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13. ABSTRACT (Maximum 200 words) 45 scientists and engineers from 7 countries participated in the "Flameless Combustion" workshop that was sponsored by Dr. Gabriel Roy of ONR. During the two and half days workshop that took place in Lund, Sweden, on June 19-21, the foremost experts in this new field of research, reviewed experimental, computational, and modeling investigations on this topic. Representatives from industry, academia, and government agencies provided their perspectives regarding this emerging technology. The workshop concluded by extensive discussions on the technology state-of-the-art and future roadmap. "Flameless Combustion" is characterized by high stability levels with virtually no thermoacoustic instabilities, very low lean stability limits and therefore extremely low NOx production, efficient and rapid oxidation of CO in the distributed flame, and a uniform temperature pattern factor at the combustor exit. The high oxidizer temperature requirement makes Flameless combustion well suited for the more thermodynamic efficient high pressure ratio propulsion and power systems that have high compressor discharge temperatures. These characteristic of "Flameless Combustion" are very desirable characteristics for future gas turbine engines and for advanced ramjet propulsion. The proceedings of the workshop are available on CD and the final manuscripts will be published in a book.				
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FLAMELESS COMBUSTION **WORKSHOP**

(LUND, SWEDEN, JUNE 19-21, 2005)

Final Report

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September 20, 2005

Submitted to:
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SUMMARY

45 scientists and engineers from 7 countries participated in the "Flameless Combustion" workshop that was sponsored by Dr. Gabriel Roy of ONR. During the two and half days workshop that took place in Lund, Sweden, on June 19-21, the foremost experts in this new field of research, reviewed experimental, computational, and modeling investigations on this topic. Representatives from industry, academia, and government agencies provided their perspectives regarding this emerging technology. The workshop concluded by extensive discussions on the technology state-of-the-art and future roadmap.

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The proceedings of the workshop are available on CD and the final manuscripts will be published in a book. All the abstracts and papers that were presented in the workshop are included in this report.

Further information is available from Dr. Ephraim Gutmark, E- mail: egutmark@hotmail.com



FLAMELESS COMBUSTION **WORKSHOP**

LUND, SWEDEN
JUNE 19-21, 2005

Book of Abstracts

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Agenda: Flameless Combustion Workshop, Lund, Sweden, June 19-21, 2005

Welcome RECEPTION on Sunday Evening, June 19, 2005	Dinner at the conference hotel in Lund	1800-2000
DAY 1 - June 20, 2005		
BREAKFAST		0700-0800
Welcoming remarks	Dr. Gabriel Roy, ONR, USA	0815-0830
Tribute to Prof. Jim Whitelaw	G. Roy, P. Lindstedt, others	0830-0900
Introductory Session	Session Chair: Dr. R. Hancock, AFRL	
Gaps in current GT technology	Ulf Linder, Head of Technology, Siemens	0900-0915
Introductory review: Current needs in airbreathing propulsion and power combustion technology	M. Cornwell, Goodrich Aerospace, USA	0915-0945
Industrial Perspective	Session Chair: Ulf Linder, Siemens	
FLOX Burner Technology - Existing and Promising Industrial Applications	Dr. J. Wuenning, WS Wärmeprozessstechnik GmbH, Germany	0945-1015
BREAK	Coffee	1015-1030
New Burner Systems for Gas Turbines – Overview about the EC NGT Project	M. Flamme, GWI-Essen, Germany	1030-1100
Modeling and Simulations	Session Chair: C. Dopazo, Spain	
Chemical Kinetics of Flameless Combustion	P. Lindstedt, Imperial College, UK	1100-1130
The Application of CFD as a Practical Design Tool for Flameless Combustors	D. Black, CFD Research Corporation, USA	1130-1200
BREAK	Lunch	1200-1330
LES as Modeling Tool for Flameless Combustion	L. Fuchs, LTH, Sweden	1330-1400
Modeling Technique for Flameless Combustion	E. Vaos, P. Lindstedt, M. Persson and V. Milosavljevic, Imperial College, UK, Siemens, Sweden	1400-1430
Airbreathing Combustion	Session Chair: Dr. G. Roy	
Application of Flox Technology to Ramjet Combustion	Dr. C. Bruno, Italy	1430-1500
Application of FLameless Combustion (FLC) for Ultra-	H. Mongia, GE Transportation, OH, USA	1500-1530

low Emissions Propulsion Engines.		
BREAK	Coffee	1530-1545
Trapped Vortex Combustion Technology	R. Hancock, AFRL, Dayton, OH, USA	1545-1615
Review of the Low NOx FLOXCOM Gas Turbine Combustion	Y. Levy, Technion, Israel Institute of Technology, Israel	1615-1700
LTH Lab visit, Demonstration of Flox Burner and visit to HP test facilities (by bus).	L. Fuchs, M. Alden, LTH, Sweden	1730-1900
Dinner: In a Swedish Castle (by bus-70 SEK/person)		1900-

DAY 2 - June 21, 2005		
BREAKFAST		0700-0800
General Comments	Dr. Gabriel Roy, ONR, USA	0815-0830
Experimental Results	Session Chair: Dr. O. Paschereit	
Experience of FLOX [®] combustion at high pressure	Rainer Lueckerath, DLR	0830-0915
On the Transition to MILD Combustion: Experimental and Computational Study	B. Dally, U. Adelaide, Australia	0915-0945
Flameless Combustion, FLOX Burner Technology, Gaseous Fuel Application	Alain Quinqueneau, Gaz de France	0945-1015
BREAK	Coffee	1015-1030
Catalytic Combustion Technology	J. McCarty, Catalytica, CA, USA	1030-1100
Dissemination of HiTAC Technology and HiTAC burner for Compact Heating Equipment	Weihong Yang, KTH, Sweden	1100-1130
Burner Technologies for Use of Low Calorific Fuel Gases in Gas Turbines	M. Flamme, GWI-Essen, Germany	1130-1200
BREAK	Lunch	1200-1330
Experimental Investigation of Flameless burners	E. Gutmark, University of Cincinnati, USA	1330-1400
Comments regarding panel discussions	V. Milosavljevic, E. Gutmark	1400-1410

Panel Summary	Session Chair: Dr. M. Aigner	
Industry Summary	M.Flamme/Wuenning	1410-1430
Aero Summary	C. Bruno	1430-1450
GT Summary	Y. Levy	1450-1510
BREAK	Coffee	1510-1530
Modeling summary	L. Fuchs/C. Dopazo	1530-1550
Chemical Kinetics	P. Lindstedt	1550-1610
Open discussion	All	1610-1630
Closing remarks	Dr. Gabriel Roy, ONR, USA	1630-1700
Adjourn		
Evening in Lund/Copenhagen TBD		

Introductory Review: Challenges and Opportunities in Flameless Combustion for High Pressure Ratio Gas Turbine Engines

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Gas turbine combustion must be stable with wide stability limits, free of thermoacoustic instability and be thermally efficient. It is also desirable for gas turbine engines, especially for commercial engines that are responsible for the majority of operating hours, to produce low emission levels of NO_x, CO and UHC. Gas turbine combustion stability has increasingly become a crucial design issue as engines operate leaner and at higher pressure ratios in order to improve engine efficiency. Military and civil aerospace engines need to have stable combustion with wide turndown ratios to prevent engine flameout over the entire operational envelope.

Industrial gas turbine engines have been switching to lean partially premixed combustion to operate lean for lower NO_x production rates. This form of combustion has proven to be very unstable and generally not well suited for aircraft engines. Some industrial furnaces and boilers, especially in Europe and Japan, have started to utilize "Flameless Combustion" where the fuel reacts with a very high temperature oxidizer with intense levels of turbulence producing a highly distributed reaction zone. The turbulence levels of the Flameless Combustion is so high that if operated at the current diffusion flame combustion technology, the heat and reactive free radicals would be rapidly and widely dispersed and the combustion would be unstable at lean conditions. When the oxidizer temperatures are very high, these high Damköhler number "Flameless" reactions become very stable. It is the distributed nature of these flame that lead to the term "Flameless Combustion". Visually what is observed is a blue glow without a discrete flame front. In the industrial furnace application of Flameless Combustion, the high oxidizer temperatures required are obtained by either preheating the air with a heat exchanger and furnace exhaust gases or by direct mixing of the air with hot recirculated exhaust gas.

The desirable characteristics of "Flameless Combustion" are the high stability levels with virtually no thermoacoustic instabilities, very low lean stability limits, efficient and rapid oxidation of CO in the distributed flame, and a uniform temperature pattern factor at the combustor exit. The high oxidizer temperature requirement may make Flameless combustion well suited for the more thermodynamic efficient high pressure ratio engines that have high compressor discharge temperatures. These characteristic of "Flameless Combustion" are very desirable characteristics for current gas turbine engines and the future higher pressure ratio engines.

The challenges in implementing "Flameless Combustion" to gas turbine engines are the high oxidizer temperature requirements and the operation at elevated pressures. To date virtually all applications of "Flameless combustion" has been at atmospheric pressure. The higher chemical reaction rates at higher operating pressure may make it more difficult to distribute the flame, resulting in operation closer to the flamelet region than the well stirred reactor region. The higher operating pressure of gas turbine engines compared to industrial furnaces will also result in more rapid relaxation of free radicals such as OH towards the lower equilibrium levels corresponding to higher pressure equilibrium thermodynamic state. This could also tend to make the flame less distributed at high pressure. The high oxidizer temperatures needed for flameless combustion requires transition from an initial combustion form, such as turbulent diffusion flame, at ignition and low power settings, when the air and exhaust gas temperatures are too low for flameless combustion. Engine compression ratio alone is unlikely to produce sufficiently high oxidizer temperatures for most gas turbine engines to operate in the Flameless mode; oxidizer mixing with recirculated exhaust gas will be needed for preheating. The required amount of mixing with exhaust gases is directly dependent upon the compressor discharge temperature available. Optimization of flameless combustion designs to produce the high levels of turbulence required for Flameless operation without an excessive pressure drop and loss of engine performance is needed. Another unknown in the operation of gas turbine engines with flameless combustion is operation at equivalence ratios near stoichiometric. Flameless combustion has been used in the industrial application where extremely low NO_x levels are desired, so very lean equivalence ratios have been used. The operational experience of Flameless Combustion for non-lean conditions is limited. Excessively lean combustion in gas turbine engines reduces engine power and efficiency. This is less of an issue in furnaces where

there is no high performance penalty of compressing the excess air to high pressure and from the high mass and drag of an oversized compressor and turbine.

The application of Flameless combustion to gas turbine engines has sufficient potential performance rewards and challenges to make it an exciting field of research and application in the gas turbine community.

FLOX Burner Technology

Existing and Promising Industrial Applications

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Flameless Combustion (FLOX^{®1}) was first developed to suppress thermal NO_x formation in burners for heating industrial furnaces using preheated combustion air.

While this technique is applied in large numbers now, there are a number of other applications emerging. The presentation will give an introduction into flameless combustion including experiments and computer simulations. Industrial applications and emerging applications which are at a research stage will be discussed.

¹ FLOX[®] - registered trademark of WS Wärmeprozessstechnik GmbH, Renningen, Germany

New Combustion Systems for Gas Turbines – Overview about the EC NGT Project

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In the frame of an EC project the burner systems of flameless combustion concept “FLOX®” and continued staged air “COSTAIR” have been investigated in depth by eleven European partners for use in gas turbine combustors. The investigations have been made for both, gaseous and liquid fuels. The tools used were experimental investigations at the relevant pressure levels associated with CFD simulation work, fundamental studies and model enhancements. Additionally, combustion chamber design was made by the gas turbine manufacturers involved. The advantages of both combustion concepts have been evaluated at two test rigs at the end of the project.

Results achieved proved:

- ***Safe and reliable operation of gas turbine combustors***
- Low emissions of NO_x, CO and UHC

These results have clear economically usefulness by improving the stability of the combustion process and avoiding the flame flash back as well as an ecological effect by protecting the environment. The application and exploitation of these results will be:

- In-house through the industrial project partners
- By offering licences to third parties
- Through publications made in journals and by students teaching at the universities involved.

Chemical Kinetics for Flameless Combustion

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The modeling of chemical kinetics for high temperature oxidation processes has advanced rapidly over the last decade. For small hydrocarbons the resulting mechanisms can now be used in a predictive sense and much progress is being made for the higher alkanes and aromatics typical of liquid fuels. The low and intermediate temperature window of 700 to 1200 K is less well established and of direct relevance to flameless oxidation. The additional complications include stabilization of oxygen adducts, such as those responsible for the NTC region, and increased sensitivity to pollutants such as nitric oxide. The application of chemistry in the context of calculation methods for high temperature devices is commonly based on the reasonable estimate that stable species concentrations and the heat release for conditions away from ignition/blow-off can be computed through the use of high Damköhler number approaches. As the temperature is reduced, such approximations are increasingly problematic as the chemistry slows down significantly. The current contribution will highlight some of the key differences between the chemistries of the conventional and FLOX[®] type devices with implications for calculation methods. Particular emphasis will be given to pollutant formation and the auto-ignition behavior of different fuels.

The Application of CFD as a Practical Design Tool for Flameless Combustors

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The application of CFD as a design tool for flameless combustors presents new challenges, as the behavior in flameless combustion is very different from what is encountered in the modeling of conventional combustor concepts. Modeling flameless combustion will require new methods to realistically capture the important physical phenomena that govern the combustion behavior. Successful simulations of flameless combustors will be more dependent on the kinetics, specifically with respect to capturing behavior at high inlet temperatures with depleted oxygen concentrations. In the design and analysis of conventional combustors, the most common approach to kinetics in turbulent flows is to use single-step chemistry with a turbulence-chemistry interaction model or the laminar flamelet model. Neither of these approaches will be adequate for the design of flameless combustors. Multi-step mechanisms that more accurately represent the kinetics in the distributed reaction zone will be needed. Computationally efficient approaches to address turbulence-chemistry interaction in the distributed reaction zones with these multi-step reaction schemes will also be essential.

In flameless combustion, high temperature products must be mixed with air, and then fuel must be injected in a way that allows for mixing to occur before reactions take place. Developing schemes capable of accomplishing this mixing within the size constraints of gas turbines is one of the key challenges in the design of flameless combustors. Increasingly accurate predictions of fuel/air mixing will make CFD a more useful tool to the combustor designer in analyzing design concepts that meet the demanding mixing requirements of flameless combustors. Other phenomena, such as flame quenching due to aerodynamic strain, that can often be neglected in the analysis of conventional combustors will also be important as well. Flame quenching can be important in characterizing the delay in the reactions when the fuel is injected.

CFDRC is actively developing CFD capabilities for RANS and LES to meet the needs of the combustion engineer for a practical design tool. A computationally efficient turbulence-chemistry interaction model for multi-step mechanisms is being developed that will be applicable to the design of flameless combustors. The new assumed PDF method has relatively modest computational expense and does not become increasingly expensive with the number of species being used. There is also a need for kinetics that accurately captures ignition delay with depleted oxygen concentrations. Techniques for automatically generating appropriate reaction mechanisms are being developed using Chemical Reactor Modeling (CRM) methods and optimization algorithms. In this approach, 0D and 1D calculations (laminar flame, opposed diffusion flame, perfectly stirred reactor, and plug flow reactor), are performed using detailed mechanisms to generate the data needed to determine the Arrhenius rate parameters in the global mechanism. This paper will present a discussion of the challenges and needs related to the application of CFD in the design of flameless combustors, along with a description of the ongoing work designed to meet these challenges.

Large Eddy Simulation as modeling tool for flameless combustion

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The flameless combustion mode has a potential for designing clean and stable combustion devices. The main idea is to avoid rapid and intense heat release in a small region within the combustion device. Doing so, one reduces the risks for the formation of local hot regions (which is often the main source of NO_x), reduces the acoustic source due to combustion unsteadiness (i.e. thermo-acoustic instabilities) and enables a better control of the combustion process. The main challenge for designing such a burner is to achieve an efficient mixing between a very lean

fuel/air mixture and hot burnt products. The dilution of the fresh gases with hot burnt gases enables to maintain the combustion.

We study numerically the flameless oxidation process in a burner designed by Siemens, Sweden. The geometry is essentially a rectangular box. The fuel/ fresh air are injected through 12 nozzles. The 12 resulting jets induce flow recirculation. Recirculating gases bring hot gases to the fresh mixture and stabilize the combustion. Since a good description of the mixing is mandatory for the combustion process, Large Eddy Simulation has been used to simulate the turbulent stirring, mixing and combustion in the device. The combustion is accounted for by a single step Arrhenius expression.

We shall present numerical results related to the case studied experimentally at the Division of Combustion Physics at Lund University. The presentation will include a description of the flow and combustion dynamics as well as comparisons with available experimental data.

Modeling Techniques for Flameless Combustion

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There is currently a significant need in industry to be able to predict turbulent reacting flow fields in practical devices such as gas turbine combustion chambers. Much effort has been put over the last few years to develop methods that take into account the interactions between flow and chemistry. The inclusion of finite rate chemistry makes it possible to accurately predict emissions and local extinction and re-ignition phenomena. The present study explores such

effects using a two-step calculation procedure. Initially, a two-scalar (mixture fraction and progress variable) presumed PDF laminar flamelet type approach is used to calculate the partially premixed reacting flow in a FLOX combustor at 20 bars. Since the combustion chamber is hexagonal, a 60° sector is modeled with 260000 cells and cyclic boundary conditions. Second moment closures are used for both the Reynolds stresses and the turbulent scalar fluxes. The presumed PDF simulation is used to generate initial/boundary conditions for a transported PDF calculation, closed at the joint-scalar level and featuring an augmented systematically reduced reaction mechanism, applied to the jet emerging through one of the nozzles. In transported PDF methods, the chemical source term appear in closed form and finite rate chemistry is included in a natural manner.

Application of Flox® Technology to Ramjet Combustion

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Combustion technology based on premixing reactants with combustion products has demonstrated that efficiency and emissions may be improved for some industrial applications, notably furnace burners.

Work in progress in EU is developing applications to gas turbines. The main advantage in this case is lower emissions and better temperature uniformity, possibly leading to better pattern factors, provided the radial and circumferential temperature profile may be tailored to the geometry of vanes and that of the turbine first stage.

An interesting question is then, what the next step could be in other aeroengine applications. Conceptually at least, the next step could be in the ramjet area. Ramjets are characterized by a simple combustion chamber, where typically air is made to recirculate sufficiently (for enough residence time) to enable good combustion efficiency. Also typically, the pressure drop tends to be rather high, as most chambers are shaped as dump combustors, and flame anchoring ensured by bluff bodies of some sort. Both these common ramjet features tend to result in large amounts of turbulent KE creation that gets eventually dissipated at the fine scales. This fact implies also large pressure drop, but is often overlooked in view of the disposability and relative cheapness of the application. This may change if there is a desire to increase performance without excessive extra costs due to technological innovation (e.g., high temperature materials).

Work performed in this group in 2003-2004 has shown that the Trapped Vortex Combustor (TVC) may be configured in such way as to mix air, fuel and hot products at turbulent scales fine enough that the combustion mode is in fact flameless, or close to flameless. This has been shown by RANS and LES simulations for three different gaseous fuels, namely hydrogen, methane and propane. Experiments planned to confirm this finding at the Italian National energy laboratories (ENEA) have been unfortunately put off for the time being, but, based on the theoretical considerations extracted from LES simulations, it seems possible that a mainly "flameless" combustion mode at high air flowrate velocity can be achieved in aeroengine combustors by means of appropriately shaping them as TVCs. Since the flameless strategy requires recirculation of hot combustion products within the combustion chamber, it seems reasonable and feasible to achieve a mostly flameless combustion based for high velocity regimes by means of trapping a toroidal vortex in a cavity. As already known, a vortex ensures a high recirculation factor, K_v , of hot combustion products, and ultimately flame stability. A flameless regime is considered achievable if $K_v > 3.5 - 4$ (it means up to 75 - 80% of the total amount of the gas in the combustion chamber is constituted by hot combustion products). In a TVC the K_v is around 18-22 (95% of recirculation means $K_v = 20$).

If this is indeed true, the immediate advantage will be in the lowered pressure drop, and reduced or totally suppressed need for flame anchoring devices such as gutters. This tentative conclusion dovetails with similar experiments done at US WPAFB to anchor SCRJ flames using cavities.

Similar work was or is still underway also in India, and in Japan (where the concept has been tested also for SCRJ flame anchoring).

The purpose of this paper is to show what to expect in simple ramjet type combustor when using a strategy based on TVC leading to flameless combustion. Both analytical results and simulations will illustrate this strategy, showing pressure drop predicted, combustion efficiency and temperature distribution at the combustor outlet. The geometry chosen for ramjet combustion chambers are different than for gas turbines, as the requirement typically dictates small cross sections. Thus a simple axi-symmetric geometry seems at this stage better than an annular one.

Flameless Combustion for Ultra-low Emissions Propulsion Engine Combustors

Dr. Hukam Mongia

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Prompted by environmental considerations, several low-emissions propulsion combustion concepts are being pursued by industry, research laboratories and academic community including TALON, Tapped-Vortex, High-g, Lean Direct Injection, Triple-Annular Research Swirlers (TARS), and Twin-Annular Premixing Swirlers (TAPS). These concepts are discussed leading to the next-generation of ultra-lean combustion concepts based partly on the exploitation of the underlying principles of flameless combustion.

Trapped Vortex Combustion Technology

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This paper presents an overview of the development and evaluation of trapped-vortex-stabilized combustor concepts for low-emissions, high-performance gas turbine engines. Trapped-vortex stabilization was first pursued by the Air Force as part of an Air Force Office of Scientific Research (AFOSR) program in 1993. Since then, it has evolved from a fundamental study to a development/evaluation program involving sector-rig experiments and small full-annular rigs operating at realistic conditions. Its development is motivated, in part, by concerns about NO_x emissions generated by gas turbine engines used for aircraft and stationary power. Trapped-vortex stabilized combustors depart from the traditional swirl-stabilized designs of the past. This combustor has two parts, a pilot for stability and a main for power. The pilot utilizes cavities to establish the recirculation zones needed for stable combustion. Each cavity is sized to provide a stable recirculation zone that is often referred to as a "trapped vortex". Fuel and air are injected into the cavities in a way that reinforces the vortex that is naturally formed in the cavities. Results indicated significant improvements in ignition, blow out, altitude re-light, NO_x emissions, and operating range.

Vortex-stabilized combustion technology is also being used in the development of ultra-compact combustors (UCC) for gas turbine engines. A very compact combustor can help reduce engine length and weight for traditional Brayton-cycle engines. Additionally, the potential exists to take a very small combustor like the UCC and put it between the high- and low-pressure turbines. Such a combustor has been called an Inter-Turbine Burner (ITB). This combustor enables a near-constant-temperature cycle that has the promise of providing large amounts of power extraction from the low-pressure turbine for a modest temperature rise across the ITB. The

additional energy can then be used to power a large fan for an ultra-high bypass ratio transport aircraft, or to drive an alternator for large amounts of electrical power extraction. Conventional gas turbine engines cannot drive ultra-large diameter fans without the use of excessive turbine temperatures, or a substantial number of turbine stages. In addition, these conventional engine systems cannot meet high power-extraction demands without a loss of engine thrust. This paper highlights some of the ultra-compact combustor (UCC) and ITB development work being conducted at the Air Force Research Laboratory Propulsion Directorate.

REVIEW OF THE LOW NO_x FLOXCOM GAS TURBINE COMBUSTION

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The present work relates to NO_x emission reduction in power plants by the utilization of flameless oxidation in adiabatic combustors. The FLOXCOM research program is concerned with the novel low NO_x combustion technology for gas turbines and jet engines. Its specific characteristics are minimum emissions while maintaining combustion stability. It is characterized by mixing a significant amount of exhaust gases with the fresh air before entering the combustion zone. This mixing takes place in the recirculation zone that is achieved through a specific design of the combustor. Such internal recirculation elevates the temperature of the reactance while modifying its chemical composition. The advantage of the technique is its ability to maintain stable combustion even at relative low local equivalence ratios, thus minimizing high temperature zones and their associated NO_x generation. The design of combustion chamber operating in the flameless oxidation regime for gas turbines and jet engines application was

patented (US Patent No. 6,826,912, 2004). Several models were built and tested through the FLOXCOM consortium, conducted within the 5th EC Framework.

The present paper is concerned with the analysis and design rules of the FLOXCOM combustor that allows systematic approach for determining its geometrical and operational characteristics. The analysis is based on modeling the combustion processes as a sequence of stages, where each one is nearly independent of the other. Each step is analyzed in terms of the local aerothermodynamic characteristics, coupled to the specific chemical reactions as determined by dedicated shock tube testing and CHEMKIN simulation. This allows defining characteristic time for each step. When characteristic velocities are determined, general dimensions can be specified.

A general description of the FLOXCOM combustor, its principal of operation, its modeling, analysis and results of current experience are described.

Experience of FLOX[®] Combustion at High Pressure

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Flameless Oxidation (FLOX[®]) has been successfully used for many years in technical furnaces under atmospheric conditions with very low NO_x emissions. In the European project NGT (*New Combustion Systems for Gas Turbines*) the applicability of this combustion system was investigated with regard to the use in gas turbines at high pressure. The size and position of the flame zone in FLOX[®] combustion depend on the strong internal recirculation of the flue gas driven by the high jet velocities at the FLOX[®] nozzles and the arising strong dilution of the fresh air/fuel mixture. The advantage of the FLOX[®] mode is a large and homogeneous flame zone

resulting in lower peak temperatures and therefore in lower NO_x emissions. This behaviour established for atmospheric FLOX[®] conditions could be also verified for typical gas turbine conditions at high pressure with NO_x and CO emissions of a few ppm. Compared to lean premixed combustion additional advantages of the FLOX[®] combustion are the extended stability range, the reduced thermoacoustic instabilities and the prevention of flashbacks.

At the high pressure test rig of the DLR in Stuttgart experiments were performed with a FLOX[®] burner with 12 nozzles operated with natural gas at pressures up to 30 bar and thermal power up to 475 kW. The influence of the mean velocity at the exit of the FLOX[®] nozzles was investigated in detail for different thermal powers. The emissions of NO_x and CO were below 10 ppm for a wide range of air/fuel ratio. In a combustion chamber with good optical access the size and position of the flame zone were visualized with an OH^{*} chemiluminescence measurements. Information on relative temperature distributions were determined with 2-dimensional laser-induced fluorescence experiments on the OH radical. From the instantaneous images of the optical diagnostics, information on the fluctuations of the size and position of the flame zone and of the relative temperature distributions were obtained.

On the Transition to MILD Combustion: Experimental and Computational Study

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It is now well established that heat and gas recirculation offer a great potential to increase thermal efficiency and reduce emission of pollutants. Moderate and Intense Low oxygen Dilution, MILD combustion is one such method which capitalize on this approach. During the last decade this approach has seen great advances mainly in furnace applications, notably in Japan and Europe. The burner designs used in these applications achieve the required combustion mode. However the optimization of the burner designs and the extension of this

technology to other applications require basic understanding of the controlling parameters of these reactions and a robust modeling approach.

A laboratory scale burner and furnace were used to investigate the detailed structure of turbulent jet diffusion flames in the transition to MILD combustion. The effect of air dilution, fuel mixture and Reynolds number were investigated experimentally.

Simultaneous planar imaging of three scalars was also conducted to provide insight into the spatial structure of the flames in the transition to MILD combustion. In addition, a computational study of these flames using well established combustion models with varied complexity is underway. These studies help provide valuable detailed experimental data at well defined boundary and initial conditions to allow accurate comparison with modeling data.

For a methane/hydrogen jet fuel mixture issuing into heated and diluted coflow, at different oxygen levels, it was found that the transition to MILD combustion leads to three fold reduction in reaction zone width, 400K drop in reaction zone temperature and three fold drop in CO and OH mass fractions. It was also found that downstream oxygen leakage can cause substantial change to the flame structure and leads to localized extinction.

The current available stability diagram is limited to methane based fuels while other hydrocarbon fuels exhibit different characteristics for similar conditions. Establishing MILD combustion via a high momentum jet does not always work and does not lend itself to high modulation ratio. Mixing the fuel with recirculated products provides a more robust and achievable approach. It opens the way to reduce the coupling of the mixing process inside the furnace and the establishment of MILD combustion. Diluting the fuel with products shift the stoichiometric mixture fraction to higher values where the scalar of dissipation is also high. Such approach extinguishes the flame at the exit plane and provides the conditions needed for MILD combustion.

Detailed chemical kinetics are required to accurately model the intermediate species and NO mass fractions. Differential diffusion effects are also important as the heated surroundings acts to laminarize the flow and enhance the molecular diffusion effects. Reduced oxygen in the oxidant

stream slows the reaction down and leads to chemical time scales closer to turbulent mixing time scales which then necessitate the use of sophisticated combustion models to account for the interaction between turbulence and chemistry.

OVERVIEW OF THE GAZ DE FRANCE R&D ACTIVITIES ON FLAMELESS OXIDATION APPLIED TO HIGH TEMPERATURE PROCESSES

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The concentration of NO_x from first generation designs of regenerative burners are known to be such that they significantly exceed the 'achievable release levels'. For more than fifteen years now, numerous studies have been performed in Japan, Germany, and USA to develop new types of burners operating with high temperature combustion air (over 1000 °C) while not only reducing NO_x emissions, but also increasing furnaces temperature uniformity (by suppressing hot spots). Today, several manufacturers have commercialized this type of burners. Industrial demonstrations have been mainly validated in Asia (slab, billet or reheating furnaces, etc). These new types of burners operate in the « flameless oxidation » mode. In Europe, the first demonstration appeared several years ago.

Massive utilization of these techniques on industrial scale installations will only be possible if reliable prediction tools are available to study the different options to modify existing or develop new furnaces. Moreover, it seems interesting to install such technologies in other industrial sectors (ceramics, petrochemicals, glass melting, gas turbines, etc.). Gaz de France is particularly active on the subject for the past few years. The main goal of its studies is to promote the diffusion of these new burners in France and in Europe, through a better knowledge of the phenomena inherent to this new combustion mode, by developing new design tools to ensure the installation efficiency, and the heating quality.

The main results obtained in the different following fields of action are presented in this paper.

Testing of new burners operating in flameless mode

Performances of four flameless regenerative burners were compared to those obtained by using a conventional system firing. Gaz de France has carried out an experimental set-up which allows studying the influence of the main operating parameters (i.e. the furnace temperature, the thermal input, the air-fuel ratio, etc.) of the burners on their combustion efficiencies and NO_x emissions. The results of the tests were obtained over several years through different studies. Globally, we show that the flameless oxidation regime allows reducing the NO_x emissions considerably while improving the combustion efficiency.

InterNOx project in collaboration with Arcelor/IRSID, Stein-Heurtey and the French environmental agency Ademe

A project was therefore initiated by Gaz de France, with joint funding from IRSID (Research and Development Division of ARCELOR), Stein-Heurtey (furnaces designer) and the French Environment Agency (ADEME), to evaluate the capabilities of the HiTAC (High Temperature Air Combustion) technology. Industrial technological monitoring and detailed study of combustion in a burner of the flameless oxidation type (detailed measurements, numerical simulations, etc.) was used during the project. In addition, a validation of these tools has been conducted on a semi-industrial scale on several test cells, which were finely instrumented and put in place for this purpose. This project allowed us to develop numerical tools to design installation of such burners into a process, and industrial constraints (control, maintenance, etc.) were studied.

Other additional activities

- Fundamental work has been carried out for several years to better understand the way flameless oxidation mode is working. Aerodynamic behaviour is one of the key factors that characterize flameless oxidation, and stabilization of this type of combustion was studied in semi-industrial scale and at laboratory scale,

Chemical kinetic work was also carried out through the development of a new mechanism and numerical simulation of flameless oxidation with a network of reactors.

Catalytic Combustion Technology

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This presentation will review the technical approach and commercialization of catalytic combustion technology for application in gas turbine engines for power generation.

Catalytic combustion [1] is a type of “flameless” technology that uses emission-less reaction of fuel and air in a surface coating to safely preheat a fully premixed lean combustion stream to short induction period (~15-ms) autoignition temperatures. The modern form of this technology emerged in the 1970s as part of NASA’s effort to develop small ceramic gas turbine engines for the transportation sector. Application to industrial gas turbines for power generation drew considerable attention in the USA and particularly in Japan from the late 1980s to the late 1990s. In mid-2001, CESI commercialized the first natural gas fired catalytic combustor utilizing proprietary Xonon Cool Combustion[®] technology for the Kawasaki Heavy Industries M1A-13X 1.4-MW gas turbine. Two commercial installations in California demonstrated their >8000-hr operating life guarantee in 2004 following a series of on-engine tests [2] at CESI’s demonstration site in Santa Clara California from 1999 through 2003.

The Xonon[®] combustion system (Fig. 1) has three distinct stages: 1) an upstream lean maximize catalyst life; 2) the catalyst monolith main stages, and 3) the downstream autoignition zone just preceding the turbine intake throat. Practical catalyst formulations (materials) and design (structures) limit catalyst inlet temperatures to at least 450°C. The modest compressor discharge pressure (~9.4-bar) of the KHI M1A does not adequately preheat the air and therefore requires continuous use of the lean preburners to maintain the minimum inlet temperature [3]. The preburners produce the majority of NO_x emissions from the combustion system. Main-stage fuel is mixed downstream of the preburners using a manifold of fuel injectors and radial swirlers. The mean gas temperature is rapidly and efficiently heated to

autoignition temperatures by reaction of part of the fuel within the catalyst coatings on 50- μm corrugated foil-substrates that comprise two (honeycomb) monolithic open-flow structures. Uniform fuel/air ratios and inlet temperatures are required to avoid localized overheating of the main-stage catalyst and thereby shortening effective catalyst life. Outlet gas temperatures in the range of 825 to 950°C are needed for autothermal ignition of the humid lean fuel/air mixture depending on specific engine conditions of compressor discharge pressure, turbine

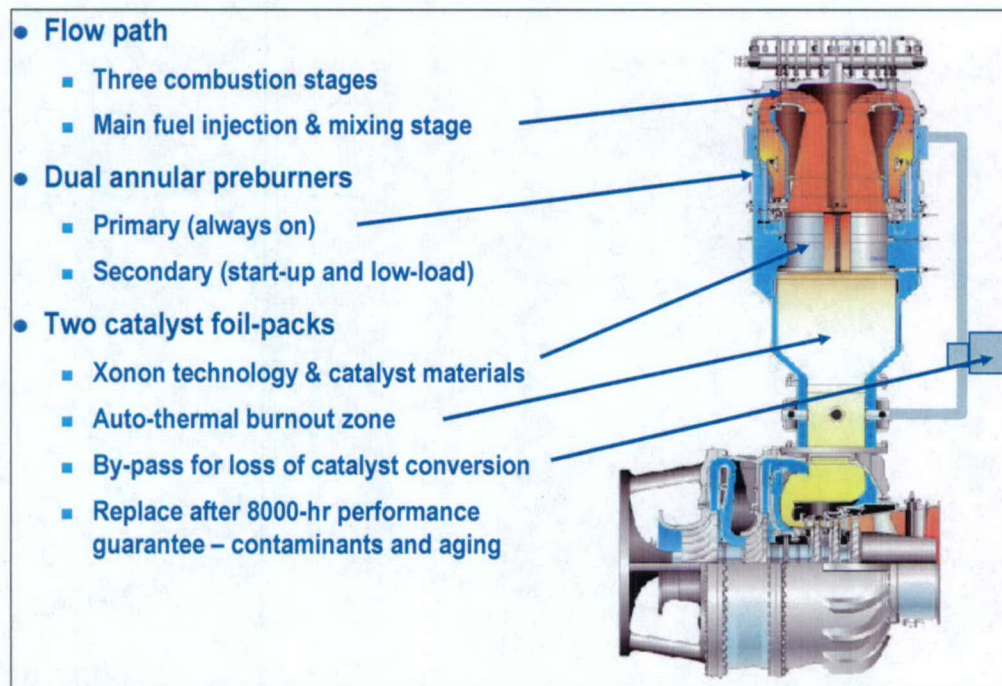


Figure 1. KHI-13X Commercial Catalyst Module – Hybrid Combustion System

temperature limits, turbine load, and post-catalyst volume.

Thermal coarsening of combustion catalysts under the conditions required for industrial gas turbine applications has been a primary technical concern since interest in this low emissions technology arose about 40 years ago. CESI's Xonon wash-coated foil technology includes several methods of controlling catalytic wall temperature profiles and CESI has invested many years of effort into detailed investigation of thermal catalyst aging and its mitigation [4].

Application of Xonon technology to other engine platforms has been underway for several years. High pressure turbines and fuels heavier than methane could greatly enhance the durability of catalysts and lower hardware costs. Many advances in materials and design for other

applications of catalytic combustion should be possible, given the very short time and limited resources invested in this already commercialized technology.

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High Temperature Air Combustion Research in Sweden

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Combustion under the condition of high-temperature and oxygen deficient atmosphere exhibits different performances which are super than the combustion with normal air. A comprehensive understanding is carried out at KTH, since 1997, in regard to the fundamental differences in the thermal, chemical and fluid dynamics characteristics of the flame, and the know-how of

industrial application. The research and development works of High-Temperature-Air-Combustion (HiTAC) in KTH can be cataloged as three aspects: a) studies of single fuel jet flames, b) tests of new burners in semi-industrial furnaces, and c) theoretical analysis and development of new combustion concepts. Both experimental and numerical investigations are adopted.

The studies of the single jet flames were performed in different experimental facilities, including cross-flow and co-flow configurations. Remark results include:

1. The effect of diluents was studied. Under certain conditions, for example, diluted air by the flue gases (major CO_2 , CO , N_2 ..), flameless or color oxidization of the fuel can be been demonstrated.
2. Some concepts were defined to describe the HiTAC phenomena since its invisible flame and volumetric heat release, including: flame volume (shape and size), flame uniformity, furnace-gas-temperature-uniformity -ratio, flame-heat-release, flame-entrainment-ratio, etc.
3. Flame volume, and flame length during the HiTAC condition were further studied numerically and systematically. A simple HiTAC flame volume can be generalized as a function of flame Froude number, Fr_f . The criteria constants of the dimensionless flame volume, V^* , to assess momentum- or buoyancy-control flame are given.
4. The effect of the mild heat release on buoyancy was examined. A correction Richardson coordinate, where the effect of the oxygen concentration (stoichiometric ratio) is included, was derived to describe the local influence of buoyancy force along the chemical flame length. It can be concluded that the buoyancy force increases with the reduction of the oxygen concentration in the oxidizer.
5. The effect of the mild heat release on the entrainment was also assessed. The global behaviour of the entrainment was revealed. The entrainment of jet flames can be identified as two regimes: (a) the near field where entrainment coefficient is positive; and (b) the far field where entrainment coefficient is negative. Corrections of entrainment rates were derived in terms of a flame Froude number, Fr_f , for momentum-buoyancy

transition jet flame under the high temperature and low oxygen concentration oxidizer condition. Furthermore, the maximum entrainments along the flame length are estimated.

6. NO emission formed by N_2O -intermediate mechanism is of outstanding importance during the HiTAC. The approximate percentage of NO production by the nitrous oxide to Zeldovich and prompt mechanism vary from 5:95 at 10% of oxygen concentration to 95:5 at 5% of oxygen concentration.

The studies of tests of the new burners in semi-industrial furnaces have also been done in order to get the know-how of its industrial applications. Two types of burners that exhibit flameless combustion were evaluated in semi-industrial furnaces. These were regenerative air-fuel burner and flameless oxy-fuel burner. The tests with regenerative air-fuel were carried out applying operation both with and without oxygen-enrichment. The parameters in-flames were obtained to show the features of the new burner. A new technique to monitor the invisible flame with a modified electrostatic probe for controlling invisible HiTAC flame was used. The dynamic features, led both by the flame fluctuation and switching of the regenerative burners, were also investigated. The studies also include the heat transfer evaluation in the HiTAC test furnace, and evaluation of optimal design for HiTAC furnace equipped with an advance burner system.

Further on, a thermodynamic analysis of combustion process is performed in order to obtain quantitatively the regime of the flameless combustion. The results show that oxyfuel combustion is able to increase the available energy of the flameless combustion, thus a higher combustion intensity. Additionally, the flameless oxyfuel burner does not need preheating the oxidizer, this extends the concept of the HiTAC.

It is generally agreed that the major characteristics of the HiTAC (or flameless oxidation) is led by the low temperature increase in the combustion process. This is the fact that a low temperature increase makes a combustion chamber more similar as a well-stirred-reactor. Again, the effect of heat release on the combustion characteristic is less at the case of a low temperature rise. This new combustion phenomenon might be named as a Quasi-Isothermal Combustion, or

QIC. Consequently, a combination with catalyst combustion and 'flameless' may be a suitable solution for the new approach of a gas turbine.

Burner Technologies for Use of Low Calorific Fuel Gases in Gas Turbines

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New combustion technologies based on the flameless combustion principle "FLOX[®]" and continued staged air "COSTAIR" have been developed at GWI in the framework of a German funded project. The goal of the this development was to use a broad qualities of low grade gaseous fuels with CH₄ amounts down to 30 % by vol. or with heat values less than 3 kWh/Nm³ efficiently in gas turbine combustors.

The optimal burner configurations were found through a combination of mathematical and experimental investigations for gas turbine conditions. Results achieved in a compact combustion chamber at atmospheric and elevated pressure up to 3 bar have shown, that both combustion systems are capable to burn a broad variety of low calorific gaseous fuels independent of their compositions. Through the new specific design of the burners' single digit NO_x and CO emission values at 15 Vol.-% O₂ in the flue gas can be achieved. Additionally, the combustion process was stable and almost free of pulsation up to a methane amount of 10 Vol.-% in the gas mixture.

With respect to the achieved results, the unique potential of the developed burner technologies will be exploited consequently in the running of future projects and for the introduction of the

new combustion systems for applications in both micro turbines and large scale industrial gas turbines.

Experimental Investigation of Flameless burners

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Traditional premixed and diffusion flames are stabilized by balancing flame speed and flow velocity. The combustor is thus designed to establish the desired flow patterns in the wake of a bluff body, behind sudden expansion or by vortex breakdown in swirling flows. In addition to the flow field needed for stabilization, the flame speed is affected by the temperature and pressure distribution, the local stoichiometry and type of reactants.

Flameless Combustion or Flameless Oxidation occurs with a "transparent" flame or without distinct flame front. Instead, the combustion is distributed in the entire volume of the combustion chamber. Flameless combustion necessitates strong mixing and high temperatures such that it occurs above the self-ignition temperature. Hot combustion products are continuously mixed with fresh reactants to achieve the high temperatures and as a result of this mixing process the oxygen concentration in the reaction is also low. The distributed combustion process results in uniform temperature field and consequently low NO_x emissions and low sensitivity to thermoacoustic instabilities.

The paper will describe experimental results of tests conducted with two different designs of flameless combustion burners. The tests are performed in atmospheric combustors. The flame

characteristics, structure, flow field, and emissions will be reported in a range of flame temperatures and output power.
