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Fuels, Combustion and Emissions for Industrial Gas Turbine

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Abstract

For economic and environmental reasons, it is important that gas turbines used in both Industrial Power Generation as well as Oil & Gas applications can burn a wide variety of fuels, with minimum impact on the environment.

This seminar will examine the types of gaseous and liquid fuels that can be considered for use in Industrial Gas Turbines, discuss the basic types of combustion system employed such as 'conventional' and 'Dry Low Emissions'. The flexibility of these systems to accept different types of fuel given due consideration to fuel quality and composition will be included along with methods employed to review and assess fuels. Common contaminants found in fuels and the impact these have on the operability and maintenance of an industrial gas turbine will also be covered. Understanding gaseous fuel composition and the impact on the combustion process will be presented along with the resultant emissions to atmosphere and pollution abatement methods available and applied to limit the impact on the environment.

Topics to be covered include:

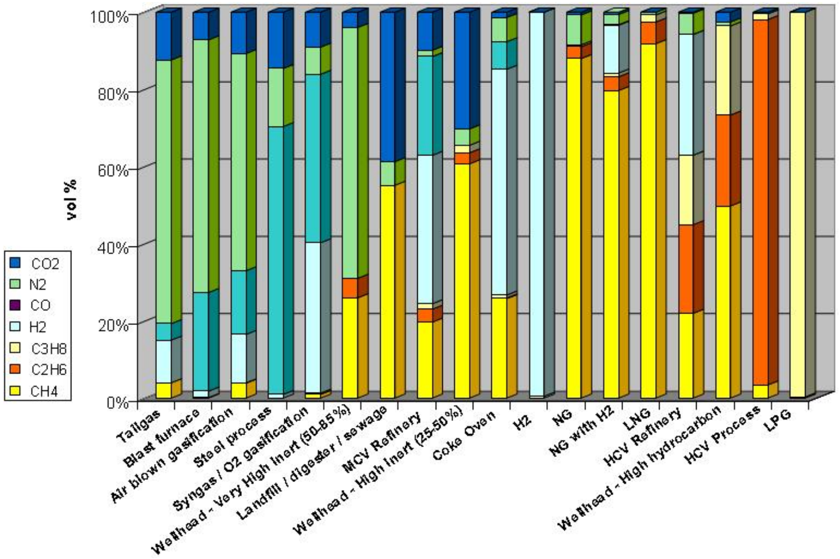
- *Fuel quality requirements*
- *Physical parameters of fuels - heating value, Wobbe Index, dew point, …*
- *Gaseous Fuels*
  - *'Pipeline' quality*
  - *Wellhead*
  - *Associated & non-associated*
  - *Unconventional*
  - *Biogas*
  - *Refinery and process off-gases*
  - *Syngas*
- *Liquid fuels*
  - *Premium – diesel & kerosene*
  - *Natural Gas Liquids and LPG*
  - *Crude Oil*
- *Contaminants*

  - *Sulfur*
  - *Metallic contaminants*
  - *Organic contaminants (tars and asphaltenes)*
  - *Water*
- *Supply and storage of liquid fuels*
- *Combustion types (Conventional and Dry Low Emissions)*
- *Combustion emissions regulated*
- *Pollution control*
  - *Wet injection*
  - *Dry Low Emissions*

1 Gas Turbine Fuel and Emission Introduction

The need to ensure fuel quality is maintained at a high standard is a key to delivering good operation in a gas turbine over long periods of time. It is not just fuel that is critical, it is ensuring all fluids entering the GT are equally kept at a high standard, thus minimizing or eliminating all sources of contaminants. Modern gas turbines operate at high temperatures, and use component designs and materials at the forefront of technology, but these are more susceptible to damage if contaminated fuel and air enter the GT through poor operating procedures. Consideration of good quality fluids entering the GT is essential why it is necessary, for example, to provide air and fuel free of contaminants is discussed to ensure the best availability and reliability of the product.

Table 1: Range of gaseous fuels



Fuel used in GT applications is very wide, table 1, with the choice based typically on availability and cost. In some cases fuels may have little or no treatment, in others they may have “added value” which results in the high quality pipeline natural gas that provides the main fuel of choice for gas turbine OEM’s and operators alike. Gas Turbines can and do operate on a wide range of fuels, but the impact that such fuels may have on turbine operation and life has to be recognized and allowed for.

It is not a case of saying these fuels are acceptable, but understanding the details of these fuels, such as the composition, hydrocarbon species in the case of a gaseous fuel, inert species, contaminants and water vapor. Detailed analysis of the fuels is necessary to determine key parameters of the fluid, such as delivery, storage and conditioning as well as key features of the fuel itself, including lower heating value, Wobbe Index, dew point and density. Understanding all of these provides the OEM and user with indicators confirming the fuel entering the GT is suitable achieving good operation across a wide range of loads and ambient conditions. It is also important to determine and understand the products of combustion and impact on the environment. Exhaust emissions are highly regulated in many parts of the world and even those areas that up until recently had no requirements have started to introduce standards or guidelines which need to be noted during the assessment stage.

2 Gas turbine Fuels and Fuel Quality

Modern highly efficient gas turbines rely on high-quality alloys to allow increased firing temperatures to be achieved, whilst still maintaining acceptable product life. To ensure this is achieved, far more attention on the use of the fluids entering the gas turbine is necessary, including air, lubricating oil and fuels. Fuel quality is a major topic of it own, with some of the fundamental requirements associated with fuel quality discussed, along with potential issues associated with poor fuel quality.

Gas Turbine OEMs provide comprehensive specifications covering fuel quality permitted for use in gas turbine. These are used to ensure fuel quality is defined at the project onset and throughout the lifetime of the turbine and are prepared for good reason. To ensure acceptable turbine operation is achieved with little or no impact on major turbine component life, it is necessary to understand fuel composition and the supply conditions in more detail. Identification of contamination is particularly necessary as this can have a detrimental impact on exotic materials used in turbine blades.

The choice of gaseous fuels as a primary fuel for use in gas turbines is dictated by widespread availability and low price. Compositions of gaseous fuels can vary quite widely, from those taken directly from wells which can contain high amounts of heavier hydrocarbons, to those containing non-combustible species (such as nitrogen, carbon dioxide and argon). In some cases hydrogen sulfide may be present, which, left untreated, can produce sulfur oxides in the exhaust, and, more significantly, can combine with halides to form compounds which readily attack the exotic alloys used in turbine blades, resulting in premature component failure.

Gaseous fuels can contain a wide variety of contaminants such as:

- Solids
- Water
- Higher hydrocarbons
- Hydrogen sulfide
- Carbon dioxide
- Carbon monoxide
- Hydrogen

The importance of providing a comprehensive fuel composition in order to determine the suitability of such fuels should not be under-estimated. Concerns and issues can be identified at an early stage to allow preventative measures, such as fuel treatment, to be taken.

Higher hydrocarbons influence the hydrocarbon dew point, hence high supply temperature is required. If the temperature is not maintained then liquid dropout (condensate) will result and can cause problems in the fuel system, or, more seriously, impinge on combustor surfaces leading to localized burning and component failure, such as indicated in figure 1 LHS (occurred very rapidly and resulted in engine shutdown).

Figure 1: DLE Pre-chamber damage resulting from hydrocarbon carry over and oxidation

Hydrogen sulfide combustion results in sulfur oxides in the exhaust (hence potential for acid rain). Of greater concern is the presence of alkali metal halides, such as sodium chloride or potassium chloride, and water vapor. These result in the formation of alkali sulfates, giving rise to aggressive corrosion attack of the nickel alloys used in modern turbine blades (figure 1 RHS). This example is after many operating hours.

3 Gaseous Fuel Assessment Criteria

A comprehensive assessment of gaseous fuels is necessary with a number of factors used to determine the suitability. Some of these discussed below can be inter-related, such as the presence of water and solid contaminants. However, before commencing, it is worth completing a visual inspection of fuel composition to ensure it fully aligns, for example: defined in mol, vol, or mass % or fraction; adds to 100% (or 1 if fraction); species covered as expected. Analysis includes:

3.1 Wobbe Index; Temperature Corrected Wobbe Index

Pipeline quality gas fuels contain mostly methane, with small quantities of ethane, and for most OEM's fall into a Wobbe Index (WI) range 35 – 50MJ/m3.

Wobbe is one parameter used to assess fuels and allows a direct comparison of different fuels to be made based on heat content. WI is the Net (lower) calorific value of the fuel divided by the square root of the fuels specific gravity (1).

$$\begin{aligned} &WobbeIndex \\ &WI^{0} = CVv^{0} / \sqrt{SG^{0}} \end{aligned} \qquad (1)$$

where CVv^0 = net calorific value (MJ/m^3) at standard conditions (288K, 1.013bara)
SG^0 = specific gravity at standard conditions

$$= \rho_{fuel} / \rho_{air}$$

where ρ_{fuel} and ρ_{air} are at standard conditions (288K, 1.013bara)

Fuels are often provided at different supply conditions. Therefore the use of Temperature Corrected Wobbe Index (TCWI) (2) becomes an important aspect when reviewing fuels. Gas fuels containing water and or higher hydrocarbon species will result in higher dew point requirements, hence the need to provide a set amount of superheat margin, ensuring the gas remains in a vapor at all times.

$$WI^{T} = WI^{0}\sqrt{{}^{288}\!/\!{}_{T_{fuel}}} \tag{2}$$

Where:

T_{fuel} *is temperature of fuel at turbine skid edge(K)*
WI^{T} *= Temperature Corrected Wobbe Index*
WI^{0} *= Wobbe Index at standard conditions, 288K*

Fuels with visually different compositions may have the same Wobbe Index and therefore same heat content. However, other factors such as dew point and density need to be evaluated.

GT OEM's have limits on ranges of fuel CV or WI before it becomes necessary to introduce changes in combustion hardware. This may be as simple as geometry changes within the same burner or more extensive and involve fuel system changes. The objective is to achieve similar fuel supply pressure and pressure drop across the burner to ensure stable combustion is maintained.

3.2 Dew Point and supply temperature

Gaseous fuels comprise a variety of hydrocarbon species, each of which has a unique "dew" point temperature, i.e. the temperature at which the gas condenses producing liquids, and fuels which also contain water will have in addition a water dew point, figure 2. Thus it is possible to determine the dew point for a known gas at a given pressure. It is normal to apply a margin of superheat over the calculated dewpoint, to prevent condensate or liquid drop out, which for Some OEM's apply a minimum of 20°C, but for other's may be higher, 25-30°C. Fuels which contain higher hydrocarbon species may require a higher margin of superheat to be applied.

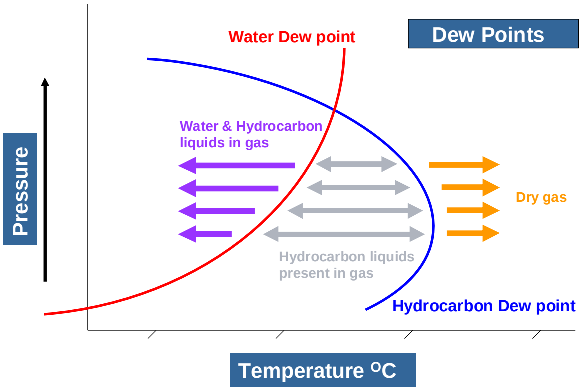


Figure 2: Water and Hydrocarbon Dewpoint

3.3 Water

Pipeline quality gas fuels are usually clean and dry, but there are occasions when fuels contain water, the presence of which can be problematic:

- Free water in the presence of hydrogen sulfide or carbon dioxide can form acids which can be highly corrosive to the fuel system and associated pipework
- Water may contain undesirable water-soluble contaminants

- Impacts dew point (water dew point), hence supply temperature will be higher than for the equivalent dry gas

Removal of water using best industrial practices should be considered.

3.4 Higher Hydrocarbon Species

The presence of higher hydrocarbon species impacts the dew point, and hence the supply temperature. Higher hydrocarbon liquids, or condensate, when passed into the combustor combust in an uncontrolled manner:

- condensate is un-metered; result in uncontrolled combustion
- detrimental effect on operation, safety
- can result in both combustion hardware damage or failure as well as downstream hot gas path turbine components
- Burner gas gallery and passage blockage due to carbonization

Temperature adjustment of fuels has a potential added benefit:

- Allows some richer fuels to be supplied at a temperature beyond that required for dew point control
- Trace heating and lagging of the gas supply pipework and fuel system would be required

3.5 Contaminants in gaseous fuels

Water is one contaminant already discussed, but there are other contaminants that are often met and need to be considered.

3.6 Carbon Dioxide

Can react in the presence of moisture producing a weak acid, but mostly acts as a diluent reducing the heat content available in the fuel.

3.7 Hydrogen sulfide

Hydrogen sulfide is highly toxic and can pose unique challenges to operators as well as in the operation of gas turbines. Besides specific health and safety requirements H_2S (also sulfur in liquid fuels) can combust producing SOx emissions to atmosphere, which react in the presence of moisture resulting in weak acid production (acid rain). Where SOx legislation exists, treatment of the fuel at source to remove or lower H_2S (or sulfur in liquid fuels) content will be required.

In the presence of sodium or potassium, such as off-shore or coastal applications, further assessment will be required. Reaction with sulfur result in the production of sodium and potassium sulfates which are highly corrosive to modern materials used in the hot gas path components, such as turbine nozzle and rotor blades.

3.8 Hydrogen and Carbon Monoxide

These readily combust and require special understanding before acceptance as a GT fuel. Both exacerbate combustor flame speed, and can result in flashback, where the flame velocity exceeds the local combustor velocities. This makes these types of fuels less suited for lean pre-mix type combustion systems. However, conventional diffusion flame combustion systems are more tolerant to such fuels, subject to full assessment and application of appropriate safety measures.

4 ‘Pipeline’ quality Natural Gas fuels

Gases extracted from underground sources – wellhead or associated gas – undergo processing resulting in a high quality product that can be used by industrial and domestic users alike. Comprising mostly methane, CH_4, natural gas can also contain small amounts of ethane, C_2H_6, and propane, C_3H_8. Inert species such as Carbon dioxide, CO_2, and Nitrogen, N_2, may be present in small quantities. The processing also ensures pipeline gas fuels are dry and free from any moisture.

Gas fuels can originate from oil wells, and termed “wellhead” or “associated” gas; gas wells and condensate wells are sources that may be entirely free of crude oil. In all of these cases, the gas requires processing to remove higher hydrocarbon species and gaseous contamination such as hydrogen sulfide, H_2S, and water to ensure gas is clean and dry before it is allowed to enter natural gas pipelines. Strict control on gas specification is made to ensure the gas fuel entering the pipeline from whatever source does not vary significantly.

“Waste” hydrocarbon products from gas processing are themselves valuable. These are often termed natural gas liquids and include ethane, propane and butane for example. Separating these and selling in the open market as, for example LPG, is a good way of ensuring all gases recovered from the wells is utilized.

5 Other Fuels used in Industrial Gas Turbines

Pipeline quality gas fuel has been shown to be the primary source of fuels for gas turbine applications mainly due to its widespread availability and low cost. However, there are many other fuels which are used or considered, especially where pipeline gas is either not available or of insufficient quantity.

5.1 Premium liquid fuels

Diesel fuel and Kerosene processed to internationally recognized quality standards are used either on their own or in conjunction with gas fuels (dual fuel operation).

Distillate fuels (No2 Diesel and Kerosene, for example) are processed from crude oil and can be made to a wide range of specifications. Other liquid fuels such as natural gas liquids or higher hydrocarbon liquids, such LPG (a mixture of propane and butane), are also produced and have been used as a gas turbine fuel, although special consideration is need in such cases. Figure 3 highlights the range of liquid fuels compared to natural gas.

The suitability of commercially available diesel fuels must be assessed and compared to the OEM’s own specification. Several international specifications exist, all with small differences that can make a huge difference in gas turbine operability. Typical Specifications include EN590 and ASTM D975 along with low and Ultra Low sulfur diesels.

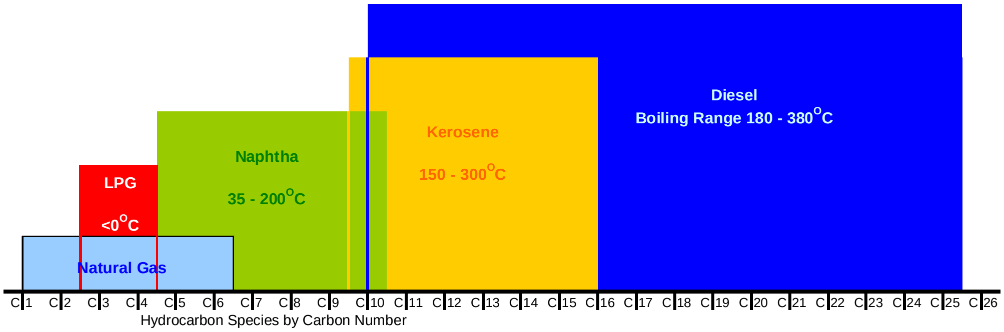


Figure 3: Liquid fuels typical encountered for use in industrial gas turbine

Alternative liquid fuels to fossil diesel are becoming more widespread, such as paraffinic biodiesel and liquids derived from natural gas, the latter via conversion techniques such as Fischer Tropsch and commonly referred to as “Gas to Liquids” (GTL) fuels. Although production quantities are small today these will grow in years to come and either be blended with fossil diesel or be used as a stand alone fuel. Specifications for such fuels are in development, such as CWA 15940:2009, covering Paraffinic bio-diesel fuel.

5.2 LNG (Liquefied Natural Gas)

LNG is available from a wide variety of sources and can vary significantly in properties due mostly to the content of Ethane in the composition (in place of methane). Such fuels tend to be higher in Wobbe Number so may require Nitrogen dilution to ensure compatibility with general pipeline quality fuel specifications and may have a higher dew point and therefore require a higher supply temperature.

5.3 Other gaseous fuels

- Wellhead Gases as a Gas Turbine Fuel
  Alternative gaseous fuel solutions for gas turbines are used, where little or no added value to raw fuel sources can make strong economic sense. Assessment and use of wellhead or associated gas fuels can allow marginal wells and locations to be developed.
- Shale Gas
  The merit of extracting shale gas is ‘unconventional’ and not discussed, rather how cleaning the extracted gas results in a conventional gas and can be treated in much the same way as LNG.
- Biogas fuels
  Tend to be weak methane-based gas fuels containing high levels of carbon dioxide, CO_2 and, or, Nitrogen, N_2. These can be naturally occurring or derived from the decomposition of waste material (Land Fill Gas - LFG), anaerobic digestion (AD) process or Waste Water Treatment Process (WWTP). All can be considered as a useful fuel for gas turbines and may be recognized as renewable fuels. Combustion capability to use such fuels exist with both conventional and DLE configurations. With LFG, for example, a contaminant generally referred to as Siloxanes may be present, which left untreated can result in Silica deposits in the turbine area of a gas turbines and potential for performance degradation. Fuel treatment methods can be applied to reduce Siloxane levels to low levels.

- Refinery; Process off-gas; Hydrogen Syngas

  Process off-gas, such as a refinery gas and coke oven gas (COG) may be used as a gas turbine fuel. These tend to contain Hydrogen and Carbon Monoxide so special consideration has to be made for these types of fuels.

  Syngas also fall into this category, but are mostly derived from the gasification or pyrolysis of waste products. These fuels are lower in heating value than biogas for example, but comprise Hydrogen and Carbon monoxide as well as large quantities of inert species, CO_2 and N_2. These need special consideration due to the impact each has on combustor flame speeds and the propensity for “flashback” and the resultant damage to combustion hardware therefore generally require the use of conventional combustion.
- Natural Gas Liquids and Liquid Petroleum Gas (LPG) fuels

  Fuels containing higher hydrocarbon species therefore require special assessment and consideration within both the fuel system and combustor injector.

  For example, LPG can be used either in vaporized or liquid form. When vaporized and maintained in gaseous form, the gas should be supplied at elevated temperatures due to the higher hydrocarbons associated with LPG (butane and propane). Special injectors will be required to ensure the metered fuel is correctly controlled. In liquid form special consideration must be made to the fuel system. LPG has a very low viscosity and special pumps are required to overcome the problem of low lubricity. Control of the fluid is critical to ensure other problems are avoided such as: Waxing (fuel temperature too low); Exceeding flash point (temperature too high); Corrosion (particularly where copper is present); Vapor lock due to premature vaporization of liquid.
- Crude Oil as a GT fuel

  Crude or Heavy Fuel Oil are viable fuels for GT applications where natural gas or premium distillate fuels are not readily available. Viscosity is one of the key parameters used when evaluating such fuels and generally should be <10cst @ 50°C (most regular diesel fuels <7.5cst @ 40C). This creates challenges that have to be handled through fuel pre-treatment and fuel injection system functionality. Heating the fuel reduces the viscosity, but noting the limitations:
    - 100°C, at which water boils off (all liquid fuels contain a small amount of water) causing cavitations in fuel pumps
    - Increasing fuel oil supply pressure allows the heating to be extended beyond 100°C, but is limited by the temperature limits within the fuel delivery system
    - Further heating can result in fuel cracking and coking in the fuel system and burners depending on the constituents within the crude oil

  Crude oils need to be treated in order to meet industrial gas turbine limits on metallic and other contaminants in the fuel as these often contain high amounts of alkali metals (Na, K) and heavy metals (V, Ni, etc) which if introduced into the combustion system can result in accelerated deposit formation and high temperature corrosion in gas turbine hot gas path components. Major corrosive constituents include Vanadium pentoxide (V2O5), sodium sulfate (Na2SO4) and aggressive low melting forms in the Na2SO4 – V2O5 and Na2O-V2O5 systems. Determination of the ash sticking temperature is usually a good feature to use, and should be >900degC if sticking to the blade is to be avoided.

  As with any liquid fuel water and sediment can be removed, or reduced, by filtration and centrifuge separation, and prevents the formation of corrosive elements and bacterial growth, a pre-cursor to fuel degradation. Removal of the water also reduces the levels of water-soluble contaminants such as the alkali metals sodium and potassium. Vanadium and other heavy metals are oil-soluble though, and can only be treated through chemical dosing so that combustion creates high melting temperature compounds.

Crude oils can also contain more volatile components with a low flash point therefore the need to include explosion proof equipment is often required.

5.4 Fuel Storage

Storage and maintenance of liquid fuels can be the difference between acceptable turbine operation and one where extensive site maintenance may be required. Storage of fuel comes under the general heading of fuel handling and best practices. It is necessary to ensure fuel is sourced from good suppliers to approved specifications. Routine monitoring and recording from sampling and analysis of fuels is critical to achieving good turbine operation. Applying best industry practice in receipt, unloading, storage and transfer of liquid fuels is essential to achieving and maintaining fuel to the highest standard and quality. Applying centrifuges, filters and coalescers to storage tanks will help maintain the fluid in the correct condition. Ensuring tank design meets best industrial standards, including, but not limited to, floating suction take-off to supply gas turbine; bottom drain for sediment and water; allowing sufficient settling time after introducing new supply to tank. Using all the fuel on a regular basis minimizes deterioration and will help in the long term quality control.

This is by no means a comprehensive coverage of the use of liquid fuels but attempts to provide the essential aspects that need to be considered.

6 Types of combustion; emissions regulated; Legislation, OEM and Customer Requirements

Over the last 25 years, increasing pressure was placed on gas turbine OEM’s to develop less polluting products. The US Clean Air Act set new standards for emissions compliance, with the European Union (EU) and other countries soon followed with more demanding legislative requirements. Consequently low emissions became the norm with a wide variety of pollutants to consider, from Oxides of Nitrogen, NOx, Carbon Monoxide, CO and un-burnt hydrocarbons, UHC.

In addition gas turbine OEM’s, along with a large number of Oil & Gas companies, have their own policies with regard to environment stewardship and offer or specify low emission equipment even in locations where no formal legislation exists, or set at a higher level.

The result of all of these drivers is to make the Dry Low Emissions or Dry Low NOx (DLE/DLN) combustion system the primary combustion system of choice, with some GT OEM’s offering DLE/DLN hardware as the only combustion system available.

6.1 Combustion Systems

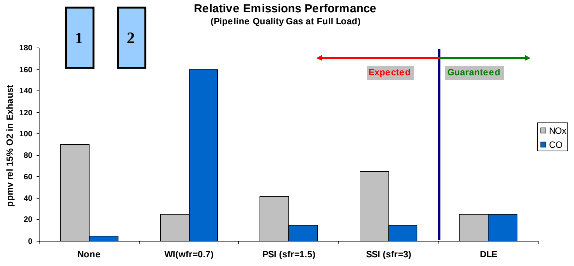
Two main types of combustion system are widely used in gas turbines: one based on the ‘conventional’ diffusion flame; the second uses lean pre-mix technology targeting low exhaust emissions signature. These are offered in both annular and can-annular arrangements.

6.2 Conventional Combustion

Conventional combustion, or diffusion flame combustion, figure 4, operates at high primary zone temperature, circa 2500K, resulting in high thermal NOx formation. Lowering flame temperature, hence NOx production can be achieved by injection of diluents such as water or steam into the primary zone, and has been employed over many years by many of the gas turbine manufacturers. Different OEMs use differing methods in water or steam injection, but all recognize the impact each has on reliability and life cycle costs. Generally such combustion systems have been more tolerant with different fuel types.

Figure 4: Conventional or Diffusion flame combustion hardware

A comparison from injecting water or steam in the primary zone with the newer dry low NOx solution is highlighted in figure 5. Other factors to note with wet injection are the need for large quantity of de-mineralized water and the impact on service regime, with more frequent planned interventions. The ratio of water, or steam to fuel (SFR or WFR) used results in lower NOx, but can impact CO emissions in a detrimental manner. Where a service retrofit of existing gas turbines was made to include DLE combustion, the environmental benefit was significant, offering 5 times reduction in NOx emissions compared to previous abatement system employed, figure 6.



wfr = Water Fuel Ratio sfr = Steam Fuel Ratio

WI = Water Injection PSI= Primary Steam Injection SSI= Secondary Steam Injection

Figure 5: Effects of wet injection on diffusion flame combustor, compared to DLE

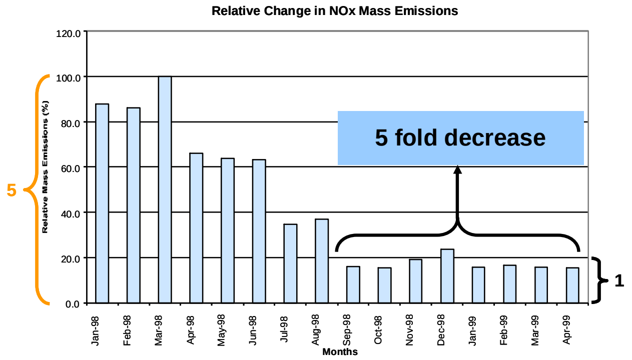


Figure 6: Conversion of multi-engine site to DLE combustion configuration

6.3 Dry Low Emissions combustion

Lowering primary zone temperatures without resorting to wet diluents is now achieved using Dry Low Emissions (DLE) or Dry Low NOx (DLN) combustion systems. These address the production of NOx at source with a design that does not rely on injected diluents, hence the term “dry” with 4 technologies identified:

1. Lean-premixed pre-vaporized combustion
2. Staged Combustion
3. Catalytic Combustion
4. Rich-burn lean quench combustion

Of these lean premixed system is the one that has been developed by a number of gas turbine OEM’s, as the combustion system of choice with many millions of operating hours now recorded. All these methods reduce the production of NOx by reduction of the reaction temperature.

Lower NOx formation has been achieved by combusting the fuel in an excess of air, hence “lean” pre-mix combustion. NOx production increases exponentially with temperature, therefore it is critical to ensure air and fuel is well mixed. During the early design and development work, there was as much attention devoted to achieving a homogeneous mixture, and burning this mixture without detrimental impact on combustion and turbine hardware.

A lean pre-mix combustor design comprises 4 main features: fuel / air injection device; stability device; pre-mixing zone; flame stabilization zone and are covered and discussed in more detail later.

Meeting emissions requirements is only one aspect of combustion design. It has also to meet operational criteria, including: component life; flexible fuel operation; reliable starting; reliable switching between fuels; reliable transient response; and all without excessive cost.

6.4 Methods of reducing NOx Emissions

There are three main ways for NOx formation: thermal NOx; prompt NOx; fuel bound NOx (FBN). Thermal NOx is the most dominant source of NOx and produced by the reaction between nitrogen and oxygen in air as described by Zeldovich. This reaction takes place above 1700K and the rate increases exponentially as temperature increases (figure 7). Prompt NOx results from the high-speed reactions at the flame front and FBN is only influenced by removal of nitrogen bearing compounds in the fuel.

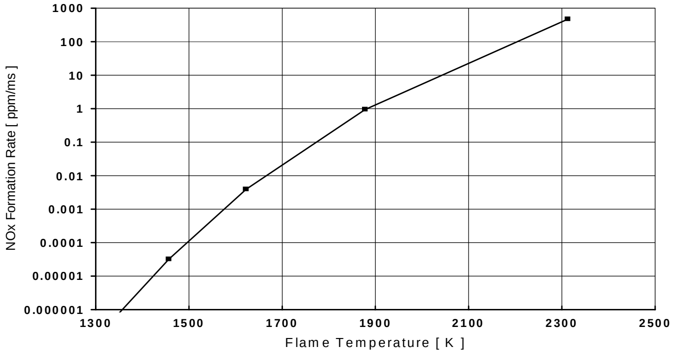


Figure 7: NOx formation rate (Zeldovich)

6.5 DLE design

Figure 8 and 9 show lean pre-mix DLE combustion these are can-annular solutions, although other manufacturers apply lean premix within an annular combustion configuration.

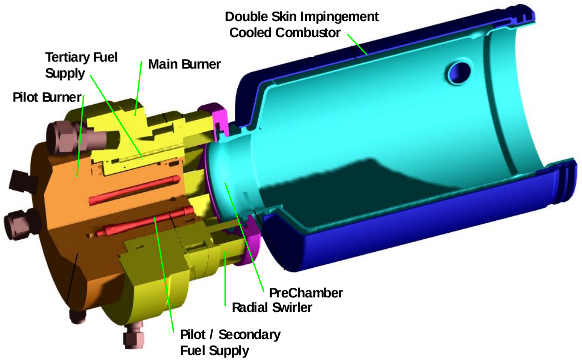


Figure 8: *DLE combustion*

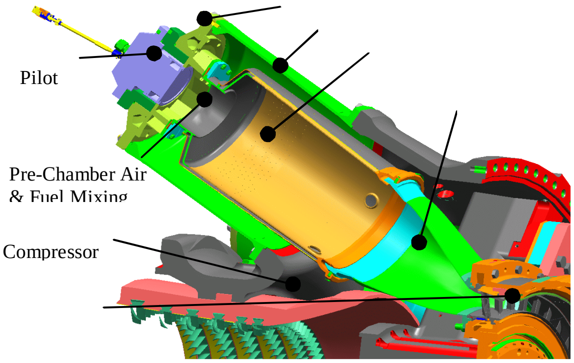


Figure 9: *DLE combustion*

A single combustion chamber is mounted around the outside of the compressor exit section of the gas turbine, with multiple burners mounted through engine casings into holes in the annular combustor, as shown in figure 10 below.

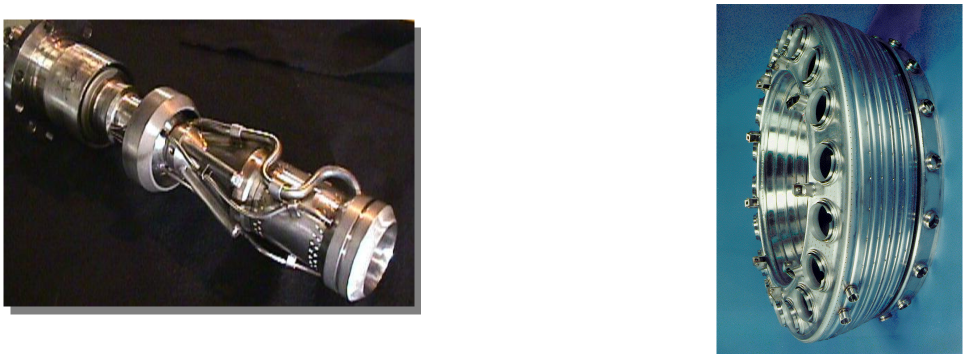


Figure 10: Annular Combustor with 3rd generation DLE burner

6.6 Diffusion flame comparisons with DLE combustion systems

In order to produce low NO_x and low CO the homogeneous flame temperature within the combustor must be strictly controlled. Conventional diffusion flame combustors, figure 11 left, has high primary zone temperature. This is due to the high turbulence region promoting mixing which can result in temperatures in excess of 2500K and leads to high NO_x production rates. In order to reduce NO_x levels either the temperature within the combustor has to be lowered or the NO_x must be removed after the turbine.

Improvements in mixing the fuel and air to achieve a homogeneous mixture whilst at the same time ‘leaning out’ the mixture within the DLE combustor, achieves the desired effect of a more uniform and lower peak combustor temperature, thus resulting in low thermal NOx production, figure 11 right.

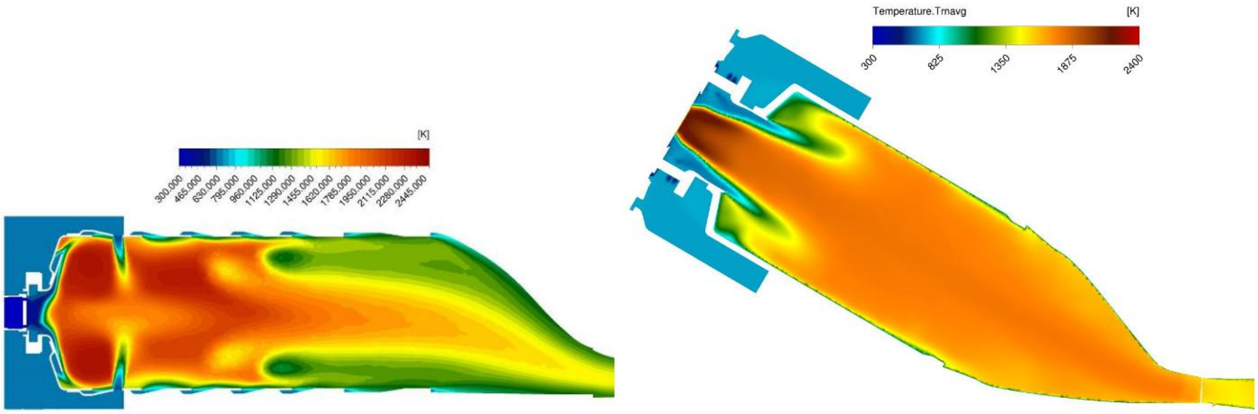


Figure 11: CFD - temperature distribution
Diffusion flame DLE lean premixed combustor

6.7 Dry Low Emissions Combustion

One approach is shown in figure 13 and uses scaled combustion geometry across the product portfolio using can-annular combustion hardware. A common design approach was adopted where scaling and adjustments for air flow have been applied depending on the rating and combustor numbers used in the GT model.

Figure 13: Scaled hardware design across the product portfolio

Figure 14 shows a schematic of the combustion concept. The main combustion air enters through a single radial swirler at the head of the combustor. Flow turns through 90degrees into the pre-chamber followed by a sudden expansion into the combustion chamber. The swirl number is sufficiently high to induce a vortex breakdown reverse flow zone along the axis. This is termed the internal reverse flow zone. In this design concept the reverse flow zone remains attached to the back surface of the combustor thereby establishing a firm aerodynamic base for flame stabilization. In the wake of the sudden expansion, an external reverse flow zone occurs with flame stabilization in the shear layers around the internal and external reverse flow zones.

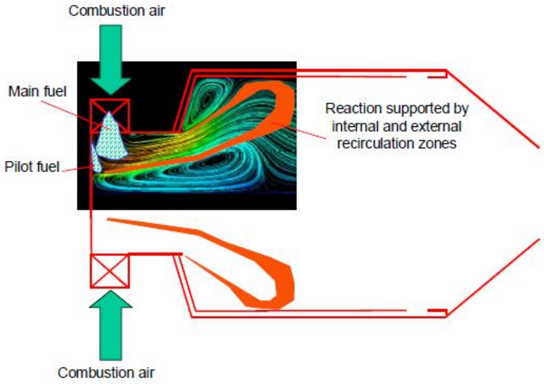


Figure 14: Schematic of the Dry Low Emission combustor concept

Gaseous and liquid fuels are introduced, in two stages:

- Main, which results in a high degree of ‘premixedness’ and hence low NOx emissions
- Pilot, which is reduced as the load demand increases is used to ensure flame stability

The pilot is arranged such that as the pilot fuel split increases, the fuel is biased towards the axis of the combustor. Describing each element of the DLE in more detail and referring to figures 8 and 9 shown earlier:

- Pilot burner:

  This component provides fuel for ignition and transient operation and a small percentage at full load for stability purposes. An ignition source is mounted in each pilot, along with a thermocouple to monitor the temperature of the face of the burner. For dual fuel units, a separate liquid fuel lance, located and accessed through the rear of the burner, provides fuel for ignition and transient operation.
- Main burner

  Flow increases as speed and then load is increased. This provides the pre-mixing via the radial swirler and numerous gas injection ports. The swirlers are fixed design with control of fuel is necessary to achieve both load and ambient temperature control
- Liquid core

  Located with the main swirler/burner when a dual fuel arrangement is required, otherwise a blank ring is used. Liquid is injected through a number of injection nozzles and results in good pre-mixing with the high velocity air results in good liquid fuel emissions characteristics.
- Combustion liner

Main swirler/burner is mounted at the head of the combustor, which comprises a double skin liner, the outer skin controlling the cooling air feeding the annulus between inner and outer liner. The head of the combustor locates the pre-chamber and is where the fuel is mixed prior to ignition

- Transition duct

Controls and directs the hot combustion gases towards the first stage nozzle and typically includes effusion cooling.

- Materials

Conventional materials typically used in this part of the gas turbine. Burners are routinely made from stainless steel, with the application of a thermal barrier coating in key areas. Combustion chambers are manufactured from Nimonic steels with thermal barrier coatings applied to the inner liner surface.

7 CONCLUSIONS

The understanding of fuels used in modern high performance, high efficiency gas turbines is a critical step in achieving the goals of high availability and reliability, but at the same ensuring the environmental needs are fully met. The impact of the wide range of fuels used in gas turbine combustion systems, especially those of the low emissions variety, has been considered.

In conclusion, the supply of the right quality fuels can result in the above requirements being met, while the use of fuels outside the advised specifications can result in increased maintenance requirements.

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