ELSEVIER

Catalysis Today 47 (1999) 391–398

CATALYSIS TODAY

Development of a catalytic combustor for a heavy-duty utility gas turbine

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Abstract

Catalytic combustion is an attractive technology for gas turbine applications where ultra-low emission levels are required. Recent tests of a catalytic reactor in a full scale combustor have demonstrated emissions of 3.3 ppm NO_x, 2.0 ppm CO, and 0.0 ppm UHC. The catalyst system is designed to only convert about half of the natural gas fuel within the catalyst itself, thus limiting the catalyst temperature to a level that is viable for long-term use. The remainder of the combustion occurs downstream from the catalyst to generate the required inlet temperature to the turbine.

Catalyst development is typically done using subscale prototypes in a reactor system designed to simulate the conditions of the full scale application. The validity of such an approach is best determined experimentally by comparing catalyst performance at the two size scales under equivalent reaction conditions. Such a comparison has recently been achieved for catalysts differing in volume by two orders of magnitude. The performance of the full scale catalyst was similar to that of the subscale unit in both emission levels and internal temperatures. This comparison lends credibility to the use of subscale reactors in developing catalytic combustors for gas turbines.

Keywords: Catalytic combustion; Gas turbine; Scale-up of catalytic combustion; NO_x emission

1. Introduction

The technologies currently practiced for controlling NO_x emissions from heavy-duty industrial gas turbines involve either diluent injection into the combustor reaction zone or lean premixed combustion. To meet the increasingly stringent emission regulations, many turbine installations must also include a selective catalytic reduction (SCR) unit on the exhaust stream to remove NO_x produced in the combustor.

GE has commercialized dry low NO_x (DLN) systems based upon lean premixed combustion technology to deliver NO_x emission levels of 15–20 ppm in exiting power plants. The latest versions of the DLN systems are designed for 9 ppm. At single digit NO_x levels, however, lean premixed systems are being pushed to the limits of flame stability; this may preclude further significant reductions in NO_x emissions via this approach. Thus there is an incentive to develop a new generation of combustion systems that can achieve NO_x levels of 3–5 ppm without incurring the capital and operating costs associated with diluent injection and SCR systems.

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0920-5861/99/$ – see front matter
PII: S0920-5861(98)00321-6

NO_x production in a gas turbine combustor occurs predominantly within the flame zone, where localized high temperatures sustain the NO_x-forming reactions. The overall average gas temperature required to drive the turbine is well below the flame temperature, but the flame region is required to achieve stable combustion. Because catalytic combustion offers the possibility of achieving full conversion of a fuel/air mixture without the presence of a flame and its associated NO_x formation reactions, it offers the potential for delivering ultra-low NO_x levels without the need for SCR or other exhaust after-treatment.

This potential of catalytic combustion has been recognized for 20 years [1], but the environment in a gas turbine combustor presents significant challenges for a catalyst. The gas temperature required at the combustor exit ranges from 1450 to 1775 K (1175–1500°C), depending upon the particular turbine design. Such temperatures are well above the stability limits of most catalytic materials. Even ceramics that can survive the combustor temperatures are susceptible to thermal shock failure during the transients that accompany turbine operation. These durability issues have been a significant barrier to the development of a viable catalytic combustion technology for gas turbines.

Over the past few years a catalytic combustion technology has emerged that successfully addresses the unique challenges of the gas turbine application. Trade named XONON, this technology uses catalysts that are designed to limit the extent of fuel combustion that occurs within the catalyst structure itself. By limiting the reactions in this way, such systems also limit the maximum catalyst temperature and thus broaden the selection of suitable catalyst components and extend catalyst life. The catalytic reactor is designed so that the temperature and composition of the gas stream leaving the reactor are sufficient to achieve complete combustion of the fuel via homogeneous gas phase reactions in the volume downstream from the catalyst. Overall, this scheme provides the energy to drive the turbine while protecting the catalyst from excessive temperatures and minimizing the production of pollutants.

This technology has been demonstrated in a number of subscale and full scale tests [2–5]. In tests of small scale (typically 51 mm diameter) units, NO_x emissions ranged from ~1 ppm at combustor outlet temperatures near 1575 K (1300°C) to ~2.3 ppm at an outlet temperature of 1775 K (1500°C) [6]. In the work reported here, the focus is on two aspects of a recently completed full scale test and the associated prototype catalyst development effort:

1. a description of the encouraging emission results achieved in the test, and
2. a comparison of the observed performance characteristics of catalysts with significantly different dimensions tested in two different kinds of reactor systems.

The cooperative technical effort between GE and Catalytica has been ongoing since 1990. The strategy has been to develop, understand, and optimize the catalyst systems at a reduced scale in Catalytica's laboratories, and then to fabricate the chosen catalyst(s) at full scale for testing at GE's Power Generation Engineering Laboratory in Schenectady. The findings in the latter tests are then incorporated into further iterations of the catalyst design and modifications of the full scale hardware to improve the performance of the full scale combustor. A key to the iteration process is the confidence that indeed the small scale tests reflect the behavior of the catalyst system at full scale; that issue is a primary topic of this paper.

2. Experimental

The subscale test rig at Catalytica is shown schematically in Fig. 1; its design and operation have been described previously [2]. Briefly, the catalyst and hot gas path are 51 mm in diameter. The unit can be operated at pressures between 100 and 2000 kPa (1–20 atm) with catalyst inlet temperatures up to 825 K (550°C) using the electric air heater and 1075 K (800°C) using the preburner. The maximum air flow is 10 000 l/min (0°C, 1 atm), and the maximum combustion temperature is 1775 K (1500°C). The thermocouples and sampling probe shown in Fig. 1 allow monitoring of conditions in the catalyst, progress of homogeneous combustion in the downstream region, and overall system emissions.

The flexibility of the subscale reactor permits characterization of catalyst performance across the complete range of temperatures, pressures, and inlet gas

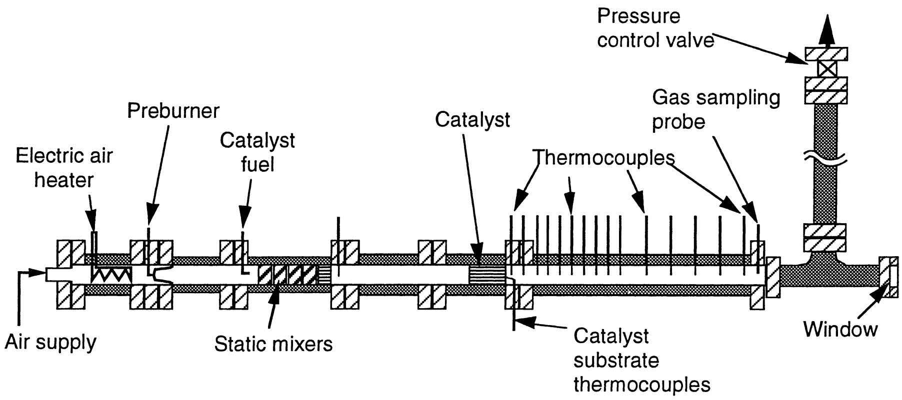

Fig. 1. Schematic diagram of the reactor for testing prototype (51 mm diameter) catalyst systems.

compositions relevant to the full scale combustor operation. Commonly, the fuel/air ratio entering the catalyst is fixed for a particular experiment, and the inlet temperature is varied to determine the range over which emission targets are met and over which the catalyst temperatures are within the desired range. Such inlet temperature scans are carried out over a series of fuel/air ratios to establish the boundaries of the catalyst operating window. In this way the expected catalyst behavior can be estimated at and near the design points of the turbine cycle, for comparison with observations in the full scale test stand.

The full scale test stand at GE is representative of the dimensions and operating conditions of a combustor on a GE Model 9001E gas turbine. The system was configured for catalytic combustion by installing a preburner and a specially designed multi-venturi fuel injector [7] upstream from the catalytic reactor. Fig. 2 shows a diagram of the major components of the test stand. The catalyst itself is 508 mm in diameter, 10 times the diameter and 100 times the volume of the subscale catalysts used for prototype development. The combustor was instrumented extensively both to characterize the details of the temperature profiles and emission levels at the various test points and to insure safe operation. The catalyst was also fitted with several thermocouples and gas sampling probes (Fig. 3) in order to measure the uniformity of the inlet conditions during the test.

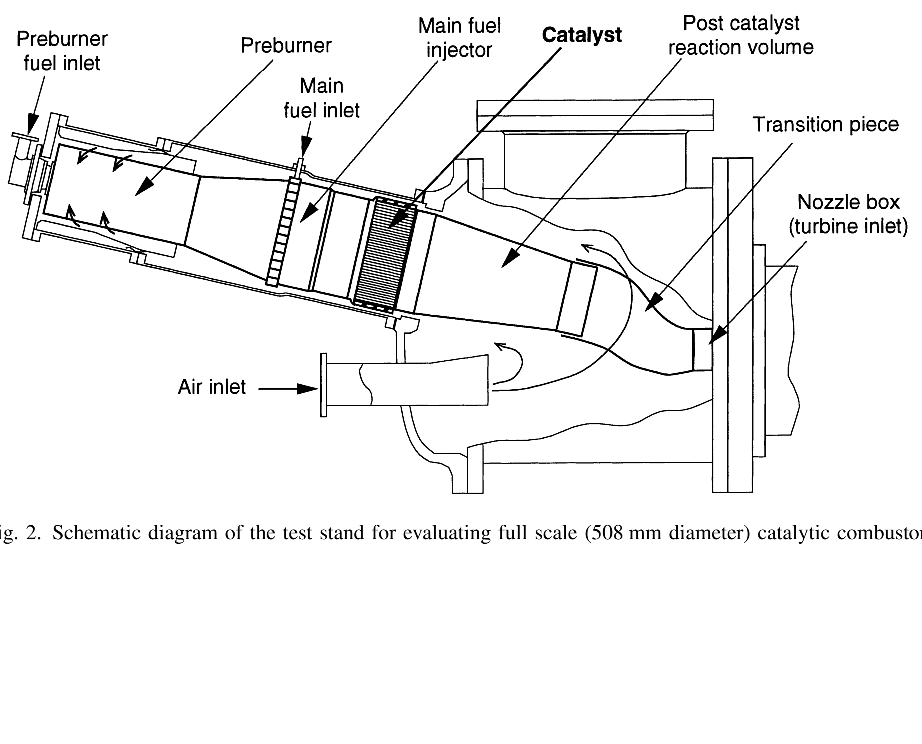

Fig. 2. Schematic diagram of the test stand for evaluating full scale (508 mm diameter) catalytic combustor.

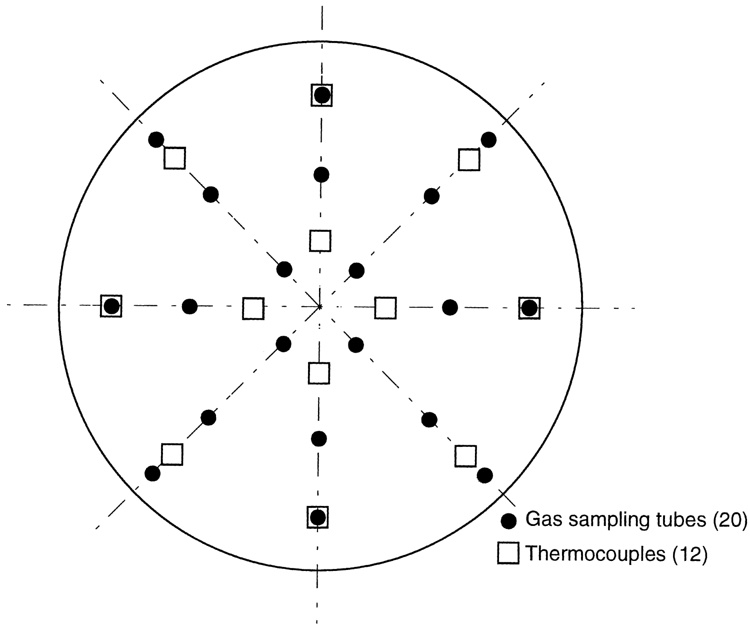

Fig. 3. Location of instrumentation on inlet face of full scale catalyst to monitor conditions during full scale test.

The sequence of full scale test points was designed to simulate the conditions in the combustor as the turbine is started and brought to base load operation. The air flow, fuel flows to the preburner and main fuel injector, inlet temperatures, and system total pressure were all adjusted to represent the individual cycle points. The primary goal of the most recent full scale test program was to attain stable operation and low emissions at the base load condition and, if feasible, at part load conditions as well.

3. Results

3.1. Subscale

As described above, one of the purposes of the subscale catalyst evaluations is to define an operating window for the system. Three basic constraints establish the boundaries of the window:

1. The inlet gas temperature must be high enough to sustain the required catalyst activity.
2. The gas temperature exiting the catalyst must be high enough to initiate homogeneous combustion and CO burnout within the available residence time.
3. The temperatures within the catalyst structure must be low enough to provide long term stability of the catalyst.

The results of several subscale tests of a particular catalyst configuration are shown in the context of the operating constraints in Fig. 4. The primary controlling parameters for the catalyst are the adiabatic combustion temperature (directly related to the fuel/air ratio) and the gas temperature at the catalyst inlet. These are the parameters plotted in the operating diagram in Fig. 4, and the diagram reveals the following:

1. When the inlet temperature was below about 400°C (675 K), the catalyst was not active enough to sustain catalytic combustion. This observation defines the ‘‘Minimum inlet’’ constraint.
2. When the adiabatic combustion temperature was below 1110–1150°C (1385–1425 K), depending upon the inlet gas temperature, the gas temperature at the catalyst exit was not high enough to promote the downstream combustion and CO burnout. This defines the ‘‘Minimum exit gas’’ constraint.

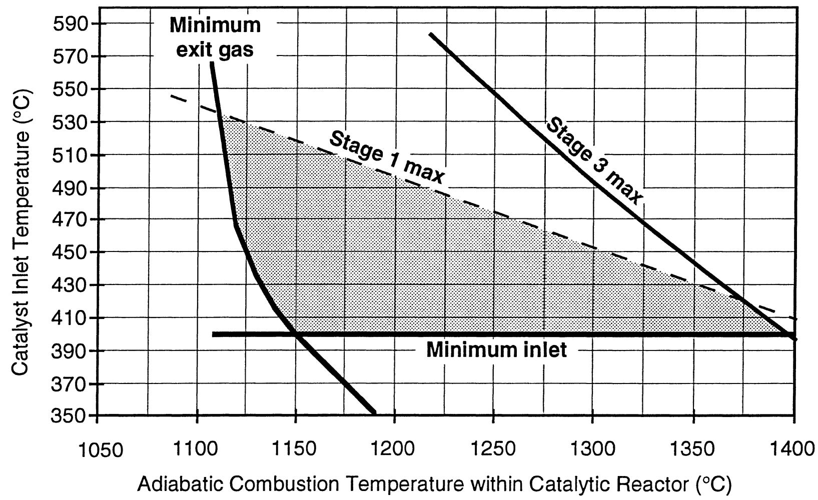

Fig. 4. Operating window (shaded) as measured using subscale catalyst system.

3. When either the inlet temperature and/or the adiabatic combustion temperature was too high, i.e., the upper right-hand region of Fig. 4, the catalyst itself reached temperatures above the design targets. The specific catalyst configuration used here was composed of three separate stages in series, each with its own maximum temperature constraint. These are identified in Fig. 4 as "Stage 1 max" and "Stage 3 max". Stage 2 was not a limiting constraint under any of the test conditions; so its constraint line is not shown in the figure.

The shaded region of Fig. 4 indicates the conditions under which all temperature and emission constraints were met for the prototype reactor. This catalyst system was designed to operate in the MS9001E combustor, where the adiabatic combustion temperature in the catalyst at base load is 1250–1300°C (1525–1575 K). On this basis, inlet temperatures of 400–450°C (675–725 K) were expected to be appropriate for full scale operation.

3.2. Full scale

The three-stage catalyst formulation developed in the subscale test program just described was duplicated in a 508 mm diameter unit, instrumented, and installed in the GE test stand. It was tested over a period of two days under a variety of conditions simulating the operation of the combustor in a GE MS 9001E machine. The program targets for emission levels were 5 ppm NO_x, 10 ppm CO, and 10 ppm UHC. The system was able to meet these goals not only at the base load conditions but also at conditions simulating turndown to about 78% load. The conditions and emissions measured at each of these load points are summarized in Table 1. With reference to Table 1, the combustor exit temperatures are ~100°C lower than the adiabatic combustion temperatures in the catalyst because the combustion products are diluted and cooled upstream of the combustor exit by air that does not pass through the catalyst.

Experiments were done in the full scale combustor to define an operating window for the catalytic reactor. In prior full scale tests [4,5] such experiments were not possible because of the limited range of operability of the combustor in those instances. In the current work, however, the preburner exit temperature could be

Table 1
System performance at base load and part load

	Base load	Part load
Simulated load (%)	100	78
Test point ID (test 5)	16	12A
Total air flow (lb/s)	48.2	43.1
Pressure (psig)	167	147
Catalyst inlet T (°C)	441	466
Combustor exit T (°C)	1192	1172
NO_x (ppm)	3.3	5.3
CO (ppm)	2.0	8.5
UHC (ppm)	0.0	1.2

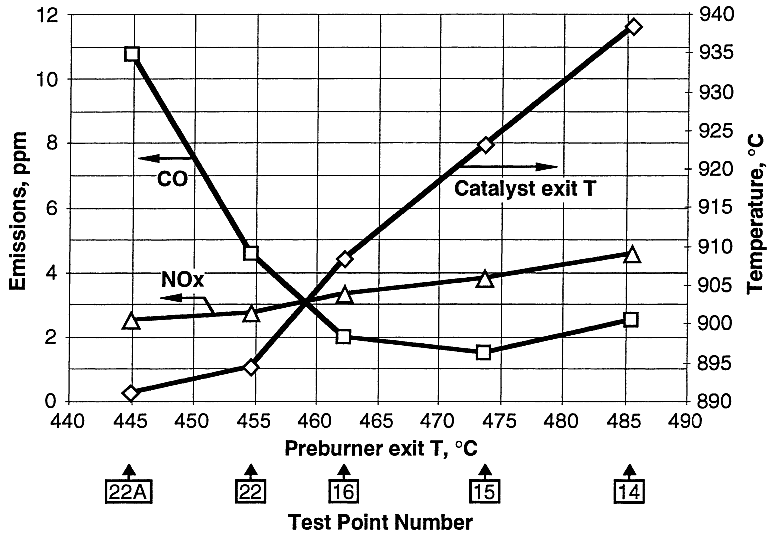

Fig. 5. Effect of preburner exit temperature on full scale catalyst performance at base load fuel/air ratio. (The test point numbers are for identification only; they do not reflect the sequence of the test.)

turned down by nearly 40 K (40°C) at the base load fuel air/ratio while maintaining emissions within the target levels. As the preburner is turned down, the catalyst exit temperature drops. This slows the homogeneous reactions downstream from the catalyst, and ultimately CO burnout cannot be achieved to 10 ppm within the residence time available in the combustor. Fig. 5 shows how the gas temperature at the catalyst exit and the CO emissions responded to the changing preburner exit temperature. According to the figure, CO concentrations were below 10 ppm as long as the catalyst exit temperature was above 892°C (1165 K). Since NO_x is produced almost exclusively by the diffusion flame in the preburner, turning down the preburner causes a decrease in the NO_x emissions. This effect is also shown in Fig. 5.

4. Discussion

The emission results and the range of conditions over which the combustor could be operated were significant improvements over the experiences during prior full scale tests of catalytic combustion. The large number of suitable operating points in the recent full scale test provides the opportunity for comparing the prototype operating window with the performance of the same catalyst system at full scale. The comparison is charted in Fig. 6.

In Fig. 6, full scale test points are overlaid on the boundaries of the window diagram created from subscale tests (same as Fig. 4). Several aspects of Fig. 6 are noteworthy:

1. The region where the prototype system operated successfully was also the region with good emission results for the full scale combustor.
2. For full scale operating points above the dashed "Stage 1 max" line, the measured temperatures in the Stage 1 catalyst were indeed higher than the design value. (This constraint was established as a long-term durability target, not as a temperature that poses an immediate threat to the Stage 1 catalyst.)
3. For the shaded data points, the emissions performance was marginal relative to the target levels, whereas the prototype results suggested that the conditions for those data points would be well within the window for low emissions. Probably the primary reason for any mismatch between subscale and full scale results is the fact that the inlet conditions for the subscale catalyst are quite uniform across the face of the catalyst, while there is a broader distribution of conditions in the full scale reactor. The dashed rectangle in Fig. 6 indicates the range of local inlet temperatures and fuel/air ratios (converted to adiabatic combustion tem-

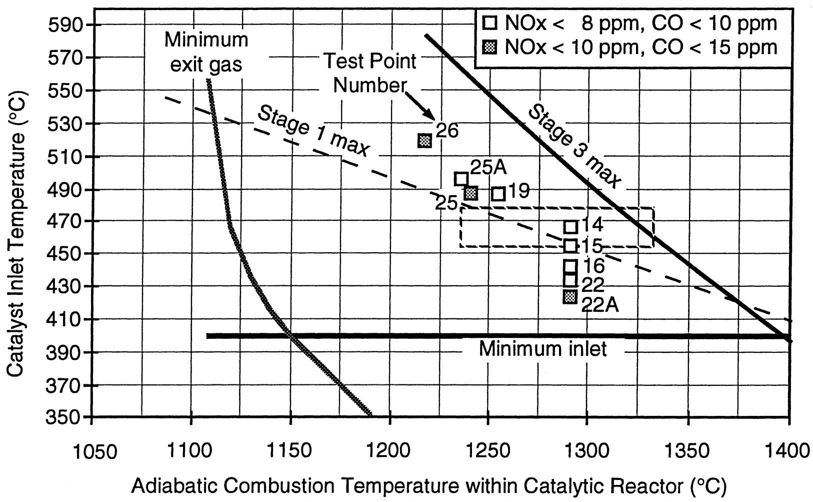

Fig. 6. Data points from the full scale test compared with the operating window measured for the subscale catalyst. Dashed rectangle indicates the range of temperatures and fuel/air ratios measured across the catalyst inlet face using the instrumentation shown in Fig. 3 during steady operation at test point 14.

peratures) measured for test point 14 using the instrumentation on the inlet face of the full scale catalyst as shown in Fig. 3. The measured local fuel/air ratios varied over a 12% range (~90 K difference in adiabatic combustion temperature), while inlet temperatures varied by as much as 25 K. Thus each of the full scale data "points" in Fig. 6 was in reality the integrated result for a range of conditions positioned around the indicated point. If any portion of the dashed rectangle falls outside of the window boundaries, it is likely that the occurrence will be noticed either in the emission levels or in localized hot spots within the catalyst.

4. Other differences between the subscale and full scale situations may affect the locations of the window boundaries. For example, the homogeneous combustion section in the prototype reactor is insulated, whereas in the GE test stand it is cooled. This difference would be expected to shift the "Minimum exit gas" constraint to the right for the full scale system.

5. Conclusions

The performance of the full scale catalytic combustor was improved significantly over prior tests and met the low emission targets with an appreciable margin. Turndown ranges of 40 K in preburner exit temperature and 45 K in combustor outlet temperature were demonstrated for the base load operating point while maintaining emissions of NO_x, CO, and UHC all below 10 ppm. Demonstration of low emissions at reduced turbine load was also a new observation in this work.

The characteristics of the full scale reactor were quite similar to those of the prototype unit tested at Catalytica during the reactor development and manufacturing process. This similarity in behavior between the subscale and full scale catalysts lends credibility to efforts to develop large scale reactor designs on the basis of prototype results. Such design activities will become increasingly important as this technology moves closer to commercial turbine applications.

Acknowledgements

The long-standing financial support for this program by the Tokyo Electric Power Company has been vital to its progress.

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