNING COAL WASHERY REJECTS

In Canada each year, millions of tons of mostly coking coal destined for export, are upgraded by washing. The washed coal is then dried, commonly in equipment fired with natural gas, sometimes in equipment fired with cleaned pulverized coal. It is recognized that the washery rejects contain ample heat for the drying process, even though they may contain more than 50% ash and up to 20% moisture. It has also been demonstrated on a pilot scale that such rejects can be burned in an adiabatic AFBC. Utilization of the washery rejects as fuel for drying would not only save expensive premium fuels, it would substantially mitigate the disposal problem the rejects presently represent.

What is needed now is a full-scale demonstration of both the practicality and economics of coal drying using washery rejects as fuel. In response to an Unsolicited Proposal, Energy, Mines and Resources Canada is now negotiating a cost-shared contract with a western Canadian coal company. Under the terms of the contract the company will prepare a conceptual design and economic analyses for a full-scale combustor to burn washery rejects and provide heat for an existing dryer. The work is expected to be completed in 1980 and hopefully will lead to a full-scale demonstration.

COMBINED CYCLE PFBC

The interest in combined-cycle PFBC stems from its potential 10% reduction in fuel requirement for thermal power generation. Ten to fifteen years of development work are expected before commercialization is achieved. In Canada the lead in development and demonstration has been taken by B.C. Hydro and Power Authority, which expects to depend progressively more on coal-based thermal power in the coming decades.

Since 1975, extensive studies have been cofunded by B.C. Hydro and EMR, in which comparisons were made of advanced cycles based on coal gasification, AFBC and PFBC. The studies concluded that a combined-cycle PFBC system is the most promising. B.C. Hydro is now considering building a demonstration plant in which a PFBC would drive a gas turbine generating 70 MW_e. Present expectations are that the proposed demonstration plant might be commissioned some time between 1983 and 1985.

BACK-UP R & D PROGRAM

Although full-scale demonstration projects prove commercial viability, their success requires a great deal of detailed information which often can be obtained from pilot-scale equipment. Performance characteristics of specific fuels, neutralization characteristics of specific sorbents, metallurgical aspects of erosion and corrosion, effects of bed depth, fluidizing velocity and bed temperature on combustion, sulphur neutralization and heat transfer, are all areas where pilot-scale research continues to provide essential knowledge.

Several agencies in Canada - academic, industrial and government - are engaged in research on fluidized-bed combustion. These include INCO Limited, Canadian Industries Limited, B.C. Research, New Brunswick Electric Productivity Council, and several universities. Much of their work is supported by EMR through contracts for specific projects. Examples are corrosion studies in a fluidized-bed combustor at B.C. Research, and studies of sulphur neutralization characteristics of various Canadian limestones at Queen's University. In addition, EMR has an ongoing in-house program at the Canadian Combustion Research Laboratory (CCRL) of CANMET. There, a small group has been operating a pilot-scale combustor, 0.25 m in diameter, for about two years. A larger, more versatile combustor is expected to be in operation early in 1980.

CONCLUSIONS

Simple fluidized-bed combustors have been available commercially for nearly two decades. As rising prices for premium fuels generate increasing interest in low-grade fuels and waste materials such as bark, sawdust, garbage, coal washery rejects and many industrial wastes, the ability of the relatively uncomplicated FBC process to cope with wide variations in fuel quality will ensure its expanded use.

For more conventional fuels, specifically coal, cooled beds are required. Operating at atmospheric pressure and integrated with steam boilers, these are on the verge of demonstration, with and without sulphur neutralization, in sizes suitable for heating plants and moderate process steam requirements. Full commercial acceptance is expected to be rapid despite relatively high capital cost because this market sector is largely dependent on oil at present.

The utility market sector is less dependent on oil, and views FBC technology primarily as an alternative to flue gas scrubbing for SO_2 control. Utility-scale AFBC equipment is some years away, but pressure for its development can be expected to increase. The strongest reasons will likely be environmental. Acid rain was recently identified as a significant problem in hitherto pristine areas of Canada. SO_2 and NO_x are thought to contribute two thirds and one third respectively. In addition to their capability for minimizing SO_2 and because of their relatively low operating temperature FBC systems are inherently low emitters of NO_x and trace elements, which increases their advantage over conventional technology.

Finally, PFBC systems with combined cycles offer the potential for more efficient generation of electricity from coal, although this objective may not be achieved much before the end of the century. In summary, fluidized-bed combustion seems firmly entrenched as the most significant advance in combustion technology since the advent of pulverized firing.

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