ABSTRACT

Fluidized bed combustion is capable of utilizing a wider variety of fuels (including solid wastes) than is any other combustion process. Thus, it has the potential for wide application in systems for recovering energy from solid wastes in industry, commercial sites, institutions, forestry, and agriculture to produce electric power, process steam, process heat, and space heating. Three fluidized bed combustion concepts are identified for near-term application: atmospheric fluidized bed boiler, exhaust-heated gas turbine or combined cycle, and closed-cycle gas turbine.

INTRODUCTION

Fluidized bed combustion systems have been operated for many years for the incineration of waste materials [1, 2]. The primary emphasis, however, has been on disposal, with heat recovery as a secondary concern. Solid, liquid, and gaseous waste materials with a varied range of chemical composition and physical characteristics have been burned in these fluidized bed combustion systems. Fluidized bed combustion can be applied to energy conversion systems for the production of a single product or for a combination of products (cogeneration). The focus of this assessment is industrial cogeneration systems.

Frequently, solid and liquid wastes have such high moisture or water content that partial pre-drying is required prior to conventional combustion processes. Fluidized bed combustion has the characteristic of being able to achieve complete combustion at temperatures as low as 1200-1300 F (922-977 K). This provides systems using fluidized bed combustion with a unique capability for utilizing solid wastes having high moisture content and low heating value. Waste materials typically have such a low sulfur content that a solid sorbent for in-bed desulfurization is not required to meet SO2 emission standards, thus eliminating the spent sorbent disposal problem generally associated with fluidized bed combustion of coal.

The suppliers of fluidized bed incineration systems are giving increased attention to heat recovery, and systems with heat recovery are being sold [3] or developed [4]. Energy conversion systems that are being developed for utility applications with fluidized bed combustion of coal can be extended to accommodate waste fuels in cogeneration systems. The basic atmospheric pressure and pressurized fluidized bed combustion concepts and plants being developed for coal-fired operation are presented in the Proceedings of the Fluidized Bed Combustion Technology Exchange Workshop [5].

SYSTEM CONCEPTS

Five system concepts using fluidized bed combustion of coal that are being considered for utility applications have been characterized for industrial cogeneration applications using solid wastes. These are:

1. Atmospheric pressure fluidized bed boiler.
2. Gas turbine or combined cycle with adiabatic fluidized bed combustion.
3. Gas turbine or combined cycle with partially indirect heating of working fluid.
4. Gas turbine or combined cycle with exhaust heating of working fluid.
5. Closed-cycle gas turbine with indirect heating of working fluid.

Any of these power generation system concepts can be converted to cogeneration systems by changing the steam turbine from condensing to back pressure or extraction or by the addition of a waste heat boiler for the production of process steam.

A schematic diagram of an atmospheric pressure fluidized bed boiler industrial cogeneration system is shown in Fig. 1. Typical throttle conditions for a back-pressure steam turbine in the 25 MW size range are 1450 psig (9996 kPa) and 950°F (783 K). Back pressures as high as 400 psia (2758 kPa) are feasible with these operating conditions. Figure 2 characterizes this cogeneration system with ideal process heat utilization (i.e., no heat or pressure losses). The ideal energy utilization factor is shown as a function of the gross process heat to electrical energy, steam conditions, and process steam supply pressure. The gross process heat to electrical energy ratio is a strong function of process steam supply pressure, but the ideal energy utilization factor is a weak function of both steam conditions and process steam supply pressure.

A gas turbine cogeneration system with fluidized bed combustion of solid wastes is shown in Fig. 3. In this case a waste heat boiler generates process steam.
steam by recovering heat from the gas turbine exhaust.

This cogeneration system is characterized in Fig. 4 for compressor pressure ratios of 4, 8, 12, and 16 and gas turbine expander inlet temperatures of 1500, 1600, and 1700 F (1089, 1145, and 1200 K), which are considered to be feasible for burning solid wastes in fluidized bed combustion since they are below the ash agglomerating temperature for most solid wastes. The plot shows that the ideal energy utilization factor is a fairly strong function of both pressure ratio and expander inlet temperature and that the gross process heat to electrical energy ratio is a strong function of pressure ratio but a rather weak function of expander inlet temperature.

A combined-cycle cogeneration system with fluidized bed combustion of solid wastes is shown in Fig. 5. In this case, a heat recovery steam generator supplies steam to a back-pressure steam turbine that supplies the process steam.

This cogeneration system is characterized in Fig. 6 for an expander inlet temperature of 1600 F (1145 K), showing that the ideal energy utilization factor is a fairly weak function of the gas turbine compressor pressure ratio but a strong function of process steam supply pressure. The gross process heat to electrical energy ratio is a moderately strong function of the process steam supply pressure and a strong function of the pressure ratio.

Figure 7 shows a combined-cycle cogeneration system utilizing indirect heating of part of the working fluid with fluidized bed combustion of solid wastes. In this system the minimum amount of excess air that will give high combustion efficiency is used. The balance of the air from the gas turbine compressor is indirectly heated in an in-bed heat exchanger. This arrangement gives a reduction of about 60 percent in the volume of combustion products that have to be cleaned ahead of the gas turbine expander. The cost of the particulate removal equipment can, therefore, be traded off against the cost of the in-bed heat exchanger. The characterization of the direct-fired system shown in Fig. 6 can be applied to this system.
tem if allowance is made for the temperature differential required for the in-bed heat exchanger.

Figure 8 shows a combined-cycle cogeneration system with exhaust heating of the working fluid using fluidized bed combustion of solid wastes [6, 7]. In this case the gas turbine expander uses air instead of combustion products. Part of the air from the expander exhaust is used for combustion air in a fluidized bed combustion air heater. A convection air heater cools the products of combustion to a temperature equal to that out of the expander. Here, again, the characterization of the direct-fired system shown in Fig. 6 can be applied to this system if allowance is made for the temperature differential required in the in-bed exchanger.

A closed-cycle gas turbine cogeneration system is shown in Fig. 9 [8]. The working fluid (air) is heated by both convection and in-bed heat exchangers following a recuperator. The heat rejection from the cycle goes to a waste heat boiler that generates the process steam. The minimum amount of combustion air required for high combustion efficiency is preheated with a recuperative air preheater. The advantages of the closed cycle are the high power density and the ability to control power output by varying the pressure level.

This cogeneration system is characterized in Fig. 10. Gas turbine design conditions of 3.75 pressure ratio and expander inlet temperature of 1325 F (1158 K) are those used in commercial units in Europe [8]. Both the ideal energy utilization factor and the ratio of gross process heat to electric energy are strong functions of the recuperator effectiveness, showing that recuperator effectiveness is a useful variable in matching the process heat and electric power requirements of a given industrial process.
ASSESSMENT OF FLUIDIZED BED COMBUSTION TECHNOLOGY FOR SOLID WASTES

Pope, Evans and Robbins have carried out extensive tests on atmospheric pressure coal-fired fluidized bed boilers, and a demonstration unit for atmospheric pressure fluidized bed utility boilers is under test at Rivesville, West Virginia [9]. Fluidyne is building an atmospheric pressure coal-fired fluidized bed air heater for an industrial application [10]. York-Shipley offers an industrial boiler with fluidized bed combustion of solid waste [3]. The above should provide a technology base for near-term application of conventional steam cogeneration systems with atmospheric pressure fluidized bed combustion of solid waste.

Combustion Power [11] has carried out extensive tests on pressurized fluidized bed combustors for gas turbines using refuse-derived fuels. Technology for handling, preparation, feeding, and burning refuse-derived fuel in a pressurized fluidized bed combustor was successfully demonstrated.

EVALUATION OF CORROSION-EROSION-DEPOSITION POTENTIAL

There are three distinct but interrelated technical problem areas in the utilization of solid fuels containing contaminants, i.e., corrosion, erosion, and deposition. Corrosion is primarily a function of the concentration of sulfur, alkali metals, vanadium, chlorine, and ash in the fuels. Sulfur in combination with alkali metals forms corrosive eutectic compounds at temperatures in the range of 1300-1500 F (978-1087 K). The alkali metals concentrations are generally controlling, so the low sulfur properties of most solid wastes are not an advantage.

Vanadium pentoxide, which forms in the combustion of vanadium-bearing fuels, is very corrosive to metal surfaces in the temperature range of 1100-1300 F (867-978 K).

Chlorine plays an ambivalent role in alkali metal sulfate corrosion. It tends to promote the release of alkali metal vapors during the combustion process, but it suppresses the corrosiveness of alkali metal sulfates in combustion products. It does, of course, create a separate corrosion problem in the formation of HCl in the products of combustion.

Vanadium corrosion is controlled by solid sor-bents for sulfur in fluidized bed combustion. When the sulfur content of a fuel is low, as for solid waste, in-bed desulfurization is not required, and a vanadium corrosion problem will be possible.

The presence of sulfur in fuel leads to cold-end corrosion due to the formation of SO3, which causes an acid condensate.

Ash in fuel causes deposits on and erosion of surfaces. Because of the low temperatures used in fluidized bed combustion, hard to remove slag-type deposits should not be a problem. Dry-type deposits which will occur on out-of-bed surfaces should be relatively easy to remove using soot blowers. The chief problem anticipated with ash particles in combustion products from fluidized bed combustion of solid waste is erosion.

The components of the various system configurations discussed herein, which are subject to one or more of these problems in utilizing coal and/or solid wastes as fuel, are as follows:

1. In-bed steam-heating surfaces.
2. Convection steam-heating surfaces.
4. In-bed gas-heating surfaces.
5. Convective gas-heating surfaces.

If it is assumed that water-side corrosion problems can be eliminated by chemical treatment, there is no real difference between steam- and gas-heating surfaces at the same metal temperature. Hot-side corrosion of heat transfer surfaces appears to be less of a problem in fluidized bed boilers burning coal than in conventional boilers. This may be due to the fact that fewer alkali metal vapors are released at the lower combustion temperatures found in fluidized bed combustion. It may also be due to reduced deposition on surfaces immersed in fluidized beds.

Laboratory corrosion tests [12] on expander blade materials where the corrosive environment expected in the products from fluidized bed combustion of refuse-derived fuel was simulated showed no corrosion phenomena, despite the presence of chlorine, alkali metal, and sulfur. Oxidation-limited blade lives, however, were projected to be only about one-half of what they are with clean fuels.

The most critical problem areas among the systems components are thought to be erosion of and deposition on the gas turbine expander. The problem of erosion by ash particles was well demonstrated in the Locomotive Development Committee [13] and the Australian [14] experiences. The ash...
particles from fluidized bed combustion are, however, friable platelets and are, therefore, not as erosive as those from pulverized fuel combustion. Deposition as well as erosion was a problem in the Australian program. Combustion Power [11] experienced severe deposition problems when they ran a small gas turbine with a fluidized bed combustor on refuse-derived fuel because of the aluminum present in the fuel.

Development of particulate removal equipment required to clean the gas and avoid problems with erosion and deposition is under way [4]. This is not a state-of-the-art technology.

Solid wastes vary widely in the amount of contaminants they contain. They tend to have low sulfur contents relative to coal. Vanadium is not expected to be present. Some, such as wood waste, have a high content of alkali metals. Chlorine is a problem in municipal refuse because of the presence of PVC wastes.

It is impossible to generalize regarding contaminants in solid waste when used as fuel. Each case will have to be analyzed when the energy recovery system is selected, and the system design should include provisions to minimize the adverse effects from the contaminants.

ENVIRONMENTAL IMPACT

Air emissions and residual solids disposition are the primary environmental concerns with fluidized bed combustion systems. Sulfur emissions will not exceed emission standards with most waste materials since they have low sulfur contents. There are exceptions, and for these cases limestone or dolomite can be utilized as the bed material to control sulfur oxide emissions during the combustion process. Nitrogen oxide formation from the combustion air is well below the emission standard since the maximum temperatures in the bed are \( \sim 1800 \, \text{F} \) (1233 K). Nitrogen oxide is a concern if the waste material contains nitrogen compounds that are released during combustion. Particulate carry-over from the bed is the result of residual solids that are released from the waste material and elutriated bed material. The inert bed material to be used with low-sulfur solid waste can be selected for low attrition so that the quantity of attrited bed material should be minimal. Use of double-screened bed material will reduce the initial concentration of bed material fines. Conventional particulate control equipment can be used with atmospheric pressure systems. High temperature, high pressure control techniques will be required with the pressurized systems to achieve maximum thermal efficiency. High efficiency (e.g., >99 percent) particulate removal equipment for these systems is being developed [4]. Trace elements are a concern and must be monitored for each waste material considered. Gas phase inorganic emissions can be expected to be minimized compared with alternative higher temperature systems such as suspension combustion. Gas phase organic emissions can be minimized by selecting design and operating conditions to allow adequate residence time. Residual solids disposal must be monitored for possible ground water leachates. An assessment will be required for each material considered.

SUMMARY

The most promising cogeneration and total energy system concepts for near-term application using FBC of solid wastes are those that do not pass products of combustion through gas turbine expanders. System concepts which should be considered are:

1. Atmospheric pressure fluidized bed boilers.
2. Exhaust-heated gas turbine or combined cycle.
3. Closed-cycle gas turbine.

REFERENCES


Key Words
Combustion
Energy
Fluidized Bed
Power
Refuse Derived Fuel
System
Utilize