CATALYTIC COMBUSTORS FOR GAS TURBINES ON NORTH SLOPE, ALASKA

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ABSTRACT

Catalytic combustors exist as an emerging technology for pollutant control for gas turbines. Advantages are catalysis of undesirable pollutants right at the site of creation in the combustor, which in turn may eliminate the need to use other techniques such as pre-mix flame or exhaust catalysis. Disadvantages are cost and suitability for retrofit to existing equipment on the North Slope oil fields, which are declining in production and are extremely cost constrained. Retrofit suitability includes a look at the ability to place this technology in the existing combustor space envelope, possible effects on flow back pressure, possible effects on firing temperature, effects on maintenance, and other considerations. Based on a summary of existing gas turbines (heavy industrial gas turbines, light industrial gas turbines, and aeroderivative gas turbines) in use by BP Alaska Exploration for North Slope Alaska oil and gas production, a review of feasibility of this remedy for retrofit will be done and some conclusions drawn. The conclusions can be used to help direct future research and development of this technology, for new and retrofit applications.

BACKGROUND

The production of oil on the North Slope of Alaska is heavily dependent on gas turbines. BPXA (BP Exploration Alaska, one of two North Slope operators) operates a fleet of turbines which represents about 3 million available horsepower. These machines are base loaded, and fall under two major load categories, machine drive and electric power generation. Some of the electric power generators that are at isolated locations that are not connected to the local oil production electrical grid need to be able to handle small, dynamically active power systems, and must be able to accommodate sudden shifts in loads. This means these machines run most of the time at part load, and need a very stable flame to accommodate load swings, while also maintaining low CO emission levels. The machine drive units are large compressors and pumps, and are run at either exhaust temperature limit or mechanical limit most of the year. Estimates currently show about 33.7 kiloton of NO_x produced per year in the 640 billion lb of air per year that passes through these turbines [1].

This is a mature oil field, and most of the turbines were installed in the late 1970s. There has been many upgrades and expansions since, but the fleet is generally a lower firing temperature, lower pressure ratio type, without very aggressive emission control. For new installations, various lean premix systems have been used, purporting to be Best Available Control Technology (BACT), and therefore required under law to be implemented. It is clear from BPXA's experience that Arctic implementation of this type of system is not fully developed.

For future expansions, it would be very valuable to have a system that had simple controls and kept NO_x levels below 15 ppm. Hence the interest in exploring the catalytic combustor option, both as a new system for new equipment, and as a possible retrofit to existing equipment. The design constraints are daunting though, as the inspection intervals have to be as long as 24,000 hours between combustion inspections because of the high cost of outages to production.

CATALYTIC COMBUSTOR

The interest for Alaska North Slope operators is to remove the problems associated with the unstable flame that is characteristic of lean pre-mix (LPM), that has proven to be very destructive to BP's turbines and production, and has required complicated control. This would also remove the need to install expensive and power-robbing selective catalytic reduction (SCR) equipment.

Originally, Pfefferle proposed a catalytic combustor that handled the entire fuel/air mixture, with homogeneous and heterogeneous conversion all simultaneously [3]. With current designs, the flame temperatures are too high to make that work, so various schemes have been developed to do catalytic combustion in a lower temperature area in the gas path, to avoid damage to the catalyst.

Design parameters of importance for combustors are internal volume, diameter, velocity[1], adiabatic flame temperature, and bulk temperature. For catalysts, another parameter of interest is space velocity [2].

A basic schematic of how ths might work follows in Figure 1:

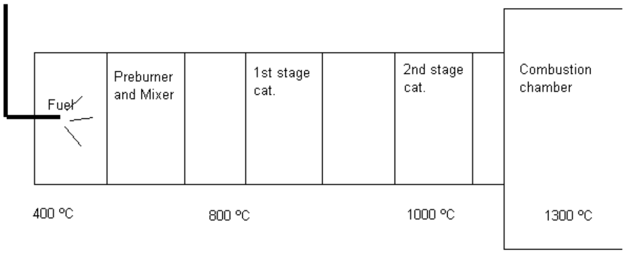

Fig.1 Basic layout of catalytic combustor

It's clear that the ability for the catalyst to withstand high temperature is a critical issue, based on this temperature profile. The preburner shown in Fig. 1 can be a problem in itself, since as it tries to raise the compressor discharge temperature to a temperature suitable for the catalyst to work, it may create NO_x itself. The catalysts used so far are limited to temperatures below 1000 ºC [4].

Pressures for gas turbines range from 6 to 30 atm.; most North Slope turbines run between 10 and 20 atm. Pressure loss of the combustor affects the overall efficiency of the unit, and must be kept within the usual design range of $< 3\%$ [5].

Therefore, the design constraints are: to not reduce bulk turbine inlet temperature to such an extent as to reduce thermodynamic efficiency; to not introduce excessive pressure drop in the gas flow; to eliminate LPM[2]; to not decrease combustion efficiency; and to not degrade the pattern factor to the first stage nozzle. All this, while of course keeping NO_x and CO emissions at very low levels, and not requiring excessive maintenance.

EXAMPLE ONE: HEAVY DUTY TURBINE COMBUSTOR

Combustors come in three main variants: multiple individual "cans" arranged in a ring around the mid-frame, a single "can" with large transition piece to the first stage nozzle, and annular design, usually associated with aeroderivative engines. This first example is of the

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[1] Velocity tends to be constant through load range, because pressure and mass flow change approximately proportional to each other, thus tending to keep volumetric flow (and therefore velocity) constant.

[2] At least one system is used in conjunction with LPM to take advantage of lower temperatures of LPM [4]; more discussion on the implications to follow.

multiple can variety, and the test was approached by building a single can prototype and supplying it with the operating conditions as if it were installed on an engine. Target is 3-5 ppm (Fig. 2). Strategy is based on the principle that the NO_x is made in localized hot spots, and that the overall bulk temperature from the combustor can be well below this and still supply the thermodynamic needs of a high performance turbine. Combustor exit temperature envisaged is 1175 to 1500 ºC.

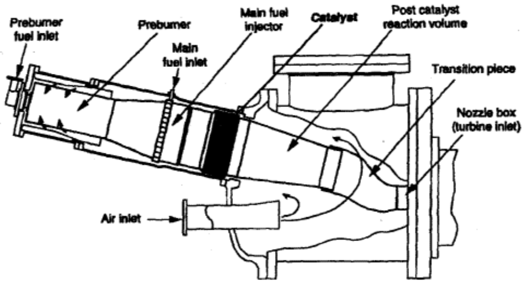

Fig. 2 Example 1 Combustor

XONON (trade name used by Catalytica) technology was used to limit temperatures reached in the catalytic part of the combustor itself, to avoid damaging it, and to allow homogeneous combustion to complete the process downstream to supply sufficient combustor outlet temperature.

Another objective was to meet emission levels at part load. Design targets were:

	Base load	Part load
Simulated load (%)	100	78
Tot. air (lb/s)	48.2	43.1
Pressure (atm)	12.3	11
Cat. inlet T (ºC)	441	466
Comb. exit T (ºC)	1192	1172
NO_x (ppm)	3.3	5.3
CO (ppm)	2.0	8.5
UHC (ppm)	0.0	1.2

This type of combustor represents a large proportion of BP's North Slope fleet, as it is a large frame GE type combustor. This represent about 2/3 of BP's total installed horsepower, or about 2 MM bhp. The associated tpy of NO_x is approximately 25 kiloton/yr, or 3/4 of the total gas turbine emission. Clearly a viable retrofit of this type would be extremely leveraging. Example One was done by Catalytica in conjunction with GE [6].

EXAMPLE TWO: 1.5 MW INDUSTRIAL GAS TURBINE COMBUSTOR

The basic principle behind this design is to combust in the catalyst only part of the total air/fuel mixture, which allows it to remain below destructive temperatures to the catalyst. Typically a 50-50 split is used between what is combusted in the catalyst and what is combusted outside, to reach 1200 to 1500 ºC combustor outlet temperatures. Design targets were:

Combustor pressure (atm)	9.4
Compress. disch. temperature (ºC)	332
Total air flow (lb/s)	17.6
NO_x (ppm)	<3
CO (ppm)	<10
UHC (ppm)	<10
Fuel	Natural Gas
Catalyst Life (hrs)	8800
Loaded turbine trips	10
Inspection interval	8800
Combustor life (hr)	20,000
System Operating constraint	90-100% load

This system relies on careful design of the bypass air to maintain a high post catalytic zone temperature, which promotes the high rate of CO decomposition to maintain low CO output. Figure 3 shows a schematic of this configuration.

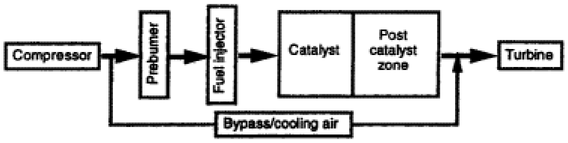

Fig. 3 Combustor schematic

This combustor had passed the preliminary tests at the time of writing and is being adapted for actual installation on a small turbine [7].

EXAMPLE THREE: 1O MW CLASS COMBUSTOR

Example three of this survey is another multi-can type combustor, but in this case, the basis is a catalytic assist of LPM. As stated above, the North Slope operators' interest is to eliminate complicated controls, if at all possible. The study brought out the fact that standard palladium catalysts used with methane fuel experience a "self-oscillation" in temperature, the peak of which limits what the average can be, due to material constraints. Fig 3 shows the layout:

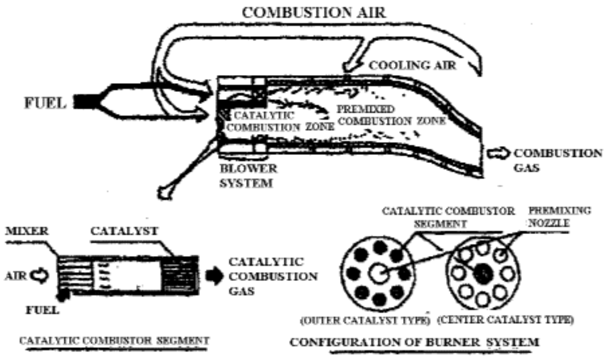

Fig. 3 10 MW Comb. Concept

Design targets were:

Combustor exit temperature (ºC)	>1300
Compressor disch. pressure (atm)	13.1
NO_x (ppm @ 16% O_2)	<5
Combustion efficiency (%)	>99.9
Air flow (lb/s)	31.9
Δp (%)	<5
Pattern factor (%)	<15
Fuel	LNG
Adiabatic Flame Temperature (ºC)	1350

Attempts to control the oscillation were of interest in this test, where the fuel concentration in the catalytic segment was kept as high as possible and ended up requiring a modified catalyst of the Pd/Pt/Rh mix that had less oscillation and less degradation than the Pd and Pd/Pt type [4].

EXAMPLE FOUR: CATALYTIC ASSIST FOR GAS TURBINE

This one is the follow up on Example Three, above, done by the same group. This is also a pre-mixed, multi-can arrangement. The Pd/Pt/Rh catalyst was used, that had been developed in the previous example. The intended turbine is a 20 MW class turbine.

Design targets were:

Combustor exit temperature (ºC)	1300
Combustor inlet temper. (ºC)	370
Compressor disch. pressure (atm)	13.5
Air flow rate (lb/s)	61.0
NO_x (ppm @ 16% O_2)	<10

This is a case where a control issue is present because the fuel conversion in the catalyst bed decreases with increasing pressure, a proportional (or more complicated?) control has to increase fuel distribution as the pressure increases. There is no reason to believe that this is not an issue in ALL catalytic combustor designs.

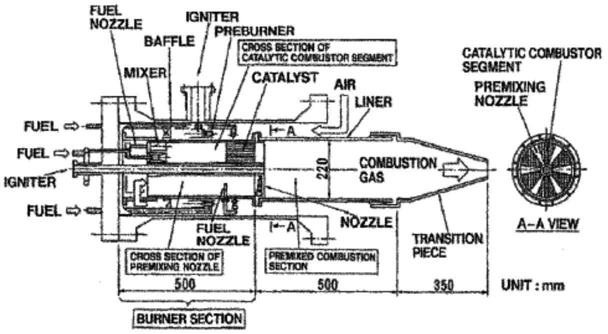

Fig. 4 Catalytically assisted combustor

This requires lean premix and careful control of the fuel flow over all loads. The primary objective was catalyst durability [8].

EXAMPLE FIVE: HIGH TEMPERATURE GAS TURBINE

Here is another proposed design for the electrical utility system. Etemad has a very good description of turn down problems with LPM systems, where a diffusion flame (often called a "pilot") has to be used to keep the combustor from blowing out, at the cost of increased emissions in that mode. This description is very consistent with the problems experienced by Alaska North Slope operators.[3] It is also noted that a successful catalytic combustor application should also remove any need for SCR or other post-combustion treatment, another potentially valuable selling point for Alaska North Slope operators.

Design targets were:

Compressor exit temperature (ºC)	>400
Combustor disch. temper. (ºC)	<1540
Compressor disch. pressure (atm)	13.5
Air velocity over cat. (ft/s)	50-100

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[3] The LPM flame has to be mapped between emission limits and lean flame blow out, while possibly being subject to acoustic coupling with the flame that can literally destroy the combustor and the downstream turbine components with it.

NO_x (ppm @ 15% O_2)	<10
CO (ppm @ 15%)	<4
Combustor residence time (ms)	10 - 20

There was another test rig done to simulate actual conditions, with the particular objective of running very low equivalence ratios to see if the flame could be maintained [9].

MATERIALS

Temperature sensitivity is a key design factor in the catalysts and supporting material for catalytic combustors. As temperature is increased, reaction is initiated at a level that depends on the reactivity of the hydrocarbon and the catalyst. The reaction is controlled by the kinetics to where heat generated by the oxidation is sufficient and mass transfer to the catalyst surface becomes rate controlling. The temperature of the system increases dramatically and homogeneous oxidation may begin in the gas phase near the catalyst. Eventually the supply of fuel or the oxygen is exhausted and the catalyst temperature stabilizes. Any further change in the fuel or oxygen supply leads to the stabilization at a new temperature.

Four key features follow:

1. Catalytic combustion must initiate at low temperature
2. Catalytic combustion must continue at low temperature
3. At higher temperatures, reaction is controlled by heat and mass transfer; the temperature increases and temperature stability becomes important.
4. Changes in temperature can create thermal shock or thermal fatigue.

The low temperature reactions are favored by precious metal catalysts, which are quite common for this application. For higher temperatures, the design can intentionally place the higher temperatures of combustion downstream of the catalysts, limiting the temperature in the catalyst to 800 ºC. A two stage design can be used to place a highly reactive catalyst where combustion needs to be initiated, and then put a less reactive, more durable catalyst downstream where the temperature is higher and the combustion more established.

Monolithic supports are built for mechanical strength and thermal stability. Cordierite, mullite, and zirconia are commonly used suitable materials. One attribute is the need to for washcoat adhesion, which requires support porosity. Washcoats are used to distribute catalysts, to enhance catalytic activity, or to improve thermal stability. Alumina is the most common material used.

Sintering is one of the prime causes of deactivation, so is a prime design constraint. Typical oxide supports of catalysts can be a difficult problem. Alumina, the most common support, has a well understood sintering mechanism. The solution usually involves the use of trace additives, the correct preparation process, and creation of new materials. Of course, the design of the combustor has to respect the temperature limit of the support and catalyst. Another consideration is the interaction between the support and the catalyst can also be a source of deactivation [15].

For the catalysts themselves, a general rule is that sintering occurs at 1/3 to 1/2 the melting point of the material, and is to be avoided. The water that is produced as a product of combustion can also become a problem with sintering, depending on the material.

Finally, the surface texture itself can be very important in the effectiveness of catalysis, and needs to be analyzed [13].

NUMERICAL SIMULATIONS

To reduce the cost of testing and prototypes, it is important to have effective mathematical models to predict the action of a new design. Of prime concern in this paper is flame stability, a weakness of the LPM method.

The flame speed of the mixture without surface reaction can be predicted numerically, and the flame speed *with* surface reaction has been shown to increase up to 19 times as high as the flame speed of the mixture without the surface reaction. This increase of flame speed is thought to be caused by the rise of mixture temperature through the surface reaction and intermediates. If the flame combustion is supported by the surface reaction, the mixture temperature rises due to the heat released from the catalytic surface.

A simulation and test shows the flame speed increases exponentially with the amount of conversion by the surface reaction. The increase of flame speed is very important from the viewpoint of flame stability, because the higher the flame speed is, the better the flame stability. For example, lean combustion from LPM has a problem that the flame becomes unstable as the fuel concentration approaches the lean limit of the mixture. This is because the flame speed reduces as the fuel concentration becomes lean.

However, if the flame combustion is supported by catalytic reaction, the flame speed increases and the flame stability can be improved. In fact, in catalytically stabilized combustion where inlet velocities are 30 to 100 ft/s, the flame can be kept safely lit without an additional flame holder [10].

Seo has suggested that there is a need to go beyond the one-step global reaction models, particularly with more complex catalysts [10]. Tsujikawa has made a model that is based on a one-step model for a particular fuel, and can be used with computational fluid dynamics (CFD) to simulate bulk temperature and the extent of homogeneous reaction. Another use for modeling is to do accurate predictions of light off and operation with gas inlet temperatures, pressures, and equivalence ratios for lean operating conditions [11].

Correa has mathematically modeled the hot and cold spots in a catalytic combustor, in hopes of proving its superiority to LPM [12]. Further study along the same lines could be done with an LPM-catalytic combustor hybrid, since the enhanced flame stability from the catalytic combustor and the increased durability of the catalysts from using LPM could actually deliver the most practical solution of all.

A system such as this has been modeled in Italy, with the layout based on lean premix to keep temperatures lower in the initial part of the combusion thus lengthening its life, and then a catalytic section used downstream to stabilize premixed combustion in the homogeneous zone. A sketch is given in Fig. 5.

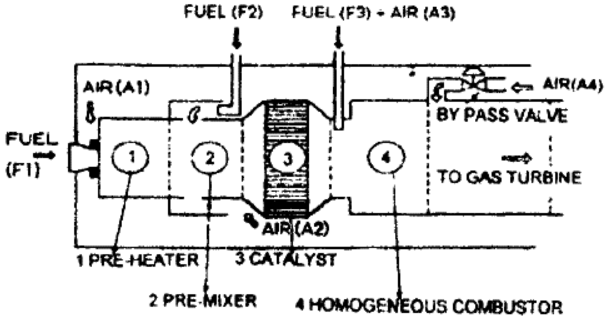

Fig. 5 Model Sketch

This is modeled in the 20 to 130 ft/s inlet velocity range. Differential equations are set up based on continuity, momentum, and energy considerations, and solved numerically. Some simplifying assumptions were found regarding the velocity profile that can be used to reduce the amount of computer time.

This model is also useful in addressing the issue of catalyst specific area, a subject of much discussion. The conclusion in this study is that the required specific area is lower in active monoliths than in washcoated ones. This suggests no washcoat needs to be used, at least in the most upstream section in the combustor.

The model also addresses scaling of test data to full scale applications. The objective is not to eliminate testing, but remove some of the trial and error by accurate modeling [14].

Another aspect of combustor performance is its transient operation and durability. From a chemical viewpoint, one study found that a step decrease in inlet temperature could result in a sudden step increase in combustor temperature, enough to damage it. From previous models of catalysts in converters, where all the reaction is considered heterogeneous, a new one-dimensional model has been made that combines both modes of reaction [16]. Thin wall, low density, and low heat capacity monoliths were favored in this model. Another very important operating condition that needs to be modeled and documented is reaction to fully loaded trips, which is stressful in general to turbines, but almost impossible to avoid, at least on occasion.

DESIGN STANDARDIZATION

As in any new technology, there are conflicting methodologies and even measurement parameters. The above examples were taken from a narrow time and publication range, yet the design objectives had non-overlapping attributes. A scan of each example show this.

Some attempts have been made to set the criteria for design and acceptance, as seen in the literature. It is important to distinguish between turbine services; a peaking unit for electrical power generation service has very different operational and maintenance constraints as opposed to a base-load machine drive. An electrical unit on a large grid also has a much different risk and usage than a few parallel units on an island. For Alaska North Slope operators' units in general, the machines are all base loaded and will be run for years if possible without shutting down. BPXA has a central power system with a local power grid, with R and P model Frame 5 single shaft turbines (combustor from Example 1 above would be suitable); BPXA also has three other production facilities *not* connected to the local grid with smaller units in parallel, two of which use aeroderivative type turbines.

Based on the above, here are some recommended design criteria:

- NO_x, CO, and HC limits (ppm @ 15% O2)
- Emissions given at 50%, 75%, and 100% load
- Flame stability, at all loads
- Combustor exit temperature (ºC)
- Combustor inlet temper. (ºC)
- Compressor disch. pressure (atm)
- Hydraulic dia. of combustor, D , (ft)
- Reynolds number
- Lewis number
- Volume of combustor (ft^3)
- % pressure drop
- Gas flow rate (lb/s)
- Gas flow rate (actual ft^3/s)
- Ambient temperature design range (-40 to 30ºC)
- Intended fuel and composition
- Space velocity (per hour)
- Gas velocity over catalyst section, v ,(ft/s)
- Heat balance on liner, with required cooling air
- Combustor residence time (ms)
- Life characteristic of catalyst
- Survivable number of full load trips
- Catalyst(s) material
- Support material and properties
- One-step or multi-step kinetics model
- Acoustic coupling characteristic

The recommendation here is to better standardize and define the design parameters for developing catalytic combustors. Data within the small selection of examples described here shows a mixture of units, lack of documentation of $\%O_2$ correction for pollutant partial pressures, multiple ways to measure process variables (e.g. air flow in lb/hr, lb/s, kg/s, m^3/hr, etc.), lack of basic geometry, etc. This would be a good precursor to eventual implementation in industry, since it is inevitable that codes and standards will eventually assign similar values for contract specifications when usage becomes commonplace.

For North Slope units, the biggest prize is found on two extremes: 1) the large Frame GE units, that produce most of the NO_x, could be adapted with a minimum of engineering (because of their basic similarity) to get rid of most of the NO_x; 2) the isolated power units and recent vintage aeroderivatives need flame stabilization to back up the inherently unstable LPM systems currently used. At least one turbine vendor finally admitted they had no operating or calculated data for temperatures below 0 ºF! Even a partial catalytic combustor retrofit, enough to guarantee flame stabilization, with a simplified LPM system, could be sufficient to make the LPM application acceptable.

BARRIERS TO OVERCOME

The current state of affairs presents these barriers to successful implementation:

1. Catalyst and support durability
2. Fuel/air preheating required (compressor discharge temperature still not within catalyst reactivity range).
3. Turndown limits (bracketed between minimum required combustor inlet and maximum allowable combustor outlet temperature)
4. Uniformity required to avoid local hot spots or local degradation of catalyst
5. High pressure drop introduced in gas path, because of large contact area required and relatively high velocity of gas passing over catalyst.
6. Reasonable inspection intervals. For North Slope requirements, an interval of 24,000 hours is very desirable.
7. Complicated control systems dependent on printed circuit board, loop wiring and transducers, redundant protection, and extensive technician training, all of which greatly increase maintenance costs.
8. Lack of awareness of Arctic operating conditions.

CONCLUSION

This paper serves to summarize the current status for catalytic combustor research, and to state what additional items need to be emphasized for development of catalytic combustors for an Arctic, base-loaded application. One possible avenue is a modified LPM system with less critical control, if the stabilization offered by upstream catalysis creates a large enough margin of safety to stop combustion oscillation and acoustic pressure generation. For retrofits of the multi-can type (e.g. GE Industrial Gas turbines), it is essential that a screening study be done to first define if the required dimensions will even fit in the intended space. An annular design suitable for aeroderivative use appears to be much less developed than the multi-can design, but is urgently needed because of the lack of reliability in Arctic conditions of the existing LPM systems for this type of combustor.

DEFINITIONS

space velocity (in catalysis): v_m, v_v, and v_a where the v represent the rate of feed of the given reactant fed per unit mass, volume or surface area of the catalyst.

combustor pressure loss : $\Delta p / p_{inlet}$.

pattern factor: $\frac{T_{\max} - T_{mean}}{T_{mean} - T_{inlet}}$.

homogeneous reaction: reactions between substances that are in the same phase, e.g. gas and gas reactions.

heterogeneous reaction: reactions between substances that are in different phases, e.g. gas and a solid catalyst.

sintering: homogeneous fusion of substance without melting

ACKNOWLEDGEMENTS

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