Catalysis Today 155 (2010) 13–17

Contents lists available at ScienceDirect

Catalysis Today

journal homepage: www.elsevier.com/locate/cattod

Gas turbine engine test of RCL® catalytic pilot for ultra-low NO_x applications

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ARTICLE INFO

Article history:
Available online 3 July 2010

Keywords:
Catalytic
Combustion
Low NO_x
Catalytic pilot
Rich Catalytic/Lean-burn

ABSTRACT

Catalytic combustion offers improved combustion stability extending the lean flame temperature limit to allow ultra-low NO_x emissions. Instead of replacing the entire lean-premixed (LP) injector with a catalytic injector, advanced Rich Catalytic/Lean-burn (RCL®) technology is developed and integrated to replace only the pilot portion of the injector. The pre-reaction within the pilot provides enhanced reactivity reducing the need to use higher temperature flames to stabilize the combustor primary zone. This concept synergistically combines the best features of catalytic combustion and conventional aerodynamically stabilized combustion technology.

The present paper discusses the development and engine testing of a set of Taurus 70 injectors equipped with RCL® pilots for natural gas applications. Testing showed engine NO_x emissions of ~2.5 ppmv corrected to 15% O_2 were achieved at baseload conditions. Engine CO emissions were less than 2 ppm. Combustor acoustics were low (at or below 0.1 psi RMS) during testing. The RCL® catalytic pilot supported the engine startup and shutdown process without major modification of existing engine controls. These initial results are promising. Further development work is needed to establish long term catalyst durability, engine transient behavior, and advancing the pilot technology to production status.

1. Introduction

In an effort to lower CO and NO_x emissions, government regulations are requiring both industrial and utility gas turbine manufacturers to improve combustor designs [1–3]. Currently, both industrial and utility engine manufacturers prefer lean-premixed combustion technology with post-combustion controls such as Selective Catalytic Reduction (SCR) used to achieve low single digit ppm NO_x. Lean-premixed combustion technology has demonstrated the ability to achieve NO_x concentrations as low as 5–9 ppm corrected to 15% O_2 during operation on natural gas [1–5].

As flame temperatures are reduced to achieve these levels of emission performance, flame stability issues arise. In addition, combustion of uniform, premixed fuel/air mixtures can lead to combustion-induced pressure oscillations (acoustics), increasing maintenance requirements and costs. To mitigate combustion instability issues with lean-premixed flames, gas turbine manufacturers frequently use higher temperature pilot flames to impart stability to the main combustion process. One such technique is the use of either a diffusion flame pilot or a partially premixed pilot [4,6,7]. Traditionally the pilot is a fuel injector independent of the main fuel injector operating as a diffusion flame or partially premixed. The remainder of the fuel is combusted in a lean-premixed flame with the pilot maintaining the stability of this main flame. The pilot also provides combustion stability during engine startup, load ramping, transients, and fuel transfer operation.

Depending on the design of the combustor, 2–10% of the fuel can be used for the piloting at baseload. If more fuel is used for piloting, more NO_x is produced due to the higher temperatures associated with pilot flames. With conventional pilots, Dry Low NO_x (DLN) combustors can operate close to the overall lean limit and achieve 9–25 ppm NO_x, however, the reliance on a high NO_x pilot can be a barrier to further NO_x reductions.

2. Catalytic combustion/catalytic pilot

Briefly, catalytic combustion has long been known [8–13] to provide stability benefits to very lean fuel/air mixtures. This has been identified and demonstrated for the production of ultra-low NO_x emission combustors. Refs. [14–16] discuss development status and challenges for the application of full catalytic combustion to large utility engines and smaller industrial engines. As an alternative to replace the entire combustor, only the pilot (typically the highest producer of NO_x in a combustor system) can be replaced. The enhanced stability provided by the catalytic pre-reaction allows stabilization of the main flame at a reduced pilot flame temperature, thus reducing NO_x production. This allows catalytic stabilization to be applied to both new engines and through

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doi:10.1016/j.cattod.2010.05.029

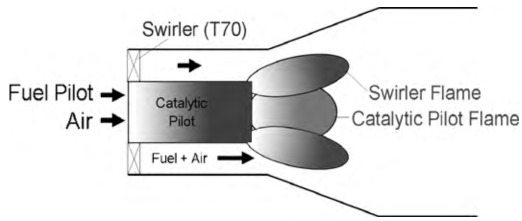

Fig. 1. Sketch of the catalytic pilot concept within a lean-premixed injector (swirler + pilot).

retrofit of the existing fleet with reduced hardware modification and cost.

This paper discusses the application and results of integration of a full combustor set of catalytic pilot with a lean-premixed fuel injector in a production DLN gas turbine engine.

3. Catalytic reactor design

There are several approaches currently practiced in the design of a catalytic reactor for gas turbines and examples of these approaches can be found in the literature [12,17–19].

Fig. 1 shows a sketch of the present catalytic pilot concept and how it integrates within a main injector for a lean-premixed combustion system. Typically the full injector consists of an annular swirler with a central pilot. A portion of the fuel/air mixture passes through the catalytic pilot and pre-reacts within the catalytic reactor before a pilot flame is stabilized downstream of the reactor.

Fig. 2 shows a schematic of the catalytic pilot concept independent of the main swirler. In this figure, all of the pilot fuel and a fraction of the pilot air are mixed inside a premixer before contacting a catalyst under fuel-rich conditions. The catalytic reactor consists of precious metal catalyst applied to washcoated high temperature metal substrates. The balance of the pilot air provides catalyst cooling. The cooling air and catalyzed fuel/air mixture are subsequently rapidly mixed after the catalyst section in the post-catalyst section to produce a fuel-lean, reactive mixture. Ignition and combustion of the now-lean reactive mixture are then achieved in the downstream combustion section to produce the pilot flame. This is called “Rich Catalytic/Lean-burn”, or RCL® combustion. This approach avoids both soot formation as discussed in the literature [20,21] and the high temperatures, which in non-catalytic RQL (Rich-burn/Quench/Lean-burn) designs lead to high NO_x formation [22].

In the RCL® system, fuel-rich reaction occurs at moderate temperatures on the catalyst surface. The catalyst also allows fuel-rich reaction outside the gas-phase flammability limits in the temperature range of 970–1170 K (700–900 °C/1533–1652 °F). This allows the partially reacted mixture to be cooler than the product of the rich section of a RQL system (which operates at the rich flammability limit). As a result there is a long auto-ignition delay time which allows mixing to fully complete without auto-ignition. In Fig. 3 (reproduced from Karim et al. [24]) the auto-ignition delay time is shown as calculated using the correlation of Spadaccini and Colket

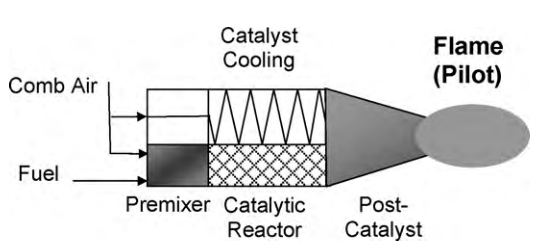

Fig. 2. Sketch of a catalytic reactor for pilot.

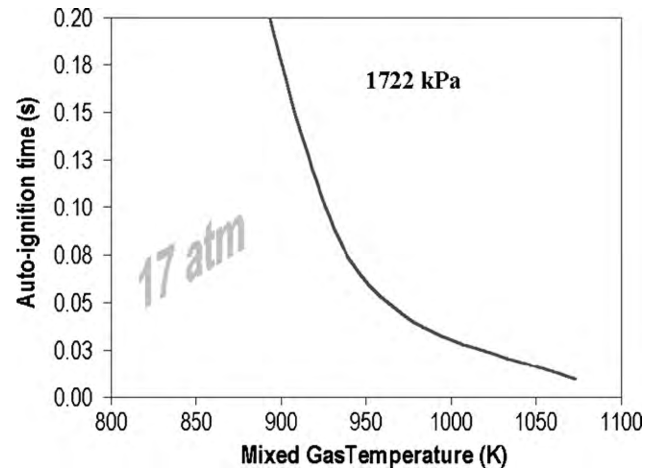

Fig. 3. Prediction of auto-ignition delay at 1722 kPa (17 atm) using the correlation of Spadaccini.

[23] for a representative gas mixture (94.9% CH_4, 3.1% C_2H_6, 0.65% C_3H_8, 0.3% C_4H_{10}, 0.1% C_5H_{12}, 0.1% C_6H_{14}, 0.05% C_7 and higher-order hydrocarbons, and 0.8% non-reactive components) mixed with air at an equivalence ratio of 0.5 as a function of mixed gas temperature. This mixture is not an exact representation of the gas composition in the post-mix section (it neglects fuel composition changes and vitiation from catalytic reaction), it will, however, give a qualitative estimate of auto-ignition delay for engineering purposes. It can be observed that at a post-mix temperature of 920–1020 K (650–750 °C/1200–1380 °F), the auto-ignition delay time is approximately 30–90 ms, which is sufficiently long to permit mixing [23].

The catalytically stabilized pilot flame anchors the main swirler flame (comprising the rest of the combustor fuel and air flows), allowing reduction of overall combustor equivalence ratio to produce very low NO_x emissions. Depending on engine combustor design and load conditions of the engine, the equivalence ratios of the main swirler flame and the pilot can be different and independently controlled.

Further details of the catalytic pilot/main lean-premixed swirler combustor are given in Karim et al. [24].

4. Experimental setup

Karim et al. [24] discusses the early results of RCL® catalytic pilot testing for application to a Taurus 70 (T70) engine. Initially the catalytic pilots were tested at atmospheric and high pressure, single- and multiple-injector test rigs. These results showed low emissions, good flame stability, and low acoustics during single injector testing. Based on the excellent single injector performance data, it was decided to test a full set of injectors in a production T70 engine. This paper presents the results of T70 production engine testing.

The Taurus 70 is an industrial engine with a design rating of 7.2 MW [25]. The engine has 12 injectors (swirler and pilot) arranged circumferentially around an annular combustor liner. A set of 14 catalytic pilots cartridges (Fig. 4(a)) were manufactured by PCI (12 for testing with two spares). Each injector was instrumented with two Type K thermocouples to measure catalytic bed temperatures. The pilots were then integrated with the T70 swirlers (Fig. 4(b)) and single injector (swirler + catalytic pilot) testing, of four randomly chosen injectors were performed. The results from these randomly tested single injectors were similar to the initial results obtained and reported by Karim et al. [24]. After completion of single injector tests on the prototype injectors, a multi-injector atmospheric pressure test was followed by an engine loop rig test.

Fig. 4. Catalytic pilot hardware. (a) Set of 12 instrumented catalytic pilot cartridge assemblies. (b) Catalytic pilots integrated with T70 swirler assemblies.

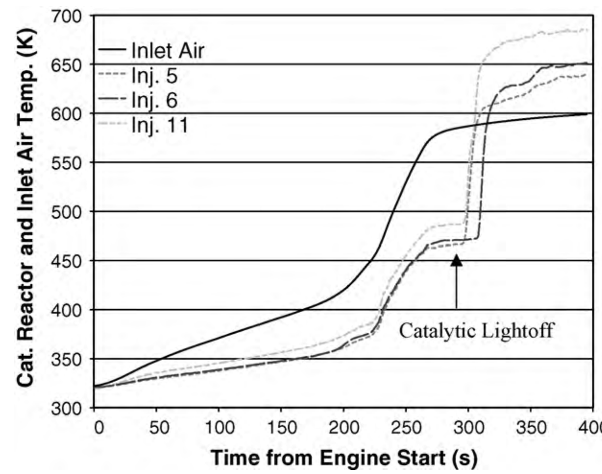

Fig. 5. Combustor inlet air and catalytic reactor temperature indicating lightoff at 600 K (325 °C) inlet air temperature.

These tests demonstrated that the combination of the catalytic pilot with the DLN swirler did not negatively impact the engine startup and shutdown capability. After approval, the 12 catalytically piloted injectors were installed in a production T70 engine and performance was tested.

Production engine testing consisted of four phases: (1) startup performance with a particular focus on inlet air temperature at catalytic lightoff, (2) at full load conditions, sweeping fuel split to pilot for determination of minimum NO_x, (3) evaluating NO_x and CO emissions performance at full load to 50% part load conditions, and (4) main combustor adiabatic flame temperature turndown at 50% part load as an indicator of overall stability. Due to engine availability and cost considerations, testing was limited to these four phases.

5. Discussion of results

5.1. Startup performance

Startup of the engine occurred without significant variation in startup procedure than a standard piloted engine. The lightoff characteristics of the catalytic reactor at engine startup are shown in Fig. 5. The data plotted is the transient data for engine performance test startup with the combustor inlet air temperature and the catalytic surface temperature of three of the 12 injectors plotted as a function of time. During prior testing, a number of the thermocouples monitoring reactor temperatures were damaged and thus were replaced. Due to the reactor geometry, the replacement thermocouples could not be attached directly to the catalytic elements, but were threaded into the fuel-rich reactor. This would allow determination of presence of catalytic activity (i.e. lightoff), however, exact reactor temperatures were difficult to measure. Injector to injector variation of temperature measurements was high because of the uncertainty of the location of the sensor tip. Prior to lightoff, the reactor temperature was reduced compared to the combustor inlet air temperature due to thermal lag of the combustor and reduction in gas temperature due to mixing of the incoming air with lower temperature fuel. It can be observed from Fig. 5 that lightoff of the reactor occurred when the inlet air temperature reached a temperature of approximately 600 K (325 °C/617 °F). Lightoff is indicated by the sudden increase of the catalytic reactor temperatures independent of the combustor inlet temperature. The measured RCL® reactor lightoff temperature is substantially lower than the 730 K (450 °C/842 °F) lightoff temperature reported in the literature for catalytic combustion of natural gas using fuel-lean catalysis [26]. The catalytic reactor heated up to a steady-state condition (constant temperature difference between catalyst surface temperature and inlet air temperature) in less than 2 s indicating rapid lightoff. This behavior is similar to what was observed during single injector testing in Karim et al. [24]. In addition, the 12 injectors lit-off nearly simultaneously, showing tolerance to injector to injector variation in fuel/air ratio variation. The injector to injector variation in catalytic reactor temperature after lightoff was likely due to imprecision in the insertion location of the thermocouples in the catalytic reactor or due to fuel/air ratio variation in the catalytic pilot.

5.2. Full load pilot fuel split variation

To optimize for reduced NO_x production by the catalytic pilot, the percent of the overall fuel flow rate to the pilot was varied (while keeping the overall injector fuel flow rate constant) while monitoring overall injector (main and pilot) NO_x emissions and catalytic surface temperature. Air flow to the pilot is geometrically controlled, thus is constant over the range of testing here. Fig. 6 shows the results of this testing. With reduction in fuel flow to the pilot, catalytic bed temperatures increased (due to catalytic region operating leaner) and NO_x production reduced to very low single digit levels through reduction in pilot flame temperatures. The maximum catalyst surface temperature was well below 1120 K (850 °C/1550 °F), a temperature much lower than the reported maximum surface temperature for fuel-lean catalytic combustion [9]. The reduced temperature plus operation of the catalyst fuel-rich decreases the occurrence of potential life limiting factors such as catalyst volatilization, catalyst sintering, and substrate oxidation. In addition, the variation of catalytic surface temperature was small

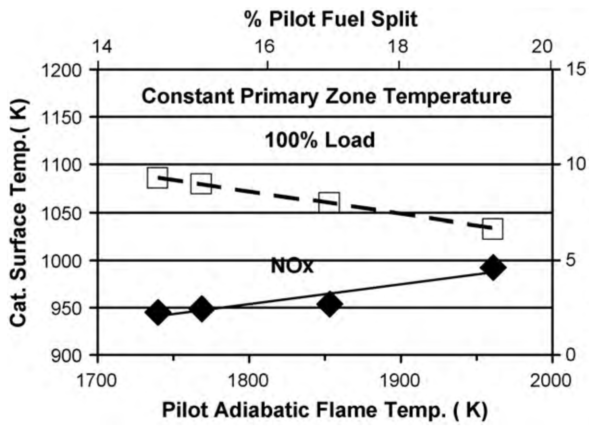

Fig. 6. Catalytic reactor temperature and NO_x emissions with constant primary zone temperature with variation in percentage of fuel to pilot.

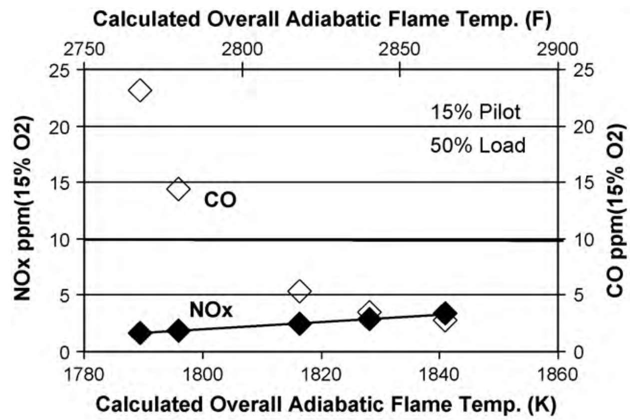

Fig. 8. NO_x and CO emission with variation of calculated overall adiabatic flame temperature showing large potential low emissions turndown (overall = pilot + main).

across a wide variation in the pilot adiabatic flame temperature. This indicates catalyst reactor robustness in that large changes in operating conditions (i.e. load shedding or acceleration) will have reduced impact on catalytic bed lifetime. A fuel-to-pilot split of approximately 15% was chosen to be the optimum based on the low NO_x emissions at reasonable bed temperatures and subsequent results will be based on this. This fuel split is higher than used for standard pilots, however, the catalytic pilot has a higher air flow rate, leading to leaner operating conditions and thus lower peak temperatures. Lower NO_x emissions could possibly be achieved by reducing the fuel split further, however, catalytic temperatures would need to be closely monitored.

5.3. Emissions performance with load turndown from 100% to 50% full load

Fig. 7 shows the emissions performance of the T70 engine with catalytically piloted injectors with a fuel-to-pilot percentage of 15%. The filled symbols indicate NO_x emissions while open symbols indicate CO emissions. A solid line indicates the trend of NO_x emissions. For the T70 engine, the combustor primary zone temperature is held constant with changes in load. The engine achieved low single digit (2.5–3.5 ppm corrected to 15% O_2) over a range of engine loads from 100% to 50% with no requirements for fuel staging. A slight increase in NO_x and CO was seen with decreased loading of the engine. As the engine load decreases, the inlet pressure and temperature to the combustor decrease, both of which potentially can have an effect on emissions, however, it was seen that, for the catalytically piloted combustor tested in this study, the change was small.

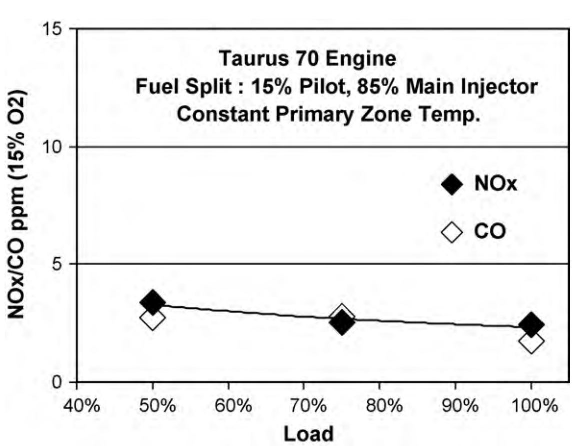

Fig. 7. NO_x and CO emission with variation of engine loading showing low single digit emissions from 50% part load to full base load.

5.4. Overall combustor adiabatic flame temperature turndown at part load (50%) conditions

In addition to the testing at baseload conditions, emission data were also obtained at 50% part load conditions (Fig. 8) to examine overall adiabatic flame temperature turndown for low single digit operation. This is a test to determine combustor stability. The catalytic reactor of the pilot maintained activity with decrease of the system operating conditions to the inlet temperatures and pressures at 50% part load, further indicating the self-sustaining capability of the reactor. The enhanced stability provided by the catalytic pilot allowed operation of the combustor at low adiabatic flame temperatures, allowing ultra-low NO_x emissions even at part load without fuel staging. The combustor at 15% pilot split also had a reasonably broad range of flame temperatures with low CO (<10 ppm) emissions indicating good flame stability at 50% load. The increase in CO is due to lower flame stability allowing incomplete combustion products escaping the combustion zone. Further optimization/adjustment of the fuel percentage to pilot may broaden this turndown range.

5.5. Combustion noise

As part of testing, acoustic levels in the engine were monitored. The magnitude of the pressure fluctuations never exceeded 689 Pa or 0.1 psi (RMS) during testing including 100% and 50% load conditions. Low acoustic emissions help ensure longer operating lifetimes of the combustor hardware by reducing acoustic driven vibrational loads.

6. Future work

Current results show promise for application of the Rich Catalytic/Lean-burn catalytic pilot technology to gas turbine engines, based on the test results showing low single digit NO_x and CO emissions and low acoustics from 50% load to baseload in production engine testing. This offers encouragement as a potential low cost alternative approach to post-combustion controls such as SCR with its high cost and polluting ammonia slip. The next steps in development will be the characterization of engine performance under transient load variation (e.g. load shedding), characterization of ambient condition effect on engine performance (hot day/cold day), evaluation of long term durability, and consideration of product commercialization including design for production and manufacturing margins.

7. Conclusions

In an effort to produce low single digit emissions of NO_x and CO without the use of costly SCR, Rich Catalytic/Lean-burn technology has been developed and integrated to replace the pilot portion of a production engine lean-premixed injector. This system focused on replacing the highest temperature zone of the LP combustion system with a catalytic pilot to reduce overall NO_x emissions. The motivation for using a catalytic pilot is that the catalytic pre-reaction provides enhanced reactivity to the gas mixture exiting the pilot and thereby negates the need to use high temperature (high NO_x) flames to stabilize the combustion of the primary fuel/air mixtures exiting the swirler. This concept synergistically combines the best features of catalytic combustion and conventional aerodynamically stabilized combustion technology.

A T70 engine was chosen as a development platform for the proof-of-concept catalytic pilot concept. The production Dry Low NO_x (DLN) injector allowed adequate space to integrate the catalytic pilot without significant modifications. As part of a DOE funded project, a set of injectors equipped with RCL® pilots with catalyst modules for natural gas applications was designed, developed, and tested in single and multiple injector test rigs for pressures ranging from atmospheric to high pressures typical of gas turbine operation. These results showed promise for the concept, so testing in a production engine was performed with a full set of 12 catalytically pilot equipped injectors. With optimization of fuel split between catalytic pilot and main swirler, NO_x emissions at baseload conditions of ~2.5 ppmv corrected to 15% O_2 were achieved. CO emissions were less than 2 ppm corrected to 15% O_2. Combustor acoustics were low (at or below 689 Pa or 0.1 psi) during testing. Reactor catalyst temperature was within the design limit and no preburner was used. The initial emissions results are promising with this technology showing capability for providing an alternative to conventional DLN technology. Further development work is needed to establish engine integration and long term catalyst durability before advancing the pilot technology to production status.

Acknowledgments

Precision Combustion Inc. gratefully acknowledges the support of the U.S. Department of Energy SBIR program and Energy Efficiency & Renewable Energy program. DOE SBIR and DOE EREN/Office of Power Technologies funding supported development of the catalytic reactor technology. In particular we would like to recognize Tom George, Doug Gyorke, Merrill Smith, Debbie Haught, Steve Waslo and Pat Hoffman from the DOE OPT program for monitoring and supporting the development of the catalytic reactor and catalytic pilot technology and engine testing.

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