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Applications of Lean Combustion to Reduce Emissions

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I have been blessed to be a part of the MC-Nair Scholar program. I have gained so much knowledge and look forward to my future expectation of graduate and doctorate levels of study. I would like to thank the MC-Nair office members who encouraged me throughout the completion of this paper. I would like to give special thanks to my faculty mentor Dr. Narayanswami, Director of the MC-Nair office Dr. Camara, assistant director Ms. Reed and graduate student Mr. Matiko; all of whom assist me to conduct this research. Without their effort my research would be incomplete.

Abstract:
Environmental regulation has constricted over the last few decades as the hydrocarbon burning engines produce primarily large amount of nitrous oxides, carbon monoxide, unburned hydrocarbons and sulphur-oxides. For this reason, gas turbine manufacturers are working towards the design of combustion system that reduces the emission of these compounds. Numerous technologic attempts such as water injection combustion, lean pre-mixture combustion, ultra-lean premixed combustion, catalytic combustion, swirl premixed combustion system or the compartment combustion design along with many other concepts have been introduced. This research paper will introduce each combustion process in brief detail and compare the emission data available from each of them and then recommend the one that is suitable for emission controls.

Applications of lean combustion to reduce emissions

Introduction:

It is widely accepted that burning of hydrocarbon fuel has a negative impact on the environment. A large number of engines used today emit environmental unfavorable substances such as Nox, sulphur oxides, carbon monoxides or unburned hydrocarbons. These oxides have an adverse effect on health, are responsible for acid rain, greenhouse effect, ozone layer depletion photochemical smog, and can form toxic substances combining with other compounds in the air. During the early 1980s, concern over these oxides emissions increased. As pollution went up, environmental regulators tolerated these emissions less therefore more advanced technology was required to address it. Most of the emissions are temperature and pressure dependent. Air contains mostly nitrogen, carbon and oxygen by volume; therefore most of the Nox and CO is produced when fuel is subjected to certain temperatures and pressures in the combustion process.

Nox forms in three mechanisms; thermal Nox, prompt Nox and fuel Nox. Thermal Nox formed in applications of "high temperature". Above 1200^{o}C, thermal NOx formation increases in very rate. Prompt NOx is formed by the fast reaction between nitrogen, oxygen and hydrocarbon radicals (Baukal, C.). Fuel NOX is formed by direct oxidation of the nitrogen within the fuel burn. Prompt and fuel Nox formation is relatively low compared to that of thermal Nox if high quality gaseous fuels are used. The following figure shows the relation between the formations of NOx at various temperatures presented by Baukal.

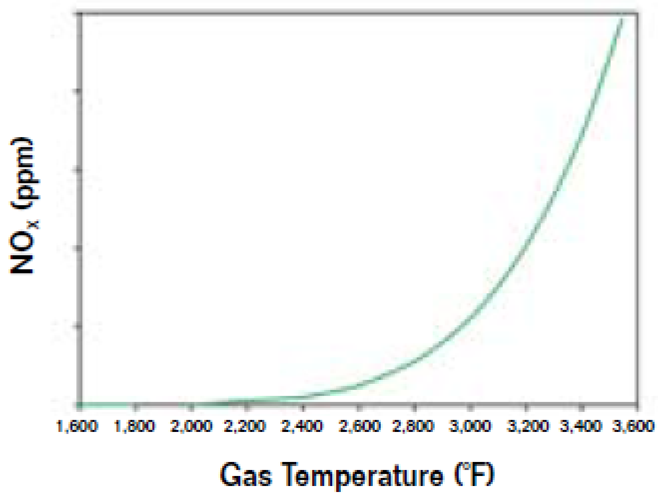

Figure 1: NOx formation vs. temperature

The graph shows that upon an increase in temperature above 2500°F, formation of NOx increases exponentially. However, in the combustion and turbine energy extraction process, higher temperature is preferred to meet the higher energy requirements. Therefore, gas turbine engine manufacturers are facing the challenges to design combustion systems that not only reduce the emissions, but also operate with higher energy extraction, flexibility in fuel, minimum impact on component operation and component life. This research paper presents the various lean combustion technologies invented in order to reduce the emissions from the gas turbine engines and discusses their emission performance.

While lean combustion was introduced in the early 1920s, a practical contemplation started only in the early1960s targeting to save fuel. Certain amount of atmospheric air is required as an oxidizer during the combustion. The amount of air is different for different types of fuel in order to burn fuel completely. The exact ratio of fuel to the air is known as stoichiometric. The fuel-air ratio divided by its stoichiometric value is called the equivalence ratio (Φ). The inverse of equivalence ratio is denoted by λ (Rankin, D. 2008). The Φ and λ are the normalized quantities used to describe the amount of fuel to the air in combustion.

$$\varnothing = \frac{(f/a)actual}{(f/a)stoi} \qquad \lambda = \frac{(a/f)actual}{(a/f)stoi}$$

Lean combustion is utilized in several types of engine designs including terrestrial gas turbine, steam furnaces, and aero engines. The use of wide range of lean combustion is because of low temperature combustion process, fuel economy and reduced emissions. Unfortunately, various complications arise in lean combustion such as low reaction rates, flame extinctions, vibration, noise, very sensitive mixing and low energy release (Rankin, D. 2008). Various research and combustion technologies have investigated these issues. Some solutions include use of highly preheated gas, heat circulating burners; and pre vaporized liquid fuel.

The following figure shows the lean limit of inflammability at different concentrations of oxygen. This chart was obtained by Parker in 1914 (Rankin, D 2008). The chart shows the mechanism of reaction in presence of different amounts of oxidizer beyond stoichiometric limit for a methane gas. In the case of other fuel types, the relation between the excess air and amount of fuel hold similar patterns.

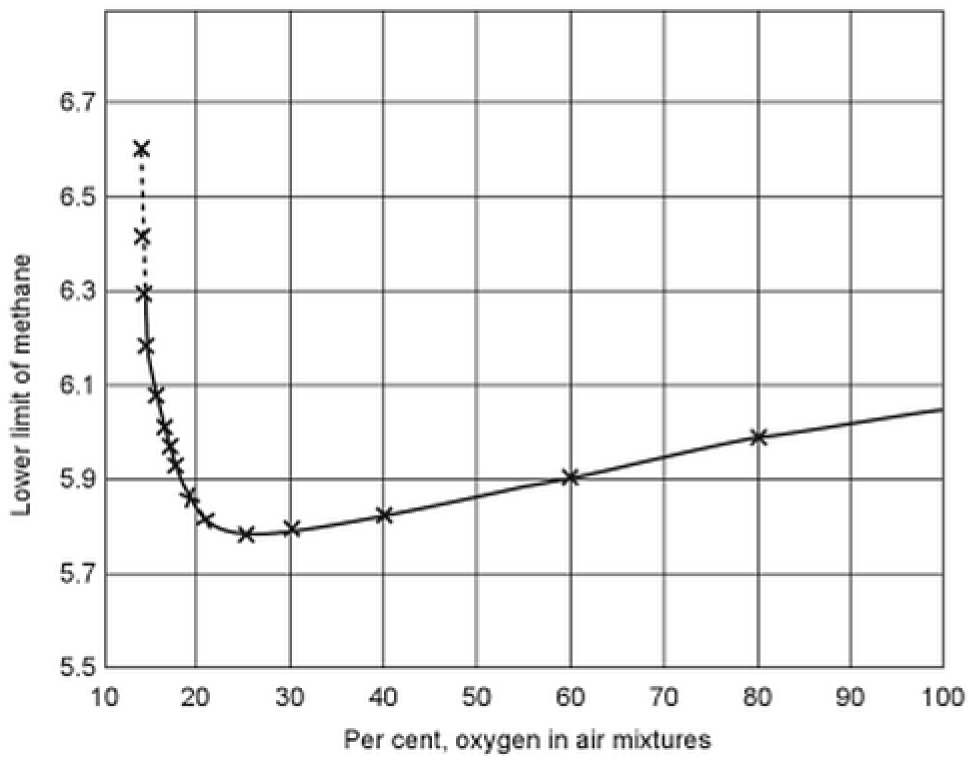

Figure 2: The configuration of NOx formation as the function of equivalence ratio

Lean combustion technology may be described in many ways. Essentially, the technology is focused on reduction of temperature, excess air supply, low residence time and proper mixing. In lean combustion, few applications of lean burn technologies are presented further.

Lean premixed combustion

As mentioned before, gas turbine manufacturing companies are constantly improving their engines to meet environmental regulations and to increase fuel savings. Lean pre-mixed combustion and catalytic combustion are two of most notable low emission technologies that have been studied. A lean pre-mixed combustion has attained the commercial track with high efficiency and good operating hours. The use of liquid fuel in lean pre mixed combustion with low emission has also already been proven. The future goal is to expand the wide range of fuel used to make energy sources cheaper and environmental friendly. By definition, pre-mixed combustion is the mixing of air and fuel before injecting to the flame for the purpose of homogeneous reaction temperature that is below the Nox production temperature.

In the lean premixed system, air (mixture of nitrogen and oxygen) acts as a diluent and the fuel mixing occurs upstream of the combustor. The air to fuel ratio typically approaches twice the stoichiometric value. The large amount of air used is the key to restrict NOx production since the lean mixture doesn't generate high temperatures that promotes for the thermal NOx. The Lean Premixed Mixing technology keeps the combustion lean at entire flight envelope. It has many challenging phases in achieving such a goal. Once the engine is operating at its lean limit, a further reduction in combustor temperature is impossible because the flame extinction might occur. Therefore, to address the issue, combustion design has two fuel supplying system so that if one extinct, the other one will help to light the fire again. Fuel staging or air staging in combustion chambers is an advanced technology to achieve proper mixing as well as achieving the low temperature flame. Staging can provide the preferred temperature in combustion chambers at all operating conditions.

Premixing combustion design is entirely different from conventional design. The main features are injection device, stability device, pre-mixing zone and flame stabilization zone. The injection component distributes the air and fuel as uniformly as possible. The stabilization zone is responsible for the supply of fuel at constant velocity by the swirling re-circulation. The main component "premixing", delivers the extra time for the mixing of fuel. Flame stabilization zone is the main burning zone. Pre-mixer helps for thorough mixing before injecting in the burner. The dangers associated with premixing are flashback, the flow pressure fluctuations and flame extinctions. The successful balance in these components will make long-lasting, durable operation possible. The overview of the combustion design is shown in the following figure.

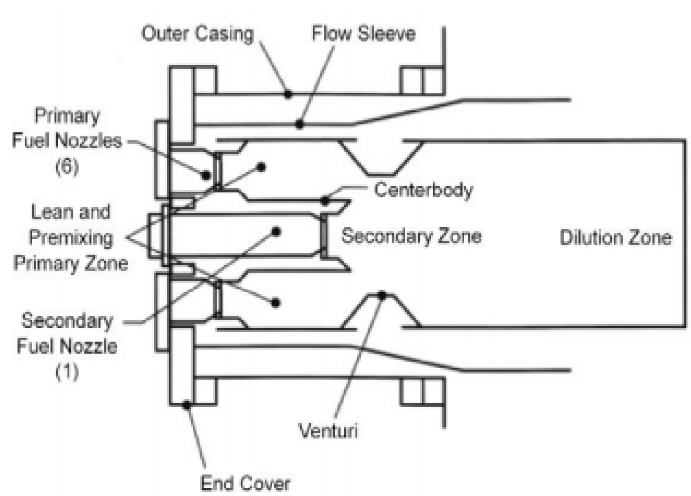

Figure 3: LPM combustion chamber

Flameless combustion

Generally, the reaction of the combustible mixture and air forms a flame front. Across the flame front there is a sharp increase in temperature (above 2000C), which is liable to produce a high amount of Nox and other emission products. Conventional combustion systems exhibit temperatures of more than 2000 degree C but in order to limit NOx, combustion must undergo below 1400 degrees C. Stable flame front is to control and ensure constant reactions and it provides safety signals to the sensor. The reduction in Nox is achieved with the aid of flameless combustion.

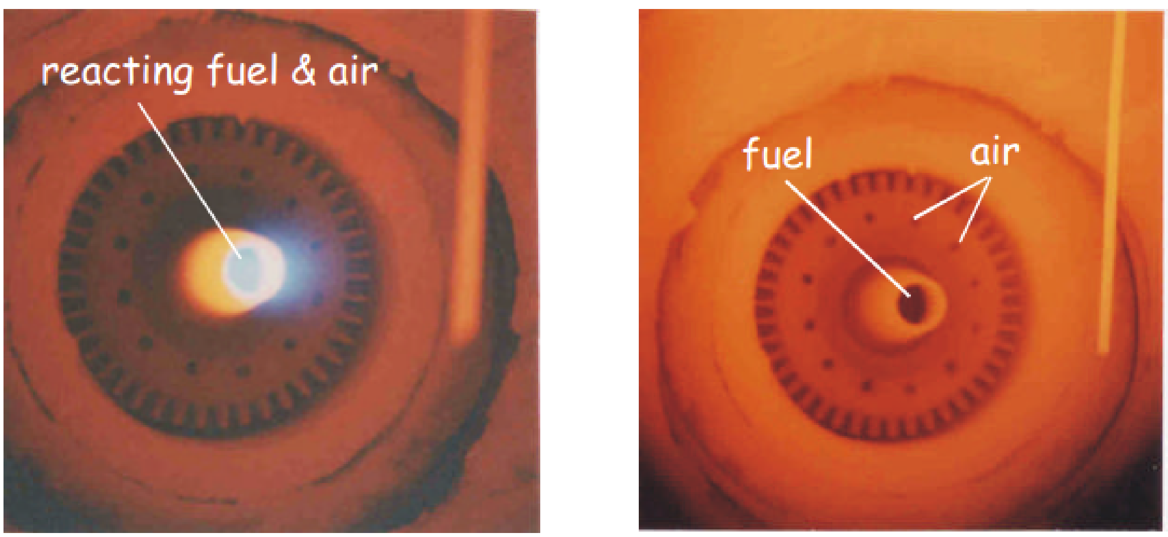

Figure 4: Flame and FLOX®

Figure 4: Picture showing conventional combustion and flameless combustion

Circulation of combustion products to mix with fuel and air in order for the necessary combustion reaction is flameless (oxidation) combustion. Mixing of products from the combustion reduces the concentration of reactants and provides the additional temperatures that would increase the efficiency of the engine. This amazing phenomenon was first observed in 1989 with a self-recuperative burner. Combustion products of about 650 degrees C and the furnace temperature of 1000 degrees C, no flame was seen and no UV rays were detected but still the fuel underwent complete reaction and NOx exhaust was under single digits. Traditional combustion generates high temperature differences compared to the flameless combustion. Flameless combustion has uniform distribution of reactant and temperature in time and space, i.e. to the entire volume, also known as "volume combustion," it also has an advantage in reduction of noise. This combustion process is named as oxidation combustion which was studied by Wunning and Wunning, and later reviewed by Katsuki. The relation between temperature and the formation of NOx is shown in figure below.

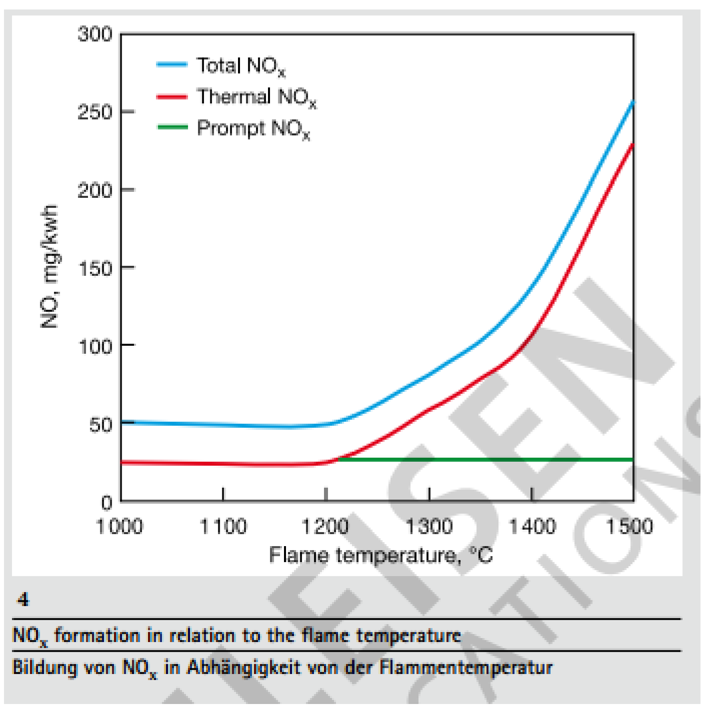

Figure 5: Flame temperature and NOx formation

This figure shows the temperature vs. NOx emission. The total NOx formation in combustion exponentially increases after 1200°C, mostly because of production of thermal NOx (Scheele, Joachim, Mats Gartz, Rainhard Paul, Michael Lantz, Jean Rigert, and Stephan Soderlund. Warme und Energie, 2008).

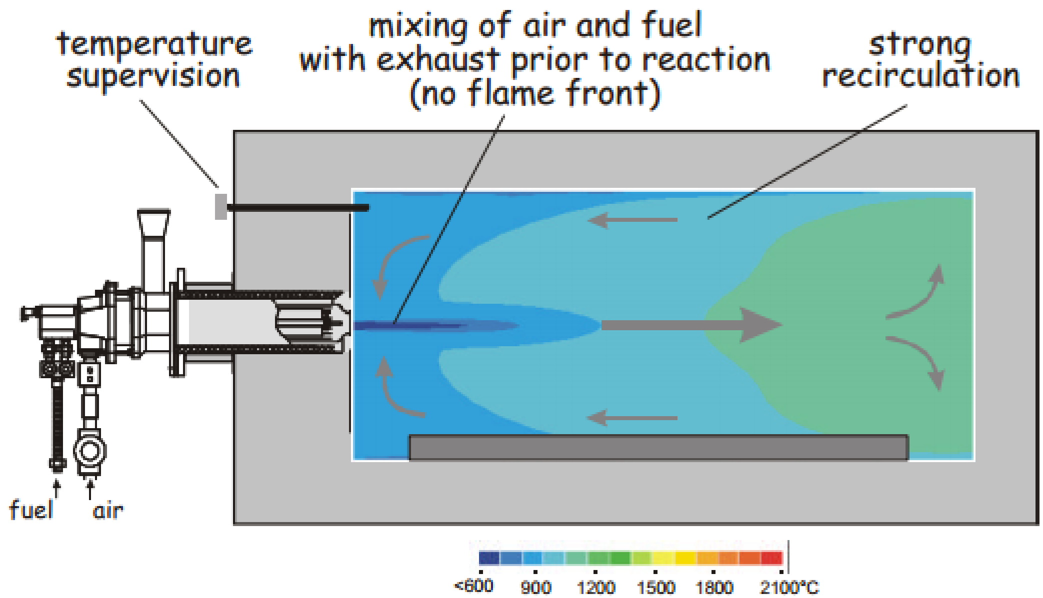

Figure 6: Schematic diagram of flameless combustion

Different forms of fuel (solid, liquid and gas) have different combustion mechanisms, energy content, and pollutions. Gaseous fuel is easier to dilute with the product of initial combustion whereas for liquid fuels there arises complications in design of fuel injectors, mixing, and droplet evaporation with subsequent combustion. Near the fuel nozzle, active flames generate very high temperatures which enable fuel to evaporate. However, in recirculating combustion process, the temperature is uniform over the chamber so the temperature is low as compared to conventional combustion. Therefore to sustain the complete reaction, a large residence time is required (Reddy, M., & Kumar, S. 2013).)

Various studies and research have been made using different fuel and different experimental set up. It is hard to generalize the emissions quantity of all these research and findings. Combustion design, fuel mixing technology, fuel types and oxygen amount play a great role in making a difference in the outcome of products. Just for example purposes, research conducted by Reddy and Kumar, with three different liquid fuels at different heat input is lighted.

The pollutant NOx, CO and hydrocarbons at different heat input and different universal equivalence ratio is presented. Experimentally measured emissions are corrected to 15% O2 level and plotted in the graph below. For thermal input of 20KW and equivalence ratio of 0.8, NOx, CO and hydrocarbon emissions are under one digit, whereas for higher thermal input, CO emissions is quite higher (23 ppm); for kerosene and diesel fuel NOx is still under one digit (8ppm) and this is due the viscosity, boiling temperatures, evaporation rate of fuel etc.

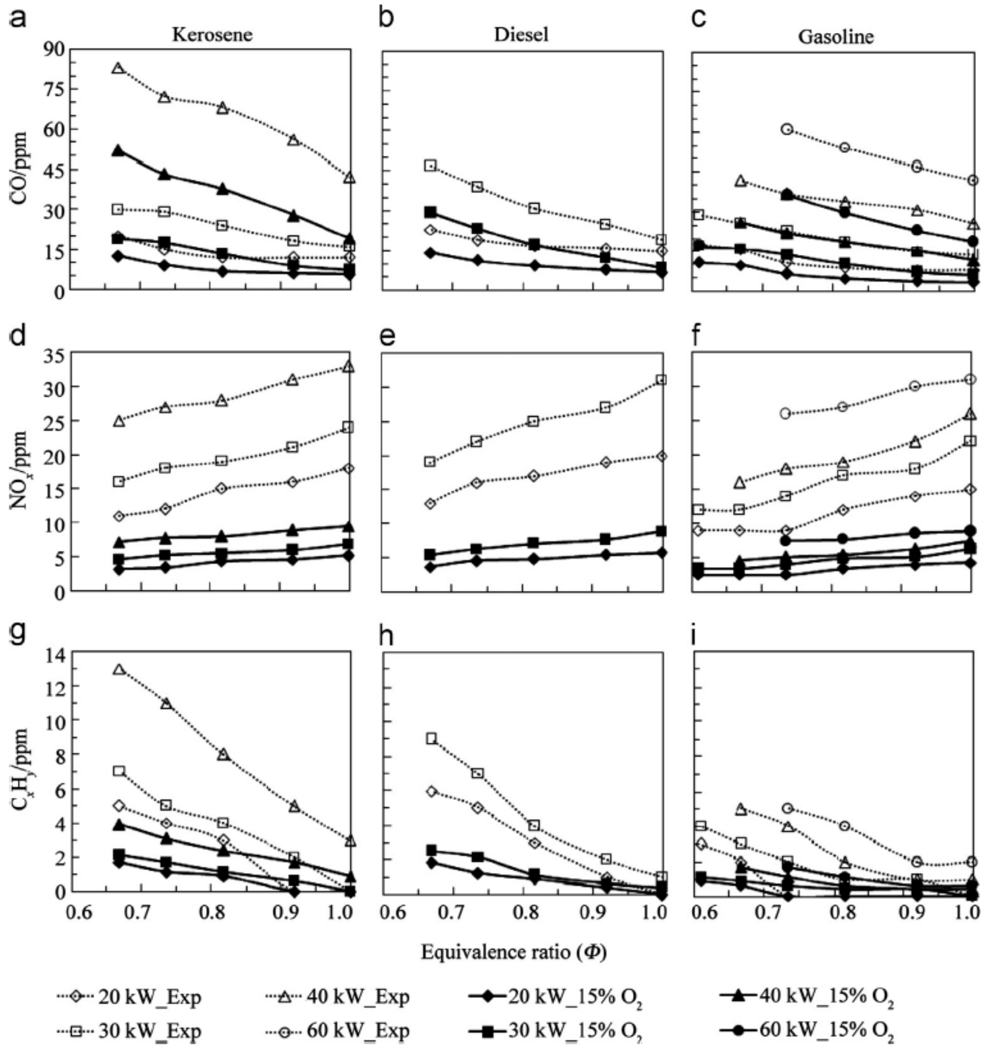

Figure 7: Pollutant emissions variation with equivalence ratio of different thermal inputs and three different fuels of kerosene, diesel and gasoline emissions.

Almost every study performed in regards to flameless combustion shows that the emissions can be reduced to minimum level. Design of recirculation of combustion products and applied to industrial scale is still another challenge. Further study and modifications oxidation combustion strategies will ensure the low emissions and high engine efficiency.

Catalytic combustion:

A catalyst is a substance that enhances the speed of the reactant but is not consumed during the reaction. First time, catalytic combustion was conducted by Pfefferle at Engelhard Corporation in the 1970s. Catalytic combustion is the combustion process that occurs in the presence of catalyst. In the gas turbine engines, variety of catalysts may be used for various purposes. Three main choices are fuel propagation, fuel oxidation with heat release and minimization of the pollutants. Presence of a catalyst enhances complete combustion at a lower temperature. The primary reason to reduce the temperature in combustion process is that it reduces the Nox emissions. Much non-catalytic combustion operates at higher than 1525^{o}C which has an emission level of more than 3ppm at 15% O2. The catalytic combustion can operate stably with low flame temperatures having low Nox emission and better combustion turndown. (Smith, L., Etemad, S., Karim , H., & Pfeffele, W. Department of Energy, (n.d.).

In combustion chambers there are two types of catalyst, one is the reduction catalyst and the other one is the oxidization catalyst. Both of these catalysts are often made from ceramic or metallic honeycomb structures, and these solid surfaces are covered with other metal catalysts: platinum (palladium is also used for economy), and rhodium. Coating of this highly conductive metal reduces temperatures necessary for the oxidation.

The Reduction Catalyst, a first stage of a catalytic converter chamber, consists of platinum or Rhodium to help in reduced emission. While the Nox molecules come close to the reduction catalyst surface, it strips the nitrogen atom from the NOx molecules leaving the oxygen free while the free Nitrogen atom combines with another Nitrogen atom forming a neutral molecule. The following reaction occurs in reduction catalyst.

$$2NO_x \rightarrow xO_2 + N_2$$

The second stage of catalyst converter uses the oxidation catalyst. Using the remaining exhaust oxygen an oxidation catalyst oxidizes the unburned hydrocarbons and carbon monoxide. The following reaction occurs in the oxidation catalyst.

$$2CO + O_2 \rightarrow 2CO_2$$

The third component is the control system that senses the emission and optimizes air to fuel ratio in the combustion chamber. Therefore, a three way control of emission by reduction, oxidation and optimization of fuel to air ratio is promisingly effective to reduce the emission down to 3 ppm. The sensor used in is "Lambda Sensor" which is mounted upstream of the catalytic converter, controls fuel injection based on the oxygen exhaust.

Hydrogen Combustion:

In recent years, decreasing amounts of fossil fuels pushed scientists to look for other forms of energy. Hydrogen could be one of the potential substitutes for the fuel energy. Hydrogen is abundant in nature, can be extracted from many chemical compounds. Water is a major source for hydrogen extraction. In addition to that, electricity generation during nuclear fusion or fission, coal gasification, steams reforming of natural gases are all sources of hydrogen production. Some modification in existing combustion technologies will be required to mix with fossil fuels. Burning of fossils fuels generates carbon compounds (mainly carbon dioxide) during the conversion process whereas, hydrogen fuel eliminates water as the byproduct, removing excessive formation of carbon dioxide – a major component for the greenhouse effect.

Hydrogen fuel offers several benefits over conventional fuel. For example, in lean burn stability of the combustion chamber is problematic but the extended flammability nature of hydrogen fuel can increases the stability of the flame. Therefore, the fuel to air ratio can be very lower then stoichiometric ratio. Additionally, lean burn lowers the combustion temperature, enhancing the reduction in emissions. Hydrogen rich fuel is easy to ignite due to its low ignition energy thus it is better on ignition of lean mixture and proceed the reaction. The low ignition can be harmful since it ignites fuel on low compression or even in exposure to hot gases or hot spots enabling premature ignition or flashback. The speed of flame in stoichiometric condition for hydrogen and air is 1.85 m/s while for CH4 is only 0.44 m/s, and also hydrogen fuel has very thin flames which helps to increase the faster burn compared to other hydrocarbon fuel.

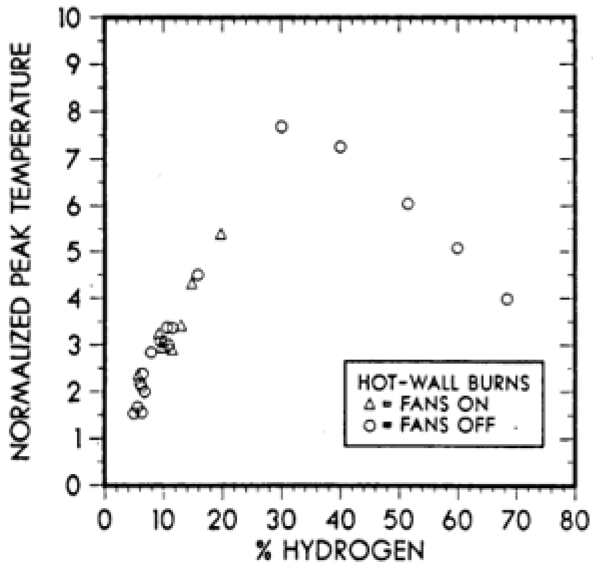

Figure 8: Normalized peak Temperature vs. % hydrogen (Marshall, B. 1986)

Figure 8 shows the peak temperature reached in the combustion chamber and the percent of hydrogen used. As it can be seen from the figure that first temperature rises for up to 25% of hydrogen fuel mixture, then it decreases significantly as the amount of hydrogen increases. (Marshall, B. (1986).Comparatively, hydrogen has a high ignition capability and with a large flame propagation velocity. The flame speed is higher than other hydrocarbon fuel which implies that hydrogen fuel behaves like the ideal engine cycle. But at the leaner mixtures the velocity of the flame lowers significantly.

Small quenching distance is another characteristics of hydrogen fuel over the other types of fuel. Small quenching distance could be disastrous since the flame gets attached to the cylinder wall, a main source of backfire to the front.   The large scale of flammability is related to the chemical kinetics of combustion and good diffusion characteristics because of the highly reactive radical H atom.

The increasing amount of hydrogen reduces the carbon content in the fuel that limits the production of carbon-monoxide. Main pollutants produced during the hydrogen combustion are therefore oxides of nitrogen (Nox). There are numerous existing problems that can be resolved by improving fuel delivery and also using thermal dilution system such as recirculation of exhaust gasses or stem injection. (2001, HYDROGEN USE IN INTERNAL COMBUSTION ENGINES*)*

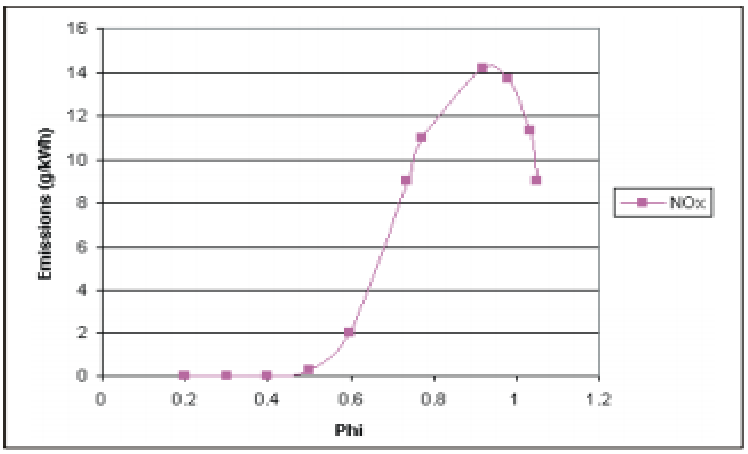

Figure 3-8 Emissions For A Hydrogen Engine

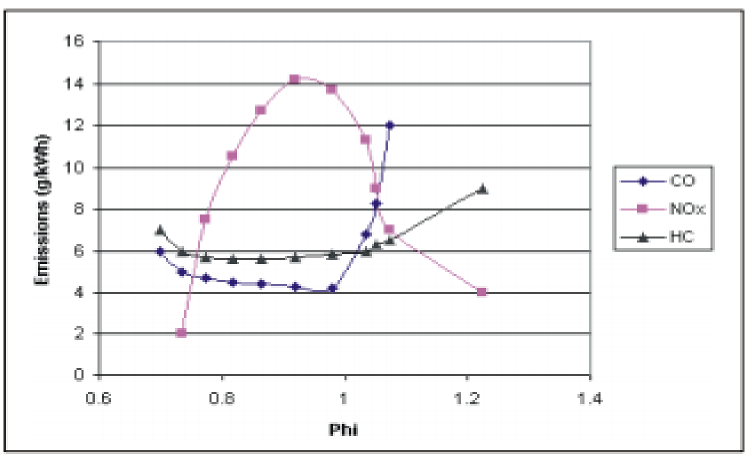

Figure 3-9 Emissions For A Gasoline Engine

Figure 9: An example showing the emission of gasses from hydrogen engine (Rankin, D)

Figure 9 shows the comparison between the hydrogen engine and gasoline engine. Hydrogen engine generates only thermal Nox whereas the gasoline engine is reliable to emit NOx, CO as well as unburnt hydrocarbon. The figure also shows that upon low equivalence ratio, hydrogen engine can reduce the emission up to zero.

Conclusion and Recommendations:

Emission control technologies are numerous. Many researches have been done and discoveries have been made. Thousands of scientists and engineers across the globe are still constantly modifying existing engines for better control of emissions and improving fuel consumption. Only a few of them have been discussed in this paper. The emission characteristic depends on temperature, pressure, fuel types, amount of air, mixing and residence time. It is nearly impossible to include all the development towards emission control in this short research. Based on the available technological advancement and its difficulties, one can be more suitable than other. In aero industry, safety is the main concern that force to compromise certain drawbacks but for land based engine, there have been considerable improvements.

Lean pre-mixed combustion with few modifications has brought down the emission level under 15 ppm (O_2 = 16%). In the land based engine, this technology has served well. Flameless combustion is more difficult to implement in aero industry because of the length coming from recirculation pipe and its weight. Still, Flameless combustion is capable of bringing down the emission level to single digits upon proper implementation. Industrially, Catalytic combustion is the main focus. As discuss earlier, catalytic combustion is most probable emission reduction technology, but the catalytic materials that can hold the high temperature is very rare and expensive. Catalyst degradation for frequent loading occurs. A low temperature reaction is not good for the complete burn (reaction) of hydrocarbon. NOx can be reduced, but the CO production and unburnt hydrocarbon would increase excessively.

Therefore, a new power resource that is environmentally favorable and also helpful to substitute a fuel crisis is the demand for today. Lean Hydrogen combustion can address both the environmental emission crisis and fuel supply issue. But much more study and advancement on hydrogen extraction, storage and combustion are required in order to acquire full benefit.

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