Hot Streaks and Deformation

Software tools from ANSYS improve durability and reduce emissions in gas turbines by helping to reduce creep in combustion liners.

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A low-emissions combustion liner is a critical system component for gas turbines. The combustion air in a gas turbine enters through holes in the combustion chamber liner and flows along the liner to keep it cool. Liners are designed to improve durability and cooling while minimizing the flow variation from liner to liner within the same engine. Reducing variation can decrease exhaust temperature spreads, engine hot streaks and emissions. By combining combustion, flow and structural modeling using tools from ANSYS, Power Systems Manufacturing (PSM) in Florida, U.S.A., designs virtual prototypes and avoids expensive physical testing until the very end of the design cycle.

Land-based gas turbines are often used in so-called "peaking" units, when the demand of the electric grid overwhelms the base-load capacity (most often handled by coal or nuclear units). This means that, in order to meet the grid demands but not to exceed them, gas turbine generators often run at partial or varying load. Modern can-annular F Class combustion systems, such as PSM's Flamesheet, are typically composed of several fuel stages designed to enable the gas turbine to ramp up or down in load during startup and shutdown, or to allow it to run at partial loads.

PSM's Flamesheet combustor is composed of three separately fueled equiangular circumferential main stages and a pilot stage at the center. The pilot stage is typically operated at low loads, and the main stages are brought online one stage at a time as the turbine ramps up. The combustion liner has only a circumferentially balanced flame during the pilot stage and full-load operation. At part-load conditions, when only one or two of the main stages are on, the flame is located on one-third or two-thirds of the liner inner surface, thereby producing a hot streak along the liner wall.

The high thermal variation and asymmetry on the metal surface of the combustion liners resulting from these hot streaks cause thermally induced stresses. Stresses can lead to thermo-mechanical fatigue that accrues on a cyclic basis and results in low-cycle fatigue failure. If the thermally induced stresses are lower than the yield limit of the material, the cylindrical liners may still deform inelastically due to creep relaxation over time. Liner deformation affects the structural integrity of the combustor as well as the circumferential fuel–air mixture distribution coming out of the premixer, which, in turn, can have a negative impact on the unit's emissions.

Engineers at PSM used a finite element (FE) technique and ANSYS Mechanical software to design a liner to mitigate such creep ovalization effects. The analysis predicted creep deformation over time of Haynes 230 alloy liner material using inputs from creep specimen testing. The engineers validated these results against field test data of PSM's Flamesheet combustion liners carried out in a fully-instrumented combustion system of a Siemens Westinghouse SW501F unit at Calpine Corporation's South Point Plant in Arizona, U.S.A. Similar inspection of 7FA DLN 2.6 combustion system liners also showed signs of creep ovalization.

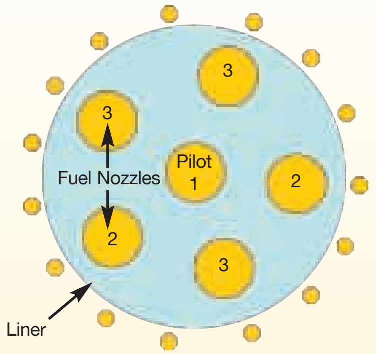
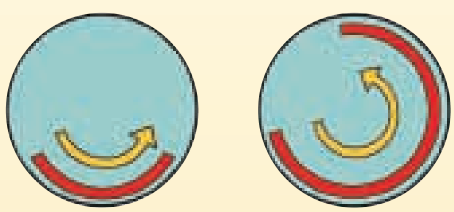


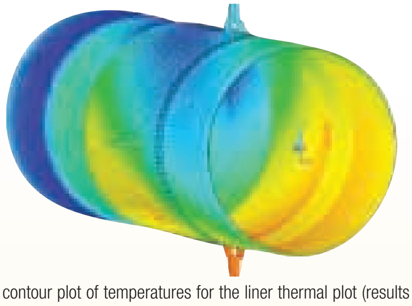
Diagram of a gas turbine combustor showing locations of burners that are operated depending upon required load. Numbers indicate burners that operate together for the various stages of operation.



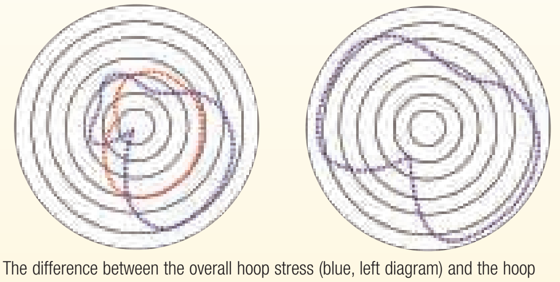
Red lines indicate the areas along the liner circumference that develop hot streaks when one stage (left) or two stages (right) are used.

Three-dimensional FLUENT computational fluid dynamics (CFD) simulations provided thermal boundary conditions for the FE analysis under part-load operating conditions. Thermal gradients were highest at the premixer exit of the liner's unsupported forward end, causing it to deform freely and assume a thermally distorted shape.

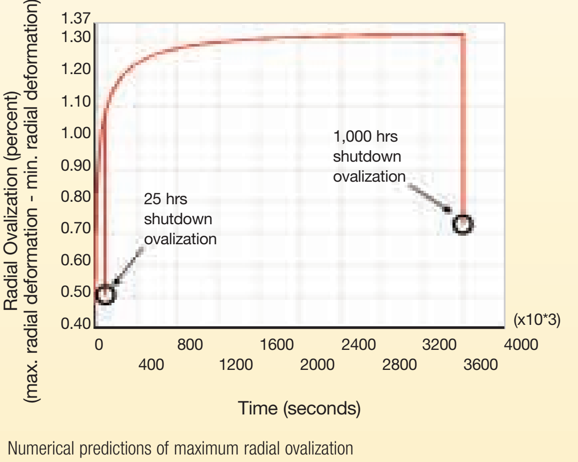
Next, the engineering team performed a linear elastic analysis on a full 3-D ANSYS Mechanical model that was constrained at the liner lugs to simulate the configuration of the installed engine. They mapped thermal profiles and pressure loads onto the model that were consistent with measured data for a two-stage part-load condition.



This contour plot of temperatures for the liner thermal plot (results for having two main stages on) shows a large circumferential metal temperature gradient on the liner surface over the entire length of the combustor. Orange indicates higher temperature, and blue indicates lower temperature.



The difference between the overall hoop stress (blue, left diagram) and the hoop stress due to radial temperature (red, left diagram) yields the stress caused by the thermal asymmetry (right diagram). The values in the left diagram were calculated based on simulation results using technology from ANSYS.



Numerical predictions of maximum radial ovalization

They then isolated the stresses caused by the circumferential temperature streak by subtracting the stress due to the radial temperature change from the total outer diameter to inner diameter hoop stress data at the liner premixer axial location. The residual deformation due to the circumferential temperature gradient was isolated in a similar fashion and compared against post-operating inspection data after approximately 20 hours of operation. The linear elastic strains from the 3-D model were used to evaluate the creep strain due to the favorable comparison with experimental data.

Using liner drop measurements separated by several days of operation, PSM engineers found radial ovalization to be approximately 0.78 percent; this indicated creep relaxation. Furthermore, the creep data for the Haynes 230 example revealed that such creep deformations occurred within the first few hours of part-load operation. The linear elastic stresses were within the elastic yield limit of the liner material. The linear elastic strains associated with these stresses created a strain control environment in which the liner thermal stresses creep relax to the Haynes 230 creep strength capability. Since there are no constant stresses and thermal stresses are within the elastic limit, engineers expect the liners to achieve a permanent set based on the ovalized linear elastic shape and to maintain that thermal shape without further deformation.

Estimating the amount of creep relaxation under strain control (permanent set) in a combustion liner required the use of an FE analysis. Complexity was introduced by 3-D variations in temperature, stresses, creep strain and strain rate across the liner. Specimen lab testing for tensile creep data revealed that the Haynes 230 example exhibited negligible primary creep.

PSM engineers estimated the material constants in Excel through best-fit coefficients to the experimental data. They constructed a complete Flamesheet liner model using 3-D ANSYS SOLID186 element types to simulate the liner's secondary creep behavior. They mapped temperature and external static pressure loads from the FLUENT results onto the model. The implicit creep routine in ANSYS Mechanical software was invoked by using the strain "rate = 1" option. The ANSYS Mechanical model simulated 25 hours of run time followed by a shutdown, then a restart and continuation up to 1,000 hours of operation followed by a shutdown.

The simulation results showed that the liner mixer exit accumulated approximately 0.55 percent (maximum radial deformation minus minimum radial ovalization) of radial ovalization after 25 hours of part-load operation. After 1,000 hours of operation, the mixer exit accumulated approximately 0.73 percent of diametric ovalization, which compares well with the 0.98 percent of diametric ovalization observed by coordinate measuring machine (CMM) inspection performed on the liner mixer exit after testing. This result also confirmed that the liner creep strain rate decreased as the liner creep relaxed to the desired thermal shape. Although the ANSYS Mechanical creep analysis under-predicts the ovalization, over-firing during testing

Simulation results for creep deformation at shutdown after 25 hours of part-load operation (left); 1,000 hours of part-load operation (center) and deformation as measured by CMM inspection after experimental testing (right). Deformed shape is exaggerated in FEA images.

may have caused the liner temperatures to be higher than those predicted by the thermal analysis, resulting in the mismatch.

Using the ANSYS Mechanical simulation to determine the effects of part-load operating hot streaks on the PSM Flamesheet combustor revealed creep relaxation of the liners under a strain-controlled environment. Numerical predictions of the residual ovalization compared well with inspection data on the liner mixer exit obtained from testing. PSM is currently using ANSYS Mechanical solutions for investigating new designs in order to mitigate such creep relaxations in Flamesheet combustion liners. ■

References

Rizkalla, H.; Strohl, P.; Stuttaford, P., "Prediction and Mitigation of Thermally Induced Creep Distortion in Gas Turbine Combustors," Proceedings of ASME TURBO EXPO 2007: Power for Land, Sea & Air, 2007, GT2007-27815.