DOE/Allison Ceramic Vane Effort

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Introduction

An objective of the Advanced Turbine Systems (ATS) program is to develop ultra-high efficiency gas turbine systems. Rotor inlet temperatures several hundred degrees greater than for the highest temperature current industrial engines will be required to meet the ATS objectives. Consequently, new technologies need to be developed and demonstrated to achieve the required ultra-high ATS efficiencies.

Objectives

Other than combustor-related components, the highest temperature parts in a turbine are the first-stage stator vanes. Ceramic vanes are being considered to enable the increased turbine inlet temperatures needed to meet the ATS program efficiency goals. However, ceramic vanes have not been proven for industrial turbines, even at current inlet temperatures. The Allison Phase 2 ATS program was modified to prove ceramic vanes at current industrial turbine conditions. The objectives of the task described in this paper are to design, evaluate, and demonstrate first-stage ceramic vanes in an industrial turbine operated at a current inlet temperature in the vicinity of 1100°C (2000°F). This could provide a stepping stone to the introduction of ceramic vanes into ATS turbines with very high inlet temperatures in excess of 1427°C (2600°F).

Approach

The program objectives will be accomplished by the following approach:

- design and analyses of first-stage ceramic vanes and mounting hardware
- ceramic vane procurement
- thermal shock proof tests of the ceramic vanes
- proof tests of the vanes and mounting hardware in a test engine
- demonstration of the ceramic vanes and mounting hardware in a long term Allison 501 turbine run at a commercial site

Project Description

Design/Analyses of Ceramic Vanes and Mounting Hardware

Ceramic vanes and mounting hardware will be specified and designed for retrofit into an Allison 501 turbine. For that engine, the first-stage vanes are exposed to an average combustor outlet temperature up to the vicinity of 1100°C (2000°F) with hot spots several hundred degrees higher. The intended vane life is 30,000 hr, comparable to the current design life of metallic vanes.

The initial mechanical design of the vanes and their mounting hardware will be based on Allison's extensive experience in the design and testing of smaller experimental automotive turbines that use ceramics. Computerized heat transfer and stress analyses will be used to evaluate the initial design and refine it, as needed. Typical ceramic properties of the vendor materials will be used in the initial analyses. The stress

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analyses will be later refined using materials data obtained from flexure and tensile test of vendor specimens formed from the same batches used to form the purchased vanes.

A probabilistic design methodology has been developed by Allison that addresses the statistical nature of a ceramic's strength distribution and the reliability requirement for the component in service. The material surface and volume strength is characterized by a two-parameter Weibull statistical treatment of the four-point bend modulus of rupture strength of test bars. The component reliability service life goal is apportioned for required reliability in customer service. Additionally, the engine operating environment is input to the sophisticated finite element modeling of the component to analytically assess the fast fracture reliability. Both steady-state and transient (startup and shut down) thermal and mechanical loads for engine operation will be considered in design analyses.

The results of the design and analyses activities will be used to specify the ceramic vane configuration to ceramic vendors. These activities will also be used to produce mounting hardware drawings for fabrication or procurement by Allison under this task.

**Procurement of Ceramic Vanes**

The ceramics suppliers will be involved in the definition of vane and mount designs. The purpose of interaction with the ceramics suppliers is to assure that the vane design is engineered not only for long life but also for acceptable production costs. Procurement of the ceramic vanes will be based on the specifications and drawings resulting from the iterative design, analyses, and supplier interactions.

**Thermal Shock Proof Tests**

Proof tests will be conducted for all ceramic vanes that are expected to operate in later engine tests. The proof tests will simulate temperatures corresponding to at least one engine startup from room temperature to full load (vicinity of 1100°C [2000°F]), a period of exposure at that temperature, and an abrupt drop in temperature to represent a generator trip in service which results in an immediate shutdown of fuel to a turbine. The purpose of this test is to screen out any vanes with undetected flaws that could initiate cracks and failure due to thermal shock in an operating turbine. After the proof test, each vane will be visually inspected and analyzed by nondestructive techniques such as fluorescent penetrant and microfocus X-ray.

**Vane/Mount Proof Test in Engine**

A full set of first-stage ceramic vanes and their mounting hardware will be operated in a 501 turbine at Allison. The purpose is a proof test of both ceramic vanes and metallic mounting components in an operating test engine prior to installation at a commercial site. The test will verify that the metallic mounting hardware does not transmit excessive contact stresses or excessive mechanical loads to the ceramic vanes due to distortions caused by the combustor temperature patterns. The test will probably consist of a normal startup of the turbine, operation for up to 50 hr at load, and a normal shutdown.

**Ceramic Vane Field Demonstration**

Since the field demonstration depends on a final agreement with the end-user, the following test plans are preliminary.

Vaness that had been screened in the thermal shock proof test and the engine proof test will be installed with mounting hardware in an Allison 501 turbine that has been taken out of commercial service for maintenance.

The turbine will reenter service at its commercial site for up to 8000 hr under its normal operating conditions. The commercial site will most likely be a cogeneration plant, at which operation is essentially continuous at full load, except for unanticipated shutdowns (such as generator trips) and scheduled maintenance (probably 6 month intervals). Inspection frequency for the ceramic vanes and their mounts will depend on the agreement with the end-user, since any additional inspection outages result in loss of plant revenues. At the end of the test, ceramic vanes will be removed from the engine and analyzed to assess their condition and expected additional life.
Results

Vane Screening Analyses

The highest stresses for the ceramic vane are expected to result from emergency shutdowns to prevent the turbine from overspinning due to loss of generator load. The fuel to the combustors is instantly shut off and the gas entering the first stator passages immediately drops in temperature by as much as 720°C (1300°F). The thin trailing edges of the hot vanes cool faster than the thicker leading edges to produce high thermal transient stresses.

Probability of survival (POS) analyses were conducted to calculate thermal transient stresses in ceramic vanes with the same profile shape as the metallic vanes in a commercial Allison 501 turbine. Materials properties of three candidate ceramics were used for the POS evaluations. Vane platform effects were neglected in these initial screening analyses.

The POS during an emergency shutdown of a full set of 60 solid ceramic vanes was calculated at about 99 percent for the best of the three ceramics. Calculations for hollow ceramic vanes indicated a reduction in thermal shock stresses. However, discussions with ceramic suppliers indicated that hollow vane production costs in commercial quantities increase significantly for vanes of the scale used in the Allison 501 turbine.

To alleviate thermal shock stresses, a new vane shape was designed by the Allison aerodynamics group. This new vane design (Figure 1) has less thickness variation over its chord to result in more uniform cooling and about 24% lower thermal shock stresses than a ceramic vane with the shape now in the 501 turbine. The calculated POS for the full set of stator vanes with the new profile approaches 100 percent. Also, the new vane shape has improved aerodynamic performance due to advances in aerodynamic computational techniques since the original design of the 501 turbine vanes.

Vane/Mount Design

In addition to long lifetimes at steady state conditions and probabilities of survival approaching 100% during startup and shutdown thermal shocks, two design goals for the ceramic vanes are:

- production costs competitive with current metallic vanes
- reduction of contact stresses between the ceramic vanes and their metallic mounts

Various design options have been discussed with ceramics suppliers and an initial design has been chosen for 3-D thermal and stress analyses. For this design, the ceramic vane is not hard mounted and the contact area at metallic interfaces is minimal. These features alleviate contact stresses and the amount of expensive diamond machining required at ceramic surfaces in contact with metallic mounts.

Vane/Mount Analyses

The 3-D stress analyses for steady state and emergency shutdown probabilities of survival (POS) of the ceramic vanes are in progress. Figure 2 shows the finite element mesh networks for both the vane and its metallic mounts. The
properties of candidate ceramics from three suppliers are being used in these evaluations. Two of the ceramics are monolithic silicon nitride materials and the third is a relatively low cost ceramic matrix composite of silicon carbide particles in a matrix of alumina.

Ceramic Vane Thermal Shock Tests

The layout design and drawings have been completed for the thermal shock test equipment to be used for proof tests of every ceramic vane expected to operate in later engine tests. The detailed design and drawings are in process.

Application

Technology advancements in metallic cooling techniques and materials will be needed if alloys are to be used for the airfoils that experience the highest gas temperatures in ATS turbines. An alternate approach is the development of structural ceramics which would need little or no cooling of the high temperature airfoils.

There are several potential benefits for ceramic airfoils over cooled metallic airfoils. Since compressed cooling air bypasses the combustor, the resulting turbine performance penalty for cooled metallic airfoils is reduced for ceramic airfoils. NOx emissions goals are more easily met if ceramic, rather than metallic, first-stage vanes are used. Since the drop in gas stream temperature between the combustor and the first rotor blades is less for ceramic vanes, a lower combustor temperature (which produces less thermal NOx) can be used to achieve a given rotor inlet temperature.

Future Activities

Upon completion of the ceramic vane 3-D thermal and stress analyses, the design will be modified, if needed, for improved POS and life. The vanes will be ordered from the ceramic suppliers upon verification of the design by these analyses. The vanes will then be proof tested in the thermal shocks rig prior to operation in engine tests.

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Figure 2. Finite Element Mesh for Ceramic Vane and Mounts.