ELSEVIER

Catalysis Today 75 (2002) 287–295

CATALYSIS TODAY

www.elsevier.com/locate/cattod

Catalytic combustion for power generation

R. Carroni*, V. Schmidt, T. Griffin

Alstom Power Technology Ltd., CH-5405 Baden-Dättwil, Switzerland

Abstract

Catalytically stabilised combustion (CST) has the potential to become the best available low NO_x combustion technology with demonstrated NO_x emissions less than 3 ppm. Gas turbines incorporating CST may therefore eventually enjoy a significant market share; as such, the leading gas turbine manufacturers are actively working in this field. However, the demands made upon catalysts are challenging indeed. The present paper discusses practical issues concerning the application of catalytically stabilised combustion to gas turbines. It additionally reports on the ongoing investigation of methane/air CST (using palladium catalysts) at conditions relevant to gas turbines (inlet temperatures up to 500 °C, pressures up to 30 bar and spatial velocities up to 10^6 h^{-1}). © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Catalytic combustor; Gas turbines; Palladium

1. Introduction

A great deal of effort has been placed on the reduction of thermal NO_x emissions from gas turbines over the past decade. The market introduction of lean-premixed combustion was accompanied by a drastic reduction of the emissions. Today, the leading producers of modern, heavy-duty gas turbines achieve NO_x emissions of 25 ppm (15% O_2) and below. However, legislation concerning such emissions is likely to become more stringent, particularly for gas turbine power plants located in or near urban areas.

An alternative approach to the reduction of NO_x emissions is catalytically stabilised combustion (first demonstrated in 1974 [1]), in which the fuel/air mixture, or a portion thereof, is converted heterogeneously over a catalyst. This technique is attractive because it offers the potential of ultra-low NO_x emissions (<3 ppm), improved flame stability and fewer pulsations than commonly found in lean-premix (LPM) burners. Furthermore, studies have shown that this approach is more economical than the various tail-end clean-up methods which are available for present gas turbine power plants.

The basic design principle of a catalytic burner is simple. Fig. 1 illustrates the concept, quoting typical temperatures encountered in modern, heavy-duty gas turbines. Fuel and air are premixed in front of a monolith on which catalytic materials are supported. Catalyst design (number of catalysts, cell density, length, catalytically active material) depends on the required operating conditions (entrance velocity, fuel/air ratio, pressure, inlet temperature, fuel type). Should the need arise, a preburner can be implemented in order to raise the gas inlet temperature to that required by the catalyst.

The premixed gases diffuse to the catalytically active surface of the honeycomb; the fuel is converted heterogeneously and the reaction products diffuse back to the main flow. The heat is transported by conduction, diffusion, convection and radiation to the bulk flow which consequently heats-up. Fig. 1 additionally shows that a homogeneous flame can be

---

[*] Corresponding author.

E-mail address: richard.carroni@power.alstom.com (R. Carroni).

PII: S0920-5861(02)00081-0

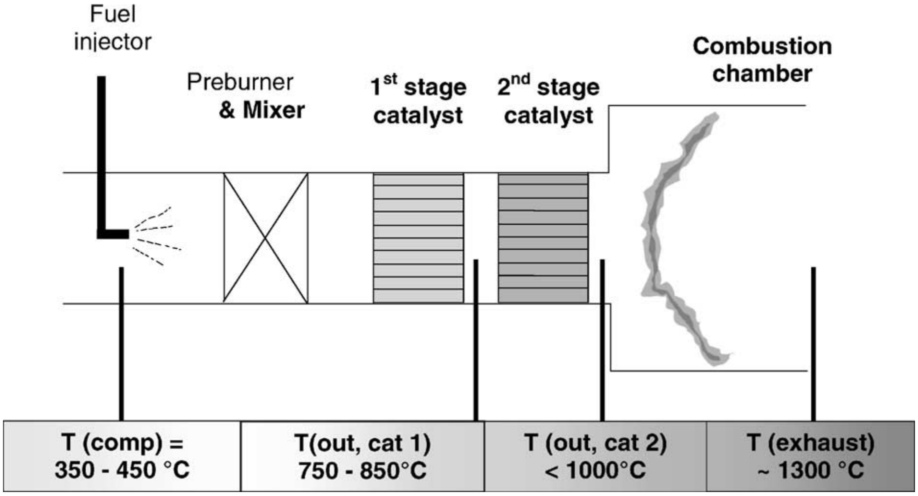

Fig. 1. Principle of catalytic combustion (note that $T_{(\mathrm{comp})}$ is nearly the same as the catalyst inlet temperature T_{in} if no preheating occurs in the preburner).

aerodynamically stabilised downstream of a catalyst system, consuming any fuel which was not converted heterogeneously. More detailed descriptions of the basics of catalytic combustion can be found in the literature [2–5].

2. Gas turbine operation

Gas turbines have developed considerably over the past three decades. Pressure ratios were originally relatively low (up to 12 bar), as were turbine inlet temperatures and consequently adiabatic flame temperatures ($<1300\,^{\circ}$C). Material improvements and novel cooling systems enabled both gas temperature and pressure to be increased, resulting in higher machine efficiencies and output; in the largest, modern machines, values of 1500 °C and 30 bar can be attained, respectively.

In the past, gas turbine combustors were of the diffusion variety. These provided a high degree of flame stability over a large operating range, but unfortunately emitted unacceptable levels of pollutants (e.g. 160 ppm NO_x). Combustion within the latest generation of gas turbines is of the LPM variety; NO_x levels of 25 ppm (15% O_2) and below are common in heavy-duty machines.

LPM burners are normally designed for typical gas turbine operating modes in such a way that their fuel/air ratio produces the least NO_x emissions during operation under full load. They are therefore operated near the lean extinction limit, which can have unfavourable repercussions upon stability and pulsations. During partial load of the gas turbine or at lower fuel feed, it is therefore necessary, in order to maintain stable operation, to shut off individual burners so that the remaining burners can continue to be operated in a stable manner. Pilot burners (diffusion flames) are still required at start-up, and can also be utilised for part-load stabilisation. These, however, increase emissions.

Gas turbine operation predominantly occurs at 50–100% load; thus, an extension of the flammability limits to cope with the lower end of this load range would be beneficial. Catalytic combustion provides a means for achieving this.

3. Design considerations for catalytic combustors in gas turbines

The operating conditions facing a catalyst within a gas turbine can be severe indeed. Listed below are the salient operational considerations concerning the application of catalytic combustors to gas turbines.

Fuel/air mixtures which have high adiabatic flame temperatures (up to 1500 °C) are typical of large gas turbines. It is important to know that for fuel/air mixtures with Lewis numbers close to unity (which is the case for natural gas) the surface temperature of an adiabatic reactor in a diffusion-controlled regime will be equal to the mixture adiabatic flame temperature. Thus the first major difficulty facing catalysts and their supports is thermal stability. Furthermore, the mechanical integrity must be maintained despite the thermal shocks encountered when rapid changes in load (and hence temperature) occur.

Catalyst inlet temperatures will typically vary between 350 and 450 °C (corresponding to 50–100% load); thus light-off temperatures are critical. Preburners (to increase the compressor discharge temperature to that required by the catalyst at inlet) should be avoided because they generate NO_x and also cause uneven temperature and velocity distributions at the catalyst inlet.

Pressures within the 50–100% load range are typically between 8 and 30 bar. Although conversion is not significantly affected when the channel flow is turbulent (conversion is proportional to $P^{-0.2}$), the risk of homogeneous ignition within the catalyst is strongly pressure dependent. This phenomenon is to be avoided at all costs because it is likely to lead to the destruction of both the catalyst and its supporting structure.

Gas turbines are characterised by very high mass flow rates and volumetric heat release rates, for which catalysts are not particularly well suited. Thus an adequately large catalytic surface must be provided, with minimal pressure losses. The total pressure loss across a catalytic combustor (including the mixer) should not be larger than that of a conventional combustor, i.e. $<3\%$. Furthermore, the high space velocities result in catalysts requiring higher activities for low-temperature light-off to occur.

Another important consideration is that of uniformly mixing the fuel and air. The mixedness in gas turbines is typically 80–85%, leading to local adiabatic temperature variations of up to 150 °C; this, however, would result in unacceptably high local fuel concentrations. For example, a nominal mixture of $\lambda = 2.3$ (typical in the range 50–100% load) could locally attain fuel concentrations corresponding to $\lambda = 1.85$, the adiabatic temperature of which would correspond to over 1500 °C, thereby overheating the catalyst. Generally, high levels of mixedness are associated with significant pressure drops across the mixers. This pressure loss must be minimised.

Gas turbines are often designed to run on several different fuels, for example natural gas and oil. This causes problems in catalytic combustion because fully atomised oil has rather different heterogeneous combustion properties to those of natural gas (e.g. lower light-off temperature); thus the catalytic combustor is a fuel-specific device. Natural gas is the preferred fuel of modern gas turbines. The exact nature of the natural gas is a further issue of importance; catalytic combustors must be able to cope with variations in fuel composition. Although natural gas contains mostly CH_4, there are often significant quantities of higher hydrocarbons which, due to their considerably higher reactivity, encourage the onset of homogeneous ignition within the catalyst. Other trace quantities, such as sulphur, can diminish the catalyst performance. For example, Kusar et al. [6] demonstrated that 25 ppm SO_2 increases the PdO light-off temperature by 300 °C (but has no effect on platinum). Industrial supplies of natural gas typically contain 1 ppm SO_2; the effect of this smaller concentration upon catalysts remains to be seen.

Many processes and systems rely upon gas turbines; as such, these machines must be reliable (non-stop operation for up to 8000 h/year) and respond quickly to changes in power requirements, whilst meeting the performance targets guaranteed by the manufacturer. Repeatability, however, is a critical issue in light of the fact that catalysts suffer from ageing, sintering and poisoning. Furthermore, catalyst design must take into account the fact that gas turbines are expected to perform within a wide band of ambient conditions, typically between -25 and $+40$ °C. This has particularly important ramifications for light-off.

A final important issue concerns the dimensions of the catalytic combustor. Ideally, these should be the same as those of current LPM burners, which are typically contained in a cylindrical envelope measuring approximately 300 mm in length and 180 mm in diameter. This similarity ensures that catalytic combustors can be retrofitted to existing gas turbines (both annular- and can-type combustors), without the need for major redesigns. This simplicity translates into economic benefits: cheaper testing/development work, and simpler maintenance/replacement.

4. State-of-the-art solutions

The original catalytic combustor proposed by Pfefferle [1] envisaged the entire fuel/air mixture passing through a single catalyst, in which all the fuel was converted (heterogeneously and homogeneously). This approach is no longer feasible, given that current gas turbine flame temperatures are significantly higher than before, thereby subjecting catalysts to extreme temperatures. A simple solution to this problem is to convert only a portion of the fuel catalytically, thereby preventing the catalyst surface from attaining the adiabatic temperature of the overall fuel/air mixture. The remainder of the fuel bypasses the catalyst. Different approaches are possible.

Furuya et al. [7] and Ozawa et al. [8] proposed a "hybrid" design, where two fuel supply systems are used. Only a part of the fuel is mixed with the combustion air upstream of the catalyst (primary fuel). Typically, the fuel is limited to an amount such that the catalyst temperature remains below a given value (e.g. 1000 °C). The rest of the fuel (secondary fuel) is mixed with the hot gases leaving the catalyst, and burns in a premixed type flame downstream of the catalyst. Serious catalyst deactivation is not to be expected from the limiting of the catalyst surface temperature. A critical issue of this concept is the premixing of the secondary fuel and the hot, low turbulent intensity, gas stream leaving the catalyst containing unburned fuel. If ignition occurs prior to perfect premixing, increased thermal NO_x emissions would be expected to result. Furthermore, such hybrid concepts require variable air and fuel flow rates, depending upon operating point, to flow through the primary and secondary air/fuel delivery systems. This adds undesired complexity to an already complex machine.

Cowell and Roberts [9] also designed a hybrid catalytic combustor. It was successfully tested in a small, recuperated gas turbine (Solar Turbines Mercury 50) where emissions were reported as <5 ppm NO_x and <10 ppm CO and unburned hydrocarbons (UHCs) (15% O_2) at 50–100% load [10]. Heat recuperation enabled the catalytic combustor to operate without the need for preburners. A similar concept was adapted to a large Westinghouse machine, where a diffusion flame pilot was required for homogeneous stabilisation for $<50\%$ load (heterogeneous conversion only above 50% load) [10].

Another approach to limit catalyst surface temperature has been proposed by Young and Carl [11] and Dalla Betta et al. [12]. All the fuel and air needed to reach the required turbine inlet temperature is mixed in front of a honeycomb catalyst. Within the honeycomb, a catalytically inactive channel is always located adjacent to a catalytically active channel. Even if the surface reaction within the catalytically active channel is diffusion-controlled, the surface temperature does not reach the adiabatic flame temperature of the fuel/air mixture, because heat is transferred to the neighbouring, inactive channel. The fuel/air mixture of the inactive channels heats up and can be burned downstream of the catalyst in a homogeneous combustion zone.

This technique has been commercialised by Catalytica [13] and successfully applied to the small Kawasaki M1A-13A; NO_x levels of 2.5 ppm (15% O_2) are reported. GE have also tested this combustor in their larger MS9001E machine [14,15]. Preburners are still utilised at part load in both cases, thereby increasing emissions. Furthermore, it is not a simple matter to scale this design up for the largest machines whose operating temperatures and pressures are much higher.

Techniques can also be applied whereby all the fuel flows through the catalyst. Dalla Betta et al. [16] proposed a physical diffusion barrier, which essentially consists of a coating applied on top of the catalytic surface. Its purpose is to limit the amount of fuel diffusing to the catalyst, thereby reducing the surface temperature. Pfefferle [17] suggested that heterogeneous activity must be limited by using a series of segmented catalysts, whereby the repetition of entrance effects promotes kinetically controlled catalysis.

5. Catalyst selection

The design considerations listed in the previous sections make it reasonably clear that a system of catalysts is required for heterogeneous combustors within gas turbines. A highly reactive catalyst for the low-temperature ($350\,^{\circ}\mathrm{C} < T_{\mathrm{in}} < 450\,^{\circ}\mathrm{C}$) conversion of CH_4 must be combined with a second catalyst which converts fuel at higher temperatures (T_{in} approx. 700 °C, $T_{\mathrm{out}} > 900\,^{\circ}\mathrm{C}$). First-stage requirements are more challenging; thus attention will be focused upon suitable low-temperature catalysts.

Methane is the most difficult hydrocarbon fuel to combust heterogeneously; the most reactive catalyst known for this fuel is the oxidised form of palladium. In-house tests back up the literature in stating that PdO is more reactive than even platinum; experiments show that, for a given fuel concentration and space velocity, Pd/PdO catalysts light-off at temperatures between 150 and 250 °C lower than in the case of Pt. However, this increased activity is attained at a price. As well as being at least as expensive as Pt, PdO also undergoes complex transformations above certain temperatures (known as the transition temperatures), which rather complicate matters. The distinctive hysteresis behaviour [18,19] means that the activity of PdO is highly susceptible to history effects. It has been suggested that the self-regulating behaviour of Pd/PdO systems can be harnessed in order to avoid excessive catalyst surface temperatures. However, the relatively high adiabatic flame temperatures (up to 1500 °C) of the fuel/air mixtures mean that this feature on its own is not sufficient to protect catalysts within large gas turbines, from the point of view of repeatability and reliability, particularly since the Pd sintering process is accelerated by exposure to temperatures above 1000 °C [10]. Thus Pd/PdO catalysts can be very beneficial for low catalyst inlet temperatures, provided that the catalyst itself does not become hotter than the transition temperature. This problem is somewhat alleviated by the fact that the transition temperature is a direct function of pressure (since the PdO → Pd transformation is dependent upon O_2 partial pressure). Since catalytic combustors can only realistically be expected to operate in the 50–100% load range, the relevant transition temperature is around 800–900 °C for the larger machines (where pressures range from 8 to 30 bar).

Selection of the second-stage, high-temperature catalyst is not quite so restricted a matter as for the first-stage. More options are available because the main problem has shifted from one of catalytic activity to one of thermal stability of both the catalyst and its support (often the same material). Traditional supports such as cordierite are not able to cope with the large thermal shocks which can be encountered during transient gas turbine operation [20]. Other materials, such as perovskites and hexaluminates, display much improved thermal stability. A review of possible candidates for high-temperature catalysts is available in the literature [21,22].

6. Experimental programme

Designing a catalytic combustor consisting of a system of catalysts requires in-depth knowledge of the constituent components. To this effect, several experiments were carried out in order to investigate catalyst light-off temperature, stability and repeatability at conditions relevant to gas turbines. Palladium was the default choice by virtue of its superior light-off capabilities. A number of commercial, as well as proprietary, palladium catalysts were thus subjected to essentially two different tests, the main purpose being to benchmark available catalysts and to quantify those characteristics requiring improvement.

Table 1 outlines the details of three commercial and one proprietary catalyst investigated. Catalysts A, C and D are off-the-shelf, cordierite-based honeycombs,

Table 1
Details of the catalysts which were tested

	A	B	C	D
Length (mm)	76.2	87	75	50
Diameter (mm)	76.2	102	102	100
cpsi	400	≈107	400	200
Cell hydraulic diameter (mm)	1.10	2.32	1.10	1.52
m^2/m^3	2709	1553	2709	1898
Monolith	Cordierite	Fe–Cr alloy	Cordierite	Cordierite
Substrate	Al_2O_3	Al_2O_3	Al_2O_3	Al_2O_3
Catalyst	Pd	Pd	Pd	Pd
Loading (g/l)	3.5–5.3	3	7	n/a
space velocity (h^{-1})	710,000	620,000	720,000	1,080,000

whilst sample B is a metallic (Fe–Cr alloy, 0.05 mm sheet thickness) monolith where only alternate channels are coated with palladium. The space velocities are high indeed; they are based on a channel entrance velocity of 15 m/s at a catalyst inlet temperature of 450 °C, which are values typical of gas turbine conditions. The pressure drops for catalysts A and B, at 14 m/s and 20 °C, are 9900 and 4450 Pa/m, respectively.

The experimental rig essentially consisted of a static mixer (for thorough fuel/air mixing), an adiabatic catalyst module (i.e. heat losses from the catalyst to the surrounding were minimised) and a burn-out zone. This latter section allowed for the eventual homogeneous combustion of fuel which had not been converted by the catalyst. Air and fuel flow rates and catalyst inlet and exit temperatures were measured. Temperatures were also recorded downstream of the catalyst, as was the exhaust gas composition. All the tests took place at atmospheric pressure.

The first experiment subjected all four catalysts to a series of heating/cooling cycles, and was designed to yield catalyst light-off temperatures and to check upon the repeatability thereof. Fuel concentrations were deliberately kept very low (ranging from $\lambda = 12.9$ to 5.5) so as to ensure that, in the rather unlikely event of 100% conversion, the catalyst never exceeded the threshold temperature at which PdO reduces to Pd (≈750 °C at 1 atm). The information thus gleaned pertained to heterogeneous activity only. The results presented below are those for fresh catalysts (aged in air at approx. 400 °C for approx. 30 min).

The second experiment exposed catalysts A and B only to fuel/air mixtures ranging from $\lambda = 3$ to 2, and inlet temperatures between 450 and 520 °C, which are typical conditions for gas turbines operating in the load range 50–100%. Stability issues regarding heterogeneous activity and subsequent homogeneous combustion downstream of the catalyst were investigated by recording data over longer periods of time (up to an hour).

7. Results and discussion

A sample set of consecutively performed heating/cooling cycles performed on catalyst B is shown in Fig. 2; these are representative of all the other catalysts tested. The suffixes h# and c# in the legend refer to heating and cooling cycle number. During

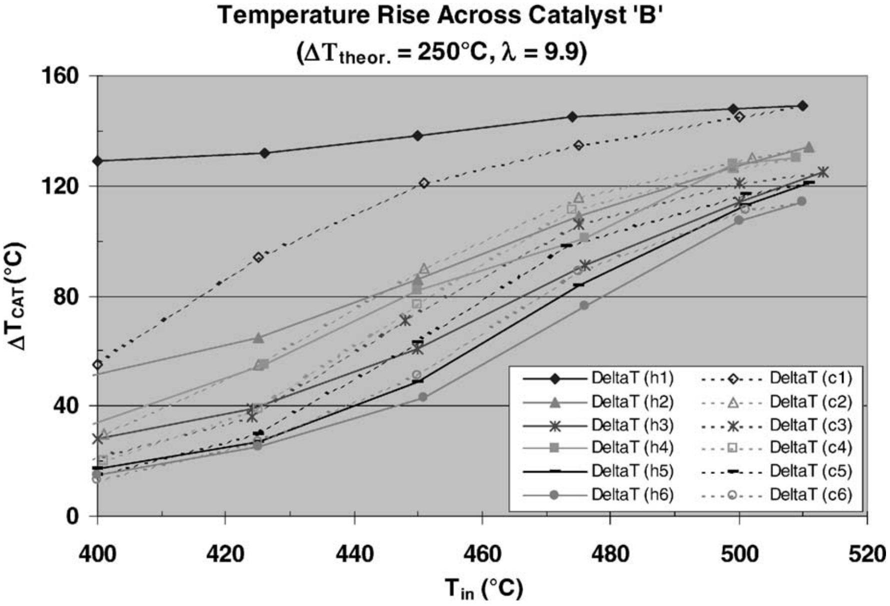

Fig. 2. Sample heating/cooling curves.

Table 2
Conversion at maximum inlet temperatures[a]

Catalyst	$\Delta T_{\text{theor.}} = 200\,^\circ\mathrm{C}$, $\lambda = 12.9$		$\Delta T_{\text{theor.}} = 250\,^\circ\mathrm{C}$, $\lambda = 9.9$		$\Delta T_{\text{theor.}} = 350\,^\circ\mathrm{C}$, $\lambda = 7.2$	
	T_{in} (°C)	Conversion (%)	T_{in} (°C)	Conversion (%)	T_{in} (°C)	Conversion (%)
A	510	90	510	84	510	84
B	515	45	515	46	510	49 (98)
C	526	39	525	36	501	51
D	–	–	526	45	500	36

[a] Note that catalyst B has only alternately coated channels.

the first cycle, the freshness of the catalyst manifests itself by high conversions at relatively low inlet temperatures. Conversion is computed by comparing the measured temperature rise across the catalyst, with the adiabatic temperature increase; this value is only valid for heterogeneous combustion where catalytic activity is fairly uniform across any cross-sectional plane. Catalytic activity is seen to decrease during subsequent heating/cooling cycles, eventually approaching an asymptote which can be defined as the 'aged' behaviour. Interestingly, similar cycles performed 24 h later did not coincide with the last cycle (#6) in Fig. 2, indicating that catalytic activity is affected by history effects (such as exposure to a 400 °C air stream for 30 min, prior to the second set of runs being performed for that catalyst).

Tables 2 and 3 summarise the conversions of the various catalysts, for three different fuel/air ratios and two different inlet temperatures. The higher inlet temperature ($T_{\text{in}} \approx 510\,^\circ\mathrm{C}$) of Table 2 corresponds to the maximum air preheating possible in the experimental rig, whereas $T_{\text{in}} = 450\,^\circ\mathrm{C}$ in Table 3 is more typical of gas turbine conditions near full load. It should be noted that only 50% of the surface area of catalyst B is catalytically coated.

Table 2 reveals that catalysts A and B convert nearly twice as much fuel as C and D at $T_{\text{in}} = 510\,^\circ\mathrm{C}$. The proprietary configuration is said to perform better if one considers that its specific surface area (i.e. ratio of surface area to volume) and cell density are considerably smaller than those of catalyst A. Table 3 shows that the catalysts are significantly less active than at the higher inlet temperature; again, catalysts A and B return higher conversions than C and D. If another glance is cast at Fig. 2, it is seen that activity drops rapidly with inlet temperature; thus, for the catalyst B, the conversion at $T_{\text{in}} = 400\,^\circ\mathrm{C}$ is about 6%. Other catalysts were less active at such low temperatures. This points to the fact that none of the catalysts examined would be able to convert sufficient quantities of fuel within the 50–75% load range of a gas turbine (T_{in} between 350 and 400 °C). A number of other catalysts had also been investigated under identical conditions, but the results remained similar.

Tests involving homogeneous combustion downstream of the catalyst were performed upon the two most active catalysts, namely samples A and B. Fig. 3 plots the time variation of the catalyst exit temperature and the measured unburned fuel for the cordierite-based catalyst A ($T_{\text{in}} = 450\,^\circ\mathrm{C}$). Catalyst exit temperatures varied continuously, ranging from

Table 3
Conversion at lower inlet temperatures[a]

Catalyst	$\Delta T_{\text{theor.}} = 200\,^\circ\mathrm{C}$, $\lambda = 12.9$		$\Delta T_{\text{theor.}} = 250\,^\circ\mathrm{C}$, $\lambda = 9.9$		$\Delta T_{\text{theor.}} = 350\,^\circ\mathrm{C}$, $\lambda = 7.2$	
	T_{in} (°C)	Conversion (%)	T_{in} (°C)	Conversion (%)	T_{in} (°C)	Conversion (%)
A	450	45	450	24	450	19
B	450	18	450	14	450	11 (22)
C	450	11	450	6	450	9
D	–	–	450	6	450	5

[a] Note that catalyst B has only alternately coated channels.

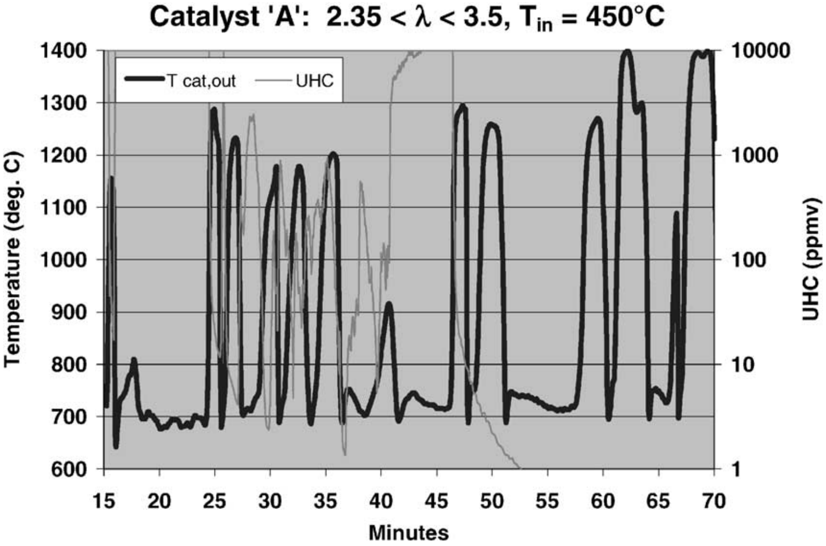

Fig. 3. Catalyst A (fully coated, cordierite honeycomb) exit temperature as a function of time.

600 to nearly 1400 °C, causing the homogeneous flame to constantly change location in the burn-out zone. High levels of UHC were measured as the flame moved close to the gas-analyser probe, which itself was located over a metre downstream of the catalyst. Observation of this catalyst during tests revealed strong hot spots which continuously migrated, thereby causing local catalyst exit temperatures to fluctuate. This behaviour is a practical demonstration of the temperature-dependent interaction between PdO and Pd. Clearly, such unsteady performance would not be acceptable in a gas turbine.

Fig. 4 is an analogous plot (shorter time on-stream, but higher inlet temperature) showing the results for catalyst B ($T_{\mathrm{in}} = 490\,^{\circ}\mathrm{C}$). During the first couple of minutes after starting up, the catalyst exhibits unsteady behaviour and hot spots, after which a steady state is attained (with negligible UHC). The catalyst exit temperature then remains constant at about 720 °C. Thus, coating of alternate channels is only seen to reduce

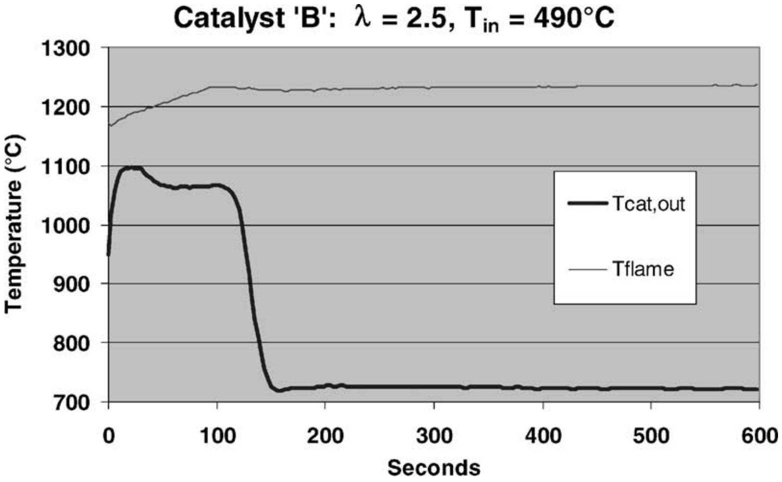

Fig. 4. Catalyst B (metallic monolith with alternately coated channels) exit temperature as a function of time.

catalyst temperatures to the extent that the transient nature of the PdO/Pd interactions is somewhat suppressed. Nevertheless, homogeneous ignition at the same conditions in subsequent repetitions of this test becomes increasingly difficult; more and more fuel is required for a flame to occur. This is an indication that the PdO reduction process is still on-going, although at a slower rate than in normal catalyst configurations. Repeatability thus remains an issue requiring resolution.

8. Closure

Catalytic combustion in gas turbines has often been put forward as a viable means for reducing NO_x and improving flame stability at lower loads. The basic principle is simple, yet actual integration of the concept into a modern, heavy-duty gas turbine is not a trivial matter. This paper has outlined many of the salient design considerations and operating requirements of catalytic combustors within gas turbines, and has also reported upon experimental investigations of catalysts. The main conclusions are listed below:

1. Current catalyst and material constraints dictate that a single catalyst cannot convert all the fuel required during GT operation.
2. A catalytic combustor can only be reasonably expected to operate within the 50–100% load range of gas turbines.
3. Durability and repeatability problems must be resolved.
4. Palladium is the most suitable first-stage catalyst; nevertheless, this material has shortcomings which need to be addressed.
5. Experimental tests on palladium catalysts has shown that
   - light-off temperatures are still too high,
   - catalyst surface temperatures must be kept at or below the so-called transition temperature.

There is an on-going effort to overcome the above problems. Palladium catalysts with sub-400 °C light-off temperatures are being examined, as are novel support structures. Tests at high pressures (up to 30 bar) are being conducted. The knowledge gained by these undertakings is being used to design and develop robust, retrofittable catalytic combustors which meet the requirements of modern gas turbines.

References

[1] W.C. Pfefferle, Belgian Patent No. 814 752 (1974).
[2] J.P. Kesselring, in: F.J. Weinberg (Ed.), Advanced Combustion Methods, Academic Press, London, 1986, pp. 237–275.
[3] D.L. Trimm, Appl. Catal. 7 (1985) 249–282.
[4] L.D. Pfefferle, W.C. Pfefferle, Catal. Rev.-Sci. Eng. 29 (2–3) (1987) 219–267.
[5] T. Griffin, M. Valk, V. Scherer, 10. DVV/1. SVV Kolloquium, Hochtemperature-Brennstoffzellen und Katalytische Verbrennung, Paul Scherrer Institut, Würenlingen, 27 September 1996.
[6] H.M. Kusar, A.G. Ersson, P.O. Thevenin, S.G. Jaras, To be Presented at the Ninth International Symposium on Catalyst Deactivation, October 7–10, 2001, Lexington, KY, USA.
[7] T. Furuya, Y. Sasaki, Y. Hanakata, K. Mitsuyasu, M. Yamada, T. Tsuchiya, Y. Furuse, Proceedings of the International Workshop on Catalytic Combustion, Tokyo, Japan, 1994, pp. 162–163.
[8] Y. Ozawa, T. Fujii, S. Kikumoto, M. Sato, H. Fukuzawa, M. Saiga, S. Watanabe, Proceedings of the International Workshop on Catalytic Combustion, Tokyo, Japan, 1994, pp. 166–169.
[9] L.H. Cowell, P.B. Roberts, US Patent No. 5 452 574 (1995).
[10] D.B. Fant, G.S. Jackson, H. Karim, D.M. Newburry, P. Dutta, K.O. Smith, R.W. Dibble, J. Eng. Gas Turb. Power 122 (2000) 293–300.
[11] W.E. Young, D.E. Carl, European Patent 0304 707 A1 (1989).
[12] R.A. Dalla Betta, J.C. Schlatter, S.G. Nickolas, A. Lodewyk, T. Shojii, M. Sasaka, S. Hung, Proceedings of the EPRI/EPA Conference on low NO_x Combustion, Miami Beach, FL, May 1993.
[13] NO_x control technologies: Catalytica combustion systems, XONON^{TM} Flameless Combustion System, Environmental Technology Verification Report, December 2000.
[14] R.A. Dalla Betta, J.C. Schlatter, S.G. Nickolas, M.B. Cutrone, K.W. Beebe, Y. Furuse, T. Tsuchiya, ASME Paper No. 96-GT-485, International Gas Turbine and Aeroengine Congress and Exhibition, Birmingham, UK, June 10–13, 1996.
[15] K.W. Beebe, K.D. Cairns, V.K. Pareek, S.G. Nockolas, J.C. Schlatter, T. Tsuchiya, Catal. Today 59 (2000) 95–115.
[16] R.A. Dalla Betta, K. Tsurumi, T. Shoji, US Patent No. 5 248 251 (1993).
[17] W.C. Pfefferle, US Patent No. 5 601 426 (1995).
[18] P. Forzatti, G. Groppi, Catal. Today 54 (1999) 165–180.
[19] G. Groppi, C. Cristiani, L. Lietti, P. Forzatti, in: A. Corma, F.V. Melo, S. Mendioroz, J.L.G. Fierro (Eds.), Studies in Surface Science and Catalysis, Elsevier, Amsterdam, 2000.
[20] R.J. Farrauto, M. Larkin, J. Fu, J. Feeley, Mat. Res. Soc. Symp. Proc. 334 (1994).
[21] G. Groppi, C. Cristiani, P. Forzatti, in: J.J. Spivey (Ed.), Specialist Periodical Reports, Vol. 13, Catalysis, The Royal Society of Chemistry, 1998.
[22] M.F.M. Zwinkels, S.G. Jaras, P.G. Menon, T. Griffin, Catal. Rev.-Sci. Eng. 35 (1993) 319.