THE SIEMENS WESTINGHOUSE ADVANCED TURBINE SYSTEMS PROGRAM

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ABSTRACT

This paper summarizes progress on Siemens Westinghouse's Advanced Turbine Systems (ATS) Program. The ATS program, which is supported by U.S. Department of Energy, Office of Fossil Energy, has the ultimate objective of introducing into the utility market electricity generating systems capable of achieving greater than 60% LHV based net plant thermal efficiency, less than 10 parts per million NOx emissions, 10% electricity cost reduction and state-of-the-art reliability-availability-maintainability. Work has been in progress over the last few years on developing the required advanced technologies and designing the W501ATS gas turbine. The main thrust of the technology development effort was in the areas of compressor aerodynamics, turbine aerodynamics, heat transfer/cooling, sealing, combustion/emissions, single crystal casting, materials, and coating systems. These technologies were incorporated into the W501ATS engine design to ensure that the ATS Program goals will be achieved.

INTRODUCTION

The Advanced Turbine Systems Program funded by the U.S. Department of Energy, Office of Fossil Energy, is an ambitious multi-year effort to develop the necessary technologies which will result in a significant increase in natural gas-fired power generation plant efficiency, decrease in cost of electricity, and a reduction in harmful emissions, while maintaining the current state-of-the-art reliability, availability, and maintainability (RAM) levels. This three-phase technology development and demonstration program was started in 1992 and will be completed in 2001 (Little et al., 1993, Briesch et al., 1994, Bannister et al., 1995, Diakunchak et al., 1996, Diakunchak et al., 1998).

The ATS plant incorporates an advanced technology gas turbine design, a new three-pressure level, two-casing steam turbine design, and a high efficiency generator. To achieve ATS Program performance, emissions, cost of electricity, and RAM goals required significant advancements in key technologies applied in the gas turbine design. These technology development efforts concentrated on aerodynamics, combustion, cooling, sealing, materials, coatings, and single crystal castings.

The W501ATS engine incorporates new technologies, as well as proven design features developed over the last 50 years and employed successfully in the W501 series of heavy-duty industrial and utility engines (Scalzo et al., 1994). These proven design features include single-shaft two-bearing rotor, cold-end generator drive, compressor blade rings, individual combustor baskets, low alloy steel rotor discs, curvic clutched turbine rotor, four-stage turbine, cooled and filtered rotor cooling air, single first stage turbine vane segments, and tangential exhaust struts. The W501ATS engine is the latest evolutionary design that builds on the success of its predecessors, such as the 186 MW W501F and 250 MW W501G (Scalzo et al., 1988, Southall and McQuiggan, 1995).

ATS DESCRIPTION

Plant Design

The ATS plant utilizes a single shaft design which incorporates a gas turbine on one end of the generator and a steam turbine on the other (see Figure 1). The gas turbine is coupled to the generator in the typical manner. However, the steam turbine is coupled to the generator through a self-shifting and self-synchronizing clutch which is connected to the generator's collector shaft. The gas turbine exhaust passes through the three-pressure level heat recovery steam generator (HRSG) before being exhausted through the stack. The high pressure steam turbine exhaust steam is utilized to cool the
transitions and the first two stages of turbine vanes. The reheated steam is returned to the steam cycle for reheat and induction into the intermediate pressure steam turbine (see Figure 2).

Steam Turbine. The two case, multi-stage, single flow reheat, axial exhaust, condensing steam turbine employs advanced aerodynamic design methods. High performance bowed impulse and reaction blades are used on the high pressure and intermediate pressure turbines, respectively. Optimized reaction blading is used on the low pressure turbine which includes 1.07 metre (42 in.) long last stage rotating blades.

Generator. The two-pole, 60 Hz, hydrogen inner-cooled generator design absorbs the combined gas turbine and steam turbine power output. The generator operates with static excitation and supports static starting of the gas turbine. To achieve high efficiency, several design enhancements, such as reduced windage and core losses and improved insulation, were incorporated.

W501ATS Engine

The W501ATS engine is a state-of-the-art 300 MW class design incorporating many proven design features as well as new technologies required to achieve the ATS Program goals (see Figure 3). Advanced two and three dimensional computer analysis methods are used in the analyses of all critical components to verify the aerodynamic, heat transfer, and mechanical performance. The W501ATS engine design incorporates the following advanced features:

- high pressure ratio compressor
- ultra-low NOx combustion system
- closed-loop steam cooling on first and second stage turbine vanes and ring segments
- active turbine blade tip clearance control
- closed-loop air-cooled rotor
- brush seals
- single crystal alloys
- advanced bond coat and thermal barrier coatings.

Compressor. The high efficiency 19-stage, 27:1 pressure ratio design, incorporating three stages of variable stators, is based on three-dimensional inviscid flow analysis techniques and custom-designed controlled diffusion airfoil profiles (see Figure 4). Controlled diffusion airfoil design technology is an improvement borrowed from the aircraft engine industry, where this concept was applied successfully over many years. The result is a two percentage point improvement in compressor polytropic efficiency compared to the W501F compressor design. Finite element analyses were employed to ensure that all blade and stator designs satisfied steady stress and endurance strength criteria, inspite of the reduced airfoil thicknesses required for optimum efficiency.

Combustion System. The 16-basket combustion system uses the lean premixed axially staged piloted ring design concept
The supply manifolds feed the steam to internal wall cooling circumferential alignment of airfoils. The first two stages, improved rotor sealing, and optimum philosophy and viscous state-of-the-art analysis codes. The airfoil in an exhaust manifold and ducted out of the engine. Circuits. After cooling the transition walls, the steam is collected airfoil closed-loop cooling, active blade tip clearance control on plant performance, the following features are included: turbine cooling requirements and increased efficiency. To further enhance minimizing airfoil solidity. The reduced solidity results in lower loadings are optimized to enhance aerodynamic performance while engine cooling technology. Closed-loop steam cooling is used on airfoil designs with thermal barrier coatings and advanced aero inlet, are closed-loop steam cooled (with air as an alternate coolant). efficiency between blade closed-loop cooling by air instead of air are required. Since the estimated difference in plant thermal airfoil cooled after it is removed from the combustor shell so that only relatively small amounts of cooling air being directed into the blade groove via disc rim holes. The third stage blade has open-loop cooling, allowing the disc material to remain a conventional low alloy steel. After cooling the first and high temperature exhaust cooling air, allowing the disc material to form the upper inter-disc cavities and protect the discs from the discs, to duct the cooling air to and from the blades. The sideplates form the upper inter-disc cavities and protect the discs from the high temperature exhaust cooling air, allowing the disc material to remain a conventional low alloy steel. After cooling the first and second stage blades, the hot cooling air is exhausted into the combustion cylinder. The third stage blade has open-loop cooling, the air being directed into the blade groove via disc rim holes. The fourth stage blade is not cooled internally, however, cooling air is supplied to the disc groove, via disc rim holes, to limit disc groove temperatures. The cooling air is exhausted through holes in the rear sideplates.

Turbine. The 4-stage turbine design employs 3D design philosophy and viscous state-of-the-art analysis codes. The airfoil loadings are optimized to enhance aerodynamic performance while minimizing airfoil solidity. The reduced solidity results in lower cooling requirements and increased efficiency. To further enhance plant performance, the following features are included: turbine airfoil closed-loop cooling, active blade tip clearance control on the first two stages, improved rotor sealing, and optimum circumferential alignment of airfoils.

The W501ATS engine utilizes advanced thin wall turbine airfoil designs with thermal barrier coatings and advanced aero engine cooling technology. Closed-loop steam cooling is used on the first two stages of vanes and first and second stage blades are cast in a single crystal alloy to provide increased creep strength and fatigue resistance compared to conventionally cast materials. The first and second stage ring segments, which are closed-loop steam-cooled and coated with an ablative TBC on the gas path side, are designed as both the gas path annulus and a part of a novel active blade tip clearance control system.

Rotor Design. The compressor rotor construction is based on proven design concepts used in W50IF gas turbines. The discs are located next to low radius spigots, with the power being transmitted through radial shear pins. Clamping of the compressor rotor is achieved by 12 through-bolts. All blades are attached using single lobe dovetail root forms. The discs are interconnected by an array of radial torque pins to prevent slippage and ensure alignment. The pins allow differential radial expansion of the discs, while maintaining their radial concentricity. Extensive computer modeling was carried out to achieve rotor stability over its entire operating range, with no possibility of slippage or gapping.

The W501ATS turbine rotor consists of four ruggedized alloy steel discs clamped together with 12 through-bolts. Low cost alloy steel is used to extend the excellent past operating experience with this material to the W501ATS engine. In this design, torque transmission and alignment is achieved by the use of a Curvic™ clutch, which is a beveled male and female tooth form. This design has been proven by use on gas turbines over the past 40 years.

Cooling air enters through the bore of the fourth stage disc flowing forwards to supply cooling to the lower inter-disc cavities. The air then passes through holes in the curbic coupling arms and into the upper inter-disc cavities. The requirement for closed-loop blade cooling on the first two stages necessitates the use of nickel-based alloy sideplates, bolted on the front and rear of these discs, to duct the cooling air to and from the blades. The sideplates form the upper inter-disc cavities and protect the discs from the high temperature exhaust cooling air, allowing the disc material to remain a conventional low alloy steel. After cooling the first and second stage blades, the hot cooling air is exhausted into the combustion cylinder. The third stage blade has open-loop cooling, the air being directed into the blade groove via disc rim holes. The fourth stage blade is not cooled internally, however, cooling air is supplied to the disc groove, via disc rim holes, to limit disc groove temperatures. The cooling air is exhausted through holes in the rear sideplates.

Steam Supply Manifold. The manifold design uses a closed-loop cooling scheme to supply and return coolant for cooling the hot stationary parts. The blade ring seals against the outer cylinder through the use of static seals to create two annular shaped cavities through which coolant can be introduced to the hot parts and returned to a heat recovery unit. Inlet coolant is externally piped to an annular chamber where it is directed through pipes and openings in the blade ring to the steam cooled hot parts. After

(see Figure 5). By using closed-loop steam cooling on transitions and turbine stationary components more compressor delivery air is available for premixing with the fuel gas in the combustor. This allows very lean premixed combustion and makes possible the restriction of NOx emissions to single digits.

Figure 5. Piloted Ring Combustor

The transitions, located between combustor exit and turbine inlet, are closed-loop steam cooled (with air as an alternate coolant). Steam enters the engine through four external connections and is routed to each transition supply manifold through internal piping. The supply manifolds feed the steam to internal wall cooling circuits. After cooling the transition walls, the steam is collected in an exhaust manifold and ducted out of the engine.

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cooling the hot engine parts, the coolant is then directed into a second annular chamber, where the coolant flows through external piping to a heat recovery unit (see Figure 6). All pipes are hard-welded to the blade ring, except where excessive flexibility and ease of assembly are needed.

Figure 6. Blade Ring Showing Steam Piping

TECHNOLOGY VERIFICATION PROGRAMS

The main objectives of the technology development and verification programs were to design, build, and test components considered critical to the success of the ATS Program. To achieve these objectives, a significant technology effort was expended in the following areas: aerodynamics, combustion, cooling, sealing, materials, casting, and coatings.

Compressor Aerodynamic Development

To verify the aerodynamic performance and mechanical integrity of the new high pressure ratio design, the full-scale W501ATS compressor was manufactured and tested in a specially designed facility constructed at the U.S. Navy Base in Philadelphia. The compressor test was carried out at subatmospheric inlet conditions to reduce the required power to that available at the test facility.

The compressor was instrumented with static pressure taps, fixed temperature and pressure rakes, thermocouples, tip clearance probes, blade vibration monitoring probes, rotor vibration probes, acoustic probes, and strain gauges. Provisions were made for radial traverses in eight axial locations in the compressor and four radial locations in the inlet duct. More than 500 individual measurements were recorded. A dedicated data acquisition system was used to collect and reduce the test data. Important performance and health monitoring parameters were displayed on computer screens in real time. After the compressor test facility was commissioned, an extensive test program was performed. The test program included design point performance verification, blade vibration and diaphragm strain gauge measurements, inlet guide vane and variable stator optimization, compressor map definition and starting characteristics optimization. The compressor testing, which was successfully completed ahead of schedule, confirmed all mechanical and aerodynamic performance predictions.

Combustion

To achieve single digit NOx emissions at the ATS firing temperature required a considerable development effort, balancing the design for efficiency, emissions, mechanical integrity, and cost. Three different combustor concepts were included in this development. The most successful candidate is the piloted ring combustor. This combustor consists of a pilot and two axially staged premixed zones, the primary and secondary zones. Premixed fuel and air is introduced into the primary zone where the combustion is stabilized by a swirled-produced recirculation zone and a centrally located pilot. The secondary zone, located downstream of the primary zone, is supplied with premixed fuel and air through an annular duct surrounding the primary zone. The piloted ring combustor has achieved single digit NOx emissions and excellent stability on low pressure tests. It is currently undergoing high pressure testing to optimize emissions and expand the operating range by improving fuel and air mixing in the primary premixing passage. To ensure that single digit NOx emissions are achieved, a catalytically enhanced combustor development program is being pursued in parallel.

Turbine Aerodynamic Development

The objective of this development program was the experimental verification of turbine performance with airfoils designed for reduced solidity (and hence reduced cooling requirement) and optimized for closed-loop cooling, performance benefits due to optimum circumferential alignment of turbine airfoils, and airfoil surface heat transfer coefficients. A 1/3-scale model of the first two turbine stages was designed, manufactured, and tested in the shock tube test facility located at Ohio State University (see Figure 7). Approximately 400 individual sensors were installed on the model turbine, including miniaturized pressure transducers, thermocouples, and thin-film heat flux gauges on both stationary and rotating airfoils. Provision was made for exit traversing. Testing was completed and detail test data analysis is in progress.

Figure 7. Model Turbine Test Rig

Cooling

Closed-loop cooling is the largest contributor to the ATS plant performance. Eliminating cooling air ejection into the turbine gas path raises the gas temperature downstream of the first stage vane, hence increasing the gas energy level during the expansion process,
and eliminates cooling air mixing losses. Closed-loop cooling provides an additional benefit in NOx reduction, by making more air available at the combustor inlet for the lean premix combustion, while maintaining the same burner outlet temperature. Without a cooling air film to shield the turbine components from the hot gases and trailing edge cooling air ejection to enhance cooling in the critical trailing edge region presents quite a challenge to a successful closed-loop cooling design. This challenge was overcome in the W501ATS turbine airfoil cooling design. In order to verify the critical closed-loop cooled designs, the following development programs were undertaken: outside heat transfer coefficient measurement, internal heat transfer coefficient measurement, and first stage vane hot cascade test.

The outside heat transfer coefficients on airfoil and endwall surfaces were measured on the model turbine tests performed at Ohio State University. Internal heat transfer coefficients and flow characterization tests were carried out at Carnegie-Mellon University on the first stage vane and blade cooling designs. These tests involved ten plastic models representing six cooling techniques utilized in the various sections of the first stage turbine vane and blade (see Figure 8). The transient liquid crystal technique was the primary measurement method. Test results confirmed analytical predictions. The first stage vane cooling design will be verified at ATS operating conditions in an integrated combustion and hot cascade test rig.

Sealing

Gas turbine performance is adversely affected by internal leakages. One percent air leakage results in about 1.5% decrease in combined cycle output power and about 0.5% decrease in thermal efficiency. In order to minimize leakages and hence optimize performance, an extensive sealing development program was carried out in the following areas: brush seals, face seals, and abradable coatings applied to outer air seal surfaces to allow reduced compressor and turbine blade tip clearances. To reduce air leakage, as well as hot gas ingestion into turbine disc cavities, W501ATS engine design incorporates brush seals under the compressor diaphragms, turbine disc front, turbine rims, and turbine interstage locations. Tests were carried on test rigs for the different brush seal locations to develop effective, rugged, reliable, and long service life brush seal systems. These tests verified the brush seal low leakage and wear characteristics.

A face seal was designed and developed for the rotor rear location to prevent rotor cooling air leakage. The non-contacting, dry running face seal has been used in aircraft gas turbines and other turbomachinery applications. Development was necessary to demonstrate that such a seal could meet the requirements of life, durability, large axial movement and turning gear operation in the W501ATS application. Two full size prototype seals were designed and tested under simulated engine conditions (see Figure 9). Test results showed that the leakage was a fraction of the target value, there was no seal wear and large axial movement could be accommodated.

Considerable performance benefits result from reduced compressor and turbine blade tip clearances. Abradable coatings are being used to reduce tip clearances by allowing minimum build clearances without fear of damaging hardware and by furnishing more uniform tip clearances circumferentially. Abradable coatings, identified for compressor and turbine applications, were tested to determine abradability, tip-to-seal wear rate, and erosion characteristics.

Materials

ATS operating conditions extend the technology envelope of current materials, hence materials development work is an important element in the evolution and success of the W501ATS engine. To ensure this success, development programs were carried out on the effect of steam cooling on materials, blade life prediction, advanced vane alloy, nickel-based superalloy for rotors, directionally solidified blade alloy properties, single crystal material data and single crystal airfoil casting. To achieve ATS program performance and mechanical integrity goals, single crystal vanes and blades are used in the W501ATS engine. Casting development programs were carried out to demonstrate castability of large industrial turbine airfoils in CMSX-4 alloy. Casting trials on first stage vanes and blades incorporating thin wall cooling design features demonstrated the viability of this concept (See Figure 10). Casting development will be continued to further improve casting processes, which will result in improved yields. Casting trials on the thick walled second stage blade were also successful (see Figure 11).
Several materials development programs were successfully completed. Preproduction casting development will continue on the single crystal thin wall turbine vanes and blades. Long term verification tests are continuing on advanced bond coat/TBC system. Future plans include manufacturing the prototype W501ATS engine and performing extensive testing to verify its performance and mechanical integrity.

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