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Application of catalytic combustion to a 1.5 MW industrial gas turbine

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Abstract

A catalytic combustor is described for a 1.5 MW gas turbine engine. The catalyst temperature is limited and the high combustor outlet temperatures required by the turbine are generated downstream of the catalyst. The combustor design places a low NO_x preburner upstream of the catalyst and uses this preburner to achieve optimum catalyst operation by providing the desired catalyst inlet temperature. The combustor system employs the catalyst during engine acceleration and loading. The catalyst design has been tested on a sub-scale rig under full pressure and flow conditions simulating turbine operation over the entire operating range including acceleration and loading. The design should achieve emissions at full load operation of <3 ppm NO_x and <10 ppm CO and UHC. Low emissions operation is expected over the 75–100% load range. In addition, long-term sub-scale rig test results are reported at simulated full load operating conditions including cyclic operation and full load trips. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Catalytic combustion has been demonstrated in numerous rig tests to achieve combustion of a variety of fuels while producing extremely low levels of nitrogen oxides (NO_x) and simultaneously low levels of carbon monoxide (CO) and unburned hydrocarbons (UHC) even at combustor discharge temperatures as high as 1500°C (2730°F) [1]. This low NO_x level is a direct result of the low average combustion temperature resulting from a complete mixing of fuel and air prior to reaction of the very lean fuel–air mixture on a catalyst. Catalytic combustion systems have typically combusted all the fuel in the catalyst bringing the catalyst to the full combustor outlet temperature. The commercial application of catalytic combustion to gas turbines has been delayed by the inability to develop catalysts that have the required stability and durability. Gas turbines with low turbine inlet temperatures could utilize catalytic combustion while operating the catalyst at temperatures that would reduce the thermal stress on the catalyst. However, the current generation of high efficiency gas turbines with turbine inlet temperatures above 1200°C (2190°F) would result in rapid thermal sintering and degradation of the catalyst.

One technological approach to achieving the required stability is to operate the catalyst at low temperature by combusting only a portion of the fuel and completing the combustion downstream of the catalyst. This is shown schematically in Fig. 1. This technology has been developed over the past seven

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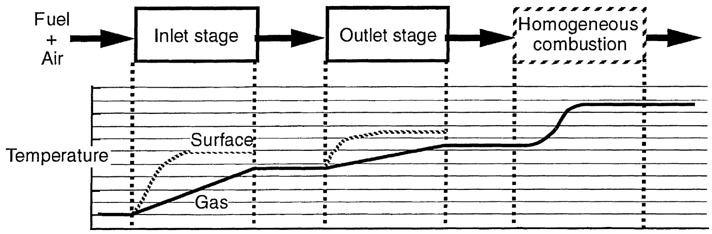

Fig. 1. Catalytic combustion scheme with partial fuel combustion in the catalyst and complete combustion downstream of the catalyst.

years and has been demonstrated in a number of subscale and full scale rig tests [2–5]. Typically, 50% of the fuel combusted in the catalyst and the remaining fuel combusted in a post catalyst zone to achieve temperatures in the range 1200–1500°C (2190–2730°F). Rig tests at high pressure and at gas velocities typical of those encountered in a gas turbine combustor have demonstrated NO_x emissions of ~1 ppm for combustor outlet temperatures of 1300°C (2370°F) and ~2.3 ppm for combustor outlet temperatures of 1500°C (2730°F) [1].

To demonstrate this technology in an operating gas turbine, a catalytic combustor system is being developed for the Kawasaki M1A-13A gas turbine. This engine was selected partially because it has a single can combustor that is mounted external to the engine through a single flange greatly simplifying the installation of a modified combustor.

2. Combustor design criteria

The criteria used in the design of the combustor are shown in Table 1. The emissions target were set at <3 ppm NO_x to meet the most stringent emissions regulations currently enforced in severe and extreme non-attainment areas in the USA and in the most stringently regulated areas in Japan and Europe. In addition, emissions levels of CO and UHC were set at 10 ppm. The catalyst durability target was set at a minimum of 8800 h, or one year of operation. This would allow catalyst change out at routine turbine inspection intervals. It is also desirable that the catalyst change out be accomplished without disassembly of the turbine. However, it is desirable that the major combustor components have a durability typical of current combustors, that is, a durability in excess of 20 000 h.

Table 1
Design criteria for the combustor system

Gas turbine full load operating conditions (ISO conditions)	
Combustor pressure (atm)	9.4
Compressor discharge temperature	332°C (630°F)
Total turbine air flow	8 kg/s (17.6 lbs/s)
Emission targets at full load (at 15% O_2 dry)	
NO_x (ppm)	<3
CO (ppm)	<10
UHC (ppm)	<10
Fuel	Natural gas
Catalyst durability	
Catalyst change out (h)	8800
Full load turbine trips	10
Combustor durability	
Inspection interval (h)	8800
Combustor component life (h)	20 000
System operating constraints	
Low emissions operating range	90–100% load
Natural gas fuel only	

The general combustion system design is shown in Fig. 2. This system configuration was selected for several reasons:

- The placement of the preburner upstream of the catalyst

1. The compressor discharge temperature is below the required catalyst inlet temperature to sustain the catalytic combustion reaction. For this reason a preburner must be located upstream of the catalyst to provide the required catalyst inlet temperature.
2. During engine acceleration and low load operation, the preburner will provide the majority of thermal energy.

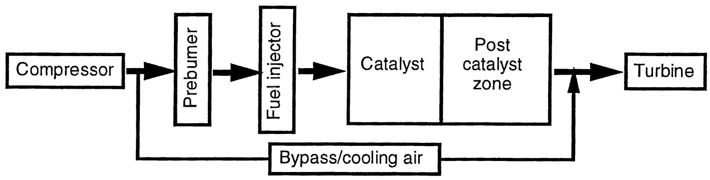

Fig. 2. Schematic of the combustor configuration showing the bypass of some air to maintain a high post catalyst zone temperature.

3. Placement of the preburner upstream of the fuel injector and catalyst limits the temperature at this location to ~800°C (1470°F) due to materials limits for the fuel injector and catalyst.

- Bypassing a portion of the air flow around the catalyst

1. To achieve rapid CO combustion to the very low levels required in Table 1, it is necessary to obtain a temperature above 1100°C (2112°F) in the post catalyst combustion zone.
2. The M1A-13A engine uses a substantial amount of compressor discharge air, ~30%, to cool the turbine inlet scroll and turbine first stage. The total amount of air bypassing the catalyst was further increased to maintain a post catalyst combustion zone temperature of 1300°C (2370°F) for optimum catalyst operation.
3. The air bypass will be a fixed ratio and will be set by proper specification of the catalytic combustor pressure drop and the dilution holes in the transition section.

3. Catalyst system performance

The catalyst system developed for this application is a two-stage catalyst using a corrugated metal support coated with the active catalytic materials. The inlet section of the catalyst is designed for low ignition temperature so that it can operate with minimal preburner heat input. The outlet section of the catalyst is designed for good high-temperature stability.

The test rig used in this development process has been fully described in previous publications [2,6]. This test rig has the capability to operate over the pressure range 0–20 atm, non-vitiated inlet temperatures up to 500°C (930°F) and simulated preburner operation up to 800°C (1470°F) consistent with the operating conditions of the M1A-13A gas turbine and the proposed catalytic combustion system. The catalyst section used in this test rig is 50 mm (2 in.) in diameter and the reactor is essentially adiabatic so that the test simulates a core through the combustor. The sub-scale test catalyst was the same length as the full scale catalyst.

A combustor operating cycle to fit the operating requirements of the engine and the catalyst operating constraints was developed and is shown in Fig. 3, where the temperature rise for the three system components, the preburner, catalyst and post catalyst combustion zone are shown. The initial portion of the rotor acceleration is accomplished with only the energy output of the electric starter motor and the preburner. At about 20% rotor speed, the energy needed for continued acceleration requires that the

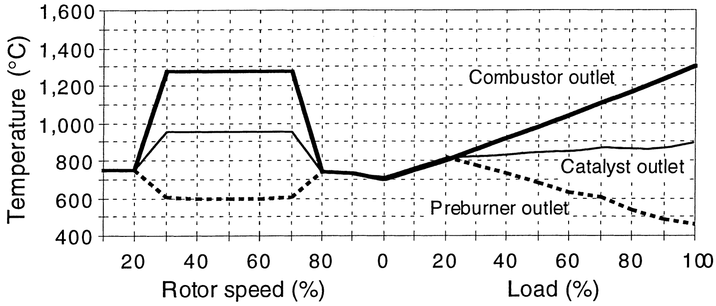

Fig. 3. Combustor operating conditions over the entire cycle shown as temperature rise in each section of the combustor.

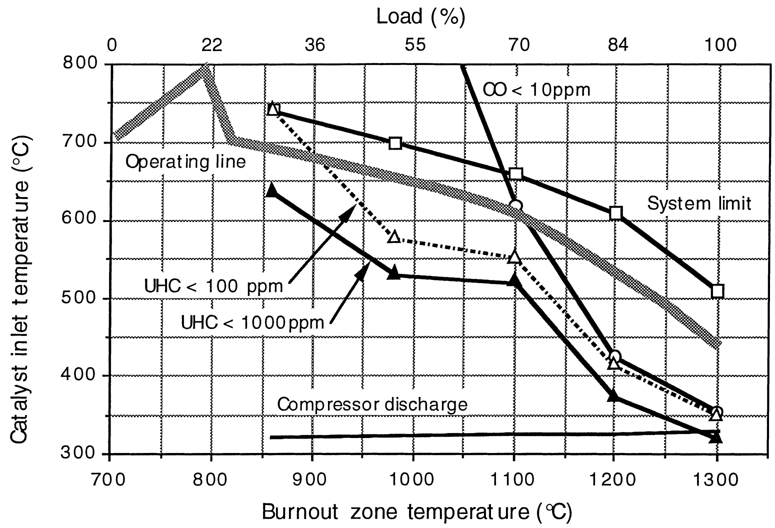

Fig. 4. Catalyst performance showing the operating window as the gas turbine load is increased. These data were determined experimentally in a high pressure sub-scale test rig under conditions simulating those present in the combustor.

catalyst be used to provide combustor outlet temperatures in excess of 800°C. Above about 80% rotor speed, the compressor efficiency is sufficiently high that the preburner can provide the required energy for the remainder of the rotor acceleration to full speed and for load up to about 20% load. Above 20% load, fuel is added to the catalyst.

The performance of the catalyst was measured in the sub-scale test rig at conditions of pressure, temperature and air flow that simulate the combustor operating conditions for load points from ~20% to 100% load. These data are shown in Fig. 4. These data are obtained as follows:

- For the given engine load, the sub-scale rig is adjusted to provide the required air mass flow and pressure.
- The electric air heater is set to provide the correct compressor discharge temperature.
- The preburner on the sub-scale rig is adjusted to provide the catalyst inlet temperature in the expected range and fuel added to the catalyst to obtain the required burnout zone temperature (i.e. combustor exit temperature).
- Subsequently, the catalyst inlet temperature is adjusted upward by increasing the preburner outlet temperature while decreasing the catalyst fuel to maintain the required burnout zone temperature. During the course of this process, the points displayed in Fig. 4 are determined from on-line emissions measurements and from thermocouples installed in the catalyst system.

The broad band in Fig. 4 is the expected operating line, that is the combustor conditions that would be selected for turbine operation. At 100% load, the inlet temperature to the catalyst would be in the range of 450°C and the CO emissions would be below 10 ppm. Load can be decreased to about 75% load (~1150°C post catalyst zone temperature) before CO emissions will rise above 10 ppm. As the load is decreased further, CO emissions remain high and at about 40% load (~900°C post catalyst zone temperature), UHC emissions begin to rise. Below ~20% load, only the preburner is used. The loading of the engine is the reverse of this process.

The catalyst performance described above and in Fig. 4 suggests that the turbine should operate with very low emissions at full load. In addition, it should provide low emissions down to about 75% load. In addition, the combination of the preburner and catalyst will provide a combustor system that can produce the required turbine inlet temperatures necessary for turbine operation from 0% to 100% load. Similar simulation rig tests have been done for the conditions during acceleration to define the catalyst operating window.

4. Long-term rig demonstration of catalyst performance

As a part of this development program, the catalyst was operated for ~400 h in the sub-scale test rig described above. The catalyst was operated at conditions consistent with full load operation with periodic shut down and start-up. In addition, several full load trips were simulated as the result of emergency shut downs initiated by the test rig control system due to cooling water failure or other problems in the test rig. The catalyst performance was periodically assessed over the course of this long-term run.

Fig. 5 shows the catalyst ignition performance as measured by providing fuel to the catalyst and slowly increasing the catalyst inlet temperature. The ignition temperature is the catalyst inlet temperature at which the catalyst shows substantial activity as shown by a significant rise in outlet gas temperature [6]. As shown in Fig. 5, the ignition temperature is approximately 305°C (580°F) for the fresh catalyst but after a short period rises to about 345°C (653°F). This initial change is due to the break-in of the catalyst in the first 20–40 h of operation. After 50 h, the catalyst ignition temperature appears to be nearly constant up to 400 h where the test was terminated.

A second test during the course of this long-term run was an extinction test preformed by slowly decreasing the catalyst inlet temperature and monitoring the catalyst outlet temperature. The full extinction scans are shown in Fig. 6 for periods up to 350 h. Again, the catalyst system appears to be very stable and the performance constant.

5. Combustor design and preburner performance

The basic combustor design is shown schematically in Fig. 7. The preburners are of a design similar to that described by Lewis and Holladay [7] and employs a fully premixed primary and secondary. The exhaust from the preburners mix in a toroidal plenum and are ducted to the main fuel injector. The main fuel injector is similar to the multi-venturi fuel injector originally described by Beebe et al. [8] for similar catalytic combustor applications. The fuel and air mixture then flows through the catalyst and a post catalyst combustion zone.

In the combustor cycle described above, the preburner is operated at full load to obtain the required catalyst inlet temperature, which is above the compressor discharge temperature. The total NO_x from the engine is the sum of the NO_x produced by the preburner and the NO_x produced by the catalyst and post catalyst combustion process. The NO_x emissions performance for the lean premixed preburner was measured in an atmospheric pressure test stand at flow conditions and temperature rise values that would simulate operation at full load. These measurements can then be corrected to the full load pressure according to the correlation developed by Magruder et al. [9]

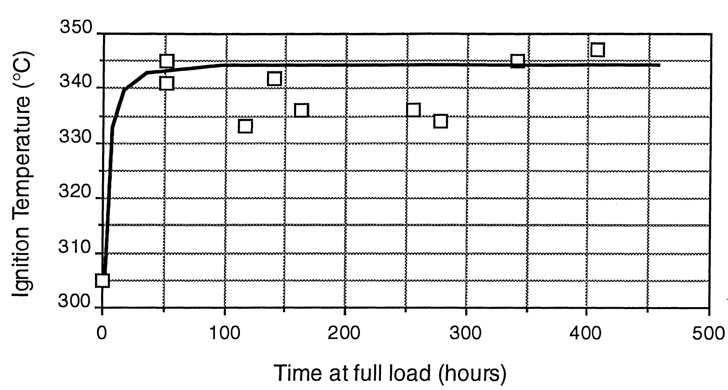

Fig. 5. Catalyst ignition temperature measured periodically during the long-term sub-scale test rig at full load conditions.

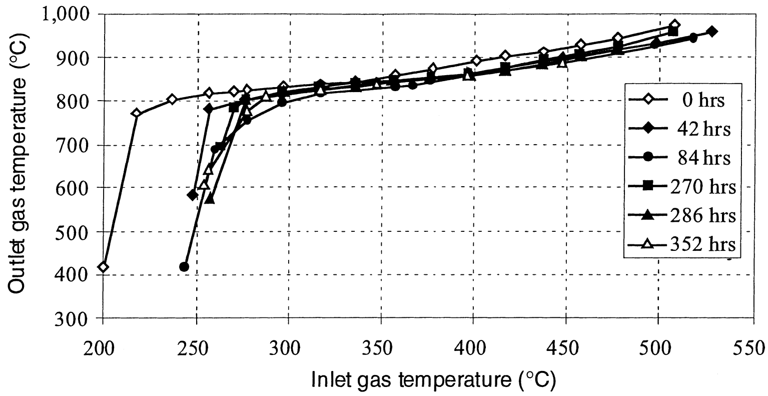

Fig. 6. Catalyst extinction test results measured periodically during long-term sub-scale rig test. Tests were done by ramping down the catalyst inlet temperature while monitoring the catalyst outlet temperature.

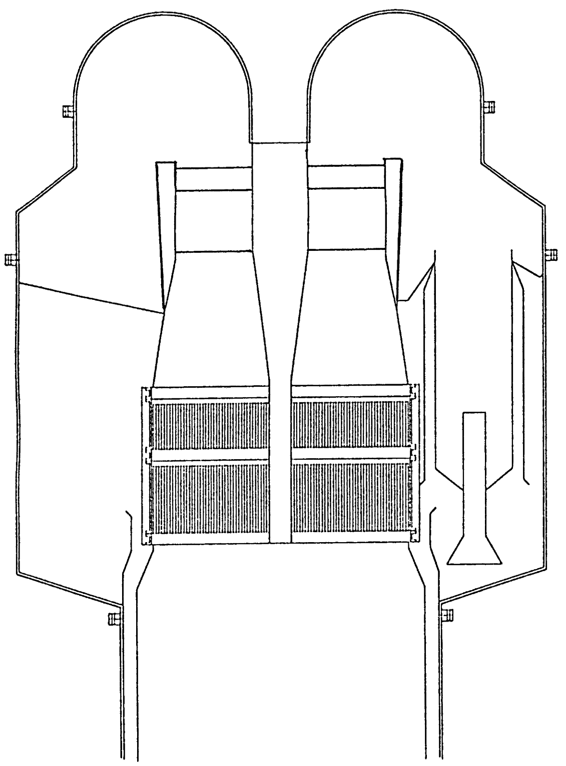

Fig. 7. Overview diagram of the catalytic combustor system showing the major components including the preburner, the catalyst fuel injector, the catalyst and the post catalyst combustion zone.

of the form shown in the following equation:

$$NO_{x_{(\text{high } P)}} = NO_{x_{(\text{low } P)}} \cdot P^{0.00221T\phi - 4.0149}, \quad (1)$$

where P is the total pressure and $T\phi$ is the flame temperature calculated from the fuel–air ratio in the primary zone. This results in expected NO_x emissions at full load of 1-2 ppmv (dry at 15% O_2).

6. Summary

A catalyst system and combustor design has been developed for a 1.5 MW gas turbine that uses a catalyst system that operates at temperatures below the required combustor discharge temperature and completes the combustion downstream of the catalyst. The catalyst has been evaluated in full pressure rig tests over the entire engine operating range and an operating line defined. The catalyst will be fueled during engine acceleration and during loading. Expected emissions during full load operation should meet the initial design targets and should be <5 ppm NO_x and <10 ppm CO and UHC. This combustor is being fabricated and will be undergoing tests in the near future.

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