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Fluid-Bed-Augmented CAES Systems

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Fluid Bed Augmented CAES Systems

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ABSTRACT

Compressed Air Energy Storage (CAES) systems are potentially attractive for future electric utility load leveling applications. A potential long-term weakness of the conventional CAES concept is its reliance on clean petroleum fuels during the power generation period. This consumption of petroleum could be completely eliminated by the use of coal-fired fluid bed combustors in second generation CAES plants. A large number of CAES power system configurations are possible using atmospheric fluid bed combustion (AFBC) and pressurized fluid bed combustion (PFBC). The fuel consumption rates for these systems are generally comparable to those for oil-fired CAES systems. The future prognosis for using PFBC in CAES systems looks good. Recent corrosion and erosion experiments in fluid bed systems suggest that gas turbines with acceptable lifetimes are a distinct possibility. The commercial status of these systems depends on the outcome of extensive corrosion/erosion testing in static and rotating test rigs. CAES systems using AFBC may be an attractive alternative to using PFBC, although the materials problem would then be transferred from the turbine to the high temperature heat exchanger surface. A reasonable expectation for the date of commercialization of fluid bed augmented CAES system ranges from 10 to 15 years.

INTRODUCTION

An energy storage system which could be attractive for future electric utility peak power applications is a modified gas turbine power system utilizing underground storage of compressed air. In conventional compressed air energy storage (CAES) schemes (see Ref. 1), synchronous gear clutches would be used to uncouple the compressor and turbine so that they would operate during different time intervals (see Fig. 1). During low-load, off-peak periods the main electric generator would be used as a motor to drive the compressor. The compressed air would then be stored underground. During subsequent peak load periods the compressed air would be withdrawn from storage, mixed with petroleum fuel, burned, and expanded through the turbine to generate power. This conventional petroleum-fired scheme represents a practical compromise between low equipment cost, relatively small storage volume, and low fuel consumption. One such system is currently in operation in West Germany, and others of this type are deemed likely in the foreseeable future.

A potential long-term weakness of the conventional CAES concept is its reliance on clean petroleum fuels during the power generation period. It seems appropriate, therefore, to investigate advanced CAES concepts designed to substitute coal for petroleum. Direct combustion of pulverized coal in gas turbines was attempted in the 1950's but proved very unsuccessful because of problems with ash slagging, erosion, and corrosion. Fluid bed combustion (FBC) is an improved method of coal combustion which offers a promising solution to these earlier problems.

Application of FBC to the CAES concept provides for a large number of possible FBC/CAES power plant system configurations incorporating atmospheric fluid bed combustion (AFBC) or pressurized fluid bed combustion (PFBC). In principle, all of these configurations would use a coal-fired FBC to replace the petroleum-fired burner of the conventional CAES arrangement.

The purpose of this paper is to present the highlights of an ongoing technical and economic assessment of the feasibility of coal-fired FBC augmented CAES system concepts. This study program is being supported by Battelle Pacific Northwest Laboratory (PNL) under Subcontract No. B-51299-A-P as part of a PNL contract (Contract No. EY-76-C-06-1830) with the Department of Energy. It is being performed by a study team managed by the United Technologies Research Center (UTRC) which includes Coal Processing Consultants, Ltd. of the United Kingdom and Acres American, Inc.

This paper summarizes the technical work completed during the first quarter of the study period. The subjects addressed include the fluid bed combustion technology review and assessment, the turbomachinery technology review and assessment, component availability and R&D requirements, alternative system configurations, and preliminary performance estimates.

FLUID BED COMBUSTION TECHNOLOGY

A fluid bed is produced by turbulent floatation of crushed inert material in a rising air stream. The principle of bed fluidization is quite simple (see Fig. 2). When a static bed of relatively dense particles is subjected to an upward, low-velocity flow of gas, the gas passes through the bed without disturbing the particles. If the velocity of the gas is continually increased, however, a point will eventually be reached at which the individual particles will be forced upwards by the aerodynamic drag force and incipient fluidization will begin. If the gas velocity is further increased, expansion of the bed occurs permitting an increase in the gas flow rate. The bed becomes highly turbulent and rapid mixing of the particles occurs. The surface is no longer well defined but appears diffuse, and bubbles of 'gas' similar to those formed in a boiling liquid rise through the bed. A bed in this state is said to be fluidized. Still further increases in gas velocity cause progressively larger particles to become entrained in and carried off (elutriated) by the gas stream. Consequently, for a particular bed with a given particle size range there will be an upper and lower limit of velocity (fluidizing velocity) between which satisfactory fluidization will be established.

In FBC, the particles forming the bed are composed of suitable inert mineral matter. For coal burning, these would probably be the residual ash from previously burned coal and graded limestone or dolomite to absorb sulfur dioxide during combustion. The fluidizing gas is the combustion air. Coal is fed continuously into the bed in the quantity required to maintain the desired bed temperature.

The design of a coal-fired FBC is significantly influenced by the operating conditions. The most important of these are bed temperature, fluidizing velocity, operating pressure, and particle size. The FBC bed temperature must be controlled within fairly narrow limits, i.e., 1425 to 1650 F (775 to 900 C). This control is necessary to achieve high combustion efficiency, obtain high heat transfer rates to in-bed tubes, maximize sulfur retention, avoid ash sintering, limit the metal temperature of heat transfer surfaces in the bed, and reduce emissions of nitrogen oxides and alkali metal salts. The fluidizing velocity must also be controlled within fairly narrow limits, i.e., 2.5 to 4.5 ft/sec (0.75 to 1.4 m/s) for a PFBC and 2.5 to 8 ft/sec (0.75 to 2.5 m/s) for an AFBC. Operation within this range will establish bed fluidization, provide oxygen for combustion, and limit elutriation of bed particles. The selection of operating pressure will influence combustion efficiency, sulfur retention, nitrogen oxides emission levels, and capital costs. Operation at elevated pressure (PFBC) will produce beneficial results for all of these parameters as opposed to operation at atmospheric pressure (AFBC). The choice of particle size is related to the choice of fluidizing velocity. The lower limit of particle size is determined by the requirement to avoid excessive carryover of combustible material, unreacted sorbent, and bed material. The upper limit is determined by the desire to achieve high

heat transfer rates to in-bed tubes and effective solids mixing without localized segregation. The design of a PFBC for CAES applications is also influenced by factors unique to the application. These include load following, hot gas particulate cleanup and alkali emission reduction.

TURBOMACHINERY TECHNOLOGY

The design of turbomachinery is also significantly influenced by the operating conditions. The operating conditions for the turbomachinery in a FBC/CAES power plant system will depend on whether an AFBC or PFBC is used. In either case, however, the operating temperature will be characteristic of conditions which were attainable twenty years ago.

The application of an AFBC would require relatively minor modifications of clean fuel-fired turbomachinery designs. The AFBC would be used as an air heater, and this heated air would be expanded in the turbine. Although the turbine would be relatively simple to design, an AFBC/CAES system would still be faced with a materials problem. In particular, the extensive heat transfer surfaces immersed in the bed and in the hot convective zone following the bed must contain the high pressure compressed air while being subjected to high temperature.

The use of a PFBC would present more of a design challenge to ensure high reliability and low maintenance for the turbine. The size and amount of particles entering the turbine would have to be controlled within narrow limits by effective hot gas cleanup to minimize turbine erosion and particle deposition. A limited amount of particles between 2 and 10 microns could be tolerated; however, essentially all particles greater than 10 microns would have to be removed from the PFBC effluent gas stream before the turbine. Small particles (2 microns and less in size) have an affinity to adhere on impact; therefore, concentrations sufficient to cause fouling of the airfoils must be avoided. The level of volatilized alkali metal salts in the PFBC effluent gas must be kept to a minimum, and corrosion resistant materials or coatings must be used to reduce the potential for excessive corrosion.

COMPONENT AVAILABILITY AND R&D REQUIREMENTS

Off-the-shelf FBC and turbomachinery equipment does not presently exist for FBC/CAES applications.

Small scale, commercial fluid bed boiler systems can be engineered now. However, the larger, higher temperature FBC equipment associated with CAES systems require continued development. The major areas in which R&D on FBC is required include feeders for the coal and sorbent, devices for ensuring efficient lateral distribution of fuel in the bed, containment for the combustor, distributors for the fluidizing and combustion air, heat transfer

surfaces for both in-bed and above-bed tubes, depressurization systems for spent sorbent and fuel ash, tube bundles for minimizing bed depth and control systems for load following.

If an AFBC were used in a CAES power plant system application, the modification of existing petroleum-fired turbomachinery should not produce any significant problems. However, the turbines for expansion of gases from a PFBC represent a major design uncertainty at this time. The major areas of turbomachinery R&D would be directed toward compatibility between the PFBC and turbine. The effect of erosion on gas turbines must be better documented, and effective hot gas cleanup systems must be developed to control particulates. Methods must be developed which will limit deposition. The corrosion mechanism must be better understood, and materials must be developed that will withstand corrosion plus the combined effects of corrosion and erosion.

Successful completion of the development activities mentioned above could lead to commercialization by the mid-1980's of an AFBC/CAES system with in-bed air heater tube metal temperature limited to 1200 F (650 C). This could be followed by the early 1990's with a PFBC/CAES system with the same tube metal temperature limitation. It is envisioned that air heater tubes in the bed could operate up to the bed temperature for both the AFBC/CAES and PFBC/CAES systems by the mid 1990's.

FBC/CAES SYSTEM CONFIGURATIONS

A number of potential CAES cycle configurations have been considered using PFBC and AFBC, with or without heat recovery steam cycles. Some of these configurations would require the coal combustors to cycle or operate only during the peak load period with the energy for off-peak compression provided from the utility grid. Others would allow the fluid beds to operate continuously and provide some or all of the off-peak energy for air compression (see Ref. 2). This paper is restricted to the former type of configuration.

One promising coal-fired PFBC/CAES configuration is depicted in Fig. 3. This arrangement is based on the preliminary oil-fired CAES system presented in Ref. 1. The major change involves substitution of a coal-fired PFBC for each of the two oil-fired burners originally placed before the high pressure expansion turbine (ET) and the reheat low pressure turbine (LT). This arrangement has the advantage of eliminating all heat transfer tubing from the beds. Also, the gas temperature entering the ET and LT turbines would be at the maximum possible temperature for fluid bed combustors, so the performance should be good.

An alternate configuration in Fig. 4 would incorporate a single PFBC. Instead of using a separate high pressure PFBC before the expansion turbine,

air going to the expansion turbine would be heated in tubes immersed in the main PFBC. This concept would eliminate the complexities of operating two combustors at different pressures with separate coal feed and control systems. Also, the problems of operating a PFBC at the very high pressures associated with air storage (where no PFBC operating data exist) would be avoided, and the expansion turbine would not be exposed to particle-laden air from the PFBC.

A variation of the preceding PFBC scheme (not illustrated) would eliminate the in-bed tubes by passing the heated air from the recuperator directly to the expansion turbine. This configuration should result in lower technical risk than the two preceding ones, but it would suffer a slight performance loss due to the reduced gas temperature entering the expansion turbine.

Alternative system configurations are possible using AFBC instead of PFBC. As depicted in Fig. 5 air from storage would be preheated in the recuperator, further heated to intermediate temperature in the AFBC, and heated to its final temperature in convective heat exchangers using hot gas effluent from the bed. The three convective heat exchangers depicted could be used in cross flow, counter flow, or parallel flow arrangements. Variations of this scheme are possible in which the convective heat exchanger before the expansion turbine could be eliminated. In still another variation, the air in the LT turbine could be extracted mid-way through the expansion, reheated in additional tubes placed in the AFBC and in an additional convective heat exchanger, and readmitted to the LT turbine for continuation of the expansion process. These AFBC schemes are of interest because they completely eliminate potential turbine erosion problems associated with particulate elutriation from the bed by passing only heated air through the turbines.

FBC/CAES SYSTEM PERFORMANCE

Preliminary performance estimates for several of the AFBC and PFBC configurations identified above are summarized in Table I. In all cases, the FBC exit temperatures and turbine inlet temperatures were selected to be consistent with maximum allowable metal temperatures anticipated for each configuration. The gas temperature at the exit of the AFBC is taken to be higher than that from the PFBC to account for the additional combustion and temperature rise expected in the AFBC freeboard.

In general, the PFBC schemes have power outputs and heat rates which are comparable to those reported (Ref. 1) for oil-fired schemes. The PFBC scheme with two separate beds has the best performance, but this also clearly requires a very high pressure PFBC which is beyond the current state of technology. In general, the performance of the PFBC schemes is about 10 percent better than for the AFBC schemes. All of the AFBC scheme variations

investigated to date seem to yield about the same level of performance.

PRELIMINARY CONCLUSIONS

Several advanced coal-fired CAES system concepts appear feasible based on the use of pressurized and atmospheric fluid bed combustors. The predicted overall level of performance of these system concepts is roughly comparable to that previously estimated for oil-fired CAES systems. The principal advantages of these systems are the use of indigenous coal resources and the lower cost of coal relative to oil.

The future prognosis for using pressurized fluid bed combustors in CAES systems looks good. Recent corrosion/erosion experiments in fluid bed systems suggest that gas turbines with acceptable lifetimes are a distinct possibility. Additional component and full size turbine testing in real fluid bed environments are required, however, to verify these preliminary lifetime forecasts.

Atmospheric fluid bed combustion systems may be an attractive alternative or backup to pressurized fluid bed combustion systems. The use of atmospheric fluid bed combustion systems would eliminate the uncertainties associated with erosion and corrosion in the gas turbines. However, the materials problem would be shifted to the extensive heat transfer surface which must be immersed in the bed or located in the hot convective zone following the bed.

The status of commercial development of coal-fired fluidized bed augmented compressed air energy storage systems is uncertain and depends on the outcome of extensive erosion/corrosion testing in static and rotating test rigs. A reasonable expectation for the date of commercialization (following testing, pilot, and demonstration phases) for this type of system ranges from 10 to 15 years.

CONCLUDING REMARKS

In closing, it is recognized that the fluid bed CAES cycles described herein represent only a fraction of the total number of configuration options available. Other configurations not yet examined might prove highly attractive. Also, capital and operating cost differences between systems have not been evaluated. Future work is planned to provide a meaningful technical and economic feasibility evaluation of coal-fired fluid bed CAES power systems.

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TABLE I

FBC/CAES SYSTEM PERFORMANCE SUMMARY

System No.	FBC Press, atm.	FBC Exit Temp, F	Turbine Inlet Temp		Power, MW ⁽¹⁾	Heat Rate		
			ET, F	LT, F		Compression, Btu/kWh ⁽²⁾	Generation, Btu/kWh ⁽³⁾	Round Trip, Btu/kWh
1	10	1560	1020	1560	242	8300	4200	12500
2	15	1560	1020	1560	247	8100	4200	12300
3	20	1560	1020	1560	247	8100	4200	12300
4	58/15	1560/1560	1560	1560	273	7300	4300	11600
5	1	1830 (6)	1020	1380	218	9200	4300	13500
6 (4)	1	1830	1370	1370	225	8900	4300	13200
7 (5)	1	1830	1270	1270	213	9400	4400	13800
8 (5)	1	1830	1270	1210/1210	224	8900	4400	13300

1. Based on constant system air flow rate
2. Based on utility grid heat rate at 10,000 Btu/kWh
3. Based on coal higher heating value
4. Counter flow heat exchangers
5. Parallel flow heat exchangers
6. Includes temperature rise in FBC freeboard

FIG. 1

Simplified CAES System

FIG. 2

Bed Fluidization

FIG. 3

Coal-Fired PFBC/CAES System With Very High Pressure Bed

FIG. 4

Coal-Fired PFBC/CAES System

FIG. 5

Coal-Fired AFBC/CAES System