Affecting component lives

DESIGN WATER-STEAM INJECTION SYSTEMS TO MINIMIZE THE NEGATIVE IMPACT ON OPERATING HOURS

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Water or steam injection is a popular option for augmenting gas turbine power and controlling emissions. But this method affects cycle performance and maintenance inspection intervals. For instance, a case study on an aeroderivative showed that a 3% injection of steam could reduce the first stage bucket life by up to 20% (Figures 1, 2).

Injecting water or steam into a combustor affects dynamic pressure within the combustor, carbon monoxide emissions, combustion stability, and flame blow out. Injecting it into the compressor inlet, inter-stage or discharge casing affects the compressor aerodynamic stability, compressor surge margin and compressor degradation and fouling.

Aerodynamic instabilities in the axial compressor and pressure oscillations in the combustor can cause blade high-cycle fatigue and subsequent catastrophic failure of the gas turbine. The injection hardware, engine control, auxiliaries and load equipment must be modified and sized appropriately as per the amount of water or steam injection and supplemental power output. The added water or steam must be of boiler feedwater quality to prevent deposits and corrosion in the hot gas path downstream of the combustor.

Operators should tune their steam or water injection methods so as to cause minimum impact on maintenance. For instance, in the case of aeroderivatives, which maintain a constant power turbine inlet temperature, the engine temperature can be reduced to minimize impact on component lives.

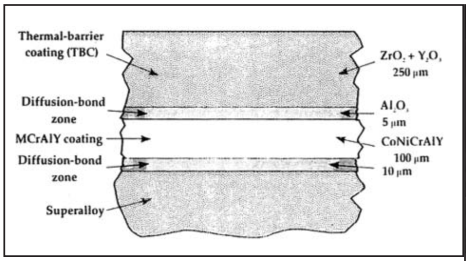
Benefits of wet injection

Nitrogen oxides are formed from the oxidation of free nitrogen in the combustion air or fuel. Thermal nitrogen oxide is formed mainly as a function of the stoichiometric adiabatic flame temperature, which is the temperature reached by burning a theoretically correct mixture of fuel and air in an insulated vessel.

Thermal NOx production rises rapidly as the stoichiometric flame temperature is reached. Away from this point, thermal NOx production decreases rapidly. This theory provides the mechanism of thermal NOx control. In a diffusion flame combustor, the primary way to control thermal NOx is to reduce the flame temperature. Introducing water or steam into the flame

Figure 1: Water or steam injection will accelerate coating loss on stage 1 buckets due to oxidation

Figure 2: Spray pattern in the water flow test on the blade shows poor film cooling coverage



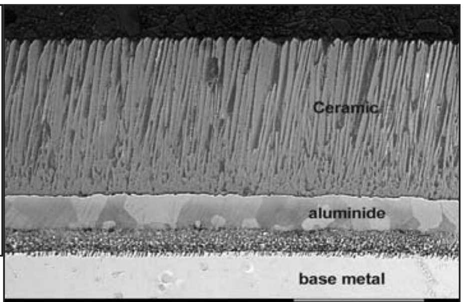


***Figure 3:* The thermal barrier coating (left) and microstructure of a ceramic top coating (right) from Electron Beam Physical Vapor Deposition (EB-PVD)**

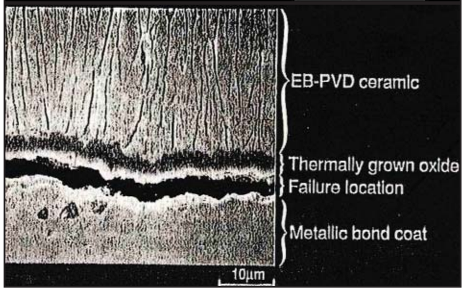


***Figure 4:* Delamination on the ceramic top coating is one of main courses of TBC failure**

zone achieves this effectively.

NOx increases with fuel-to-air ratio, firing temperature, and residence time in the flame zone. It decreases exponentially with the increase of water or steam injection.

Injecting water or steam into a gas turbine increases the mass flow and, therefore, the output. When water or steam is injected for power augmentation, it can be introduced into the compressor discharge casing of the gas turbine, as well as the combustor. In combined-cycle operation, the cycle heat rate increases with water or steam injection due to additional fuel required to heat the water to combustor temperature. Water or steam injection for power augmentation can result in a power increase of 15% to 18% by injection of up to a 5% mass flow of steam to the compression discharge.

For the relatively low levels of NOx reduction required in the 1970s, it was found that injection of water or steam into the combustion zone would produce the desired NOx reduction with minimal detrimental impact to the gas turbine cycle performance or parts lives. Additionally, at the lower NOx reductions, the other exhaust emissions were generally not affected adversely.

With the greater NOx reduction requirements imposed during the 1980s, further reductions in NOx by increased water or steam injection began to cause detrimental effects on cycle performance, parts lives and inspection criteria. Also, other exhaust emissions began to rise to measurable levels of concern. More expensive technologies such as Dry Low Emission (DLE) and catalytic combustion were then introduced.

In a typical maintenance procedure recommended by OEMs, a gas fuel unit operating on continuous duty, with no water or steam injection, is established as the baseline condition. This condition sets the maximum recommended maintenance intervals. For operation that differs from the baseline, factors are established that determine the increased level of maintenance required. For example, a maintenance factor of two would indicate a maintenance interval that is half of the baseline interval. A maintenance factor of three or four may be required for water or steam injection applications.

Impacting aeroderivatives

The impact of steam injection on the life or a hot section component of an aeroderivative gas turbine has been studied. Stage 1 blades in the High Pressure (HP) turbine section were selected as the most representative hot section component in relation to expected change in component temperature, degradation rate and serviceable life produced by the introduction and variation of the amount of steam injection.

The twin spool aeroderivative consists of a five-stage Low Pressure (LP) compressor, a 14-stage HP compressor, a two-stage, air-cooled HP turbine, and a five-stage LP turbine. NOx suppression is achieved by the injection of water or steam into the single annular combustor at a controlled rate. Depending upon the injection rates, NOx emission of 100 ppmvd ~ 25 ppmvd (or lower) can be achieved. The gas turbine OEM permits continuous operation at 25ppm NOx.

During service, the hot section components undergo various types of time-dependent degradation due to exposure in the operating environment. Oxidation, hot corrosion, creep and thermal mechanical fatigue can all potentially lead to component failure. The life of turbine components and factors that limit the life vary significantly from component to component due to a combination of design, material, coating and operating condition. By identifying the specific characteristics of degradation for each component and predicting the rate of damage occurred, economical repair, replacement and overhaul interval can be established.

A review of the operational history of the aeroderivative gas turbine revealed the coating losses on the leading edge of the HP turbine stage 1 blade. The standard material for the HP turbine stage 1 blades is Rene-142; a nickel-based, directionally solidified superalloy. Metallurgical analysis identified the most likely root cause as oxidation spallation of the Thermal Barrier Coating (TBC).

The onset of the oxidation damage occurring at 10,000 hours - 22,000 hours was reported. Water-flow testing on service-run blades showed a poor film cooling coverage on the suction side with the TBC.

TBC spallation causes increased blade operating temperature and eventual oxidation of the base material. Since the effectiveness of the coating in protecting the base metal from oxidation attack has been identified as the primary life limiting factor — a major decision point in determining engine overhaul period — this analysis is focused on the prediction of the impact on the oxidation life of a stage 1 blade with steam injection. The calculated life change is converted into an Equivalent Operating Hour (EOH) factor with reference to the engine design base condition.

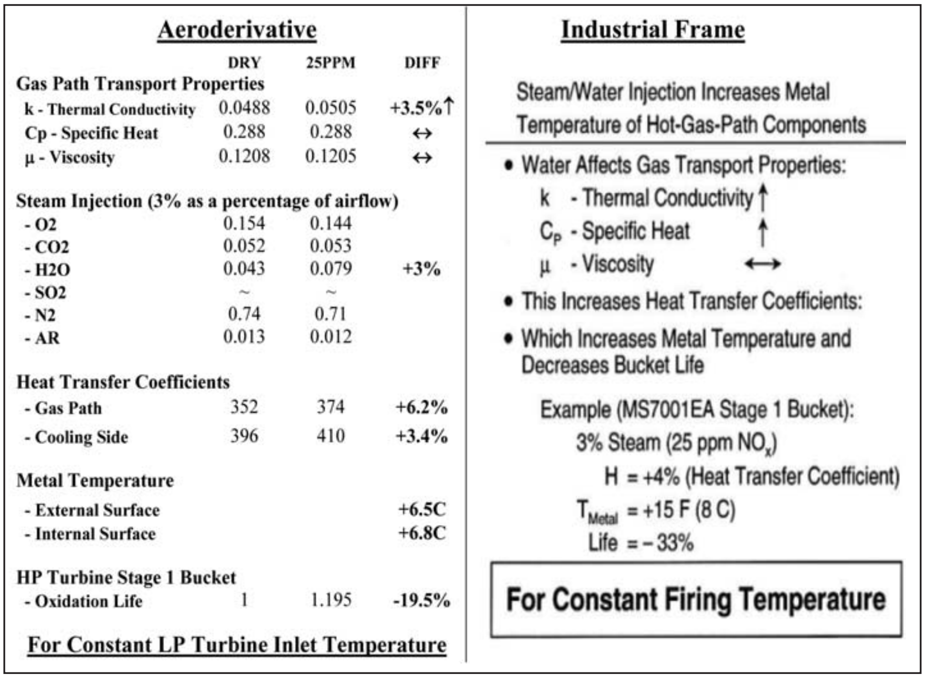
Analysis and modeling

To simulate the blade operating environment, an aerothermal performance model of the engine has been developed. The aerothermal model consists of a compressor stage-stacking program, turbine mean line aerodynamic analysis, and through-flow thermodynamic analysis with state-of-the-art loss calculations. The aerothermal model calculates the average inter-stage temperature, pressure and flow of the hot gas path. The calculated aerothermal values were then used as the boundary condition for heat transfer analysis.

A composition-dependent gas property model was also developed for the calculation of gas-side mixing transport properties. For example, thermal conductivity of typical combustion gas species was first compiled as a function of temperature.

The thermal conductivity of water increases significantly at elevated temperatures. The gas path mixture transport properties were calculated. For air-cooled blades, heat transfer coefficients on both sides of the blades have to be established before a detailed heat transfer calculation can be performed.

Heat transfer coefficients and gas stream properties were first established, and a detailed heat transfer calculation throughout the blade was then performed. A steady-state energy balance approach



Aeroderivative

	DRY	25PPM	DIFF
Gas Path Transport Properties			
k - Thermal Conductivity	0.0488	0.0505	+3.5%↑
Cp - Specific Heat	0.288	0.288	↔
μ - Viscosity	0.1208	0.1205	↔
Steam Injection (3% as a percentage of airflow)			
- O2	0.154	0.144	
- CO2	0.052	0.053	
- H2O	0.043	0.079	+3%
- SO2	~	~	
- N2	0.74	0.71	
- AR	0.013	0.012	
Heat Transfer Coefficients			
- Gas Path	352	374	+6.2%
- Cooling Side	396	410	+3.4%
Metal Temperature			
- External Surface			+6.5C
- Internal Surface			+6.8C
HP Turbine Stage 1 Bucket			
- Oxidation Life	1	1.195	-19.5%

For Constant LP Turbine Inlet Temperature

Industrial Frame

Steam/Water Injection Increases Metal Temperature of Hot-Gas-Path Components

- Water Affects Gas Transport Properties:
  - k - Thermal Conductivity ↑
  - C_p - Specific Heat ↑
  - μ - Viscosity ↔
- This Increases Heat Transfer Coefficients:
- Which Increases Metal Temperature and Decreases Bucket Life

Example (MS7001EA Stage 1 Bucket):

3% Steam (25 ppm NO_x)

H = +4% (Heat Transfer Coefficient)

T_{Metal} = +15 F (8 C)

Life = – 33%

For Constant Firing Temperature

Figure 5: Comparison of life impact of steam injection on aeroderivative (left) and industrial frame (right). The life of a stage 1 bucket on the High Pressure turbine could be reduced by up to 20%

was used to calculate heat conduction over a composite cylinder (e.g., TBC and blade wall thickness). The internal cooling flow heat pick-up was calculated along the radial path. The model was calibrated using estimations of metallurgical temperature.

Once the gas path properties were established, the impact of different load conditions was modeled. In the aeroderivative under study, the external coating of the HP turbine blade was identified as a TBC, with a ceramic top coating from Electron Beam Physical Vapor Deposition (EB-PVD) and a platinum diffusion aluminide as the bond coating (Figure 3). EB-PVD has excellent strain tolerance with columnar microstructure. TBCs normally fail by spallation due to delamination of the ceramic layer along the vicinity of the Thermally Grown Oxide (TGO) and TBC interface (Figure 4).

The failure process involves several mechanisms including oxidation of the bond coat, thermal mechanical fatigue, sintering, and spallation of the TBC. The formation of TGO and the corresponding compressive growth stresses at the TBC-bond coat interface remain one of main causes of failure in TBCs. Activation energies associated with the bond coating oxides were used to determine the oxide growth rate as a function of temperature, and equivalent oxidation life was calculated. This was then converted into an Equivalent Operating Hour (EOH) with reference to the design conditions specified by the OEM.

For the aeroderivative turbine, with the constant LP turbine inlet temperature control, a 3% steam injection (25ppm NOx) increases the hot-gas-path thermal conductivity by 3.5% (Figure 5). This would increase gas-side heat transfer coefficient by 6.2%. The internal heat transfer coefficient increased by 3.4%, which can be explained by the fact that steam injection increases the compressor discharge pressure and the cooling flow extraction. The overall heat transfer results increase the local metal temperature by 12°F (6.6°C) resulting in a 20% reduction in the part life.

In an example given by GE for the stage 1 buckets of the MS7001EA gas turbine, for constant firing temperature control, a 3% steam injection (25 ppm NOx) increases the heat transfer coefficient by 4%, which would result in a 15°F (8°C) increase in the bucket metal temperature and a 33% reduction in life.

The engine control for industrial frames is different from aeroderivative turbines. The MS7001EA is controlled at constant firing temperature, while the aeroderivative is controlled at constant LP turbine inlet temperature. It was found that the firing temperature of the aeroderivative turbine decreases with steam injections. This would counter the effect of the higher heat transfer on the gas side. Secondly, the criteria used for the MS7001EA may not be oxidation life, which is used in the aeroderivative engine analysis.

Maintenance strategies

Engine maintenance intervals are affected by the amount of water or steam injection, the engine control, and how the water or steam is injected. The impact of water or steam injection on the maintenance interval can be optimized by careful planning in equipment selection, operation disposition and water or steam injection design.

First, for relatively low levels of NOx reduction, injection of water or steam into the combustor is effective with minimal impact to the cycle performance or parts lives. Further reductions in NOx by increasing the amount of water or steam may have a negative impact on cycle performance, part lives and inspection intervals. Rather than going to Dry Low Emission (expensive and less power), some operators use water or steam injections to reduce NOx to a certain level (e.g., 45ppm) and then use Selective Catalytic Reduction (SCR) to do the final cleanup. This could be a cost-effective option that minimizes the impact on maintenance intervals.

Secondly, impact on part life due to water or steam injection is related to the way the turbine is controlled. On many industrial-frame gas turbines operating on base load, the control system automatically decreases the firing temperature when water or steam is injected. This counters the effect of higher heat transfer on the gas side, and results in less or no impact on the lives of hot gas path parts.

However, in most of the aeroderivatives, the LP turbine or power turbine inlet temperature is maintained constant. Decreasing the engine temperature manually during water or steam injection will produce less power augmentation but reduce impact on component lives.

Lastly, most of the first stage buckets, and first and second stage nozzles are internally cooled by air. If water or steam could be properly mixed with the cooling air before the air enters into the internal cooling passages of the air cooled parts, it would increase the heat transfer coefficient on the coolant side and reduce the metal temperature.

Author

Hugh Jin, is responsible for aerothermal analysis, component upgrade and hot section parts life prediction in Liburdi Turbine Services Inc. He provides a full scope of engineering services, including commissioning, auditing and performance testing of combined cycle plants and pipeline turbocompressors.