DESIGN AND EVALUATION OF A SINGLE-CAN FULL SCALE CATALYTIC COMBUSTION SYSTEM FOR ULTRA-LOW EMISSIONS INDUSTRIAL GAS TURBINES

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ABSTRACT

The goal of the Advanced Turbine Systems (ATS) program is the design and development of high thermal efficiency gas turbines with pollutant emissions at single digit levels, through the development of advanced recuperated gas turbines. Following successful subscale catalytic reactor testing, a full scale catalytic combustion system was designed to be representative of a single can in a multi-can gas turbine combustor configuration. The full scale catalytic combustion system is modular in design and includes a fuel/air premixer upstream of the catalytic reactor and a post catalyst homogeneous combustion zone downstream of the catalyst bed to complete the homogeneous gas-phase reactions. System start-up was accomplished using a lean-premixed (LP) low emissions fuel injector. The system transitions to catalytic operation using a variable geometry valve that diverts air flow into the catalyst at loads greater than 50% of full load. The variable geometry valve is used to operate the catalyst within the narrow operating window due to limited fuel/air turndown allowed by the catalyst. A catalyst design with preferential catalyst coating on a corrugated metal substrate to limit catalyst substrate temperatures was selected for the system. Mean fuel concentration measurements at the inlet to the catalyst bed using an instrumented catalyst module showed the fuel/air premixing to be within catalyst specifications. Preliminary combustion tests on the system were completed. The catalytic combustion system was tested over the 50-to-100% load range. Using variable geometry control, emissions goals (< 5 ppmv NOx, < 10 ppmv CO and UHC corrected to 15% O2) were achieved for the system operation between 50-and-100% load conditions. The system was started and operated under part-load conditions using the LP injector. Efforts are under way to accomplish successful transition from LP mode of operation to catalytic mode of operation using the variable geometry system.

INTRODUCTION

The goal of the Advanced Turbine Systems (ATS) program is the design and development of high thermal efficiency gas turbines with NOx emissions at single digit levels over the 50 to 100% load range, while achieving high thermal efficiency, through the development of advanced recuperated gas turbines. Catalytic combustion was selected as an approach capable of attaining the emissions goals of the ATS gas turbines. Initial work focused on the subscale evaluation of catalytic reactors under simulated gas turbine conditions, and the results from the subscale development tests have been reported elsewhere (Topical Report, 1996). Following successful subscale catalytic reactor testing, a full-scale catalytic combustion system configuration was designed. On successful evaluation of this catalytic combustion system, a full set of hardware will be procured for an engine demonstration. This paper discusses the concept and design of a full scale catalytic combustion system and preliminary test results from rig testing at simulated gas turbine conditions.

BACKGROUND

Catalytic combustion is a lean-premixed combustion process where a catalyst is used to initiate and promote chemical reactions in a premixed fuel-air mixture at leaner conditions than are possible in homogeneous gas-phase combustion. This allows stable combustion of lean fuel/air mixtures with adiabatic combustion temperatures less than 1650 K, so that NOx emissions less than 5 ppmv can be achieved.

Even though the concept of catalytically stabilized combustion was demonstrated in the early '70s (Pfefferle, 1975), the technology has not yet been applied to field gas turbine combustors. During the initial development stages, materials issues related to high substrate temperatures, problems of sintering and deactivation of catalyst, and thermal shock resistance prevented the successful application of the technology in gas turbines. Recent development efforts are concentrated on innovative catalyst and system designs to circumvent the non-availability of reliable high temperature catalysts. There are currently three primary approaches to the design of catalytic combustion systems for gas turbine combustors: 1) systems using high temperature catalysts (e.g. Mn/Ba/La substituted hexaaluminates); 2) systems where only a part of the fuel is injected upstream of the catalyst (to limit catalyst temperatures) and the rest of the fuel is injected downstream of the catalyst (to obtain the desired temperature rise in the combustor); and 3) systems where all the fuel is injected upstream of the catalyst and partially reacted in the catalyst bed, and combustion is
completed in a post-catalyst combustor. The latter two approaches rely on keeping substrate temperatures low to prevent problems of thermal sintering and catalyst deactivation. Other gas turbine integration issues include engine start-up, acceleration, part load operation, turndown of catalyst, combustor cooling, transition to the turbine section and engine controls.

It is felt that many of the limitations of conventional catalytic combustors may be overcome through appropriate combustion system design. For example, catalyst designs that limit substrate temperatures well below the adiabatic combustion temperature may help resolve the substrate durability issue. This work presents a new system approach where start-up and part load operation of the system are accomplished using a conventional lean-premixed injector, and transition to catalytic combustion is achieved using variable geometry design. Further development and evaluation of the system is required before the technology is applied to gas turbine combustors. The catalytic combustor will then be integrated in an existing gas turbine. One option for integrating a catalytic combustor in a gas turbine is shown in Fig. 1, where a canted multi-can catalytic system may be interchanged with a canted annular lean-premixed system.

FULL SCALE SYSTEM DESIGN

The design of the full scale catalytic combustion system was based on subscale test results. Details of the subscale work are available in a Topical Report (1996), and only a summary of the significant results are given below:

1. For all test conditions, the contribution of the catalyst to NOx measurements was consistently less than 3 ppmv. The attainment of less than 10 ppmv (corrected to 15% O2) CO and UHC was highly dependent on a combination of overall equivalence ratio, catalyst exit temperature and combustor residence time.
2. Successful operation of the catalyst required very uniform fuel/air profiles at the inlet to the reactor. Inhomogeneities in fuel concentration (> 10% peak to peak variation) led to catalyst damage and high CO and UHC emissions.

3. Catalyst fuel/air turndown was found to be inadequate for operation of the catalyst over a wide range of engine loads. Air staging is required to maintain ultra-low CO emissions over the 50-to-100% load range (see Dutta et al., 1997).

4. In short-term testing, the catalysts showed the desired chemical activity and no observable change in performance between tests. Multiple light-off sequences were performed, and no detrimental effects on catalyst performance were observed.

The design of the single full scale catalytic combustion system follows the catalytic and primary combustor arrangement of Cowell and Roberts (1995). Engine start-up and operation to 50% load is accomplished using a conventional lean-premixed (LP) fuel injector. At 50% load, the system transitions from LP mode of operation to catalytic mode of operation. Figure 2 shows the scheme of operation of the combustion system. A medium pressure ratio (~9 atmospheres) recuperated thermodynamic cycle (thermal efficiency 40%) is chosen for the ATS gas turbine. The gas turbine is operated to keep the combustor inlet temperature relatively constant between 50-and-100% load. For the present gas turbine cycle, at loads higher than 50%, the catalyst inlet temperature (recuperator exit temperature) is sufficiently high to allow catalyst ignition. This may not be the case for simple cycle gas turbines. Operation between 50-and-100% loads requires a change in the air flow distribution between the catalyst and the dilution region. This allows the catalyst outlet temperature to be kept relatively constant over the 50 to 100% load range in order to overcome limitations of narrow fuel-air turndown of the catalyst. The required combustor outlet temperature is obtained by diverting more air flow into the dilution section at lower gas turbine loads.

START-UP AND PART-LOAD INJECTOR

Start-up and part load operation of the combustion system is accomplished using a lean-premixed fuel injector. The basic concept of fuel injection of such a fuel injector is shown in Fig. 4, and variations of this design have been used in various low emissions gas turbine combustor designs (Rawlins, 1995). The injector consists of a swirl and an annular premixing duct into which natural gas is injected using a number of fuel injection spokes. The injector delivers a well-mixed fuel/air mixture to the combustor primary zone. The injector incorporates a central pilot fuel flow system for light-off and to enhance flame stability at leaner fuel-air ratios at lower engine loads. The part-load injector has been designed to meet combustor air flow requirements at 50% load at the desired pressure drop.

FUEL-AIR PREMIXER

The subscale catalytic combustion work (Topical Report, 1996) illustrated the importance of delivering homogeneous fuel/air mixtures to the catalyst. A multi-venturi premixer design with multi-point fuel injection (using fuel spokes) similar to the work of Tacina (1977) was chosen. A set of annular static mixers (similar to the ones used in the subscale work) was also fabricated in order to establish a baseline premixing level for the combustion system.

The narrow catalyst fuel/air turndown necessitated the use of a variable geometry valve at the inlet to the premixer. The valve is conical in shape, and serves to change the effective flow area at the inlet to the premixer in order to modulate the air flow into the catalyst as required. An electric actuator is used to move the valve using a slider mechanism. Anti-galling material combinations (e.g., Nitronic 60 and stainless steel) were used for critical valve actuation components to reduce the possibility of failure at the elevated combustor inlet temperatures.

CATALYTIC REACTOR

Catalytic reactors similar in design to the ones tested in the subscale work were used in the present work. Details of the catalyst design have also been reported earlier (Topical Report, 1996). The full scale design incorporates an annular catalyst enclosed in an annular catalyst container, so that a part-load fuel injector can be included at the center of the combustor. The catalyst uses a FeCrAl-alloy substrate and is preferentially coated with the active compound (Pd0). A combination of this design and the unique thermodynamic characteristics of the oxidation and reduction of palladium (McCarty, 1994) allows the catalyst substrate temperature to be maintained at relatively low levels (<1000°C). As part of the overall development program, durability testing has been carried out on subscale catalyst modules (5 cm diameter). In atmospheric pressure tests, catalyst activity was sustained for over 8000 hours (duration of the test). Durability testing at design pressure was limited to approximately 1000 hours, and no appreciable reduction in catalyst activity (as measured by the ignition temperature and emissions) was observed.

HOMOGENEOUS COMBUSTION ZONE

The post-catalyst homogeneous combustion zone is a critical component of the overall system. Partial conversion of the fuel is completed in the catalyst, and gas-phase reactions are completed in this combustor. Adequate combustor residence time is required to achieve CO concentration.
reduction to less than 10 ppmv levels. The combustor size is determined by the overall equivalence ratio and catalyst exit temperature. In order to determine the size of the post catalyst combustor, laminar one-dimensional premixed flame calculations were performed using the PREMIX code of the CHEMKIN package (Kee et al., 1985). These calculations provide reasonable agreement with experimental measurements as seen in earlier work (e.g., Vortmeier, 1996).

COMBUSTOR COOLING

Under catalytic combustor operating temperatures (1500 to 1650K), conventional film cooling is likely to quench "primary"zone reactions and lead to high CO emissions. The combustor used in the present work was designed with continuous round wire turbulence generators welded to the outside of the liner. The design of the turbulence generators was based on data available in the literature (Norris, 1970; Evans and Noble, 1978). These data show an average three-fold augmentation in convective heat transfer when compared with similar geometries without the turbulence generators.

INSTRUMENTATION

The test rig includes standard instrumentation to meter all air and fuel flow rates, pressure and temperature. The catalyst bed is instrumented with...
multiple thermocouples to obtain substrate wall temperatures and catalyst exit gas temperatures. A water-cooled sampling probe located at the exit plane of the combustor (downstream of the dilution holes) is used to obtain representative (area averaged) gas samples for analysis using standard gas analyzers. A set of six thermocouples located near the center (axially) of the combustor is used to determine the radial and circumferential uniformity of gas temperatures downstream of the catalyst, and to monitor progress of gas-phase reactions.

Similar to subscale work, a catalyst module was instrumented with multiple (~30) sampling probes in order to measure mean fuel concentrations directly upstream of the catalyst. In this test, the catalyst foil was not coated with the active species so that inadequate premixing did not lead to catalyst damage during premixing measurements.

RESULTS AND DISCUSSION

Initial work concentrated on measuring the combustor component effective flow areas as a function of valve position and establishing the desired flow distribution between the catalyst, part-load injector and dilution region at various simulated engine loads. Following these initial tests, a series of premixing measurements was conducted in order to characterize premixing levels at the catalyst inlet. Premixing levels meeting catalyst specifications (<10% peak-to-peak variation in fuel concentration) were established through design modifications.

The catalyst was designed through subscale tests (5 cm diameter) in a high pressure test rig. The operating window of the catalyst was determined through measurements of temperature and gas concentrations in the post-catalyst region. The measured operating window is shown in Fig. 5 and demonstrates some of the advantages (such as catalyst ignition without a preburner) associated with the current engine cycle.

Catalytic combustion tests on the full scale rig were initiated by closing the central flow control valve and distributing the air flow between the catalyst and the dilution zone. Rig conditions were set to the full-load operating temperature and pressure (~865K, ~8.6 atmospheres). The catalyst was fueled to achieve the desired fuel/air ratio at full load. The rig was allowed to attain steady-state conditions before a set of data was acquired. Measurements of exhaust emissions, catalyst wall and exit gas temperatures and combustor exit temperatures were recorded. The rig operating conditions were then changed to simulate off-design engine operation down to 50% load. The inlet temperature was kept constant between 100- and 50% load. The pressure was changed to 7.5 atm., 6.9 atm., 5.9 atm. at 80%, 70%, 60% and 50% loads respectively.

At each test point (100, 80, 70, 60, 50% load), data was obtained under steady state rig operation. Emissions measurements at various test points are shown in Fig. 6. Consistent with subscale test results, NOx emissions
below 3 ppmv (corrected to 15% O₂) were measured at all test points. In order to meet CO and UHC emissions goals below 10 ppmv (15% O₂), the airflow into the catalyst was modulated using the variable geometry valve.

Measurements of catalyst wall temperatures and exit gas temperatures (normalized by the mean temperatures) at 70 and 100% load are shown in Fig. 7. The catalyst wall temperatures varied from 1145K to 1210K, and were below the desired maximum temperature of 1273K. The relatively uniform temperature measurements verify the fairly homogeneous fuel-air profiles at the catalyst inlet. The effects of a well mixed gas mixture at the catalyst exit are also seen in the relatively uniform combustor exit temperatures (based on 9 thermocouple measurements) shown in Fig. 8. The combustor wall was instrumented with 5 thermocouples equally spaced in the axial direction. Preliminary measurements showed acceptable wall temperatures (<800°C) at 100% load.

FIG. 7 - CATALYST WALL AND EXIT GAS TEMPERATURES AT TWO OPERATING POINTS

After the preliminary investigation of the system under catalytic mode of operation, the variable geometry valve was closed to divert airflow into the part load injector. Using a standard torch ignitor (shown in Fig. 3), start-up of the part load injector was accomplished. The fuel injector was then operated under a number of part load (<50%) operating conditions. In order to evaluate the possibility of heat release in the injector premixing duct (due to autoignition or flashback) at ATS full load combustor inlet temperatures (>620°C), a series of combustion tests was conducted with a number of similar injector designs at similar inlet temperatures in an existing high pressure single-injector test rig. Based on these tests, all the injector designs appeared to be resistant to flashback at ATS full load inlet conditions. Further investigation of this aspect will be conducted on the full scale system.

Development efforts are currently underway to allow the systematic evaluation of the following: a) transition of the system from lean premixed (LP) mode of operation to catalytic mode of operation; b) effect of air leakage on catalyst emissions; and c) effect of combustor heat transfer augmentation in maintaining desired wall temperatures.

CONCLUSIONS
Preliminary testing on a single-can full-scale catalytic combustion system representative of a multi-can engine configuration has been completed. Initial test results are encouraging, and more extensive evaluation is under way to explore the viability of the concept. Preliminary tests have demonstrated the feasibility of obtaining ultra-low emissions over the 50-to-100% load range using variable geometry control. Start-up and part-load operation of the system using a lean-premixed fuel injector has been demonstrated. The catalytic combustion system incorporates several technological advances over conventional lean-premixed systems, and successful full scale testing will be a significant step towards the ultimate goal of using a catalytic combustor in a future ATS engine.

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REFERENCES


