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Catalytic combustion system for a 10 MW class power generation gas turbine

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Abstract

In early 2000, GE Energy launched a program to develop a catalytic combustion system for one of its small power generation gas turbines, the GE10-1 engine. The target was to release to the market a new combustor able to guarantee NO_x emissions lower than 2.5 ppmvd (referred to 15 vol.% O_2). Today, a full-scale engine test campaign has been completed, during which measured NO_x emissions were as low as 1 ppmvd in the 90–100% load range.

The article is aimed to illustrate the developed technology and the results obtained. The combustion system's configuration is briefly described, focusing on the XONON® catalyst module installed. Reported data show combustion system's performances, mainly in terms of pollutant emissions and operability. Perspectives for future development of such combustion system are outlined.

Keywords: Catalytic combustion; Gas Turbines; PGM-based catalysts

1. Introduction

In the last two decades, gas turbine manufacturers have been developing combustion systems compliance with the more and more stringent exhaust emissions regulations, especially in terms of nitrogen oxides (NO_x), which are the pollutants of major concern, since they participate in acid rain and photochemical smog formation.

Lower NO_x emissions are attainable by simply reducing flame temperature, but limitations arise due to flame instability, pressure pulsations and poor combustion efficiency (emissions of CO and UHC). To date, dry low NO_x (DLN) combustion systems have been developed and consolidated for emission levels as low as 15 ppmvd, when burning natural gas in lean premixed mode: more tighten limits are achievable through advanced DLN systems or NO_x removal from exhaust gases in selective catalytic reduction (SCR) units. Anyway, the extremely low limits imposed by an increasing number of agencies in the world (with areas in California where less than 2.5 ppmvd are required) seem to be practicable only by means of catalytic combustion, where fuel is converted into heat at a lower temperature than in ordinary lean premixed combustion, drastically reducing NO_x emissions, without incurring in stability issues.

So far, catalytic combustion systems have been developed with particular focus on methane and natural gas oxidation, since these fuels are the common choice for current low-emission gas turbine applications. Main requirements for a commercial acceptance of catalytic systems are low activation temperature and high specific activity, but the key challenge is making such characteristics as stable as possible over standard hot parts' maintenance intervals, minimum 8000 h, in gas turbine applications.

As in gas turbine combustors the average fuel–air ratio is well below stoichiometric value, research efforts have been focused first on fuel-lean operating catalytic systems. Palladium based catalysts are those best fitting the requirements for integration within a gas turbine combustion system: high activity, resulting in low activation temperature; self-stabilizing behavior associated with the PdO/Pd reversible transformation; resistance to volatilization of Pd species when operating at high temperature, high flow velocity conditions [1]. Pd-based fresh catalysts usually activate in a temperature range of 350–450 °C, depending on individual design requirements: unlikely, as

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many other types, these catalysts exhibit a loss in activity (aging) proceeding with accumulated operating time, which also results in a drift-up of the activation temperature. Over the 8000 h target operating life, such drift may be not negligible. Aging mechanisms comprise vaporization and sintering of catalytic particles, and their rates increase with temperature [2,3]: thus, in order to improve catalysts durability, operating temperatures must be limited, typically well below 1000 °C. Since sintering rate increases as catalyst temperature increases, even short-period operations beyond safe temperature levels dramatically accelerate thermal aging and reduce catalyst life.

In terms of combustion systems, gas turbine manufacturers have been developing various designs, the most part based on the so-called hybrid catalytic combustion concept [4]. Fuel and combustion air are premixed in an upstream section: then, only a fraction of the fuel is oxidized in the catalytic section, while the remainder is burned downstream the catalyst in homogeneous combustion mode. In many applications, in order to ensure catalyst activation at turbine start-up or part load operation (when compressor discharge temperature is well below 400 °C), inlet combustion air is heated by burning a portion of the fuel in non-catalytic combustion mode, generating undesired NO_x. Also, in many of the hybrid concept designs, all the fuel required by the turbine is mixed with air before entering the catalytic reactor, raising the risk of catalyst failure due to the onset of gas-phase reaction within the catalytic reactor itself: this is a potential limit of such technology for high firing temperature (>1400 °C) gas turbine applications [5].

In recent years, a novel approach based on fuel-rich catalytic combustion has received an increasing interest. In such technology, the fuel is mixed with a small portion of combustion air to form a fuel-rich mixture, which is fed to the catalytic reactor to produce a stream of both partial and total oxidation products, and unburned fuel. Such mixture is then mixed with remaining combustion air: fuel conversion is finally completed downstream the catalytic module in a homogeneous combustion mode [6].

Fuel-rich operating catalysts are claimed to have some advantages respect to fuel-lean operating ones [7]: higher activity (included Pd-based catalysts), leading to lower light-off and extinction temperatures; improved durability, due to the non-oxidizing environment in which the catalyst operates; limited operating temperature, consequent to the limited oxygen content in the fuel mixture contacting the catalyst (thus eliminating the risk of catalytic bed failure, even should gas-phase reaction occur within the catalytic reactor).

Among the several field tests carried out in the last years, aimed to demonstrate the feasibility of catalytic combustion in gas turbine applications, only few were focused on validating such technology in terms of commercially acceptable durability. So far, the most mature technology seems to be the XONON Cool Combustion System, developed by Catalytica Energy System, Inc.; a XONON combustor, installed on a Kawasaki Heavy Industries M1A-13X gas turbine (rated at 1.5 MW electrical power), showed durable performance over more than 8000 h [8]. The test evidenced the need to increase inlet gas temperature from 470 °C at start-of-life to 530 °C at end-of-life, in order to maintain emissions targets; anyway, since the XONON combustor is equipped with a lean premixed preburner, measured NO_x emissions were below 2.5 ppm throughout the guaranteed operating load range (70–100%).

Regarding fuel-rich catalytic technologies, the most promising systems seem to be those developed by Precision Combustion Inc., and trademarked as Rich-Catalytic Lean-Burn (RCL™). A catalytic RCL combustor was developed and tested on a modified version of a Solar Turbines' recuperated Saturn T1200 engine, rated at 750 kW power [9]. Tests, focused on demonstrating the operability of such technology, were limited in load in a range between 30 and 60% of nominal power, over which measured NO_x emissions were below 3 ppm. Some other published data describe tests on RCL systems, installed as pilot stabilizers in lean-premixed burners [10]. Anyway, in order to confirm fuel-rich catalytic reactors' expected potentialities, more extensive tests are necessary, with particular focus on system's durability.

In the present work, full-scale engine test of a catalytic combustor designed for installation on a 10 MW class gas turbine is reported and discussed. The test engine was located at Nuovo Pignone manufacturing site, in Firenze, Italy. The combustion system's configuration is briefly described, with focus on the XONON catalyst module installed. The test was aimed to demonstrate full operability of the turbine, at both start-up and load operating conditions. Also, pollutant emissions were measured and demonstrated to be within the target. No catalyst durability issues have been evidenced during the accumulated 50 h operation. Long-run test over thousands hours was not practicable at such facility.

2. System configuration

The engine used for testing is a GE10-1, a single-shaft simple-cycle gas turbine for power generation applications, rated at 11 MW and equipped with a single can combustion system. The turbine drives a grid-connected generator, which delivers electrical power to the Italian national utility for electric energy (ENEL). Nominal pressure ratio and aspirated airflow are, respectively, about 16:1 and 47 kg/s at ISO conditions. The engine consists of an 11 stages high efficiency axial compressor (equipped with variable Inlet Guide Vanes, IGVs) and a 3 stages reaction-type turbine, directly coupled to the compressor. The combustor axis is perpendicular to the engine axis: hot gases exiting the combustor are turned and distributed to the first nozzle of the turbine through a special component, called transition piece (TP).

The catalytic combustion system is schematically shown in Fig. 1. The combustor is arranged in a reverse-flow configuration and comprises a bypass system, intended for combustion air modulation. The hot side of the combustor can be functionally divided in four sections: the preburner, the multiple-venturi-tube fuel mixer (MVT), the catalyst, and the burn-out-zone (BOZ).

In the preburner section, some fuel is burned in order to increase gas temperature up to catalyst activation level. The burner consists of an ordinary diffusive nozzle, located at the top of the combustor: the choice for diffusive combustion

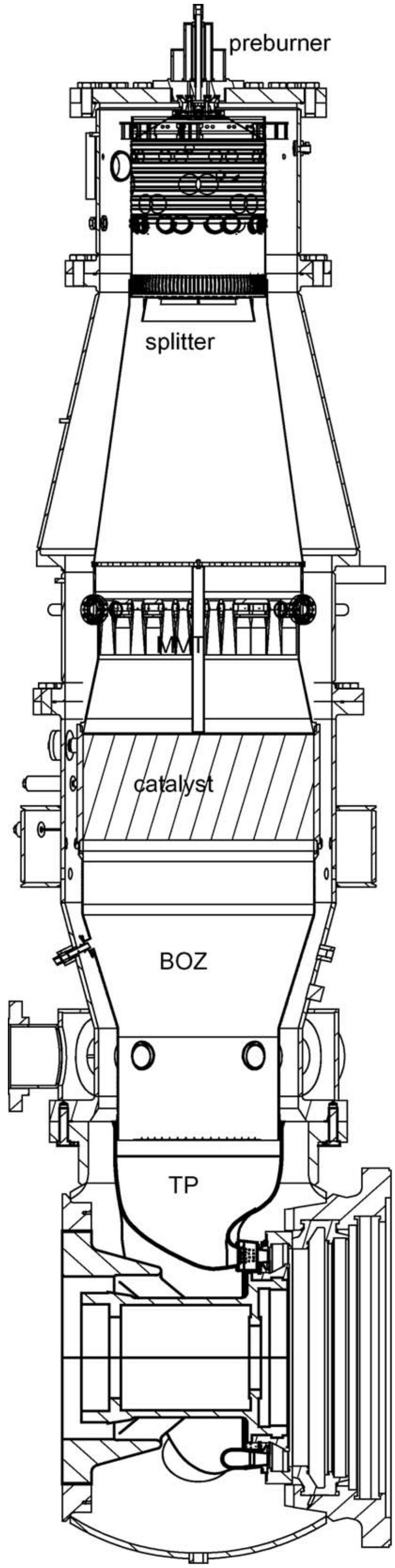

Fig. 1. GE10-1 catalytic combustion system's sectional view.

concept was driven by the need of minimizing risks of flame instability and pressure oscillations, usually accompanying lean-premixed combustion. The preburner section also comprises a liner, through whose holes the combustion air enters the hot side. The liner is closed at the exit by a splitter; this latter is in turns a flow conditioner, which imparts a swirling component to the heated gases and promotes their temperature uniformation. Downstream the splitter, there is a conical diffuser and finally a perforated plate, acting as flow distributor.

Heated gases are fed through the perforated plate into the MVT section. The main component is the MVT itself, which is a fuel mixer consisting of 129 venturi tubes distributed over the entire combustor section. The MVT inlet gases uniformity in terms of temperature and velocity (as provided by the perforated plate), combined with the injection of fuel at the throat of each venturi, ensures a relatively high uniformity of fuel concentration at the MVT exit section. Downstream the MVT, there is a short conical diffuser, directly faced onto the catalytic module front area.

The catalyst module assembly (XONON technology) consists of two serial stages assembled within a 28 in. diameter container with axial support structures at each stage inlet and outlet location. Each stage consists of high temperature metallic foils, coated with Platinum Group Metals (PGM) based catalytic material: the foils are shaped and assembled together to form a cylindrical monolith. More details about catalytic reactor are given later.

In the burn-out-zone, the conversion of the unburned fuel exiting the catalysts is completed in homogeneous combustion mode. The BOZ is confined by the exit section of the catalyst, the post-combustion liner (PCL) and the TP inlet section. The PCL is a conical converging component, backside cooled by the airflow from the compressor discharge. Heat is removed only by convection, the heat removal being enhanced by several rows of turbulators, located on the outer surface of the PCL.

For optimal catalyst module operation, the combustion airflow is regulated by means of the bypass system. Part of the air from the compressor discharge is extracted and diverted through a regulating valve to a distribution manifold, integrated within combustor casing; bypass flow is re-injected into the combustion chamber downstream the BOZ, i.e. in correspondence of the TP inlet section.

The described layout permits to keep gas temperatures below 1350 °C everywhere in the combustor, except at the preburner flame front, where stoichiometric flame temperatures are achieved due to the diffusive combustion mode. As a consequence, NO_x emissions decreases as the required temperature rise across the preburner decreases.

3. XONON catalytic module

The adopted catalyst consists of thin metallic foils, acting as substrate, over which a thin layer of catalytic powder is applied. The catalytic powder is usually called washcoat and in turn consists of a porous refractory ceramic oxide supporting the catalytically active components, mainly Pd and PdO. The size of the catalytically active crystallites is $<10^{-7}$ m: different active surface areas per unit volume of catalyst are achieved by varying crystallite loading in oxide support. Foils, coated with catalytic powder, are shaped in a herringbone pattern, packed together and finally rolled in a spiral-wrapped assembly, resulting in a multi-channel cylindrical monolith.

The installed catalytic module has been designed on the basis of combustion airflow, total fuel flow and compressor discharge temperature and pressure, specified for various turbine operating conditions. Catalyst's inlet and outlet gas temperature design targets have been determined as tradeoff between contrasting needs. For the inlet temperature, on the lower bound there must be enough margin respect to catalyst deactivation; on the upper bound, preburner temperature rise must be limited to keep NO_x emissions below the limits. Regarding exit temperature, the target is limited on the top by the risks of accelerated rate of thermal aging and non-catalytic combustion onset within the catalyst, on the bottom by the need for complete fuel oxidation in the BOZ, reducing UHC and CO emissions to a minimal amount.

An additional parameter involved in catalyst design is the adiabatic flame temperature (T_{ad}). This is a virtual parameter, representing the temperature of the flame when the inlet mixture is burned with 100% combustion efficiency (all fuel completely burned, no heat loss to the surroundings): in the essence, such parameter determines the amount of combustion air to be diverted through the bypass system, in order to keep fuel–air concentration in the combustion zone within an optimal range.

The adopted catalyst has been designed for a start-of-life inlet gas temperature target of 420 °C; the conversion is about 51% at baseload operation. At catalyst end-of-life (8000 h), baseload inlet temperature design target is raised to 440 °C, while catalyst's efficiency is expected to drop down to about 47%. Additional design parameters specify system's capability in terms of inlet gas uniformity: at baseload operation, local fuel–air ratio over catalyst inlet front area can vary within ±5% of bulk average, temperature within ±10 °C.

The catalytic reactor is arranged in two serial stages. The inlet stage consists of a high activity catalyst formulation, suitable for operation at low inlet gas temperature: the stage is designed to increase gas temperature up to outlet stage's full activation level, well below the level at which inlet stage aging becomes significantly fast. The outlet stage has been designed using the most advanced materials in fuel-lean catalytic combustion technology. Such materials have been developed in the effort of increasing both catalyst operability and durability, and are characterized by a lower thermal aging rate than that of previous formulations. A reduced aging rate implies more room between operating target and temperature limits: moreover, a lower loss of conversion efficiency over stage's life requires a lower reduction of combustion airflow, by means of the bypass, at end-of-life operation (thus limiting the increase of BOZ flame temperature, with the risk of relevant NO_x generation in the BOZ).

Before installing the catalyst on the engine, a comprehensive qualification process was carried out using samples of the catalytic foils from the production material used in the full-scale engine test module. Such qualification process consisted of:

(1) acceptance tests, to verify the target baseload operating conditions;

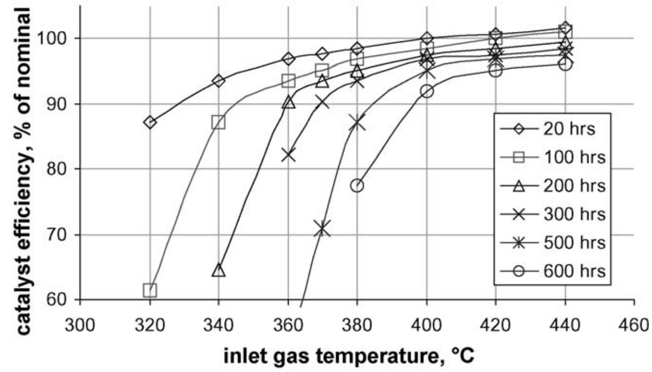

Fig. 2. Catalyst activation temperature drift with accumulated operating hours. Tests performed on the subscale 2 in. diameter HPR facility (courtesy of Catalytica Energy Systems, Inc.; adapted by Nuovo Pignone SpA).

(2) performance tests, to map conversion efficiency over different operating conditions;
(3) durability tests, aimed to show the rate of catalyst degradation over time of operation at baseload conditions.

The entire qualification process was performed by Catalytica Energy Systems, Inc., using a subscale (2 in. diameter) high pressure reactor (HPR).

Steps (2) and (3) of qualification process have shown stable operation well below the target inlet temperature, but also that there is a significant increase in activation temperature over few hundreds hours of operation: from about 340 °C for a fresh catalyst, to 380 °C after about 500 h running at baseload condition (Fig. 2). During this same period of time, no acute loss of catalyst conversion efficiency was observed (about 1% inlet stage conversion efficiency drop).

In addition, results from the qualification process have offered an important database of information to predict catalyst's behavior even under turbine's transient operating conditions. Two transient phenomena, affecting catalyst's efficiency, have been put in evidence: "burn-in" and "hysteresis". "Burn-in" consists of an initial over-reactivity of about 5% that disappears progressively over 20–30 h of operation at high temperature (Fig. 3); "hysteresis" is a short term reactivity variation

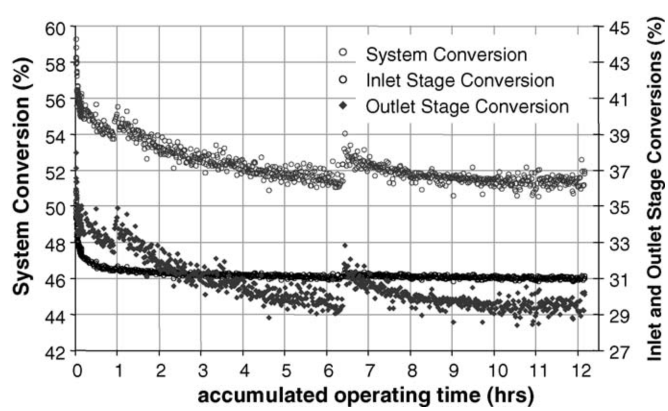

Fig. 3. "Burn-in" effect. Tests performed on the subscale HPR facility. Sample tested at baseload design targets (420 °C inlet). Load limited during the first hour to avoid catalyst overheating. Reactor stopped and restarted after 6.5 h. Courtesy of Catalytica Energy Systems, Inc.

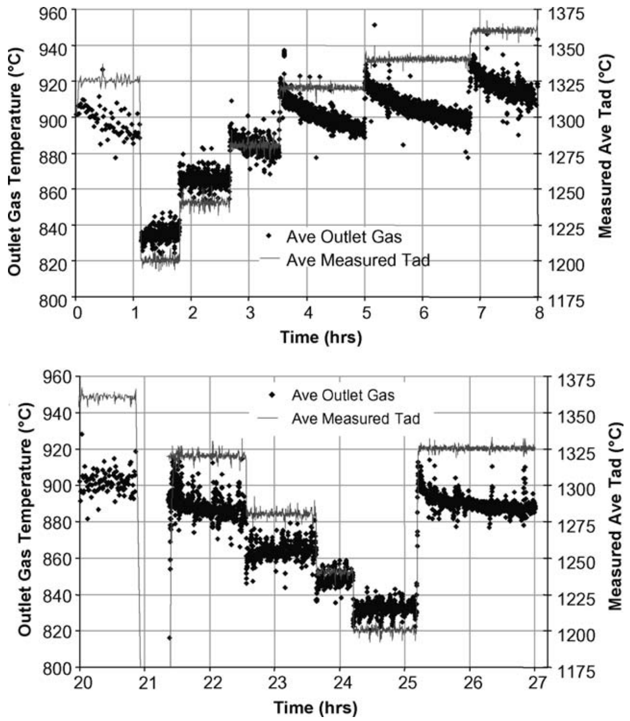

Fig. 4. "Hysteresis" effect. Tests performed on the subscale HPR facility. Sample tested at baseload design target (420 °C inlet). Courtesy of Catalytica Energy Systems, Inc.

appearing every time there is an operating condition change, and extinguishes over minutes. Both these transient phenomena are driven by time necessary to reach the Pd/PdO concentration equilibrium along the outlet stage's channels of the catalyst: PdO is more active than Pd in catalyzing fuel conversion, but as the temperature increases it reduces to Pd until the equilibrium concentration is reached (the transition becomes significant above 800–850 °C). Such mechanism automatically explains "hysteresis". Fig. 4 shows "hysteresis" as appearing from T_{ad} step-up and step-down tests: roughly, conversion efficiency is up to 2% greater than steady state value when temperature level is rising, and is recovered within a hour; on the other hand, conversion decrease by less than 2% when the operating temperature is going down, and the recovery is within few minutes. Different recovery times are explainable considering the slower rate of PdO → Pd transition respect to Pd → PdO one.

For a complete understanding of "burn-in", it's necessary to consider that a fresh catalyst is only partially stabilized, in terms of activity, at the end of the manufacturing process, i.e. the outlet stage is mostly PdO when installed on the combustor. Since the conversion-loss associated with "burn-in" is significant compared with target catalyst's efficiency, the initial transient is expected to be important for bringing the system to full operability. Once the burn-in process is complete (20–30 h) the system is expected to be routinely able to achieve all engine conditions.

4. Test campaign

Test campaign was performed on a full-scale prototypical engine, located at Nuovo Pignone manufacturing site in Firenze, Italy, and carried over during January 2005. The system has been run for an overall time duration of more than 50 h, at ambient temperatures ranging between 0 and 10 °C; more than 20 start-up ramps have been performed, in both cold start and hot restart conditions.

The entire system was operated by means of specific engine control software, and monitored through a large amount of special instrumentation, the most part of which located on the combustor. Such additional instrumentation consisted of measurement orifices (for fuel and air flows calculation according to ISO5167), static and dynamic pressure probes, metal and gas temperature thermocouples, and two independent emission analyzers (for NO_x, CO, UHC and O_2 concentration measurements). A huge amount of instrumentation was dedicated to detailed catalyst spatial monitoring: 16 thermocouples and 24 fuel–air concentration probes (the latter acquirable on-line, but only from one probe each time) at the inlet section, 20 thermocouples at the interstage section, 20 thermocouples at the exit section.

In order to prevent the catalyst from operating in jeopardizing conditions, protection logics have been implemented causing a turbine's trip as soon as local measured temperatures are above the specified limits.

The tests performed were focused on characterizing NO_x, CO and UHC emissions over the entire load range: at this purpose, 175 steady-state test points have been recorded at various power level. Also, catalyst performances have been investigated in terms of both steady-state behavior (ability to operate within safe temperature limits and to provide the desired fuel conversion over the entire load range) and system operability, i.e. interactions with the whole turbine, with particular attention to transient operating conditions such as start-up ramps, load ramps, breaker openings or closures.

5. Results

One of the main results achieved at the end of the test campaign has been the definition of a control logic for accelerating the system to FSNL in a robust, reliable and repeatable way. Only 5 trips occurred over 29 start attempts: 3 of them were non-combustion related trips, while the remaining two were caused by high catalyst temperatures, during the initial phase of control tuning.

Turbine's start-up sequence proved particularly challenging: respect to standard (diffusive) or DLN combustion systems, the catalytic one requires to prevent the catalyst from operating above its temperature limits. While this need constitutes an upper boundary for the fuel–air ratio, a minimum value of the fuel–air ratio is necessary to accelerate the turbine, given the limited power of the starting motor. These two boundaries define a fuel–air ratio operating window, for the acceleration ramp, that is narrower than those relative to other combustion systems (where the upper limits are relative to hot parts structural integrity and are normally much higher).

The bypass system has been used to modulate the airflow directed to the catalyst in order to keep the temperatures within the desired limits, and has permitted a satisfactory system

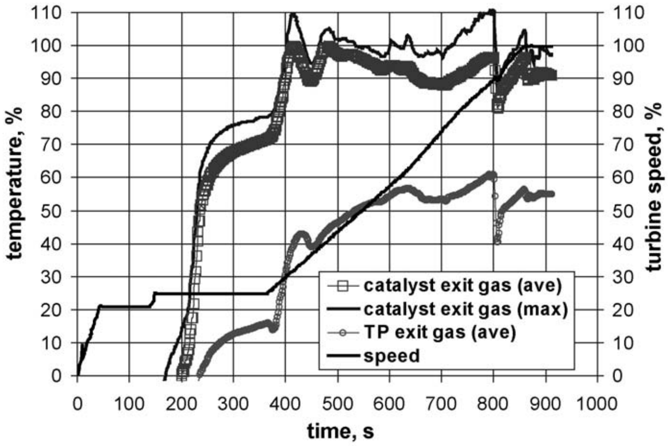

Fig. 5. Catalyst exit gas temperature and TP exit gas temperature at turbine's start-up.

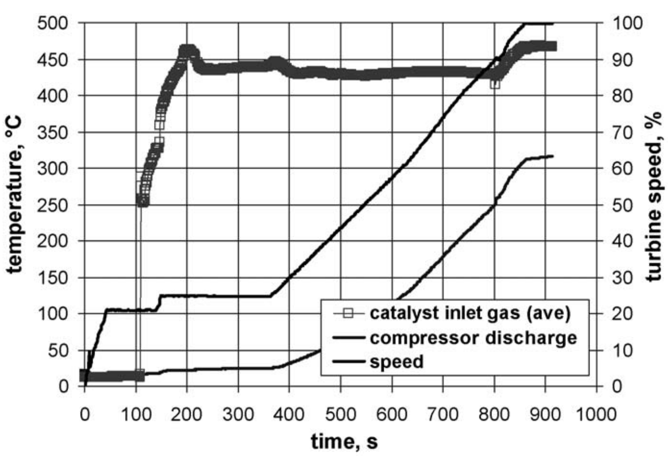

Fig. 6. Compressor discharge temperature and catalyst inlet gas temperature at turbine's start-up.

operation even in correspondence of some particular transient events, like starting motor cutoff and anti-surge valve closure (occurring during the start-up ramp), synchronization, breaker closure, small level load rejections (25% load rejection has been successfully tested). The start-up sequence basically requires 10–15 min: the acceleration ramp, beginning at full catalyst activation and ending at sync speed, requires about 8 min, while the remaining time is needed for engine purge sequences, preburner ignition and catalyst activation. Typical trends of some combustion parameters during turbine's start-up are shown in Figs. 5–7. All the temperatures downstream the catalyst are reported in a non-dimensional form, corresponding to the following formula:

$$T_{\text{adim}}(\%) = \frac{T_{\text{meas}}\,(^{\circ}\text{C}) - 420}{T_{\text{nom}}\,(^{\circ}\text{C}) - 420} \times 100$$

At load conditions, the system has proven to be fairly operable. The main limitation observed during tests was the need to stay below 95% electric load for the first hours of operation, due to the initial catalyst's over-reactivity ("burn-in" period). The outlet stage conversion efficiency has been observed to reduce by about 5% over the entire campaign duration, during which the catalyst has been run for about 10 h at 90% load or higher (Fig. 8). While the outlet stage performance did track closely to qualification process results, engine tests did not give any indication whether the "burn-in" is completed or not, since neither efficiency stabilization has been observed during tests, nor was the test campaign prosecuted for this purpose.

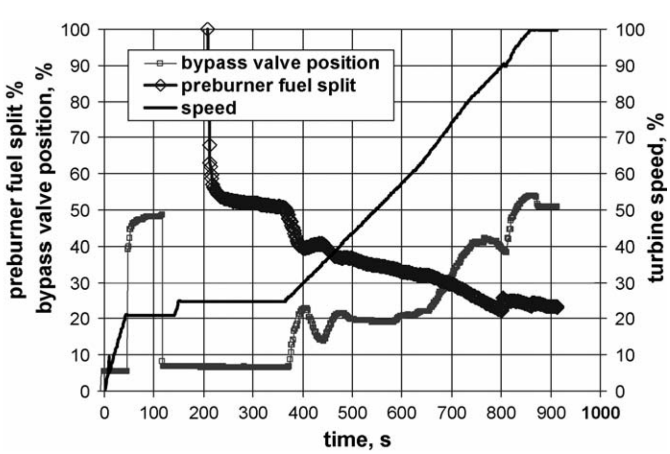

Fig. 7. Preburner fuel split and bypass valve position at turbine's start-up.

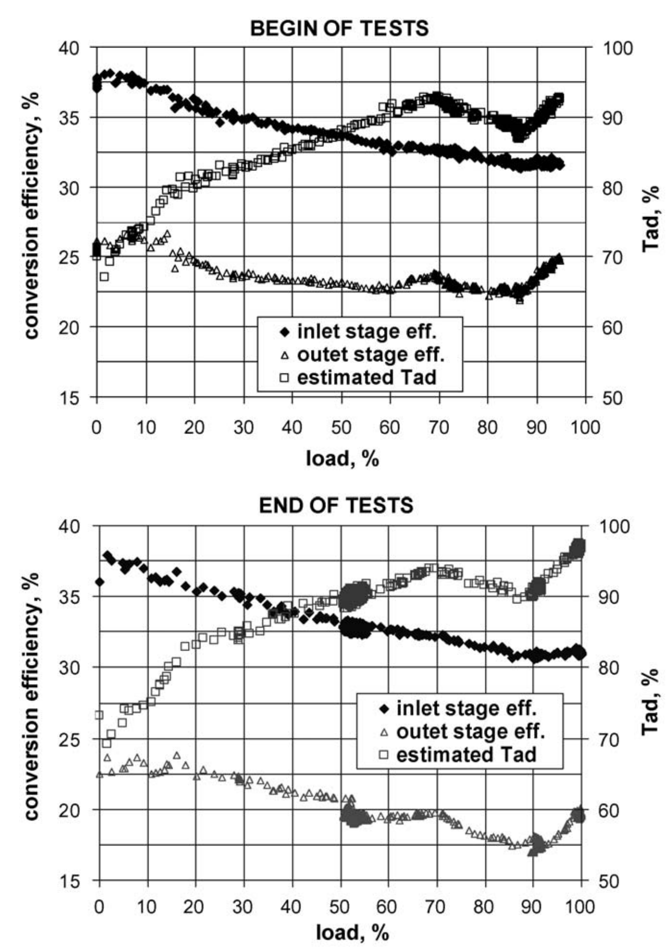

Fig. 8. "Burn-in" effect. Outlet stage's efficiency reduced by about 5% after few hours operation at high temperatures. Max load at begin of tests limited by catalyst outlet temperatures.

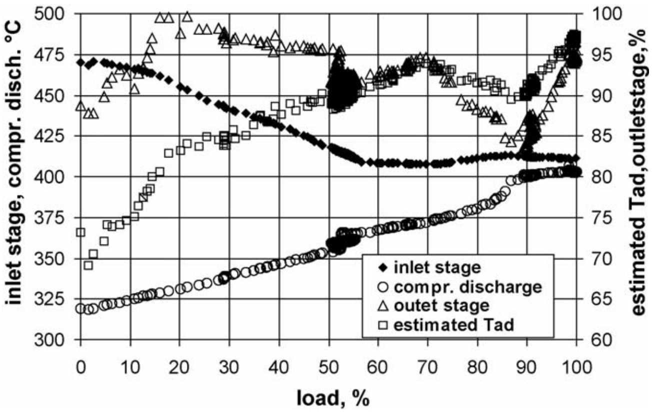

Fig. 9. Gas temperatures at load-up.

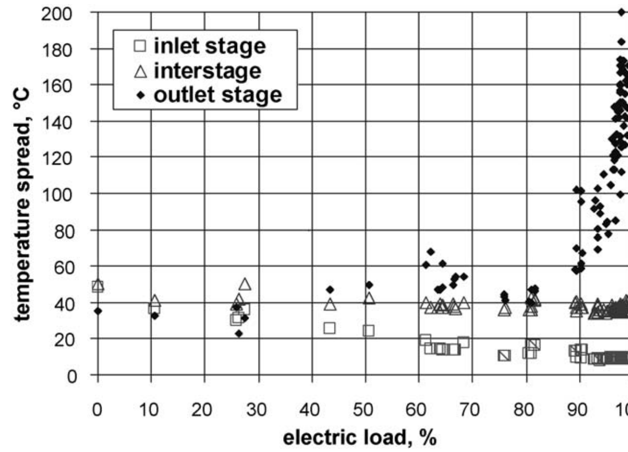

Fig. 11. Catalyst gas temperature spreads.

Anyway, before the end of the test campaign, baseload was obtained without approaching the trip limits (Fig. 9): this indicates that this issue may impact engine operation only during the initial catalyst ''burn-in'' period.

The ''hysteresis'' effect has been observed at the end of load ramps, as the one shown in Fig. 9; as expected, almost the totality of the temporary over-reactivity is driven by the outlet stage. Anyway, the ''hysteresis'' magnitude was so small that never limited system's operability during tests (Fig. 10).

No issues came out during tests about catalyst's durability (fast increase of activation temperature or unexpected loss of efficiency due to sintering). Anyway, some undesired high temperature spread (>150 °C minimum to maximum) was observed at the catalyst exit section in the range of high loads, as shown in Fig. 11. This spread can be only partially explained in terms of fuel–air ratio non-uniformity: results from several concentration mappings (performed by means of the 24 probes located at the catalyst inlet section) showed a fluctuation of about ±5% of the average, corresponding to about 60 °C spread minimum to maximum; moreover, a spatial correlation between exit temperature spread and inlet fuel concentration spread has been evidenced. The remaining spread can be explained in terms of both increased catalyst conversion rates associated with operating at higher local fuel–air ratios and direct BOZ flame heating on catalyst exit section's thermocouples. Such spread represented a limitation in system operability while it was occurring, since some temperature measurements were too close to trip limits; furthermore, it can affect catalyst durability, since promotes an accelerated aging in the hottest spots and may reduce outlet stage's efficiency below the prediction over catalyst life, potentially requiring more air diversion through the bypass system and inducing some NO_x generation in the BOZ.

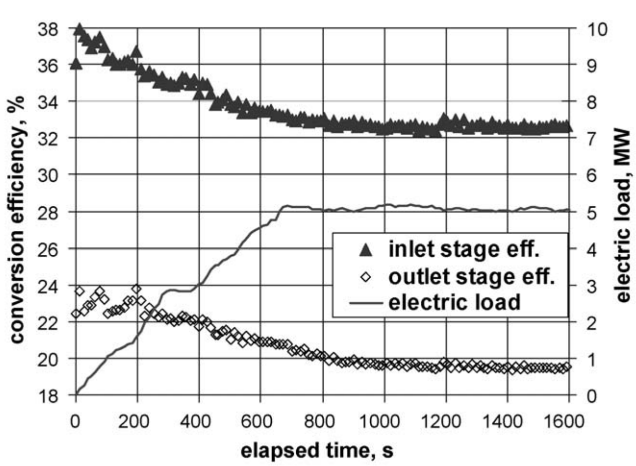

Fig. 10. ''Hysteresis'' effect during load operation. Catalyst conversion above steady-state values right after a load ramp (transient recovered in less than 5 min.).

In terms of emissions, even with the installed diffusion flame preburner, above 90% load range it was possible to measure NO_x concentration lower than 2 ppmvd (corrected to 15% O_2). Due to the low catalyst inlet temperature design target (420 °C), which is close to the compressor discharge temperature at baseload (or even lower, at hot days), the fuel delivered to the preburner becomes so low, while approaching baseload, to cause preburner flameout. In such condition, NO_x emissions lower than 0.5 ppmvd have been measured (Fig. 12), thus indicating the ultra-low emission capability of the catalytic system itself, BOZ included, at target T_{ad} level. However, emission performances at part load have been fairly poor, as expectable using a diffusive combustion preburner. NO_x emissions over the entire load range are shown in Fig. 13.

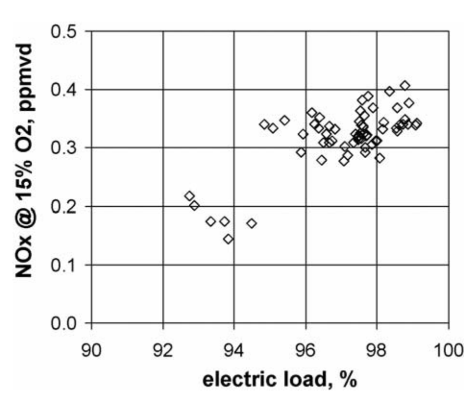

Fig. 12. NO_x emissions after preburner flameout.

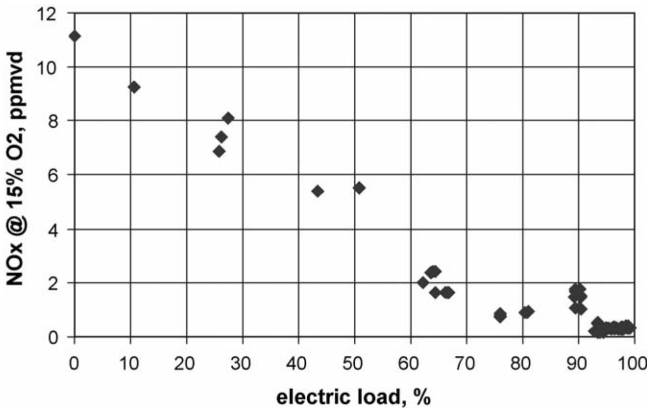

Fig. 13. NO_x emissions over the load range. Target NO_x variable with load: 7 ppm in the 50–75% load range, 5 ppm in the 75–90% range, and 2.5 ppm in the 90–100% range.

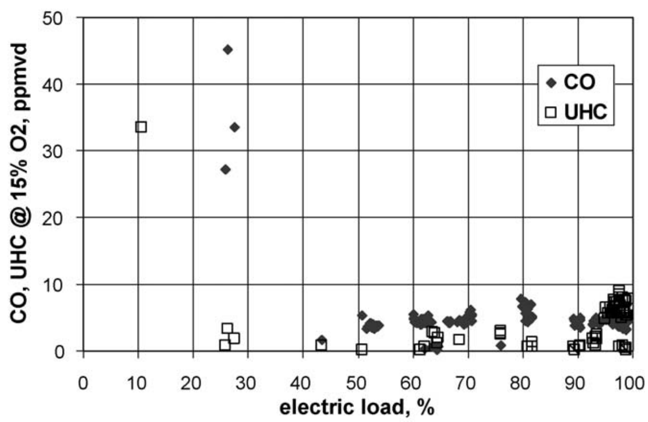

Fig. 14. CO and UHC emissions vs. load. Target at 9 ppm in the 50–100% load range for both CO and UHC.

CO and UHC emissions below 10 ppmvd (corrected to 15% O_2) have been measured in the 50–100% load range, as reported in Fig. 14.

6. Conclusions

On the whole, the test campaign demonstrated that the selected gas turbine equipped with a catalytic combustion system is operable in the frame of power generation applications. Anyway, the way to commercialization is not completed, since many issues still need to be solved.

While measured CO and UHC emissions were within the limits, indicating a satisfactory performance of catalyst and BOZ, the fairly poor NO_x emissions observed at part load operation, even if expected, clearly raise the need for a complete redesign of the preburner.

Although at a first sight this could appear as a catalyst-independent issue, it's necessary to recall that the achievement of NO_x emission target depends also on which is the end-of-life catalyst activation temperature. So far, the actual durability of the adopted catalyst (for which an end-of-life target of 440 °C was specified) has to be demonstrated. Preliminary expectations, based on data collected during qualification process at the sub-scale HPR facility, seem to indicate that the catalyst is not able to meet durability requirements, when designed for end-of-life 440 °C inlet temperature operation. Besides that, where successfully validated, the XONON catalyst was operated at inlet temperature which increased from 470 to 530 °C consistent with the catalyst design over the 8000 h target life service, i.e. at an inlet temperature much higher than in GE10-1 application.

In other words, a lean-premixed preburner is probably sufficient to guarantee NO_x emissions below 2.5 ppm over a wide load range, even should catalyst's activation temperature be well above 440 °C end-of-life, but in the meantime research efforts must be focused on enhancing catalyst durability for low inlet temperature operation. Potentially, a catalyst with an activation temperature well below compressor discharge temperature at any load operating condition would require an assisting burner only for turbine's start-up. As demonstrated by the tests, NO_x generated in the catalyst and BOZ is less than 0.5 ppm: thus, the key toward zero NO_x emissions is the durability of catalysts with low activation temperature.

Improvements are also desired in the area of catalytic combustion system's robustness respect to fuel concentration and temperature non-uniformities, with particular focus on MVT redesign for enhanced fuel concentration uniformity.

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