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ABSTRACT

A major national effort is directed to developing advanced turbine systems designed for major improvements in efficiency and emissions performance using natural gas fuels. These turbine designs are also to be adaptable for future operation with alternate coal and biomass derived fuels. For several potential alternate fuel applications, available hot gas cleanup technologies will not likely be adequate to protect the turbine flowpath from deposition and corrosion. Consequently, ruggedized versions of ATS turbines will probably be needed. This paper describes ruggedization approaches, particularly to counter the extreme deposition and corrosion effects of the high inlet temperatures of ATS turbines using alternate fuels.

INTRODUCTION

The U.S. Department of Energy is supporting a major national effort to develop advanced turbine systems (ATS) that will provide ultra-high efficiency, environmental superiority, and cost competitiveness. Although developed for natural gas fuels, the ATS turbine designs are to be adaptable to future firing with coal and biomass derived fuels.

Hot gas cleanup components are being developed to protect gas turbines in advanced alternate fuel systems from flowpath degradation due to deposition, erosion, and corrosion (DEC). Cyclone inertial separators have demonstrated a capability to greatly alleviate DEC under first generation, coal fired, pressurized fluid bed combustion (PFBC) turbine conditions (inlet temperatures less than 871°C (1600°F)). Promising turbine durability performance is apparently being shown (de Piolenc, 1993) at the Tidd, Värtan, and Escatron plants that use these technologies. Hot gas ceramic filters are also being tested, which could greatly reduce ash particle loadings entering turbines compared to cyclone inertial separators. Assuming adequate durability can be achieved for the ceramic filters, these cleanup devices should further reduce deposition

and erosion and improve turbine lifetimes for first generation PFBC plants.

In spite of the past success of commercial cyclone separators and corrosion protective turbine coatings in addition to the promise of ceramic filters, the question arises whether these technologies alone can adequately protect future ATS turbines for operation with alternate fuels. ATS turbine life using hot gas cleanup for alternate fuels is still an issue because of the greatly different flowpath environments for ATS turbines compared to those for turbines operating at first generation coal-fired PFBC plants. The primary (but not the only) significant difference is that the inlet temperatures for the ATS turbine designs (rotor inlet temperatures up to 1327°C (2600°F)) are up to 556°C (1000°F) higher than for the coal-fueled PFBC turbine experience mentioned earlier. Even for the extremely clean natural gas fuel, these ATS temperatures will strain the limits of turbine cooling and materials technologies to achieve commercial flowpath lifetimes. The additional burden of even minute carryover rates of alternate fuel contaminants passing the best hot gas particulate cleanup systems could substantially degrade turbine durability.

This paper discusses data that suggest that hot gas particulate cleanup alone will probably not be sufficient to protect ATS turbines designed for natural gas when operated in some advanced clean coal plants. Turbine flowpath modifications to ruggedize ATS turbines for improved lifetimes are then discussed.

ALTERNATE FUEL PLANTS Contaminants Entering Turbine

Table 1 identifies plant types that are being developed for alternate fuels. Also shown are levels of corrosive alkali and particulate that could pass the cleanup systems to enter the turbines in these plants using coal fuels. Although these levels are lower than current environmental emissions standards, they are of concern for gas turbines and other plant

equipment. Alkali and particulate levels entering indirect fired turbines are low because they result only from filtered inlet air. However, the deposition and corrosion issues are significant for the heat exchanger which would operate on the order of a thousand degrees higher surface temperatures than heat exchange surfaces in coal boiler plants. Turbine inlet alkali and particulate levels are also low for ATS turbine operation at coal gasification plants using cold gas cleanup. The wet scrubbers condense the alkali and reduce particulate to comparable levels to clean fuels. However, economics, complexity and system efficiency are issues for gasification systems that utilize cold gas cleanup which also usually require oxygen plants.

Air blown coal gasification plants using hot gas cleanup should offer economic, simplicity, and energy conversion efficiency advantages over oxygen blown plants using cold gas cleanup. Advanced PFBC and direct fired turbine plants using hot gas cleanup are also candidate systems for future utilization of coal. Depending on hot gas filtration temperatures, coal type, etc, test plant measurements and thermodynamic projections indicate that alkali levels in excess of 1 ppmw and possibly up to 10 ppmw could enter turbines operating in these plants. This level is more than an order of magnitude greater than allowed by conventional fuel specifications to protect turbines from corrosion.

Data from coal-fueled test plants (e.g., Phillips and Dries, 1993; Jalovaara, et. al., 1993) indicate that 3 to 5 ppmw particulate could pass ceramic filters to enter an ATS turbine operating at an advanced PFBC plant, direct coal-fired turbine plant, and coal gasification plant using hot gas filter cleanup. This corresponds to 2400 to 3900 kg (5200 to 8600 lbs) ingested by a 15,000 hp ATS turbine in an 8000 hr operating year. A large utility turbine could ingest over 40 tons in an 8000 hr operating year at a 3 ppmw inlet particulate loading.

Residual Oil Turbines

The above particulate levels (3 to 5 ppmw) entering ATS turbines operating with hot gas filters are similar to levels entering peaking turbines for one of the highest ash turbine fuels (washed residual oils treated with corrosion inhibiting additives) used commercially to date. For this fuel, deposition in the turbine flowpath has required removal of the turbine from service for water washing for periods as long as a day at intervals as frequent as 200 hr (EPRI, 1979). While acceptable for peaking service, such frequency and duration of turbine outages would not likely be acceptable for ATS cogeneration, intermediate load and base load generation plants.

EFFECTS OF HIGH ATS TEMPERATURES

The residual oil maintenance intervals given above were based on commercial experience for turbines with inlet temperatures less than 1038°C (1900°F) and inlet particle loadings similar to those expected to pass hot gas filters in some future ATS coal plants. The ATS turbines will be designed with inlet temperatures up to 1427°C (2600°F). Increased gas temperature greatly increases rates of deposition and usually makes deposits less susceptible to removal as shown in tests of alternate fuels. For example, tests (Whitlow, et. al., 1981) with a commercial washed and treated residual oil turbine fuel showed thirty times higher deposition rates on specimens exposed at 1260°C (2300°F) compared to a 1038°C (1900°F) gas temperature, corresponding to inlet temperatures and experience described above for commercial residual oil turbines. Heavy deposits were also formed at a 1260°C (2300°F) gas temperature in a 100 hr test of a coal derived liquid fuel that produced 2 to 3 ppmw particulate loading in the gas stream (Mulik, et. al., 1985). Tests with coal water fuels (Wenglarz and Fox, 1990) showed a factor of 100 increase in deposition rates for a 110°C (200°F) increase in gas temperature. Furthermore, the higher gas temperature in these coal water fuel tests resulted in an extremely aggressive and unusual type of attack of a corrosion resistant coating (Wenglarz, et. al., 1991).

Magnified rates of deposition and corrosion occurred in past tests of alternate fuels at elevated temperatures because the gas stream temperatures were higher than the melting point of a significant fraction of the fuel ash particulate. Molten particulate sticks upon delivery to turbine surfaces, capture solid particulate, and tends to form tenacious deposits that are difficult to remove. Molten ash phases are also more chemically reactive (corrosive) than gaseous or solid phases.

The high levels of ash (e.g., up to 40 tons/yr for a utility turbine) that can enter turbines protected by hot gas filters were indicated earlier. Much of this ash would be delivered to the expander airfoil surfaces. Since nearly all of this ash would be molten for the high inlet temperatures (up to 1427°C (2600°F) rotor inlet temperature) of an ATS turbine, extreme deposition and corrosion will occur unless additional measures (over hot gas filtration) are taken to protect the engine for several types of advanced coal fired plants.

RUGGED TURBINES

Combustion turbines have traditionally been designed to operate with clean fuels. Except for corrosion resistant coatings, little or no accommodation has typically been made in their expander flowpath designs to tolerate the deposition, erosion and corrosion effects from alternate fuels. Two exceptions have been catalytic cracker expanders (Mathers and Schonewald, 1980) and the 15MW PFBC turbine used in the first generation PFBC plants referenced earlier (de Piolet, 1993). These commercial turbines have shown that modification of turbine flowpaths for increased erosion tolerances can be technically and economically feasible.

Rugged versions of ATS turbines might well be needed for plants which available hot gas cleanup systems is insufficient to protect the turbine flowpath. Such turbines

TABLE 1.
CONTAMINANT LEVELS ENTERING TURBINES FOR HOT
GAS FILTRATION

SYSTEM	ALKALI (PPMW)	PARTICULATE (PPMW)
INDIRECT FIRED	LOW	LOW
COAL GASIFICATION		
-COLD GAS CLEANUP	LOW	LOW
-HOT GAS CLEANUP	UP TO 10	UP TO 5
ADVANCED PBFC	UP TO 10	UP TO 5
DIRECT FIRED	UP TO 10	UP TO 5

TABLE 2.
TURBINE MODIFICATIONS TO IMPROVE TOLERANCE

TURBINE DESIGN MODIFICATIONS	TURBINE TOLERANCE IMPROVEMENTS	RELATIVE DEGREE OF TOLERANCE IMPROVEMENTS*
Increase flow annulus area	- decreases particle impact velocities	1
Increase number of stages	- decreases frequency of particle impacts on rotors and impact angles	1
Decrease flow acceleration through stators	- decreases particle impact velocities on stator T.E. and rotor L.E.	1
Redistribute work between stages	- provides more uniform erosion for all stages	2
Increase blade and vane axial chords	- decreases frequency of particle impacts	1
Coatings or armoring	- more erosion/corrosion resistant materials	1
Boundary layer fences	- inhibits high particle concentrations at roots and tips	2
Deflector rings	- redistributes high particle concentrations near roots and tips	3
Boundary layer suction	- removes high local particle concentrations at roots and tips	1
Increase trailing edge thicknesses	- decreases high particle concentrations at roots and tips; increases T.E. erosion life	1
Decrease turbine inlet temperature	- decreases formation of molten corrodants and deposit bonding media	1
Increase vane and blade cooling	- decreases formation of molten corrodants and deposit bonding media	2

*1 indicates greatest relative turbine tolerance improvement

are designed for increased tolerance to deposition, erosion, and corrosion.

Previous works (Wenglarz, 1982) have identified a range of turbine ruggedization approaches, shown in Table 2, along with relative judgments on their effectiveness. The most effective approach in Table 2 to alleviate the ATS turbine deposition and corrosion effects described earlier would be to lower the ATS turbine inlet temperature. However, this counteracts a major ATS objective of ultra high turbine efficiency.

The next most effective approach in Table 2 to alleviate turbine deposition and corrosion is to reduce flowpath surface temperatures through increased cooling. Highly cooled surfaces can freeze molten ash particles to substantially reduce sticking, deposit strength, and rates of corrosion.

Tests (EPRI, 1981) at typical turbine gas temperatures have shown very low corrosion rates from fuel contaminants such as sodium, sulfur and vanadium at turbine alloy surface temperatures below the 538° to 649°C (1000 to 1200°F) range. Cascade tests using ash bearing fuels (Rose, 1982), including coal-water fuels (Horner, 1989), have demonstrated the benefits of airfoil surface cooling to below

the 538°C (1000°F) to 427°C (800°F) range. Deposition rates significantly decreased and the cleanability of deposits substantially improved in that surface temperature range.

Based on the above considerations, the use of extreme cooling to ruggedize the turbine flowpath is being evaluated for ATS turbines to be operated with coal and biomass fuels. The remainder of this paper identifies an initial cooling specification and investigates alternate approaches to achieve the specified degree of cooling.

ATS TURBINE COOLING Surface Temperature Specification

Based on evaluations of past test data, the following initial cooling specification has been chosen to ruggedize ATS turbine flowpaths for operation with alternate fuels:
surface temperatures ≤ 427 to 538°C (800 to 1000°F)
for

flowstream gas temperature $> 927^{\circ}\text{C}$ (1700°F)

Cooling of downstream turbine rows at gas temperatures less than 927°C (1700°F) may not be necessary, as suggested by coal-fired PFBC cascade and turbine tests in which tolerable deposition occurred below the 927°C (1700°F) temperature range.

Coolant Flow Requirements

Using the above specification, two stator rows and two rotor rows would need to be cooled to 427 to 538°C (800 to 1000°F) for an ATS turbine designed for natural gas fuels with a rotor inlet temperature of 1427°C (2600°F). First order heat transfer analyses were conducted to evaluate coolant flow rates for alternate cooling approaches to achieve a 538°C (1000°F) average surface temperature in this turbine.

Air and Steam Cooling

Gas turbine cycle efficiency optimizes at increasing pressure ratio as the turbine inlet temperature increases. This results in a compressor discharge air temperature greater than 538°C (1000°F) for the ATS turbine with a rotor inlet temperature of 1427°C (2600°F). Consequently, an intercooler is needed for expander flowpath cooling to less than 538°C (1000°F). Assuming intercooling to 232°C (450°F), Table 3 shows air flow rates (expressed as percent of total compressor flow) needed to cool the airfoils of the first four rows of the ATS turbine to an average surface temperature of 538°C (1000°F). Also shown are flow rates of saturated steam at a temperature of 232°C (450°F) needed to cool the first four rows of the ATS turbine to the same average surface temperature. The steam flows are also expressed as percent of compressor air flow. Because steam has a higher specific heat than air, the steam coolant flows for each airfoil row are 57 to 66% of the air flows.

Table 3 indicates that air cooling flow requirements appear excessive. Over 35% of the total compressor discharge flow is needed to cool only the airfoils. Additional cooling flow is also needed for endwalls, seals, etc.

Steam cooling flow requirements also are excessive. The total steam coolant flow for all four airfoil rows is 40% greater than can be generated from the heat in the turbine exhaust using a heat recovery steam generator.

TABLE 3.
PERCENT RATIO OF AIRFOIL COOLANT TO
COMPRESSOR FLOW RATES FOR 538°C (1000°F)
SURFACE TEMPERATURE

Coolant	First stator vanes	First rotor blades	Second stator vanes	Second rotor blades
Air	13.6	10.5	8.1	3.1
Steam	8.9	6.9	4.6	1.8

TWO-PHASE COOLING Cooling Approach

A very high degree of surface cooling results from water evaporation at that surface. A two-phase cooling approach using compressor discharge air to atomize water into small droplets that impinge and evaporate on the interior surfaces of turbine airfoils is being evaluated by Allison for both a gas fired ATS turbine and a coal-fired ATS engine. For stator vanes, the atomization is accomplished interior to the airfoils.

Figure 1 shows the two-phase cooling concept for a stator airfoil as developed for the Allison ATS program. Holes in an impingement tube within the airfoil distribute the air/droplet stream to the interior surfaces of the airfoil. A portion of the air/droplet mixture flows from the rear of the impingement tube, past pin fins, and out the rear pressure surface of the vane. This cools the thin trailing edge surfaces.

For rotor blades, the water atomization is accomplished exterior to the airfoils, with the centrifugal pumping effects of the rotating blades drawing the air and droplet stream into the blades. This bypasses the difficulties of transporting water across a moving interface into the rotating blades, but increases the challenge of properly distributing the droplets for impingement on the interior blade surfaces. Two-phase cooling requires very high water purity (deionized and demineralized to steam turbine quality) to minimize deposition of minerals on the interior airfoil surfaces.

Figure 1. Two-phase cooling applied to an airfoil.

Coolant Flow Rates

Use of two-phase cooling for the two fixed stator vane rows and use of steam cooling for the two rotor blade rows was considered for the 1427°C (2600°F) rotor inlet turbine. The quantity of steam that could be generated from the turbine exhaust using a heat recovery steam generator (HRSG) is just sufficient to cool the rotor blades, end walls, seals, in addition providing for leakage. However, previous economic analyses for a steam cooled turbine with lower inlet temperature (1093°C (2000°F)) suggest that the capital cost for the HRSG, without revenues from process steam obtained in a cogeneration plant, would result in an unacceptable reduction in the plant internal rate of return (Wenglarz, 1994).

Table 4 gives water and atomization air flows (expressed as percentage ratios of compressor discharge flow) for two-phase cooling of the four highest temperature airfoil rows of the ATS turbine with a 1427°C (2600°F) rotor inlet temperature. For a 538°C (1000°F) average surface temperature, total water and atomization air flow ratios for all four airfoil rows are about 2.5% and 8.2%, respectively, of the compressor flow. Table 4 also shows cooling flows for 427°C (800°F) surface temperatures. Two-phase cooling limits are approached if 427°C (800°F) rather than 538°C (1000°F) surface temperatures are required to control deposition and corrosion. Although the second through fourth airfoil rows can be cooled to 427°C (800°F), a lower temperature capability for two phase cooling of first stator airfoils is about 482°C (900°F) for the conditions assumed. Decreasing the water and air temperature, decreasing the airfoil skin thickness, or water cooling appears necessary to achieve 427°C (800°F) average surface temperatures for the first stator vanes.

SUMMARY AND CONCLUSIONS

Hot gas particulate cleanup will be necessary but probably not sufficient to protect high temperature ATS turbines operating in future coal-fired advanced PFBC plants, direct fired turbine plants and the highest efficiency gasification plants. A supplementary approach to achieve adequate ATS turbine maintenance intervals could be ruggedization to increase the flowpath tolerance to ingested particulate and condensing corrodants. Flowpath ruggedization for erosion control has been successfully demonstrated in the past for catalytic cracker expanders and first generation PFBC turbines.

TABLE 4.
PERCENT RATIO OF TWO-PHASE AIRFOIL COOLANTS TO
COMPRESSOR FLOW RATE*

Average surface temp. Coolant	First Stator vanes	First rotor blades	Second stator vanes	Second rotor blades
538°C (1000°F) water/air	0.70/2.0	0.82/2.6	0.48/1.9	0.50/1.7
427°C (800°F) water/air*	0.85/2.0**	1.02/2.6	0.61/1.9	0.63/1.7

* 93°C (200°F) water/260°C (500°F) air at atomizer

** flows for surface temperature of 482°C (900°F)

Past tests have indicated that, for flowpath gas temperatures greater than 927°C (1700°F), cooling turbine airfoil surfaces to temperatures in the 427°C (800°F) to 538°C (1000°F) range could ruggedize a high temperature turbine flowpath to alleviate deposition and corrosion. Using this specification, the first four expander rows would need to be highly cooled for a candidate 1427°C (2600°F) rotor inlet, ATS turbine that was evaluated. First order analyses indicate that coolant flow rate requirements using either compressor discharge air or steam are probably excessive to achieve the 538°C (1000°F) surface temperature. The initial analyses also showed that two-phase cooling offers the most attractive method of those explored to protect a coal-fueled ATS turbine from deposition and corrosion.

Several additional applications issues will be considered in the future to further evaluate extreme cooling for turbine ruggedization. These include the effect of lowering the turbine inlet temperature on cooling requirements, overall turbine performance for high degrees of cooling, and airfoil skin stresses due to the large temperature difference between the flow stream and the coolant.

Past experience with coal-fired PFBC turbines (de Piolenc, 1993) suggests that cyclone hot gas cleanup can adequately protect a turbine from erosion if deposition and corrosion from molten ash phases is not an issue. Consequently, flowpath ruggedization (including two-phase cooling) and cyclone cleanup, (without requiring ceramic filters) might be adequate to protect future coal-fueled ATS turbines.

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