LOW EMISSION COMBUSTION TECHNOLOGY
FOR STATIONARY GAS TURBINE ENGINES

by
Stuart A. Greenwood
Group Manager
Solar Turbines Inc.
San Diego, California

Stuart A. Greenwood is the Group Manager of the Advanced Turbines System Combustion Group, with Solar Turbines Inc., in San Diego, California. He was responsible for the design of the low emission combustion system used in the Mercury 50 engine that was produced under a joint contract between Solar Turbines and the Department of Energy. Prior to joining Solar Turbines (in 1994) he spent 30 years working in the field of combustion system design and development for all types of gas turbine engines.

Mr. Greenwood received a B.Sc. degree (Mechanical Engineering, 1963) from Manchester University in the United Kingdom. He is a United Kingdom Chartered Engineer and Member of the United Kingdom Institution of Mechanical Engineers.

ABSTRACT

The need to control exhaust emissions from stationary power sources is dictated by environmental regulations that limit the amount of smoke (particulates), sulfur dioxide, carbon monoxide, hydrocarbons, and oxides of nitrogen or NOx that can be exhausted into the atmosphere. In areas where atmospheric pollution is a serious concern, as in the Los Angeles basin, very low emission levels are demanded.

A brief review of the emission regulations in force in the United States and Europe is given. The mechanisms that give rise to the formation of the regulated pollutants in a gas turbine combustion system burning hydrocarbon fuels are described and the conflicting requirements for producing low emission levels of nitrogen oxides while at the same time controlling carbon monoxide and hydrocarbon levels are explained.

The operation of a conventional diffusion flame combustion system is discussed and the concept of using water injection in such a system to control nitrogen oxide emissions is explained. The emission levels achievable with this type of system are given.

A lean premixed low emission combustion system is described and the problems that must be overcome if the operation of the gas turbine is not to be compromised are referred to. The features of an ultra lean premixed combustion system are described that allow this system to produce single digit emission levels.

The operation and attributes of a catalytic combustion system are described.

INTRODUCTION

The objective of this paper is to give people who have little or no combustion knowledge a basic understanding of the design and operation of a stationary gas turbine (SGT) combustion system burning hydrocarbon fuel and the changes that have to be made to meet emission regulations.

Prior to the introduction of regulations that limit the emission of oxides of nitrogen (NOx) the principal requirements of a combustion system in relation to the chemical reactions taking place were that the fuel was fully consumed, the exhaust was free from visible smoke, and the reaction was completed in as small a volume as possible. Combustion systems designed to these requirements emit very little unburned products, that is hydrocarbon species and carbon monoxide. These substances are atmospheric pollutants and hence the thermodynamic objectives of good efficiency, i.e., consuming all the fuel, are in harmony with environmental needs. Unfortunately the combustion process in these, conventional, combustion systems leads to the emission of concentration levels of NOx that can be much higher than the environmental regulations allow.

The paper describes the most common design approach used in SGT combustion systems to control NOx emissions, the lean premixed combustion system. In recent years NOx emission requirements have tightened to require very low emission levels and this need has been answered by the creation of ultra lean premixed combustion systems. Additionally catalytic combustion systems are being developed since they offer the promise of near zero emissions.

The author's experience in SGT combustion systems is associated with the SGTs produced by Solar Turbines Inc., and as such is limited to gas turbines of less than 15 MW (20,000 hp) power output and confined to fully annular combustion chambers as opposed to the multican arrangements. However the principles and design features discussed are in general applicable to SGTs of any power rating.

EMISSION REGULATIONS IN FORCE IN NORTH AMERICA AND EUROPE

Emission regulations for stationary gas turbines (SGTs) have been in force in the USA since the mid 1970s. Over the years the regulations have become more stringent and more complex. The primary pollutants controlled are nitric oxide/nitrogen dioxide (NOx), oxides of sulfur (SO_x), unburned hydrocarbons (UHC), carbon monoxide (CO), and combustion generated particulate matter. With regard to SGTs the major objective of the regulations is NOx reduction. Almost all the sulfur present in the fuel is converted to SO_x during the combustion process and there are no practical ways of inhibiting this process so either the concentration of sulfur in the fuel must be controlled or the SO_x must be removed from the engine exhaust. UHC, CO, and particulate matter are rarely a problem with SGTs, particularly if the fuel is natural gas.

In the USA the "New Source Performance Standards" (NSPS) (Clean Air Act, 1990) limit the amount of NOx emitted by SGTs irrespective of the site location. Additionally the ambient air quality standards established by the Environmental Protection Agency (EPA) determine whether the proposed site location is in an attainment or nonattainment area relative to NOx and CO emissions. If the source is in an attainment area and the NOx emission exceeds 250 tons per year (100 tons per year for certain sources) then a "Prevention of Significant Deterioration" (PSD)

(Clean Air Act, 1990) review must take place and the emissions cannot cause the EPA air quality standards to be exceeded. It is required that the "Best Available Control Technology" (BACT) (Clean Air Act, 1990) be used which is defined as the best technology that has been demonstrated as practical and economically viable for the installation in question. If the site is in a nonattainment area then a "New Source Review" (Clean Air Act, 1990) is performed and the regulations, which can be state and region specific, then require different degrees of control. The most stringent is "Lowest Achievable Emission Rate" (LAER) (Clean Air Act, 1990), which is the best technology possible irrespective of the economic consequences.

Figure 1 shows the NOx emission nonattainment areas and their degree of nonattainment for the USA. There are very few CO emission nonattainment areas, Los Angeles and Phoenix being notable examples.

Figure 1. Nonattainment Areas in USA.

Table 1 shows the USA NOx emission standards as they apply to SGTs. The standards are expressed as the volumetric concentration of NOx in the turbine exhaust, i.e., parts per million by volume or ppmv, corrected to an exhaust oxygen volumetric content of 15 percent. Note that NSPS limits are obtained from a formula that includes engine thermal efficiency so that engines with a higher efficiency than 25 percent are allowed to produce more NOx. With an efficiency of 30 percent, for instance, 20 percent more NOx is allowable. The lower 75 ppmv level applies to SGTs that are used to provide more than one-third of their output as electrical power to the grid. A range of NOx levels is quoted for BACT and LAER because the actual level will depend on site specific conditions and the control technology deemed to be appropriate. In the Los Angeles basin where the nonattainment is extreme the lowest possible emissions are required. Figure 2 shows the approximate relationship between volumetric pollutant concentration and tons of pollutant emitted per year assuming an engine operating for 8000 hours with a thermal efficiency of 33 percent.

Table 2 shows the European NOx emission standards for SGTs. In this table the word "thermal" means the energy contained in the fuel burned, which is of course greater than the power generated by the SGT. Because of the complexity of the regulations the information provided in Tables 1 and 2 can only be taken as a guide to illustrate the NOx emission levels required.

The regulation of "greenhouse gases" and in particular CO_2 was proposed under the Kyoto Protocol of 1997 (1997). Several countries in Europe have introduced CO_2 taxes that are dependant on the amount of CO_2 emitted into the atmosphere. In terms of fossil fuel burning SGT combustion systems, there are only two methods of limiting CO_2 emissions, namely using fuels with lower carbon content (natural gas instead of oil) and increasing the thermal efficiency of the SGT. Natural gas is already the preferred SGT fuel. Cogeneration can boost the overall thermal efficiency of the plant in which the SGT is installed.

Table 1. United States NOx Emission Standards.

Standard	Emissions levels (ppmv @ 15% O_2)
NSPS (New Source Performance Standard)	<30Mw* 150 x(efficiency/25) >7.5MWe** 75x(efficiency/25)
BACT (Best Available Control Technology)	9 to 25
LAER (Lowest Achievable Emission Level)	3 to 5

* for mechanical drives . ** for electrical power generation

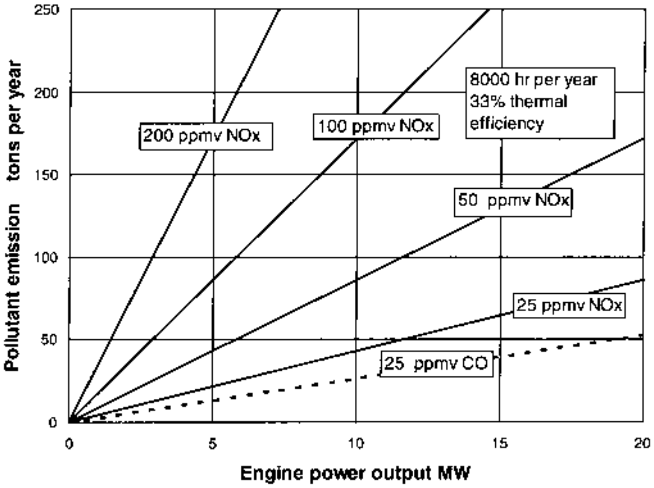

Figure 2. Volumetric Emission Levels Expressed as Tons by Year.

Table 2. NOx Emission Standards in Europe and Canada.

Country	Size, MW	Using gas fuel, ppmv	Using liquid fuel, ppmv
Austria	All	72	96
Denmark	<50 (thermal)	215	215
France	<10 (thermal)	72	96
	10-100(thermal)	48	72
Germany	<100 (thermal)	72	96
Italy	<8 (thermal)	72	72
	8-15(thermal)	48	-
Netherlands	All cogen	38	38
	Non cogen	120	-
Spain	All	~300	-
	8-15	48	-
UK	<50 (thermal)	60	80
Canada	All	42	-

MECHANISMS THAT GIVE RISE TO THE FORMATION OF POLLUTANTS

Hydrocarbon fuels when completely combusted produce water vapor (H_2O) and CO_2. Incomplete combustion is indicated by the presence in the engine exhaust gas of CO and UHC. In general the amount of UHC is small and CO is the principal pollutant generated from incomplete combustion.

The rate of chemical reaction is a strong function of the temperature of the combustion process—the hotter it is the faster the reaction. If the temperature is lowered more time is needed to complete the reactions, in particular the oxidization of CO to CO_2, which means that the volume of the combustion chamber has to be increased.

The principal mechanism for NOx formation is the oxidation of the nitrogen in the air when exposed to the high temperatures generated by the combustion process. The amount of NOx created by this mechanism, called "thermal NOx," is dependant on the temperature of the combustion gases and to a much lesser extent the time the nitrogen is exposed to this temperature. This is an endothermic reaction that only proceeds at significant rates if the gas temperature is above approximately 2500°F hence thermal NOx can be controlled by lowering the flame temperature.

Fuel bound NOx is produced by oxidation of the chemically bound nitrogen that can be contained in hydrocarbon fuels. The NSPS NOx emission limits are increased if fuel bound nitrogen (up to 0.25 percent by weight) is present in the fuel.

Figure 3 shows the effect of flame temperature on NOx emissions. The richer the mixture strength (higher the fuel/air ratio) the higher the flame temperature and hence NOx. However if the fuel/ratio becomes richer than the stoichiometric value, i.e., insufficient oxygen to burn all the fuel, then the flame temperature and NOx falls. Rich conditions like this produce significant amounts of UHC and CO of course.

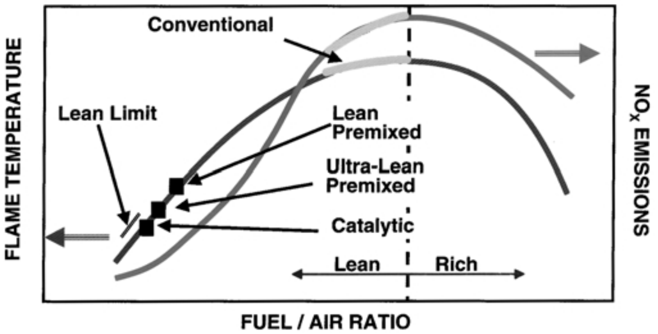

Figure 3. Effect of Flame Temperature on NOx Emission.

It will be apparent from the above that the requirement of lower flame temperatures for NOx control is directly opposite to that desired for prevention of UHC and CO emissions. This is illustrated in Figure 4, which shows the variation in NOx and CO emissions with fuel/air ratio. The lower the NOx required the more difficult it is to ensure the oxidation of the CO to CO_2.

The engine pressure ratio influences emissions since the reaction rates are also pressure dependant. In particular CO oxidation rate reduces with pressure. This causes CO emissions to rise as the engine load is reduced and the combustion air pressure falls.

CONVENTIONAL COMBUSTION SYSTEMS

The term conventional combustion system is used to describe a combustion system in which the fuel is injected directly into the reaction zone with little or no premixing of the air and fuel. A diffusion flame is produced since the fuel has to mix with the air before it can burn. Because the air and fuel are not premixed the fuel/air ratio is very heterogeneous within the reaction zone. High gas temperatures are produced as the fuel burns close to the stoichiometric mixture strength even though the overall bulk fuel/air ratio is leaner. This is particularly so for liquid fuels where burning takes place at the rich conditions that surround the partially evaporated fuel droplet. It is important to differentiate between the actual flame temperature and the bulk flame temperature—i.e., the temperature at the flame front itself compared with that which would occur if the mixture were perfectly premixed before combustion. The high flame temperature ensures a rapid reaction rate and low CO and UHC emissions. However the high flame temperature produces high levels of NOx. Although leaning out the bulk mixture strength by adding more air is somewhat effective in reducing NOx, particularly with gaseous fuel, low NOx levels cannot be achieved by this means because of the inherent heterogeneity.

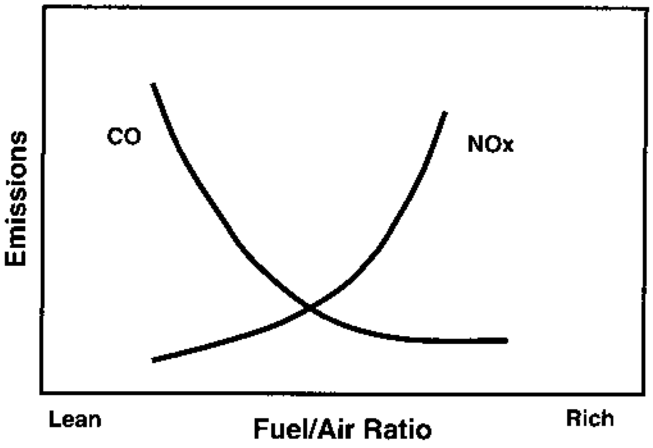

Figure 4. Effect of Flame Temperature on CO and NOx Emission.

This type of combustion system has been used since the early days of the gas turbine engine. NOx was not an issue then and complete combustion (minimal CO and UHC emission) and freedom from visible exhaust smoke (particulate matter) were important. Because the reaction is fast the combustion chamber volume can be kept small to minimize the surface area of metal to be cooled.

Figure 5 shows a cross section of conventional fully annular combustion chamber and the main features are indicated. The major combustion reaction region is the primary zone where the fuel is introduced to a limited amount of air to achieve an overall mixture strength slightly leaner than stoichiometric. The flame temperature in this zone is typically 3500°F, which ensures a high rate of chemical reaction but because fuel/air mixing is far from perfect the combustion reactions, principally the oxidation of the intermediate product carbon monoxide (CO) to carbon dioxide (CO_2) is not complete. In the secondary zone more air is added to complete the reaction and all the fuel should now be consumed and the gas temperature is about 2500°F to 3000°F. The remaining air is now added in the dilution zone to dilute the hot gases down to the temperature level required by the turbine, 1800°F to 2200°F.

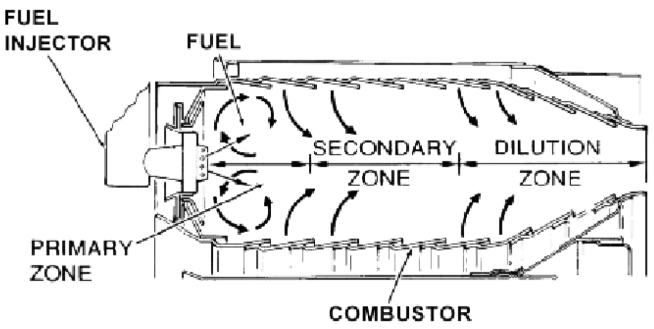

Figure 5. Conventional Combustion System.

The NOx levels generated by this type of combustor burning gaseous fuel are shown in Figure 6 for engines with which the author has experience. The emission levels are plotted against engine power for convenience and no specific correlation between power and emission levels is implied. Generally NOx emission levels increase as the engine pressure ratio increases if the flame temperature is held constant. When operating on liquid fuel the NOx emissions are approximately 70 percent higher. The figure shows that the NOx emission can be reduced to less than 50 ppm by injecting water into the combustion chamber. Water is injected via the fuel injector into the primary combustion zone and this reduces the flame temperature and hence NOx. However this temperature reduction of course reduces the CO oxidation rate and therefore there is a tendency for CO emission to rise. With a fuel/water ratio of unity the NOx can be reduced by 80 percent but CO emission levels will become an issue and can easily rise above 100 ppmv. In general one can say that a conventional combustion system burning gaseous fuel can achieve the USA NSPS 150 ppm NOx emission limit quoted in Table 1 when used to drive mechanical devices such as compressors and, with water injection, the lower 75 ppm limit when used for electrical power generation.

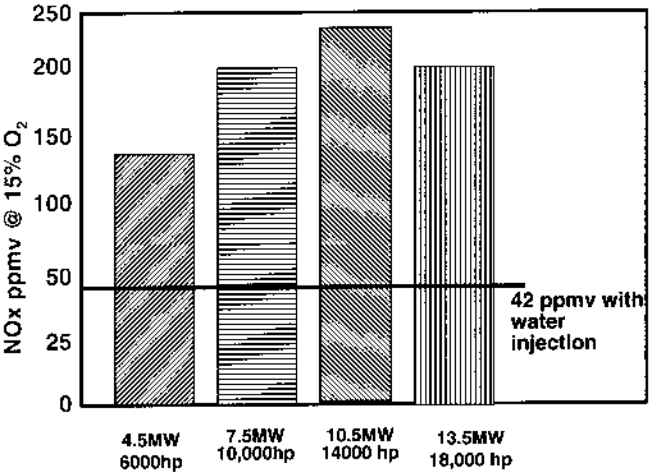

Figure 6. NOx Emission Levels for SGTs with Conventional Combustion Systems Operating on Natural Gas Fuel.

As the engine load is reduced the overall combustion chamber fuel/air ratio becomes leaner, the flame temperature is lower and hence NOx is lower. The lowering of the temperature plus the fact that the combustion inlet air temperature and pressure also reduce means that incomplete oxidation of CO can become an issue. The combustion chamber volume is selected with part load operation in mind. Hence as load is reduced and the bulk flame temperature falls there is time for the oxidation of CO to be completed. In essence the volume is established to ensure that the combustion process is efficient over the main operating range of the engine—typically from 30 percent load upward.

Because the flame temperature of conventional combustion systems operating at full load is near the peak of the flame temperature curve, it is well away from the lean limit temperature, i.e., the lowest temperature at which the flame can be sustained. Therefore there is a wide range of flame temperatures that the combustion system can operate over. As the lean limit is approached UHC and, in particular, CO emissions build up rapidly. Figure 3 attempts to diagrammatically illustrate this. The conventional combustion system therefore has a wide stability range and is normally free of any stability issues that might arise during engine starting or rapid off-load transients.

Although high flame temperatures ensure CO oxidation the flame temperature across the combustion chamber cross section is not uniform because of the lack of fuel air mixing. Figure 7 shows a typical wall cooling scheme in which air at the combustor inlet temperature (600°F to 900°F at full load) is "filmed" onto the hot gas side of the combustion chamber wall hence protecting it from direct contact with the hot gases. The convector shown in this figure is used to control the velocity and uniformity of the air flowing along the "cold" air side of the wall. Since the cooling air film mixes with the hot gases, its cooling effect is quickly lost and a new film has to be initiated. Figure 5 shows that the walls of the combustion chamber are covered with film cooling devices spaced out at approximately 1.5 to two inches apart. The mixing in of the cooling air lowers the hot gas temperature in the near wall region. Therefore CO oxidation can be arrested or slowed down. The relatively cool walls, typical wall temperatures being 1300°F to 1600°F, also contribute to this effect.

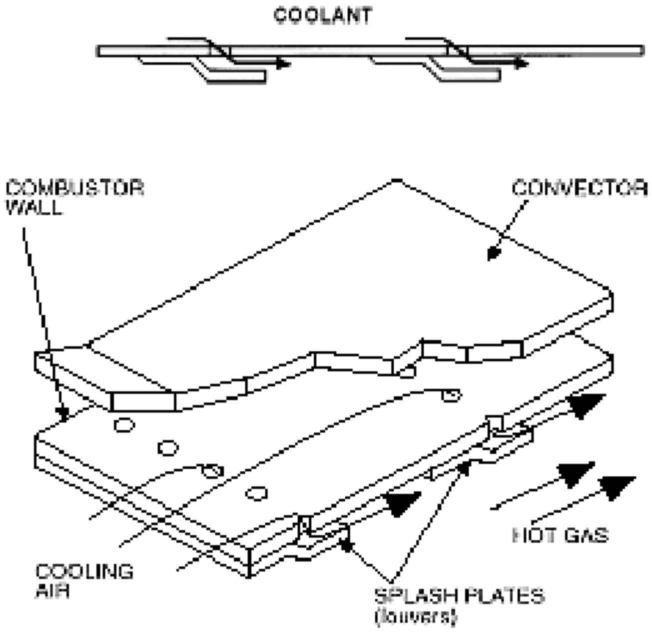

Figure 7. Film Cooling on a Conventional Combustion Chamber Wall.

Because of the high flame temperature, lack of fuel/air uniformity, small volume, and the "cold" gas regions near the walls, conventional combustors are incapable of achieving concurrently NOx and CO emissions less than 50 ppmv. As previously mentioned water injection can significantly reduce NOx but CO emissions increase.

Figure 8 shows the emissions from a state-of-the-art conventional combustion system burning natural gas fuel.

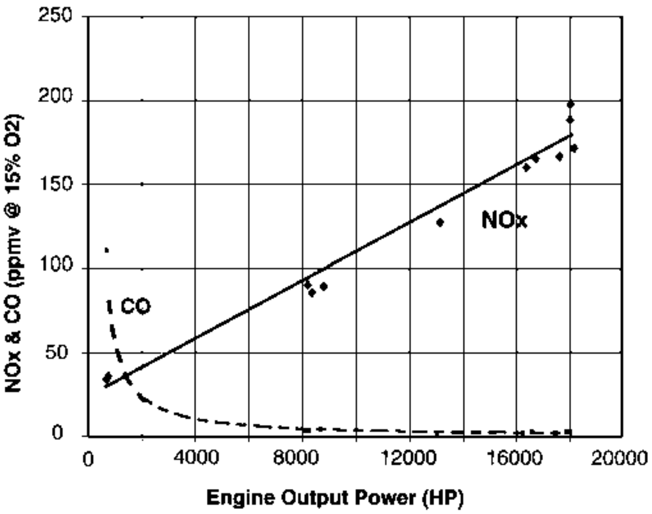

Figure 8. NOx and CO Emissions from a Conventional Combustion System.

LEAN PREMIXED COMBUSTION SYSTEM

For SGTs the use of a lean premixed (LP) combustion system to achieve low emissions has been universally adopted. This system addresses the issues, described above, associated with a conventional system. The principal features of an LP combustion system are the premixing of the fuel and air before the mixture enters the combustion chamber and leanness of the mixture strength in order to lower the flame temperature and reduce NOx emission. Reference to Figure 3 shows that this action brings the full load operating point down the flame temperature curve and closer to the lean limit. It is not surprising therefore that controlling CO emissions can be difficult and rapid engine off-loads bring the problem of avoiding flame extinction. It should be noted that if flame extinction occurs the combustion process cannot be safely reestablished without bringing the engine to rest and going through the restart procedure.

Figure 9 shows a comparison of the LP and conventional combustion systems. In both cases a swirler is used to create the required flow conditions in the combustion chamber to stabilize the flame. The LP fuel injector is much larger because it contains the fuel/air premixing chamber and the quantity of air being mixed is large, approximately 50 to 60 percent of the combustion air flow.

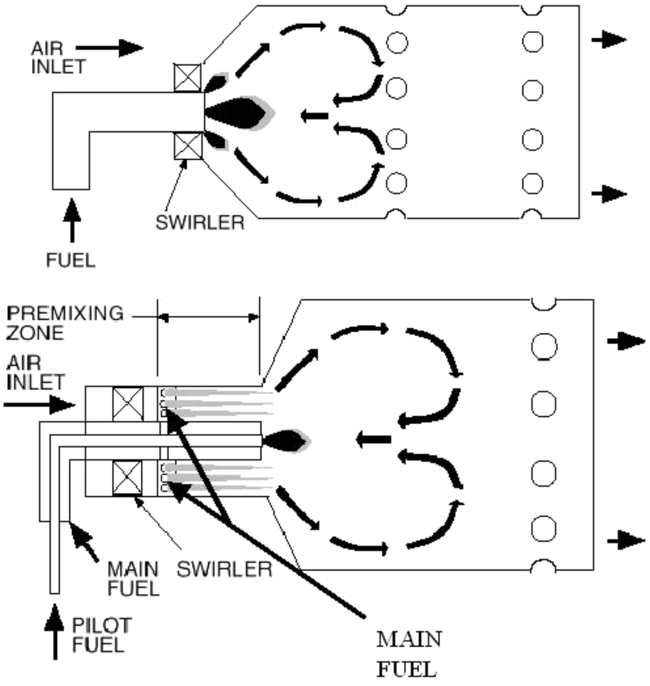

Figure 9. Comparison of Combustion Systems. (Top: Conventional Combustion System. Bottom: Lean Premixed Combustion System.)

The LP injector has two fuel circuits. The main fuel, approximately 97 percent of the total, is injected into the air stream immediately downstream of the swirler at the inlet to the premixing chamber. The pilot fuel is injected directly into the combustion chamber with little if any premixing. Figure 10 shows details of an LP fuel injector for use with gaseous fuel. Note how the gas is injected just upstream of the premixing chamber using radial gas spokes to distribute the fuel across the air stream. Figure 11 shows, side by side, an LP and conventional fuel injector.

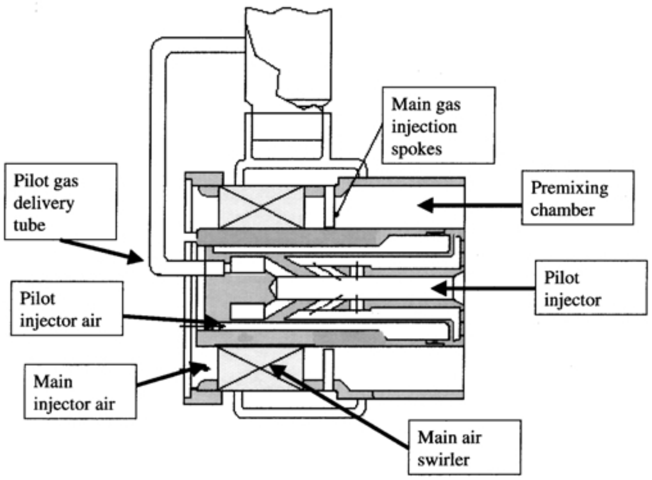

Figure 10. Lean Premixed Fuel Injector.

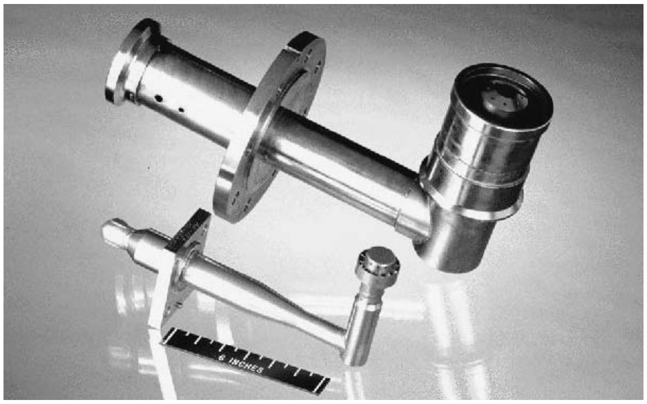

Figure 11. Conventional and Lean Premixed Fuel Injectors.

LP systems are designed to hold NOx emission levels in the 20 to 50 ppmv range, CO to less than 50 ppmv, and UHC to less than 15 ppm from 100 percent engine load down to at least as low as 50 percent load. To achieve this NOx level the flame temperature is in the 2800°F to 2900°F range at full load conditions. Because of this low temperature the rate of CO oxidation is slower and therefore more time is needed to complete this reaction. This translates into the combustion chamber requiring a much greater volume than that of a conventional one. Figure 12 illustrates this by comparing a conventional and lean premixed fully annular combustion system for the same engine. Since the engine rotating assembly is common the length available for the combustion system is the same and consequently the LP version is much wider.

Because of the bigger volume the surface area of the combustion chamber walls is large and hence more air has to be used for cooling. Although the flame temperature is lower and much more uniform than in a conventional combustion system the hot gases are still too hot to pass directly into the turbine section of the engine: some air has also therefore to be reserved for diluting the hot gas. In general after allocating the air required for wall cooling very little if any is left for dilution purposes.

In order to limit the amount of cooling air needed, more efficient wall cooling methods are used. Figure 13 shows the use of impingement and effusion cooling. The cooling air passes through an array of holes (0.070 to 0.150 inch diameter) in the impingement shield and the air jets so produced impinge on the hot combustor wall. After impingement the air passes through an array of small diameter effusion holes (from 0.020 to 0.040 inch diameter) laser drilled through the hot wall at an angle of approximately 25 degrees to the surface. The air is therefore "effused" through the wall cooling it as it passes through but more importantly forming a protective film of cooler air on the gas side of the wall. As shown in the figure a conventional film cooling device is normally used to create the initial cooling film and the effused air continually replenishes the film so that only one or two film cooling devices are needed on each wall. This form of cooling is much more efficient and much less air is needed to cool the walls than would be the case with solely film cooling.

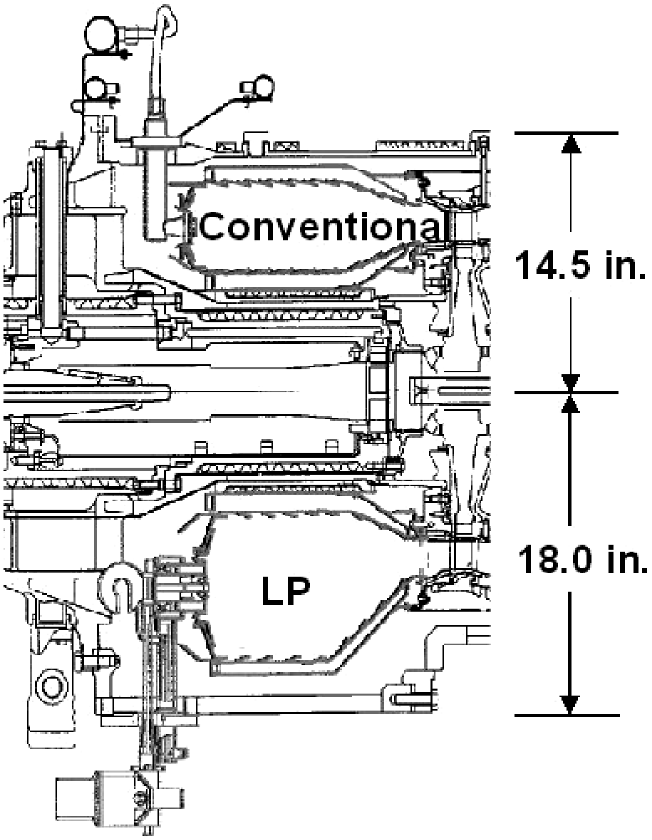

Figure 12. Conventional Versus Lean Premixed Combustion Systems.

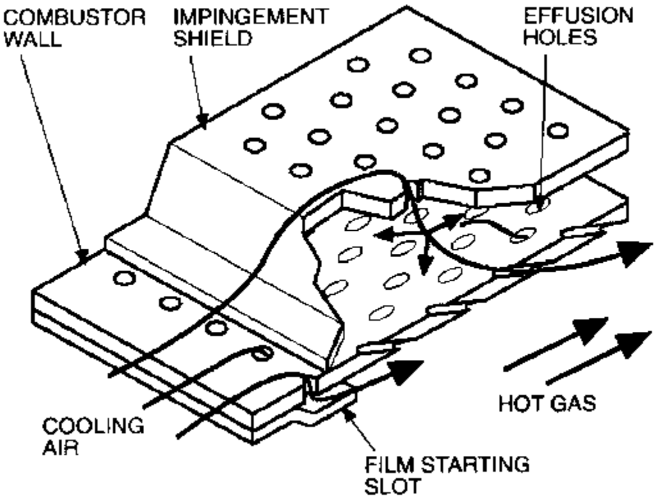

Figure 13. Impingement/Effusion Cooling.

Because cooling air is still filmed on the combustion chamber wall the problem of arresting CO oxidation in the near wall region is still present. This limits the lowest flame temperature that can be used and hence the lowest NOx level that can be achieved.

With the flame temperature being much closer to the lean limit than in a conventional combustion system, some action has to be taken when the engine load is reduced to prevent flame out. If no action were taken flame out would occur since the mixture strength would become too lean to burn.

One method is to close the compressor inlet guide vanes progressively as the load is lowered. This reduces the engine air flow and hence reduces the change in mixture strength that occurs in the combustion chamber. This method, on a single shaft engine, generally provides sufficient control to allow low emission operation to be maintained down to 50 percent engine load. Another method is to deliberately dump air overboard prior to or directly from the combustion section of the engine. This reduces the air flow and also increases the fuel flow required (for any given load) and hence the combustion fuel/air ratio can be held approximately constant at the full load value. This latter method causes the part load thermal efficiency of the engine to fall off by as much as 20 percent.

Even with these air management systems lack of combustion stability range can be encountered particularly when load is rapidly reduced. To increase the stability range a pilot injector is introduced. The pilot fuel is injected directly into the combustion chamber either with no premixing or premixed with a small quantity of air so that pilot mixture strength is richer that stoichiometric. This creates a small diffusion flame similar to that in a conventional combustion system within the body of the main premixed low temperature flame. With 4 percent of the fuel admitted by the pilot, the pilot flame provides a significant increase in combustion stability preventing flame extinction as the load is reduced. This stability enhancement is achieved at the expense of an increase in NOx emission. This increase can be significant, 4 percent pilot can double the NOx level. However with a well designed pilot the use of 2 percent pilot fuel can provide a useful improvement in stability without significantly increasing NOx. It is common practice to use 2 to 3 percent pilot fuel when the engine is running in low emission mode at steady-state conditions above say 50 percent load. The pilot fuel is increased temporarily to cope with off-loads. Below a certain load level the pilot fuel is increased permanently and the combustion system is therefore brought out of low emission mode.

It is necessary to ensure that combustion does not occur in the premixing section of the injector since this region is not designed to endure high temperatures. As the mixture is only in this section for 1 to 2 msec, spontaneous or auto-ignition is normally not a problem with gaseous fuels. It can however be an issue with liquid fuels, which have a much lower auto-ignition temperature because they contain high molecular weight hydrocarbon species that have much shorter auto ignition times. If heavy hydrocarbons, referred to as natural gas liquids, are not removed from the gas fuel then auto-ignition becomes a real issue particularly for high pressure ratio or regenerative engines where the combustion inlet air pressure and/or temperature can be high. Although engine manufacturers take care to specify the quality of the gas fuel to be used experience has shown it is wise to fit the engine with coalescing filters to provide the necessary protection.

A more likely occurrence is combustion in the premixing section due to flame flashback from the combustion chamber. Flame cannot propagate upstream if the flame speed is lower than the downstream velocity of the mixture. The bulk velocity of the mixture stream in the premix section is much higher than flame speed but areas of low velocity or even local flow reversals can occur if care is not taken in the design of the premixing section and the method of introducing the fuel.

Many customers require dual fuel capability, i.e., operation on either gas or liquid fuel, and the ability to switch from one fuel to the other when under load. This can lead to very complex fuel injectors an example of which is shown in Figure 14. Liquid fuel must be vaporized as well as premixed with the air in the injector. If liquid fuel, while still in the liquid state, is allowed to contact the interior walls of the injector premixing section then fuel coking can occur and this can seriously affect the performance of the combustion system. Coking can also occur in the liquid fuel passages within the injector if residual liquid fuel is not adequately purged out of the system when the engine is switched to gaseous fuel operation.

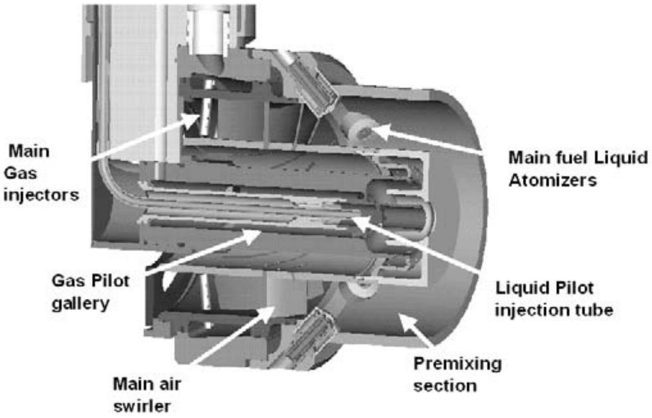

Figure 14. Dual Fuel Premixing Injector.

A difficult problem with lean premixed combustion systems is that of combustion induced pressure oscillations. These can produce large fluctuations in the combustion pressure, ± 5 psi or greater is not uncommon. Significant damage can occur to the combustion system in a very few hours of operation at these amplitude levels. The oscillations are audible as a "howling or singing" tone at frequencies between approximately 200 to 1000 Hz.

Small pressure fluctuations, ± 0.2 psi for example, are always present in the combustion process of both conventional and lean premixed combustion systems due to small variations in the heat release rate. Because lean premixed combustion systems operate close to the lean stability limit they are much more prone to producing pressure oscillations. The frequency of the oscillation is a function of one of the natural acoustic frequencies of the combustion chamber.

Pressure fluctuations, generated by variation in the rate of heat release, propagate throughout the combustion chamber in the form of a pressure wave. The wave causes variations in the instantaneous fuel/air mixture strength in the fuel injector. If the transit time of a "packet" of rich fuel/air mixture, from the point of fuel injection to the position of the flame front, is in phase with an increase in heat release this amplifies the heat release and high combustion pressure oscillations result. Figure 15 shows diagrammatically this phenomenon. In most cases increasing the pilot fuel flow will prevent the buildup of large amplitude pressure oscillations but of course this increases NOx emissions so the emission level may exceed the required limit.

The precise mechanisms that lead to combustion pressure oscillations are not fully understood. Oscillation problems can be encountered in the field on engines that have been setup for oscillation free operation during the engine factory acceptance test simply because of the difference in ambient conditions at the customer's site. It is often necessary to "tune" the pilot fuel flow for the specific site conditions and on occasion this may lead to emission compliance issues.

The engine control system is much more complex than with a conventional combustion chamber as the flame temperature and pilot fuel must be adjusted for different engine conditions. Since flame temperature cannot be measured directly, because of the high temperature, this has to be inferred from indirect measurements such as air and fuel metering or from a knowledge of the engine exhaust gas temperature, temperature drop across the turbine, and combustion chamber flow distribution.

ULTRA LEAN PREMIXED COMBUSTION SYSTEM

The ultra lean premixed (ULP) combustion system is an extension of the lean premixed technology just described, the demarcation at the author's company being that the ULP system is capable of achieving single digit emissions, i.e., NOx, CO, and UHC are all less than or equal to 9 ppmv.

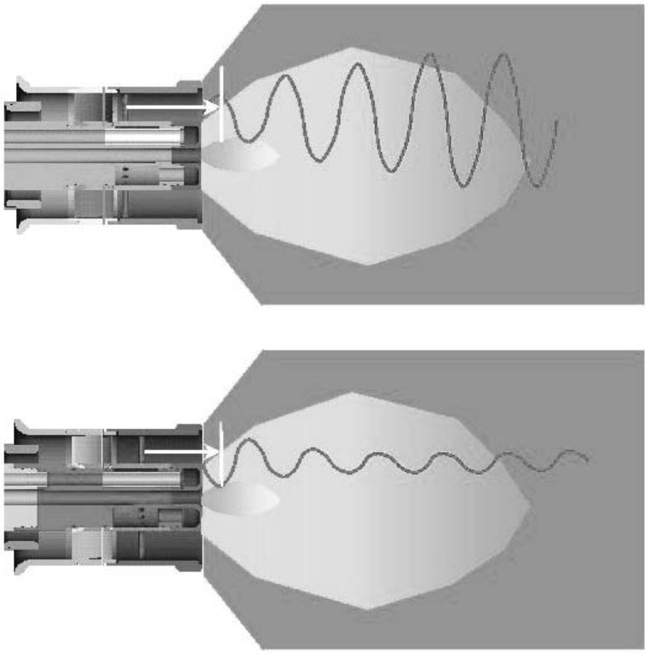

Figure 15. Combustion Pressure Oscillations. (Top: Oscillations present when the fuel transit time is in phase with heat release frequency controlled by the combustion chamber acoustics. Bottom: No oscillations when the fuel transit time is out of phase with the heat release frequency.)

By limiting the flame temperature to a maximum of 2650°F single digit NOx emissions can be achieved. To operate at a maximum flame temperature of 2650°F, which is up to 250°F lower than the LP system previously described, requires premixing 60 to 70 percent of the air flow with the fuel prior to admittance into the combustion chamber. With such a high amount of the available combustion air flow required for flame temperature control, insufficient air remains to be allocated solely for cooling the chamber wall or diluting the hot gases down to the turbine inlet temperature. Consequently some of the air available has to do double duty, being used for both cooling and dilution. In engines using high turbine inlet temperatures, circa 2400°F to 2600°F, although dilution is hardly necessary there is not enough air left over to cool the chamber walls. In this case the air used in the combustion process itself has to do double duty and be used to cool the chamber walls before entering the injectors for premixing with the fuel. This double duty requirement means that film or effusion cooling cannot be used for the major portion of the chamber walls. Figure 16 shows emission levels measured on a ULP system.

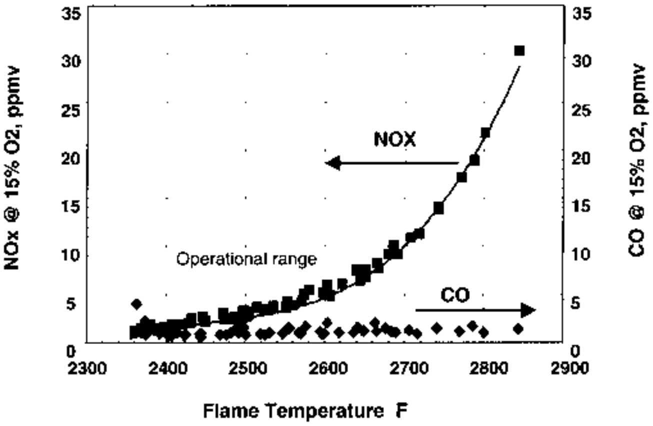

Figure 16. Emission Levels from ULP Combustion System.

Figure 17 shows a cross section of a fully annular ULP system. In this particular design 65 percent of the combustion air flow is fed to the fuel injectors and the remaining 35 percent is caused to do double duty as wall cooling and dilution air. The cross section is taken out of the plane of the fuel injectors, which are located on the dome as per all previous systems discussed. The entire combustion chamber flame zone is cooled by impingement cooling and this air is not allowed to enter the chamber until the exit section, which is downstream of the combustion reaction zone. This type of cooling scheme, where no cooling film is generated on the hot gas side of the combustion chamber walls, is usually called “backside” or “augmented backside” cooling. The exit cones are cooled with film and effusion cooling as previously described. Some of this air is used for dilution purposes passing through the combustion chamber walls immediately downstream of the flame zone. Because this particular combustion system operates with a high inlet air temperature the hot gas side of the flame zone dome and walls are coated with thermal barrier coating (TBC) which has a low thermal conductivity and hence insulates the metal. This is a ceramic material that is plasma sprayed on during combustion chamber manufacture. The temperature drop across the TBC, typically 300°F, means the combustion gases are in contact with a surface that is operating at approximately 2000°F, which also helps to prevent the quenching of the CO oxidation.

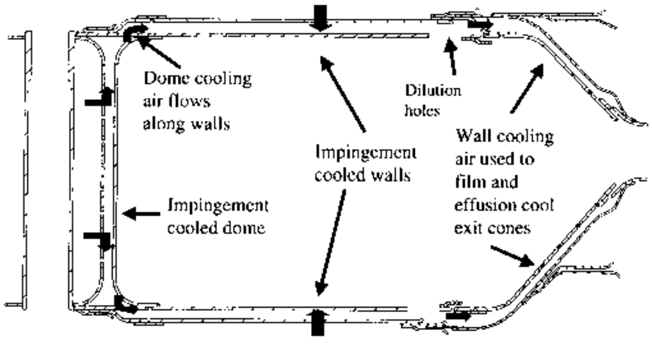

Figure 17. ULP Combustion Chamber.

Figure 16 shows that the CO emission level is very low even when the combustion system is operating close to its extinction point, which occurs at a flame temperature of about 2350°F. Although this in part is due to the high inlet air temperature of this particular combustion system (1150°F), the main factor in preventing CO emissions is the backside cooling scheme and the TBC. This ensures that the CO oxidation in the near wall region is not arrested.

A ULP fuel injector, for use with a gas fuel only combustion system, is shown in Figure 18 and it can be seen that it has essentially the same features as the LP version. The difference lies in the “cleanness” of the aerodynamics. The swirler vanes are more aerodynamic in shape and the gas fuel is injected through the leading edge of the vanes rather than through radial spokes.

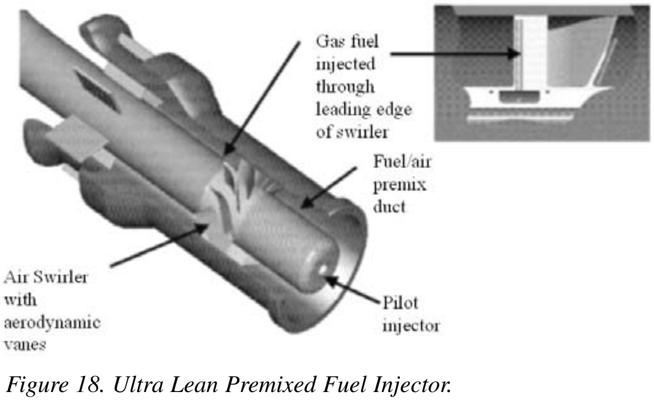

Figure 18. Ultra Lean Premixed Fuel Injector.

With the maximum flame temperature of 2650°F being much closer to the lean limit than an LP system, modulating the combustion air flow by means external to the combustion system, like closing the compressor inlet guide vanes, is not sufficient to control the flame temperature as load is reduced. Therefore the combustion system includes a variable geometry system that allows the air flow entering the injector to be reduced as engine load is lowered. An injector incorporating such a system is shown in Figure 19. A plug valve positioned in the air entry section of the injector can be moved to restrict the air flow. The pinion wheel on each injector is driven by a ring gear that is moved by an electric actuator. This particular injector happens to be used in an LP combustion system where it is used to eliminate air bleed from the combustion system section of the engine and hence avoid part load thermal efficiency fall off.

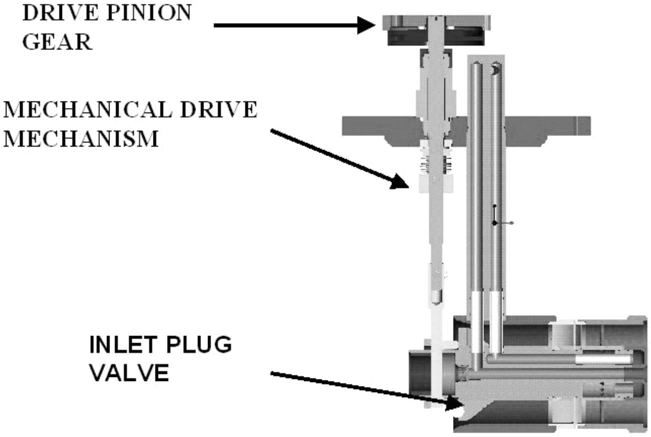

Figure 19. Variable Geometry LP Injector.

By using a multistage ULP combustion system the need for variable geometry can be avoided. This type of system contains two or more combustion reaction zones, which are tailored for the different engine loads. One stage is used for low loads, the second for intermediate loads, and maybe both stages for full load. The air flow in each stage is tailored for its own particular load range and the fuel is introduced into each stage in such a manner as to prevent the flame temperature exceeding 2650°F.

As with LP systems the control of the combustion system can be complex. In order to consistently achieve single digit emissions, the control of the flame temperature in a ULP system has to be very precise. This can be a problem because of the difficulty in determining the flame temperature. Direct measurement of the flame temperature by nonintrusive flame radiation sensors is currently being investigated. Work is also being undertaken on the development of low cost, reliable, NOx and CO sensors that can be permanently installed in the engine exhaust and used to provide a closed loop feedback control.

ADD-ON DEVICES FOR CONTROLLING EMISSIONS

Postcombustion controls, referred to as “add-on” controls, treat the pollutants after the combustion process. In contrast to a reciprocating engine, exhaust gases from a gas turbine contain large amounts of oxygen and small amounts of carbon monoxide and hydrocarbons. Consequently a catalyst similar to that used on an automobile cannot be used. A selective catalytic reduction (SCR) system is used in which ammonia is added to the exhaust gas stream to act as a reducing agent prior to the stream passing through the catalyst bed. The ammonia (NH_3) reacts with the NOx in the presence of oxygen to form nitrogen and water. The ammonia flow has to be varied to control the outlet NOx below the required limit and minimize the amount of unreacted ammonia exhausted to the atmosphere. Since ammonia itself is a hazardous pollutant, the control system for an SCR has to be very reliable and, if the engine load fluctuates as in a nonbase-load application, quite complex.

A newer catalytic system called the SCONOx™ system uses an oxidation/absorption cycle where the NOx is first oxidized to NO_2 and this is absorbed onto the surface of the catalyst. At the same time CO is oxidized to CO_2. When the catalyst is saturated it must be regenerated by passing a hydrogen dilute reducing gas, produced from natural gas and steam by an auto thermal reforming gas generator, across its surface. Water and nitrogen are exhausted during this regeneration process.

Both these systems are capable of reducing the concentration of the pollutant by 90 percent but the system cost and complexity are significant.

CATALYTIC COMBUSTION SYSTEM

In order to consistently achieve NOx emission levels of less than 5 ppmv catalytic combustion systems are being developed. These systems have the ability to limit the flame temperature to 2500°F and hence negligible NOx is produced. Catalyst combustion systems are still in the development phase and their ability to successfully operate under field conditions has yet to be demonstrated. It is beyond the scope of this paper to describe these systems in detail and only a very cursory explanation of their method of operation is given.

Figure 20 shows a schematic drawing of a catalytic combustion system where the main features are shown. The catalyst bed is a honeycomb like structure that provides a large surface area exposed to the fuel/air mixture. The surface of the honeycomb is coated with noble metals. Air and fuel are premixed upstream before entering the catalyst and downstream of the catalyst there is a post catalyst combustion zone. The mixture strength is leaner than used in a ULP system and 70 to 80 percent of the available combustion air is used. The combustion reaction commences in the catalyst as the fuel/air mixture comes into contact with the catalyst noble metals. Typically the temperature of the mixture entering the catalyst has to be a minimum of 750°F. If this temperature is higher than the engine compressor provides, then a combustion chamber is required upstream to provide the necessary boost in temperature. This upstream preheating combustion system must be designed along lean premixed lines in order to ensure that only a very small amount of NOx is created, but fortunately CO and UHC need not be controlled since this will be consumed either in the catalyst or the post catalyst combustor. The proportion of the fuel combusted in the catalyst depends on the high temperature capabilities of the honeycomb structure. If a metal structure is used then the maximum gas temperature is limited to 1750°F, whereas in the case of a ceramic structure a higher temperature can be tolerated. This temperature is controlled by adjusting the catalyst reactivity rate, the surface area exposed to the mixture, the transit time of the mixture through catalyst bed, and ensuring that the fuel/air is very uniformly premixed. The hot partially combusted gases exit the catalyst and enter the post catalyst combustion chamber. Because of the high exit temperature the gases auto-ignite and combustion is completed at a temperature level that is controlled by the initial inlet mixture strength, i.e., 2500°F.

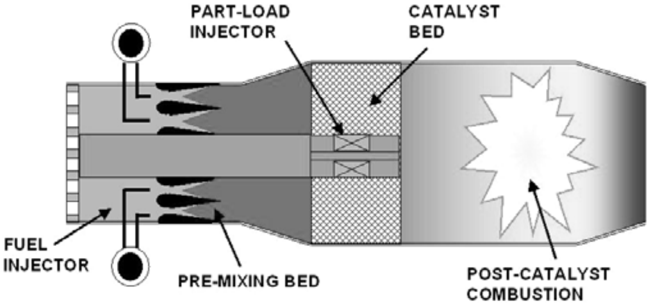

Figure 20. Catalytic Combustion System.

As with a ULP combustion system, backside cooling must be used to prevent CO emissions and the air flow through the catalyst must be reduced by some form of variable geometry system as engine load is reduced to maintain the required mixture strength. If the mixture strength becomes too lean then high CO and UHC emissions result because the catalyst bed outlet temperature falls and combustion can cease in the post catalyst combustion chamber.

If a preheater is installed upstream of the catalyst to boost the catalyst inlet temperature, then this is also used to start the engine and typically bring the machine up to no load or idle. Figure 20 shows a system that can be used when an upstream preheater is not needed to boost the catalyst inlet temperature. In this case a diffusion type flame is created in the post catalyst combustion chamber by using a part load injector that passes through the center of the catalyst system and injects fuel directly into the post catalyst combustion chamber. This injector is used to start the engine and bring it up to an operating condition where the air inlet temperature to the catalytic system is high enough to "light-off" the catalyst. Fuel to the part load injector is then turned off and the catalyst system takes over.

As far as the author is aware, all catalyst combustion systems currently being developed are for use with gaseous fuels only. Because the catalyst reactivity is optimized for the fuel being used it would seem extremely difficult if not impossible to design a system that could cater for operation on both liquid and gaseous fuels.

REFERENCES

1990 Clean Air Act, 1990, United States Environmental Protection Agency, Washington, D.C.

"Kyoto Protocol of 1997," 1997, United Nations Framework Convention on Climate Change, United Nations, New York, New York.

BIBLIOGRAPHY

Maurice, L. Q. W. and Blust, J. W., 1999, "Emission from Combustion of Hydrocarbons in a Well Stirred Reactor," AIAA 99-1039.

ACKNOWLEDGEMENT

The author would like to acknowledge the assistance and advice received from colleagues in the Combustion Department at Solar Turbines and also the senior management of the company for allowing this paper to be presented.

SCONOx™ is a proprietary system produced by Goal Line Environmental Technologies LLC.