CATHLEAN: Catalytic, Hybrid, Lean Premixed Burner for Gas Turbines

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Abstract

CATHLEAN (an EU FP5 project) addresses the research and development of an advanced, ultra-low NOx, hybrid burner for gas turbines (present and future), that combines catalytic and lean-premix combustion components. Such a hybrid design enables this new technology to be introduced in a lower-risk manner. The catalytic elements serve to pre-treat the fuel in order to enhance performance in terms of emissions (<3ppmv NOx and <10ppmv CO @ 15% O_2 at 50-100% load, for natural gas fuel), part-load stability (reducing the lean blowout temperature by over 100°C) and thermoacoustic phenomena (pulsations << 0.3% of pressure). The principle scientific objective is to quantify the advantages of the hybrid burner in terms of the above-mentioned criteria, relative to traditional, lean-premixed combustors. The present paper describes the technical and organisational aspects of the project, including an outline of state-of-the-art catalytic combustion technology, technical specification of the advanced burner and a description of the methods used to attain project goals.

Key words: Catalytic combustion, advanced hybrid burner.

INTRODUCTION

Extensive effort has been placed on reducing thermal NOx emissions from gas turbines over the past decade. The market introduction of lean-premixed combustion was accompanied by a drastic reduction of these emissions. Today, the leading producers of modern, heavy-duty gas turbines (running on natural gas) achieve NOx emissions of 25ppm (15% O_2) and below. However, legislation concerning such emissions has, or is likely to, become more stringent, particularly for gas turbine power plants located in or near urban areas [1], where the lowest achievable emissions rate (LAER) standards may be required.

An alternative approach to the reduction of NOx emissions is catalytically stabilised combustion (first demonstrated in 1974 [2]), in which the fuel/air mixture, or a portion thereof, is converted heterogeneously over a catalyst. Detailed descriptions of the fundamentals of catalytic combustion can be found in the literature [3,4,5]. This technology is now commercially available in several guises, and has been demonstrated to consistently achieve <3ppmv NOx for several small machines [6,7]. The principle is also compatible with the trend of increasing gas turbine firing temperatures, which contribute to higher machine efficiencies and hence reduced CO_2 emissions.

Traditional catalytic combustion is mainly seen as an alternative vehicle for NOx emissions abatement. Unlike tail-end systems such as SCR and SCONOX, catalytic combustion actively reduces the formation of pollutants, rather than cleaning up the flue gases. It enables essentially all applications and sizes of gas turbines to approach zero NOx emissions, thus broadening their applicability. In contrast to the tail-end, cleanup systems, catalytic combustion also has the potential to positively influence the following:

- reduce pulsations [8],
- enhance lean blowout limits,

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- net reduction of CO_2 by burning biogas-containing fuels in a clean manner [9],
- reduce turbine cooling requirements, thereby increasing component lifetime [10].

Thus, for a similar cost as SCR [11], catalytic combustion provides additional benefits.

Current designs for gas turbine catalytic combustors, however, tend not to be fully compatible with the requirements of machine manufacturers and operators (an overview of relevant design and performance considerations is available in [12]). Typically, extensive combustor and casing modifications are necessary, and reliability and operability issues are not fully addressed. Little evidence exists to suggest that the current, state-of-the-art is directly applicable to larger machines characterised by higher firing temperatures.

Catalytic combustion is also of interest for other fuels, such as biogas, syngas and combinations of these fuels with natural gas. Whilst such systems assist with CO_2 abatement as well as reducing NOx [9,13], past research has not resulted in specific, validated designs for heterogeneous oxidation.

An advanced, ultra-low NOx burner containing catalytic elements has therefore been proposed. The hybrid design combines catalytic technology with novel aerodynamic components and new operating concepts, for introduction in current and future gas turbines in a lower-risk manner.

A 10-member EU consortium (whose members are listed in table 1) has been created within the context of a 3 year EU Framework 5 programme, in order to research, design and develop a prototype hybrid burner. Several US groups have been selected for cooperation in this project, in order to benefit from natural synergies and also to further promote existing ties.

The present paper describes the novel burner and its operating requirements, and outlines the manner in which the resources are allocated in order to attain the goals of the Cathlean (Catalytic Hybrid Lean Premixed Burner for Gas Turbines) project.

Organisation name	Country
1. ALSTOM Power Ltd	UK
2. Cranfield University	UK
3. ALSTOM Power Switzerland	CH
4. IFP	F
5. Gaz de France	F
6. awtec AG	CH
7. DLR - Deutsches Zentrum für Luft- und Raumfahrt	D
8. Ruhr Universität Bochum	D
9. Politecnico di Milano	I
10. KTH Stockholm	S
US Partners	
11. Catacel	USA
12. NanoCat Technologies	USA
13. MIT – Massachusetts Institute of Technology	USA
14. University of Maryland	USA

Table 1: List of partners participating in the Cathlean EU FP5 project.

STATE-OF-THE-ART

An overview of various catalytic combustor configurations is available in the literature [5,12,14]. Hybrid configurations are referred to, in which the term ‘hybrid’ is indicative of significant quantities of fuel bypassing the heterogeneous reactor. Two non-hybrid systems have been commercialised recently, and are considered to be state-of-the-art. The first involves heterogeneous oxidation of lean fuel/air mixtures [15], whilst the latter is characterised by fuel-rich catalytic combustion [7,16,17,18]. Tables 2 and 3 provide an overview of technical data for tests conducted with these two promising catalytic technologies. The first table refers to catalytic combustors tested in actual machines, whilst the latter refers to single, gas-turbine burners equipped with catalytic units. The data principally demonstrates that low emissions can be attained with the aid of catalysts. Pulsations were reported as having been dramatically reduced.

	Fuel-lean Catalyst	Fuel-rich Catalyst
Engine	Kawasaki M1A-13X (1.4MW)	Solar Turbines Saturn (1MW), **forecast performance.**
Emissions	< 3ppm NOx, < 10ppm CO (dry, 15% O_2)	<3ppm NOx, <10ppm CO (dry, 15% O_2)
Pulsations	< 31.7mbar (rms)	<10.3mbar (peak-peak)
Other	• 13500 hours, EPA certification • TIT = 1010°C • preburner required	• 6atm • no preburner, light-off at 250°C • fuel flexibility

Table 2: Catalytic combustors tested in gas turbine engines [6,7].

	Fuel-lean Catalyst	Fuel-rich Catalyst (Pilot)
Burner	GE MS9001E (105MW)	Solar Turbines Taurus 70 (7.2MW)
Emissions	3 – 5ppm NOx (dry, 15% O_2) (9ppmv NOx with DLN-1 retrofit)	2 - 9ppm NOx, < 10ppm CO (dry, 15% O_2)
Pulsations	< 17.3mbar (rms)	< 34.5mbar (rms)
Other	• 12.2atm • TIT = 1180°C • preburner required	• 17atm • TIT = 1121°C • no preburner, light-off at 325°C • fuel flexibility

Table 3: Catalytic combustors tested in gas turbine burners [16,19].

MACHINE INTEGRATION

Gas turbine emissions reduction and flame stability can be significantly enhanced by means of catalytic combustion, as indicated by tables 2 and 3. Nevertheless, a number of issues regarding machine integration and operation must be successfully addressed prior to commercialisation on a larger scale. An overview of these considerations is given in Carroni et al [12].

It is vital that the risks associated with the introduction of such new technology are minimised. A method of limiting the technical and commercial uncertainties is to ensure that this technology be as compatible as possible with gas turbine designs and operating conditions. One of the main issues hindering the widespread acceptance of this technology is that of retrofittability. At present, catalytic combustors cannot simply replace lean premix burners in gas turbines and guarantee the full operability and reliability of the current burners. In the event of extensive catalyst deactivation, the burners become inoperable, resulting in costly machine down-time. The trend for gas turbines is to increase the inspection intervals to over 20000 hours, which is considerably higher than what has so far been demonstrated by catalytic units (13500 hours [15]). Preburners may be required in order to increase the operating life of the catalysts, but they generate emissions and add further bulk and complexity.

State-of-the-art systems have only been validated for small gas turbines (1.5 - 10MW) with relatively low firing temperatures (< 1200°C). These technologies have yet to be demonstrated for larger machines with higher firing temperatures (currently 1300°C, to be extended up to 1500°C). No published data exists concerning long term (i.e. > 1000 hours) catalyst activity at such temperatures (up to 1500°C). Catalytic systems must convert a significant amount of fuel (chemical kinetic computations indicate a fraction typically > 40%) in order to minimise thermal NOx at these high temperatures. The target catalyst activity must be maintained over long periods of time, to avoid excessive thermal NOx generation.

INNOVATION

In order for catalytic technology, and its considerable benefits, to become more accessible to gas turbine operators and manufacturers, it is crucial that the issues of retrofittability, reliability and operability be addressed. These aims are met by developing an advanced, hybrid, retrofittable burner, based on the patent of Eroglu et al [20].

The design contains both catalytic and lean premix elements as a means of simultaneously benefitting from the advantages of catalytic combustion (ultra-low emissions, stability over a wide load range) and lean premix technology (reliability, back-up operation). Unlike previous designs, the term ‘hybrid’ in this case refers to the heterogeneous and homogeneous combustion modes of the burner. Combustion is normally supported by catalysts, but in the event of excessive deactivation, the burner is able to operate in 100% lean premix mode and to deliver the performance expected from current lean premix burners. Although 100% lean-premix operation no longer reduces NOx to ultra-low levels, it does permit continued functioning of the gas turbine in the event of extensive catalytic deactivation. This addresses the issue of machine availability.

Retrofit considerations result in stringent overall boundary conditions for the advanced, hybrid burner. Typical conditions derived from a gas turbine of the 100 – 150MW class are listed in table 4.

Parameter	Boundary Condition
Burner dimensions	Cylindrical envelope: ≈ 450mm long, 200mm diameter.
Inlet velocity	20 – 30m/s @ 400 – 450°C.
Pressure	15 – 25 bar
Total pressure loss	< 3% of engine operating pressure
Total heterogeneous fuel conversion	> 40% of total fuel flow

Table 4: Overall boundary conditions for the retrofittable, hybrid burner.

Figure 1 depicts the hybrid burner and its constituent components. The goal of retrofittability imposes tight operating constraints and requires the development of a number of novel components. Extensive research and development is mandatory in order for the new designs and concepts to comply with the overall operating conditions. The burner is primarily designed for natural gas (permitting liquid fuel operation in homogeneous combustion mode), but applied catalytic research will also be undertaken for the cleaner combustion of other gaseous fuels such as biogas, syngas, and mixtures of these with natural gas.

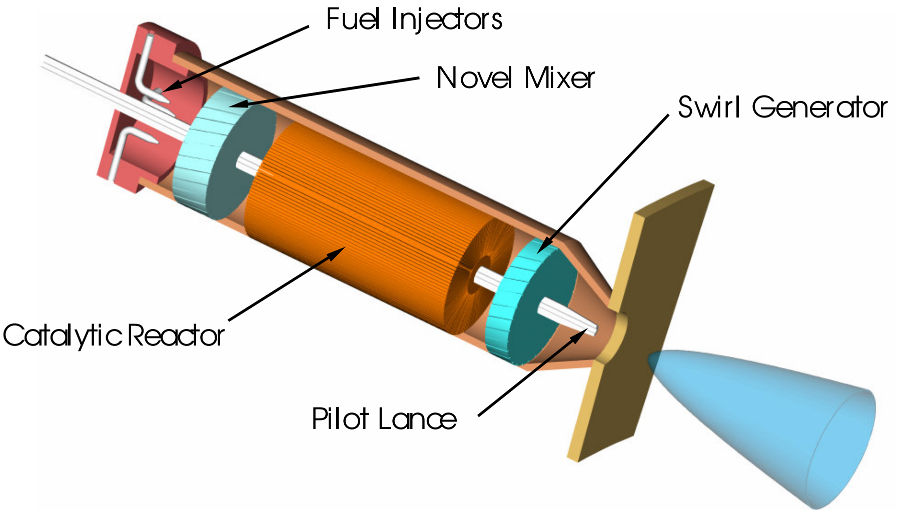


Figure 1: Illustration of the advanced, hybrid burner and its constituent components.

The following considerations provide an overview of the component duties and the challenges that need to be overcome from the research & development perspective:

- The short length and high linear velocities result in large space velocities (≈ 10^7 hr^{-1}) within the catalytic reactor, thereby compounding the problems of light-off and conversion. Novel catalytic formulations and synthesis and deposition methods must be researched in order to promote a) low light-off temperatures (i.e. < 400°C) and b) long-term stability at high temperatures (up to 950°C). Existing collaborations have led to significant advances in catalytic combustion of methane using novel, nano-structured catalysts. Notably, low-temperature catalysts were developed which allow methane light-off temperatures as low as 350°C. The resulting Palladium Oxide nanoclusters are highly dispersed, thereby allowing excellent activity to be achieved at relatively low noble metal loadings. These developments, in conjunction with others (such as those described in the patent of Carroni et al [21]), mean that light-off can potentially be attained without the use of a preburner. Catalyst improvements will in any case be accompanied by the development of new operating concepts, involving both the catalytic main reactor and the catalytic pilot. These will promote catalytic activity even when the available gas temperature is lower than the nominal light-off temperature.

- Catalysts dictate that extremely high (by lean premix standards) mixing qualities be attained prior to entry into the catalytic reactor. This is necessary in order to avoid local overheating. Only a small volume is available for the fuel injection and mixing processes. High levels of fuel/air mixedness must be attained in very short distances (typically of the order of 100mm), at high velocities, and with minimal pressure losses. The mixing process must additionally deliver a uniform axial velocity profile to the catalyst inlet zone. Devices which meet all these criteria are currently not commercially available.
- A novel swirl generator is necessary for aerodynamic flame stabilisation, which must be strong enough to firmly anchor homogeneous combustion in the event of large-scale deactivation of the catalytic reactor. This unit is exposed to the high temperatures (up to 950°C) of the catalyst exhaust stream. It can integrate additional functions, such as arresting flashback of the homogeneous flame front, and providing further heterogeneous conversion.
- A low-emissions piloting lance is often necessary for flame stabilisation, especially at lower loads and during startup and transitions. This unit may contain catalytic components (as described by Griffin & Senior [22]), particularly those designed for fuel-rich heterogeneous oxidation which provides chemical flame stabilisation (an example of which is outlined by Ruck et al [23]). In the event of failure of the catalytic units, the lance must be able to revert to the diffusion flame mode commonly used in present applications. Furthermore, the piloting lance should also maintain the liquid fuel capability of current, lean-premix burners by injecting the liquid fuel from the lance tip into the combustion zone downstream of the catalytic reactor and swirl generator. This is to be achieved by providing sufficient space for liquid fuel ducts along the entire lance length, and for the atomisation nozzle at the lance tip.

RESEARCH & DEVELOPMENT PROGRAMME

Objectives & Component Specification

Development of a commercially-viable, hybrid burner for gas turbines is hindered by a number of hurdles facing present, state-of-the-art catalytic systems. A number of innovative features, described in the previous section, need to be researched and developed. The overall technical goals of the hybrid burner are to:

1. Provide a low-risk introduction of new technology which will extend the lean blowout limits, minimise emissions and reduce thermoacoustic instabilities and pulsations.
2. Establish (or, in some cases, extend) the knowledge base in order to design the hybrid burner.
3. Maintain (or improve) original gas turbine output and efficiency levels; design to be compatible with goals for reaching 60% CCGT efficiency.
4. Minimise machine changes necessary for the integration of the catalytic burners in gas turbines, by using the hybrid approach.

The specific scientific and technical objectives are to:

1. Develop a hybrid burner consisting of catalytic and lean premix (LPM) elements, which is retrofittable to existing gas turbines. This involves the following aspects:
   - Development of catalysts for (a) low (< 400°C) light-off temperatures and (b) high-temperature (950°C) stability, and of catalytic reactors which achieve fuel

conversions > 40% at T_{in} • 400°C and 15 to 20bar (the remaining fuel conversion taking place in the lean premix combustion section). The catalyst reactors must retain these characteristics after completing lifetime (1000 hours) tests at high pressure. Activity will be extrapolated to 20000 hours with appropriate models.
   - Aerodynamic design of a fuel/air mixer (mixedness better than ± 15K at 1800K) and a catalytic swirl generator.
2. Quantify the effect of catalytic combustion, by means of full-scale, atmospheric tests, on:
   - NOx and CO abatement (target: <3ppmv NOx and <10ppmv CO @ 15% O_2 at 50-100% load, for natural gas fuel).
   - extension of stability limits (reduce lean blow-out temperature by 100°C).
   - pressure pulsations (<< 0.3% of pressure).
3. Aim for high reliability levels of the hybrid burner by:
   - optimising catalyst formulations and support structures.
   - designing such that operation in 100% lean-premix mode is possible in the event of extreme deactivation of the catalysts.
4. Enhance fuel flexibility by:
   - undertaking research for the catalytic combustion of other fuels (such as biogas and syngas, and mixtures of these with natural gas); findings could be used to develop future catalytic modules in the hybrid burner for, say, NOx reduction in biogas combustion.
   - allowing for the post-catalytic combustion of liquid fuels such as petroleum distillates.
5. Develop an operational concept for the successful operation of a gas turbine. This would include start-up, shut-down and load-change routines that allow the hybrid burner, using both main and pilot catalytic reactors, to cover as large as possible a load range, over which emissions and pulsations are minimised.

Table 5 summarises the specifications of the various components of the hybrid burner.

Component	Specification
Catalytic reactor	• Overall air/fuel ratio: $\lambda \approx 2$ • Length ≈ 200mm, consisting of multiple stages • $\Delta P < 2.0\%$ at 20bar • Performance targets: – 1st stage: $T_{in} \leq 400°C$, $T_{out} \leq 750°C$ – 2nd stage: $T_{in} \geq 750°C$, $T_{out} \leq 950°C$
Mixer	• Mixing quality target: $\lambda = 2.0 \pm 1.5\%$ ($T_{ad} = 1800K \pm 15K$, based on $T_{in} = 450°C$) • Length < 200mm • $\Delta P < 0.5\%$ at 20bar.
Swirl generator	• Provide aerodynamic stabilisation in event of deactivation of the catalytic reactor. • Length < 50mm • $\Delta P < 0.5\%$ at 20bar.
Piloting lance	• Target: produce sufficient syngas for homogeneous flame stabilisation • Diameter ≤ 50mm • $\Delta P < 3.0\%$ at 20bar • Compatible with current liquid fuel injection designs.

Table 5: Component specification table.

Description of Work

It is clear from the previous discussions that the advanced, hybrid burner consists of a number of novel components which require considerable research and development. These devices must be individually designed and tested, and subsequently integrated to form the burner in its entirety. Figure 2 illustrates the design process. Optimisation of each component dictates that the design & test process be iterated several times until the specifications listed in table 4 are matched. The complete burner will then be subjected to full-size, atmospheric tests which, it is anticipated, will reveal the need for further component optimisation. Full-scale tests will subsequently be conducted upon the prototype hybrid burner, in order to assess its technical merits.

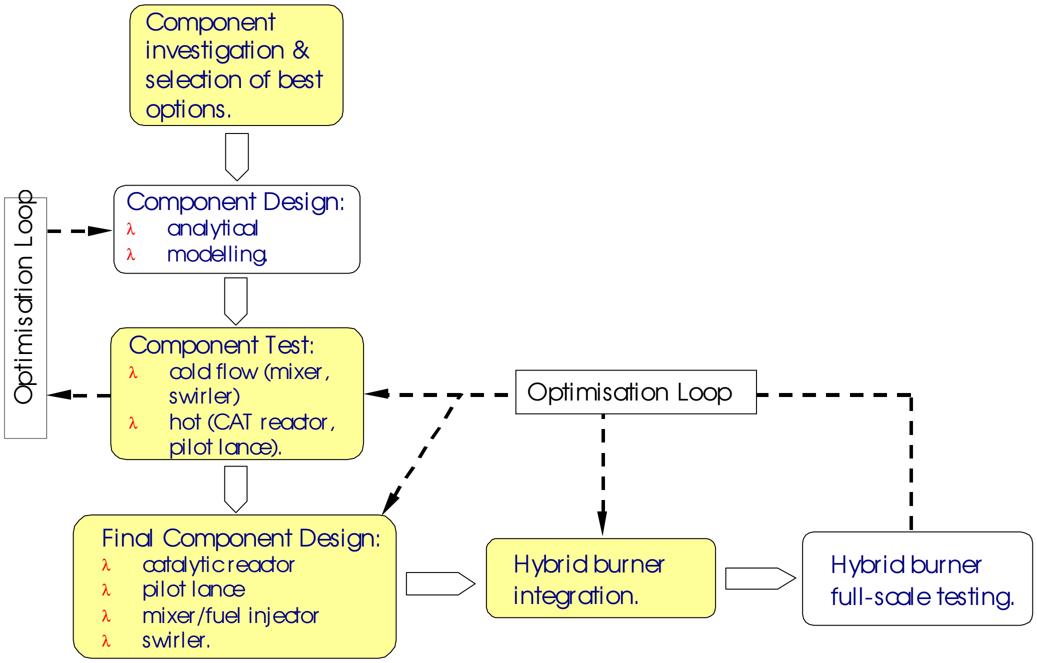
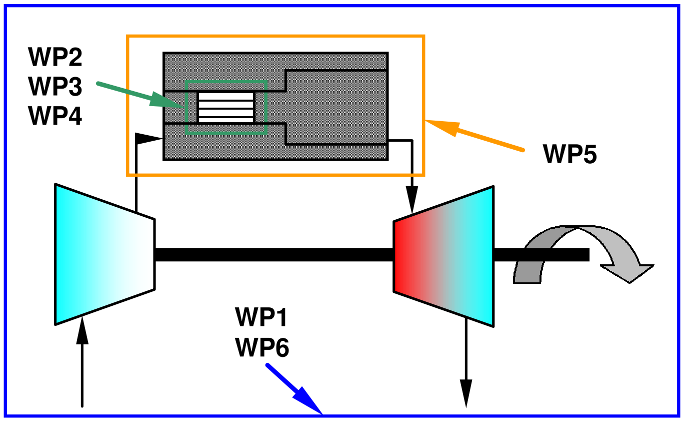


Figure 2: Illustration of the design and integration process.

Extensive background research must be undertaken in order to design the catalytic reactors to the specified performance requirements. In light of these research requirements, the tasks within the project have been split up into the discrete, self-contained work packages depicted in figure 3. Overall project management is the focus of work package (WP) 1. The hybrid burner is composed of a number of distinct components that are the subject of individual work packages and tasks. Work packages 2, 3 and 4 focus on the development, testing and optimisation of the catalytic elements within the burner. The specific goals of these work packages are catalytic material development, catalyst reactor design, and catalyst component testing, respectively. Work package 5 focuses on the aerodynamic design of the hybrid burner, including the fuel/air mixer, swirl generator, piloting lance and design of the post-catalyst burnout zone. It also involves the integration of all the catalytic and aerodynamic devices to form the full-scale, hybrid burner, and its subsequent atmospheric testing. Work package 6 deals with the integration of the burner concept within gas turbines to determine boundary conditions for design and testing, as well as developing operating concepts.

The programme content is structured such that each of the partners develops its individual know-how in its particular area of expertise, and delivers concepts, designs and components which can then be integrated to form the advanced, hybrid burner, via the processes and organisation highlighted in figures 2 and 3. The necessary work packages are organised in a clear and logical manner, with the tasks allocated so as to avoid overlap between the partners' core competencies.



1. Project management
2. Catalyst material development
3. Reactor design
4. Catalyst component testing
5. General burner design
6. GT integration

Figure 3: Inter-relationship between work packages.

Consortium

The project consortium draws its members from six European nations. The fields of expertise of the various partners are vertically integrated in a manner which spans an entire spectrum of activities, from fundamental research to the development of machinery. Such a grouping contributes unique knowledge, skills, experience and facilities, the combination of which are vital for the undertaking of the Cathlean project. Additionally, several US groups have been selected for collaboration in this project. This permits existing ties to be further promoted, and provides benefits associated with synergistic activies. Figure 4 provides an overview of the key partner activities. It is evident that such a significant array of expertise and facilities can only be assembled within the framework of a large, international R&D programme.

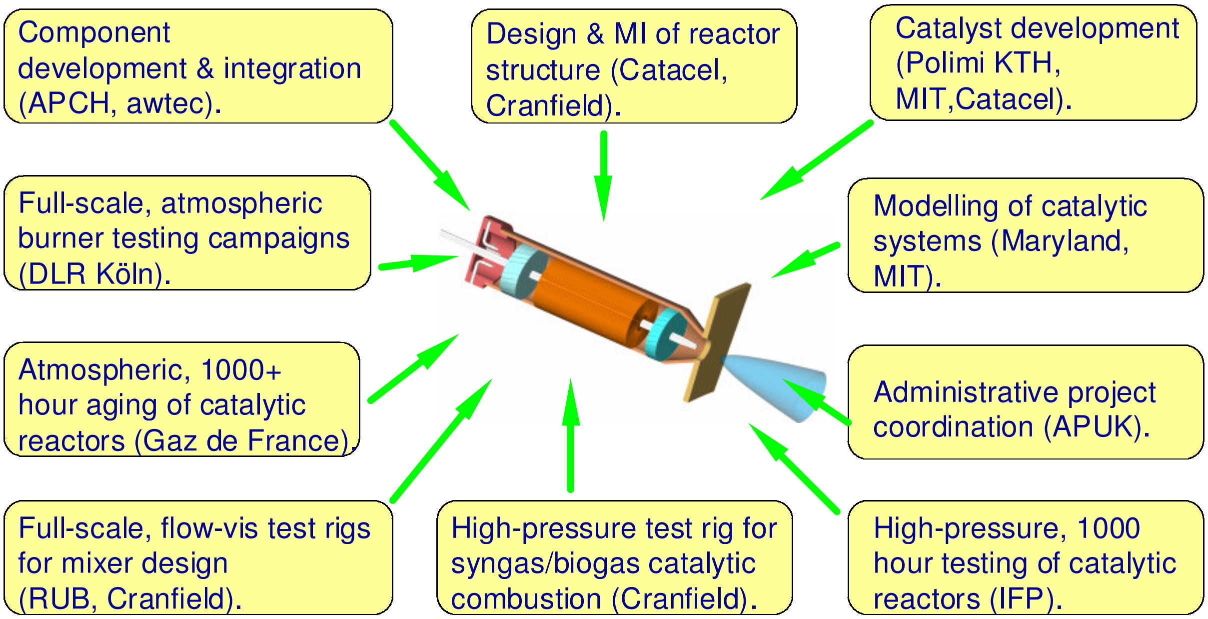


Figure 4: Key activities of the various consortium partners.

SUMMARY

The state-of-the-art has been presented for catalytic combustion application to gas turbines, and important machine integration issues have been discussed. Consideration of integration issues has revealed that this technology could be more widely accepted by gas turbine manufacturers and operators if it were designed for greater compatibility with machines, particularly in terms of retrofittability. An advanced, hybrid burner, designed to introduce the benefits of catalytic units in a lower-risk, retrofittable manner, has been described, and the stringent boundary conditions for this burner have been set. The ultimate goal of the 3 year EU project is to develop a prototype burner and compare it in full-scale tests with current, lean premixed technology in terms of:

- NOx and CO abatement (target: <3ppmv NOx and <10ppmv CO @ 15% O_2 at 50-100% load, for natural gas fuel).
- extension of stability limits (target: reduce lean blow-out temperature by 100°C).
- pressure pulsations (target: << 0.3% of pressure).

Detailed component specifications have revealed that novel solutions are required in both catalytic and aerodynamic subject areas. The manner in which the fruits of the research will be transferred into the component design and burner integration processes, has been defined. Finally, the overall organisation of the project was outlined, demonstrating that the programme, despite its extensive scope and consortium volume, is structured in a clear and logical manner and enjoys the support of the consortium's extensive experience, skills and facilities necessary for attaining the ambitious goals.

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