DOE/MC/30247-96/C0640 CONF-9510109--16

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APR 0 9 1996
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Contractor:

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Contract Number:

DE-AC21-93MC30247

Conference Title:

Advanced Turbine Systems Annual Program Review

Conference Location:

Morgantown, West Virginia

Conference Dates:

October 17-19, 1995

Conference Sponsor:

U.S. Department of Energy, Office of Power Systems Technology,
Morgantown Energy Technology Center

Contracting Officer Representative (COR):

Richard Johnson

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Introduction

Westinghouse's experience with land based gas turbines started in 1945 with the development of a 2000 hp gas turbine-generator set that consisted of a single reduction gear, compressor, 12 combustors and turbine. A thermal efficiency of 18%* was obtained. By 1954, Westinghouse had developed a 15 MW unit (with a regenerator and intercooler) that was designed for a full-load simple cycle efficiency of 29%. As the initial step in the Advanced Turbine Systems (ATS) program, Westinghouse has already developed a 230 MW gas turbine that has a simple cycle efficiency of 38.5% without the use of regeneration and intercooler concepts.

In 1967, Westinghouse developed its first gas turbine combined cycle, a synergistic combination of the Brayton and the Rankine cycles. In a combined cycle the heat rejected by the higher temperature topping cycle is recovered in the lower temperature bottoming cycle to produce additional power from the energy initially released by the fuel. In this first Westinghouse combined cycle, a 1450°F burner outlet temperature gas turbine, rated at 25 MW, supplied exhaust heat which was used in a boiler to furnish steam to drive an 85 MW steam turbine. This plant achieved an annual average efficiency of 39.6%.

In the early 1990's, Westinghouse combined cycle efficiencies were in the 53 to 54% range. Today, with a Westinghouse 501G gas turbine, a net efficiency of 58% is obtainable for a 350 MW single-shaft gas turbine and steam turbine combined cycle arrangement.

As applicable, technology advances from the ATS Program are being incorporated into our 501G design. This paper reviews some of the natural gas-fired and coal-fueled cycle concepts that have been evaluated by Westinghouse to support ATS objectives. Also, features of the Westinghouse single-shaft ATS combined cycle are highlighted in this paper.

Objective

In cooperation with the U.S. Department of Energy's Morgantown Energy Technology Center, the Westinghouse Electric Corporation

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Research sponsored by the U.S. Department of Energy's Morgantown Energy Technology Center, under Contract DE-AC21-93MC30247 with Westinghouse Electric Corp. 4400 Alafaya Trail, Orlando, FL 32826-2399, telefax: 407-281-5014.

* All efficiency values in this paper will be lower heating value

is working on an 8-year, four-phase program to develop and demonstrate a highly efficient (greater than 60% plant cycle efficiency), environmentally superior (NOx < 10 ppmv), and cost-competitive (busbar energy costs 10% less than current technology) utility for baseload utility scale power generation. The natural gas-fired gas turbine must be capable of being adapted to operate on coal or biomass fuels. Availability is to be equivalent to modern advanced power generation systems, and the concept must be commercially available by the year 2000.

Approach

In Phase 1, Westinghouse concluded that a plant efficiency greater than 60% can be obtained with an advanced combined cycle, which includes an increased gas turbine firing temperature (2600°F), increased component efficiencies, and reduced cooling air usage (Little et al., 1993). In Phase 2, in which Westinghouse is currently working with DOE, gas turbine cycle efficiencies were reevaluated using established principles such as intercooling and recuperation, and newer concepts such as thermochemical recuperation and partial oxidation. Also, efficiency enhancements within the ATS cycle were evaluated to determine the best approaches to raising overall thermal plant efficiencies (Bannister et al., 1994). Within Phase 2, Westinghouse has developed a conceptual gas turbine design for an advanced combined cycle.

Project Description

Current large natural gas-fired combined cycle power generation systems are capable of net efficiency levels in the range of 58%. Within the ATS Program, Westinghouse was given the opportunity to reevaluate cycle efficiencies. Results of some of the analyses are summarized in this paper. In addition, efficiency enhancements within the ATS selected cycle have been evaluated. The concepts considered in the Westinghouse analyses are required to be capable of demonstration within a two-to-three year time frame. From a baseline cycle definition, this paper reports briefly on how different concepts will affect the overall plant thermal efficiency (Briesch et al., 1994).

The Phase 2 Westinghouse ATS Program is defined within eight major tasks. Task 1 (Management Plan), Task 2 (National Environmental Protection Act [NEPA]), Task 3 (Select Natural Gas-Fired Advanced turbine System [GTFATS]), and Task 4 (Conversion to a Coal-Fueled Advanced Turbine System [CFATS]) have been completed. The remaining tasks, Task 5 (Market Study), Task 6 (System Definition and Analysis), Task 7 (Integrated Program Plan), and Task 8 (Design and Test of Critical Components), have started.

Cycle Studies

Baseline Cycle

In order to evaluate different technologies and concepts applicable to combined cycle power generation systems, a baseline combined cycle configuration was developed to provide a basis for comparison of all the cycle concepts and technologies to be considered. A conventionally configured combustion turbine coupled with a three- pressure level reheat steam cycle was modeled to provide a baseline cycle. The gas turbine rotor inlet temperature (RIT) was set at 2600°F to approximate near-term temperature capabilities. Compressor pressure ratio was set at 18. High pressure steam conditions entering the steam turbine were specified at 1450 psi and 1000°F, and the hot reheat steam temperature was also set at 1000°F. This configuration utilized turbine rotor cooling air heat to produce additional low-pressure steam in the steam cycle via a heat exchanger located in the heat recovery steam generator (HRSG). Also, the natural gas fuel was preheated by feedwater recirculation flow.

Steam Cycle Enhancements

The basic reason for raising the steam pressure and temperature of the Rankine cycle is to improve the potential thermal efficiency. The cost effective steam cycle was determined to be at 1800 psi with 1050°F high pressure superheat steam and 1050°F reheat steam.

Closed-Loop Cooling

Most current technology gas turbine engines utilize air to cool the turbine vanes and rotors. This allows the turbine inlet temperature to be increased beyond the temperature at which the turbine material can be used without cooling, thus increasing the cycle efficiency and power output. However, the cooling air is a detriment to cycle efficiency. First, air is ejected from the turbine air foils earning a disruption in the surrounding flow field. Secondly, the cooling air is ejected from the airfoil into the gas path which results in irreversible pressure losses due to non-ideal mixing. The third loss mechanism is caused by the reduction in gas path temperature which reduces the work output of the temperature. Finally, the turbine cooling air must be pumped to pressures significantly higher than gas path pressure to assure that cooling flow rate is sufficient. By using a closed-loop cooling concept, the loss mechanisms can be reduced while still maintaining turbine material temperatures at an acceptable level.

Higher Compressor Pressure Ratio

Aircraft gas turbine engines are designed with high overall pressure ratio to maximize simple cycle efficiency. For a Westinghouse type industrial gas turbine engine with a 2600°F RIT, the simple cycle efficiency curve is relatively flat above a pressure ratio of approximately 40. In a combined cycle, steam cycle efficiency decreases with increasing gas turbine pressure ratio due to the reduction in gas turbine exhaust temperature. This in turn reduces the maximum steam temperature and pressure and the steam's availability, and results in lower steam cycle efficiency.

Compressor Intercooling

Compressor intercooling reduces the compressor work, because it compresses the gas at a lower average temperature. Since the gas and steam turbines produce approximately the same output as in the non-intercooled case, the overall cycle output is increased. Since the compressor exit temperature is lowered, the amount of fuel that must be added to reach a given turbine inlet temperature is greater than that for the non-intercooled case.

The ratio of the amount of compressor work saved to the amount of extra fuel energy added is about equal to the simple cycle efficiency. Intercooling adds output at approximately the simple cycle efficiency. Since combined cycle efficiencies are significantly greater than simple cycle efficiencies, the additional output at simple cycle efficiency will reduce the combined cycle net plant efficiency for the intercooled case.

Recuperation

In recuperative cycles, turbine exhaust heat is recovered and returned to the combustion turbine combustor usually via a heat exhange between the turbine exhaust gases and the compressor exit air flow. The discharge from the compressor exit is piped to an exhaust gas-to-air heat exchanger located aft of the gas turbine. It is then heated by the turbine exhaust and returned to the combustor.

Since the resulting combustor air inlet temperature is increased above that of the non-recuperated cycle, less fuel is required to heat the air to a given turbine inlet temperature. Because the turbine work and the compressor work are approximately the same as in the non-recuperated cycle, the decrease in fuel flow results in an increase in thermal efficiency.

Other Cycles

Some of the other innovations studied included use of a reheat gas turbine, design of a partial oxidation gas turbine and the concept of thermal chemical recuperation. The analytical results for these cycles were interesting, but the concepts are not ready to be demonstrated by Westinghouse within the two-to-three year time frame required by the ATS Program.

ATS Cycle Analyses

As an initial step in the ATS Program, Westinghouse developed a 230 MW gas turbine that has a combined cycle efficiency of 58%. Parameters evaluated during the ATS cycle analyses helped set the 58% efficiency level. (Features of Westinghouse's 501G gas turbine are discussed in a paper by Southall and McQuiggan, 1995.) Incorporated into our latest commercial offering are aerodynamic engine design codes, materials and design concepts, including directionally solidified blade materials and thermal barrier coatings. Full three-dimensional viscous flow modeling, analysis and optimizations have been used in the design of compressor and turbine blades and vanes.

The cycle analyses discussed in this paper were used along with an in-depth evaluation of emissions, cost of electricity, reliability availability-maintainability, and program schedule requirements to select the best ATS. Features of the Westinghouse ATS single-shaft combined cycle include:

- Advanced Aero/Heat Transfer/Materials Technology
- Closed-Loop Cooling
- Single Crystal and Directional Solidified Blades
- Improved Thermal Barrier and Anti-corrosion Coatings
- Ceramic Ring Segments
- Active Tip Clearance Control
- Brush Seals
- Reduced Inlet and Exhaust Losses
- Fuel Preheating
- Advanced Steam Turbine Design Technology

Conversion to Coal-Fired ATS

A number of advanced, coal-fired power generation technologies have been under development that could be applied to a natural gas-fired ATS. These include a broad range of coal gasification technologies (fixed bed, fluid bed, and entrained bed), second generation pressurized fluidized bed combustion (PFBC), and a direct coal-fired turbine. Two advanced, coal-fueled technologies have been selected for consideration as a coal-fired ATS: air-blown integrated gasification combined cycle (IGCC) with hot gas cleaning based on the KRW fluidized bed gasifier; and second generation PFBC (Newby et al., 1995).

The selection of a coal-fired reference system for the conversion of the natural gas-fired ATS to a coal-fired ATS was based on performance potential (power conversion and emissions), cost potential and state of development. Estimated thermal conversion performance, cost potential, and the status of development of several advanced, coal-fueled technologies that could achieve the desired turbine inlet conditions were considered. Comparisons were made to natural gas-fired turbine cycles, as well as to conventional coal-fired power plants - atmospheric pressure fluidized bed combustion and pulverized coal combustion boilers with flue gas desulfurization. The air-blown IGCC technologies with hot gas cleaning (Newby et al., 1993) and second generation PFBC appeared to have the greatest thermal performance and cost potential with combined cycle efficiencies in the range of 51 to 53%. Their respective status of development is categorized as early demonstration which is suitable for the ATS Program.

Conceptual Design of ATS Engine

The ATS engine will be the next model in the series of large heavy-duty gas turbines developed by Westinghouse. Westinghouse gas turbine genealogy began in 1943 when the first wholly American designed and manufactured jet engine went on test (Scalzo et al., 1994).

From the first industrial turbine introduced in 1949 (5000 hp) to the 501G (230 MW) introduced in 1994, improvements in turbine performance and mechanical efficiency improvements have been made continuously. Since 1949, Westinghouse has made the technological advances in the areas of combustion, aerodynamic design, cooling design, mechanical design, leakage control, and materials to advance gas turbine power generation for simple cycle and combined cycle applications.

When Westinghouse started the ATS Program in 1991, the fifth generation Westinghouse gas turbine (501F) was rated at 160 MW with a combined cycle thermal efficiency of 54%. As part of the Westinghouse ATS Program, the 501G engine was introduced that has a combined cycle efficiency of 58%.

Information on the 501G and a discussion of the component development programs under way to support the ATS engine (Task 8) are given in a companion paper presented at the 1995 ATS Annual Review Conference by Diakunchak and Bannister entitled, "Technical Review of Westinghouse's Advanced Turbine Systems Program."

Market Assessment

Westinghouse is in the process of forecasting the worldwide market potential for the ATS gas turbine technology. The time period of interest is the year 2000 through the year 2014. The objective is to develop a forecast of the market based on the proposed size and performance characteristics of the ATS gas turbine. Market feedback on unit size preferences and interest in the product will also be obtained, through telephone interviews with utilities and independent power producers.

For the years 2000 through 2014, a worldwide market for natural gas-fired power generation of 473 GW is predicted. Coal power generation additions are estimated at 530 GW. The majority of the power generation additions will be in the Asia/Pacific area.

Within this study markets that are inaccessible to the ATS concept will be estimated. (For example, countries and regions too small to absorb the ATS output or technology, markets for small gas turbines, and non-gas turbine gas-fired technologies, etc.) For this analysis we are looking at both the potential for natural gas-fired combined cycles with a plant efficiency greater than 60% and also the large simple cycle market whose efficiency is greater than 40% due to the incorporation of the

ATS technology. For the coal additions we are estimating the world-wide IGCC market.

Conclusions

This paper presented an overview of the Westinghouse ATS Program. Our proposed approach is to build on Westinghouse's successful 501 series of gas turbines. Our 501F engine offers a combined cycle efficiency of 54% and our 501G increased this efficiency to 58%. The proposed single-shaft 400 MW class ATS combined cycle will have a plant cycle efficiency greater than 60%.

Westinghouse's strategy to exceed the ATS Program goals is to build upon the next evolution of technological advances in the areas of combustion, aerodynamics, cooling, leakage control, materials and mechanical design. Westinghouse will base its future gas turbine product line, both 50-Hz and 60-Hz, on ATS technology.

The 501G, just introduced by Westinghouse, shows early influences of ATS. Some key components to support the ATS Program have already been evaluated and incorporated into advanced design processes.

Acknowledgment

This program is administered through the Morgantown Energy Technology Center under the guidance of METC's Program Manager, Dr. Richard A. Johnson. The period of performance is August 1993 through July 1996.

References

Bannister, R. L., Cheruvu, N. S., Little, D. A., and McQuiggan, G., 1994, "Development of Requirements for an Advanced Gas Turbine System," ASME Paper 94-GT-388.

Briesch, M. S., Bannister, R. L., Diakunchak, I. S., and Huber, D. J., 1994, "A Combined Cycle Designed to Achieve Greater Than 60 Percent Efficiency," *Modern Power Systems*, Oct., pp. 23-28.

Little, D. A., Bannister, R. L. and Wiant, B. C., 1993, *ASME Cogen Turbo Power '93 Proceedings*, IGTI - Vol. B, pp. 271-280.

Newby, R. A. and Bannister, R. L., 1993, "Hot Gas Cleaning Makes Promising Progress," *Modern Power Systems,* Sept., pp. 51-57.

Newby, R. A., Archer, D. H. and Bannister, R. L., 1995, "Conversion of an Advanced Natural Gas-Fueled Combustion Turbine to Coal-Base Fuel Applications," ASME Paper 95-GT-162.

Scalzo, A. J., Bannister, R. L., De Corso, M., and Howard, G. S., 1994, "Evolution of Heavy-Duty Power Generation and Industrial Combustion Turbines in the United States," ASME Paper 94-GT-488.

Southall, L. R. and McQuiggan, G., 1995, "New 200 MW Class 501G Combustion Turbine," ASME Paper 95-GT-215.