First-Generation Circulating Pressurized Fluidized Bed (CPFB) Combustor Power System with Industrial Components

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Introduction

The development of circulating pressurized fluidized bed combustor technology in the U.S. has been dependent on the availability of suitable turbomachinery. Until now, most development and conceptual design of commercial sized systems have been based on the turbomachine offerings of one or two vendors. In the case of the second generation of this technology, involving topping firing to achieve firing temperatures in the range of current gas turbine practice, this link is based on the cooperation and interests of the manufacturers of commercial gas turbines.

The first generation version of CPFB technology can, however, be based on other available turbomachinery, not just commercial integrated gas turbine designs. If the broad range of available turbomachinery is contemplated for use in the first-generation CPFB, more complete optimization of the thermodynamic cycle and the CPFBC island design may be possible. Then the turbomachinery may be selected to fit the needs of the cycle, rather than the cycle and CPFB equipment specified to fit the available gas turbines.

Objectives

The first objective of this study was to perform thermodynamic cycle analyses to determine which thermodynamic cycles offer the best opportunity to optimize a first-generation CPFB using industrial components. Following definition of promising cycles, the next objective was to identify available commercial compressors and expanders that may be assembled along with the CPFB components to create a complete plant. Finally, a conceptual design for an entire CPFB power plant will be developed, along with capital cost estimates and plant economics.

Approach

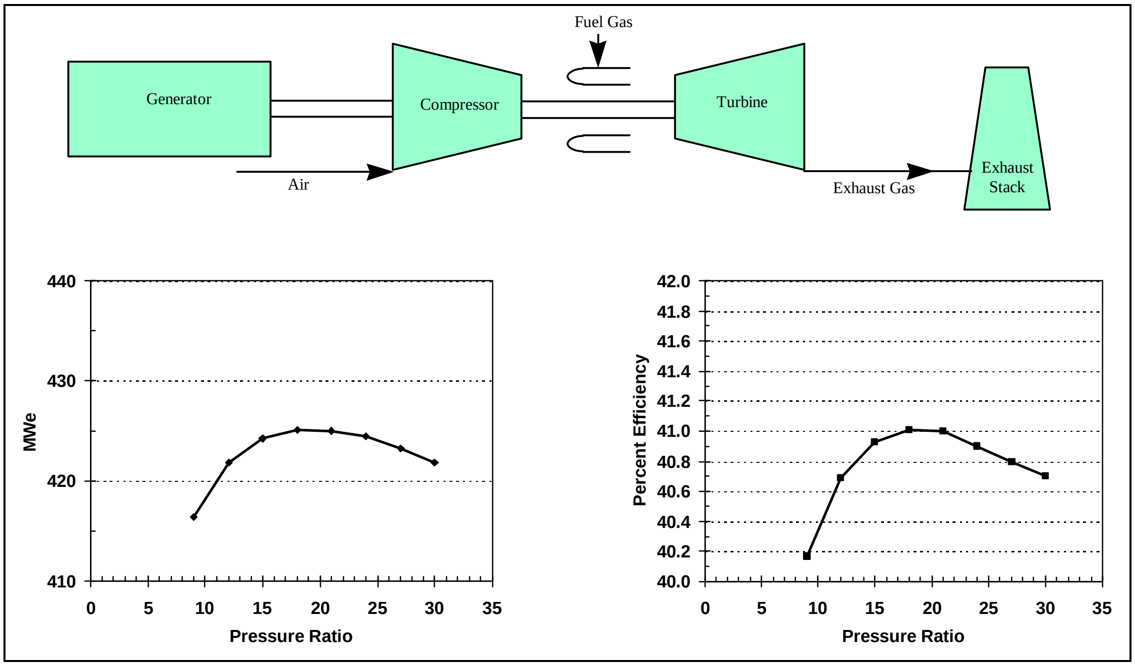
The state of the art in turbomachinery was evaluated, and component efficiencies and other performance characteristics representative of modern industrial equipment were established. The component performance levels used in this study are as follows:

Compressor Efficiency	90% (polytropic)
Expander Efficiency	90% (polytropic)
Electric Generator Efficiency	98%
Intercooler Delta P	2%
Regenerator Delta P	2%
Regenerator Effectiveness	80%
Heat Recovery Unit Delta P	10 in. wg

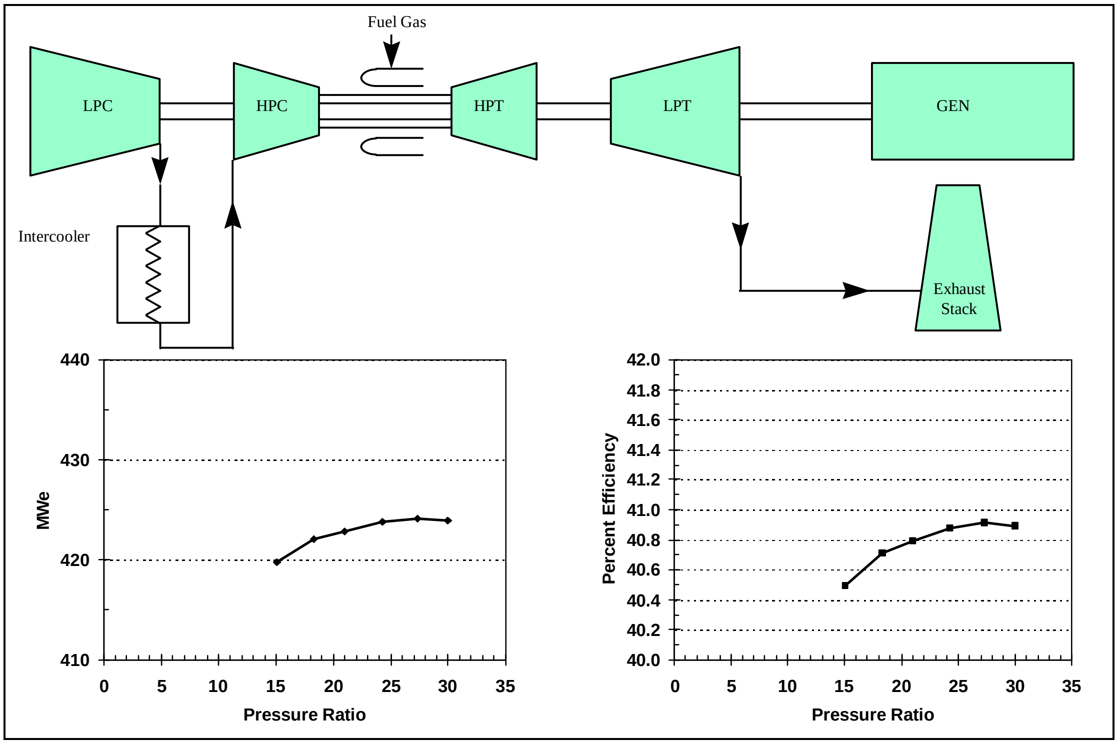
For the intercooled cases, the overall compression process is divided into two steps, each step providing roughly the square root of the overall process pressure ratio. The air is cooled to 110F between compression steps.

Following establishment of component performance levels, Brayton cycle models were developed using the ASPEN flow sheet simulation software. For this study, four cycle configurations were evaluated: a simple cycle, an intercooled cycle, a regenerative cycle, and an intercooled-regenerative cycle. The CPFB bed exit temperature (coinciding with the turbine inlet temperature for these non-top-fired cases) was set at 1575F. At this temperature, for this study, no attempt was made to establish a level for or model the use of turbine cooling air for the first stage of the expander.

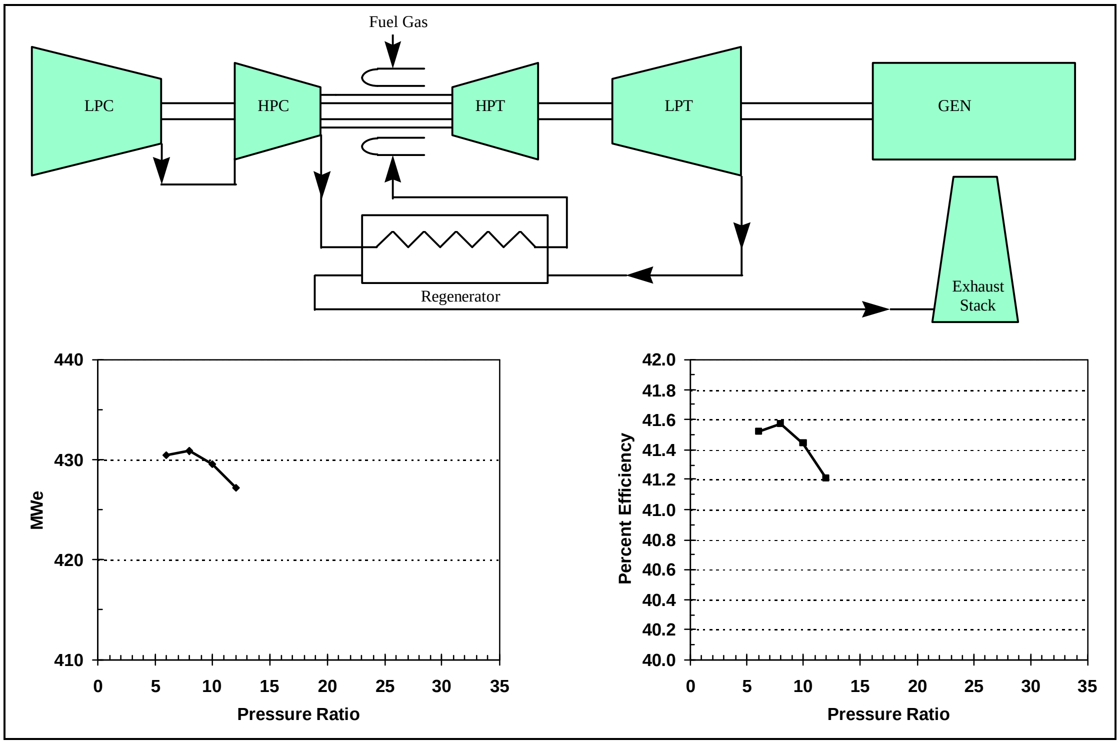
Cycle performance was calculated for a range of pressure ratios in an effort to define the optimal pressure ratio for each case. The results of these calculations are presented in the following graphs, along with simplified schematic diagrams of the component arrangement for each cycle.



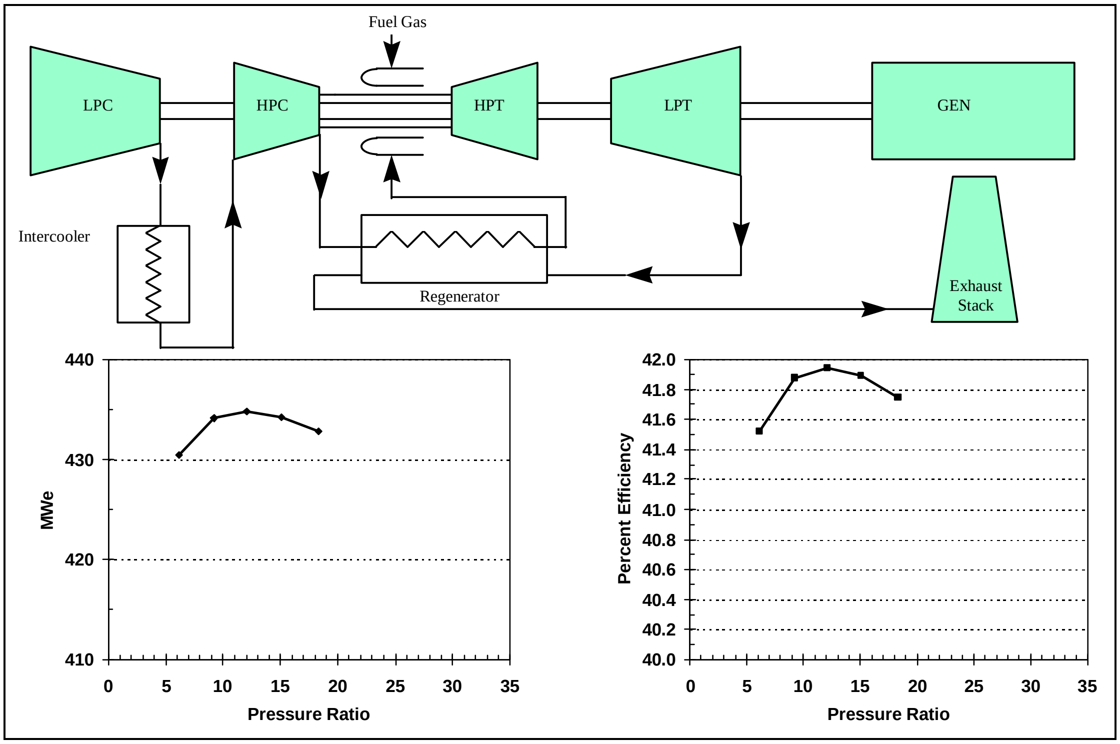
Simple Brayton Cycle
(Natural Gas Fired)



Intercooled Brayton Cycle
(Natural Gas Fired)



Regenerative Brayton Cycle
(Natural Gas Fired)



Intercooled-Regenerative Brayton Cycle
(Natural Gas Fired)

In a first-generation CPFB, the steam cycle typically provides about 80 percent of the plant gross power output. It is therefore desirable to utilize an efficient state-of-the-art steam cycle in this type of power configuration. Although the most efficient steam cycles are supercritical, high temperature cycles, with double reheat and other enhancements (including as many as ten feedwater heaters), the US power generation market has not embraced these aggressive measures in recent years. The power cycle of choice has tended to be the subcritical, 2400 psig/1000F/1000F configuration, with approximately six or seven feedwater heaters. Recent advancements in steam turbine design and manufacture have improved adiabatic efficiency levels by several percentage points, increasing steam cycle output and efficiency for this cycle to levels approaching those formerly achieved only by the more aggressive cycles noted above.

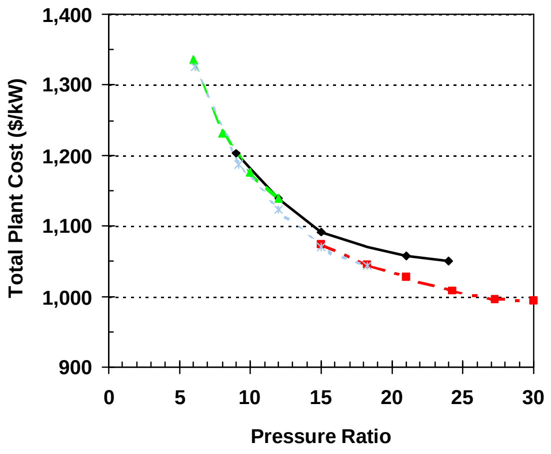
For this study, the 2400 psig/1000F/1000F cycle is used in conjunction with a new current model steam turbine. The steam turbine selected for this study is a tandem compound design, exhausting to a condenser at 2.5 in. Hga. The condenser heat is rejected to a cooling water loop incorporating a modern evaporative mechanical draft cooling tower.

Results

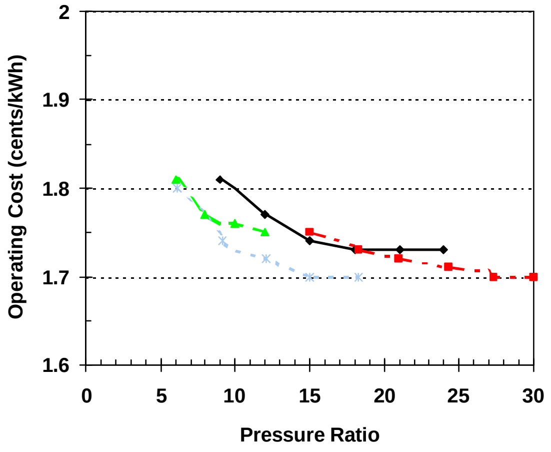
Each type of gas turbine cycle displays a specific characteristic, with net power per pound of inlet airflow and efficiency peaking in a particular range. Coupling a steam cycle to the Brayton cycle does not alter this characteristic, but adds an additional degree of freedom to the cycle analysis. An analysis of the combined Brayton and Rankine (steam) cycles for each case was performed to determine thermodynamic performance. However, the selection of the best overall cycle must be based on economic performance and not solely on thermodynamic performance.

Therefore, the next step in the study was to estimate the capital costs of the various configurations over the range of performance that was calculated. This was accomplished by starting with a capital cost model of a first-generation CPFB established in prior DOE studies (Ref. 1), and embedding the model in a spreadsheet that is equipped with algorithms for adjusting capital costs based on the size or rating of the various components that comprise each complete system.

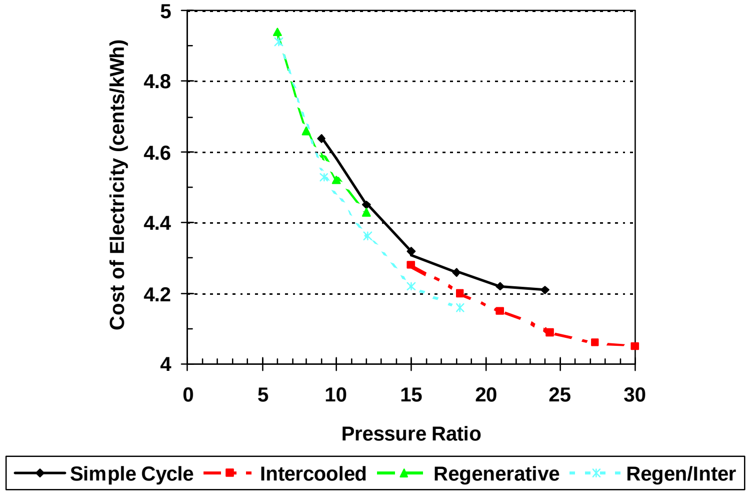
The spreadsheet model was used to calculate capital costs and Cost of Electricity (COE) for the various cases. This information is presented in the following graphs:



First Generation PFBC Capital Costs



First Generation PFBC Operating Costs



First Generation PFBC Cost of Electricity

Selection of economic optimum cycles can be more complex than simply seeking the cycle configuration with the lowest COE. The projected performance of a system in actual power generation service, considering dispatch preferences, time of day electricity pricing, part load performance, and other factors must be considered. This type of analysis, often termed a "production costing evaluation" is, however, beyond the scope of this limited study. The estimated COE is used herein as the figure of merit to select the desired configuration.

The results of the COE analysis indicate that an intercooled cycle with an overall pressure ratio of about 25 to 1 offers the most promise. The COE of this case appears to be approximately 10 percent lower than the COE for a simple cycle operating at a pressure ratio of 14 to 1, which is representative of the cycle provided by complete packaged heavy frame gas turbines previously considered for this application. In addition, the operating costs of the intercooled cycle are among the lowest of those evaluated. This indicates a high potential for competitive dispatch in either regulated or unregulated markets. Therefore, use of COE as a figure of merit is reinforced, in this case, by the lower operating costs for the intercooled cycle. The focus of the study from this point on will be to evaluate commercially available components, principally compressors and expanders, in an attempt to identify a complete system that can be built from these components.

References

1. Weinstein, R.E., et al., "Repowering the L.V. Sutton Steam Station with Advanced Pressurized Fluidized Bed Combustion, Draft of Parsons Report No. EJ-9616, prepared for the U.S. DOE under Contract No. DE-AC01-94FE62747, Task 20.