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# Combustion and Emission Issues in Gas Turbines

by

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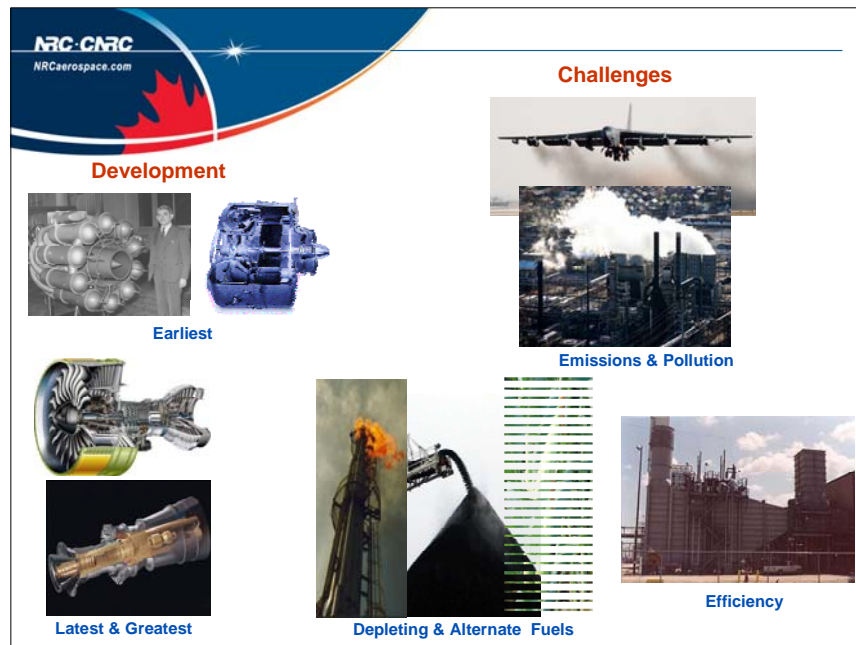
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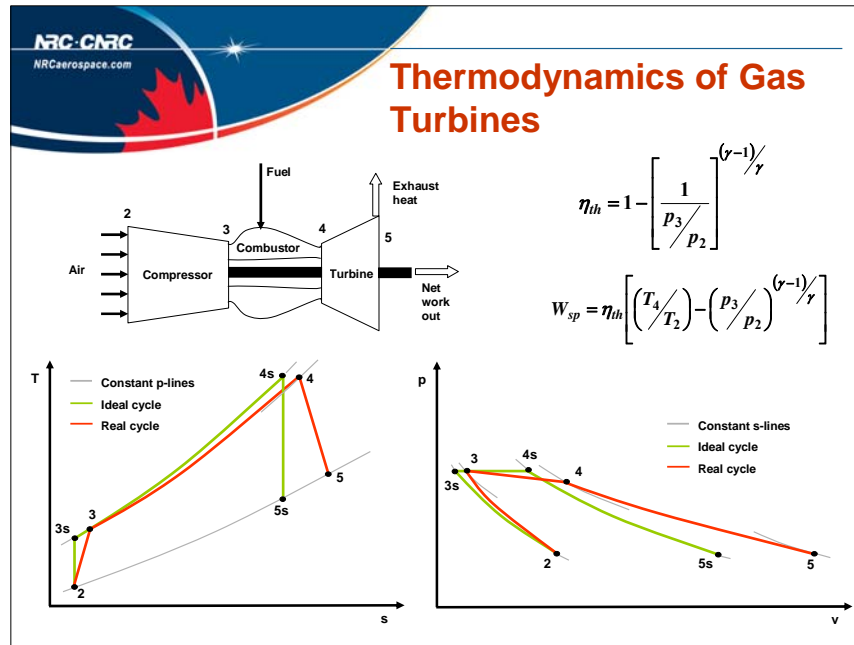
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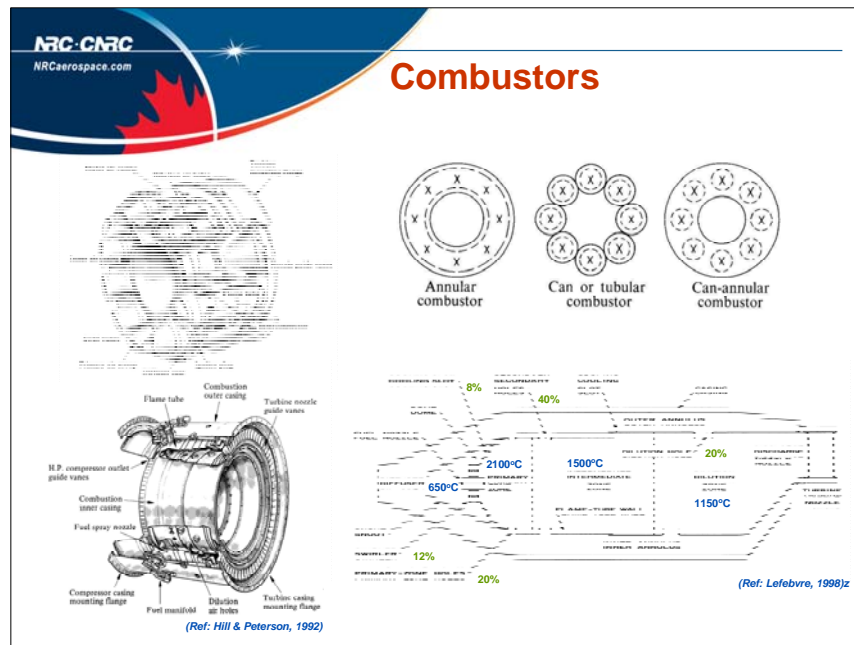
The principles of combustion are to a large extent well understood and have achieved a maturity level where they can be reliably applied towards heating, power generation, and propulsion. The challenges that are currently faced in this field reflect the changes in the society and environment. The growing awareness about environmental safety, concerns about depleting resources of fossil fuels and realization of economic impact, have led the technology towards innovating environmentally benign, versatile and cost effective combustion systems. The identification of the basic chemical and physical mechanisms and how they couple under these new developments is the challenge of today.

The purpose of the training session is to present an overview of the basic concepts and some of the issues related to gas turbine combustion.



The major components of a gas turbine engine are the compressor, combustor and the turbine. At start up, air is sucked in the compressor by an auxiliary source. The air is pressurized and raised in temperature by the compressor and is introduced in the combustor where it is mixed with fuel and burned. The hot combustion gases then enter the turbine where they expand causing the turbine to rotate and generate mechanical work. The mechanical work is used in turn, to drive the compressor and other auxiliary components on the engine and may also be used to produce electric power. In case of propulsion applications, the turbine exit flow is drawn through a nozzle to produce thrust.

Gas turbines usually operate on an open cycle and are represented by a Brayton cycle. The actual behaviour differs from the ideal Brayton cycle in terms of process irreversibilities, heat losses and pressure losses. On the cycle basis, the performance of a gas turbine is characterized by the thermal efficiency and net specific work. Under steady and isentropic flow and cold-air-standard assumptions the thermal efficiency is dependent on the compression ratio while the work output is a function of both compression ratio and temperature rise in the cycle.



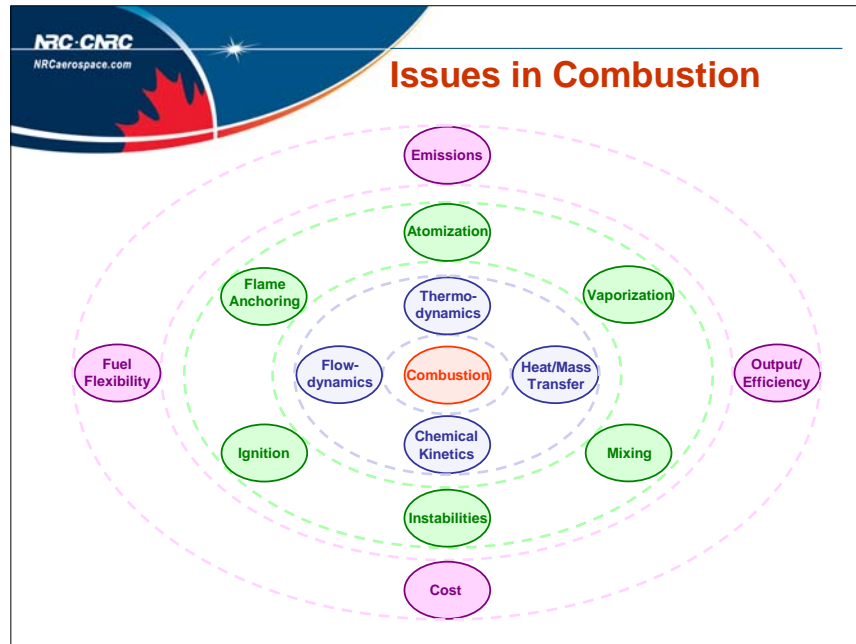
The gas turbine component, which contains the highest energy density and where most of the processes are taking place, is the combustion chamber. There are three basic types of combustor configurations: tubular, annular and can-annular. Each type has its advantages and disadvantages in terms of accessibility, structural strength and size. The choice of a particular configuration is dependent on the overall design and application of the engine.

Typically the main parts of a combustor are the casing, diffuser, flame tube(s), fuel nozzle(s) and ignitor. Air swirler(s) may also be provided to achieve better fuel-air mixing and flame stabilization. In addition, cooling holes and slots are provided for the purpose of dilution and completion of combustion process.

One of the critical combustor requirements is to minimize the pressure drop across the combustor. Two types of pressures losses are incurred in the combustor, one in pushing the airflow through and the other associated with the addition of heat. Diffuser is provided at the inlet of the combustor to recover as much of the dynamic pressure as possible and also to reduce the velocity of air entering the combustor.


The flame tube or liner provides an enclosure for the combustion process and is divided into three zones. The function of the primary zone is to provide anchoring of the flame and to provide required turbulence and temperature to the incoming fuel-air mixture to achieve complete combustion. The intermediate zone, which is typically provided in conventional combustor designs, helps in dropping the temperature and encourages burning of carbon monoxide, soot and other unburned hydrocarbons. The function of the dilution zone is to mix the remaining air with burned gases to achieve a temperature distribution acceptable for the turbine inlet guide vanes.

The combustor performance is measured by its efficiency, pressure drop across the combustor, the evenness of the outlet temperature profile and the ability to operate under transient conditions.



In order to understand the cause and effect relationship between combustion and societal, environmental and economical challenges, it is imperative to address two layers of concepts, which provide links to this understanding. The first layer is a realization that combustion is a dynamics process involving the complexities of all three major areas of thermal-fluid sciences as well as chemistry, namely, Thermodynamics, Fluid Mechanics, Heat and Mass Transport and Chemical Kinetics. The second layer comprises of the processes involved in combustion, some of them being “rate controlling” processes.

A brief introduction to these concepts and processes is presented here.




## Fundamentals of Combustion

- **What is combustion?**
  - Rapid oxidation generating heat, or both **light** and **heat**
  - Chemical reaction between a **fuel** and an **oxidant**
$$\text{CH}_4 + 2\text{O}_2 \longrightarrow \text{CO}_2 + 2\text{H}_2\text{O} + \text{Heat}$$
  
- **What is flame?**
  - A **self-sustaining** propagation of **localized** reaction zone at **subsonic** velocities

Combustion is the rapid oxidation of a combustible medium, generating heat and normally accompanied by light emission. Combustion occurs as a result of an exothermic chemical reaction between a fuel and an oxidant.

Flame is a self-sustaining propagation of localized reaction zone at subsonic velocities. The existence of flame indicates that there is a continuous supply of fuel and oxidant to the flame front. The flame is also a localized phenomenon and occupies only a minute portion of the combustible mixture at any one time. The flame propagation occurs at subsonic velocity. In such a case, combustion wave is called a “deflagration” wave. This is typically the case in gas turbine combustion. However, combustion wave or flame front may also travel at supersonic velocities and under such a situation the wave is termed as “detonation” wave.



## Combustion Terminology

**Fuel-air ratio**

$$FAR = \frac{\dot{m}_{fuel}}{\dot{m}_{air}} \quad (1)$$

**Stoichiometry**

$$C_xH_y + a(O_2 + 3.76N_2) \rightarrow xCO_2 + \left(\frac{y}{2}\right)H_2O + 3.76aN_2$$

$$a = x + \frac{y}{4} \quad (2)$$

$$(FAR)_{stoic} = \left(\frac{\dot{m}_{fuel}}{\dot{m}_{air}}\right)_{stoic} = \frac{1}{4.76a} \frac{(MW)_{fuel}}{(MW)_{air}} \quad (3)$$

**Equivalence ratio**

$$\phi = \frac{FAR}{(FAR)_{stoic}} \quad (4)$$

**Autoignition**

**Ignition delay**

**Flame speed**

**Flashback**

**Lean blowoff**

**Pattern factor**

$$PF = \frac{(T_{4,peak} - T_{4,avg})}{T_{4,avg}} \quad (5)$$

**Fuel-Air Ratio:** Ratio of mass flow rates of fuel and air available for combustion, Equ (1).

**Stoichiometry:** Stoichiometric quantity of oxidizer/air is just the amount needed for complete combustion of a given quantity of fuel. For a chemical reaction between a hydrocarbon fuel and air, Equ (2), the stoichiometric fuel-air ratio may be calculated using Equ (3).

**Equivalence Ratio:** Quantitative indicator that determines whether a fuel-air mixture is lean, stoichiometric or rich. Equivalence ratio is calculated using Equ (4). If  $\Phi < 1$ , the mixture is fuel lean; if  $\Phi=1$ , the mixture is in stoichiometric proportion; and if  $\Phi > 1$ , the mixture is fuel rich.

**Auto-ignition:** Spontaneous ignition achieved without any external stimuli when a reactive mixture is formed and raised to a definite temperature and pressure.

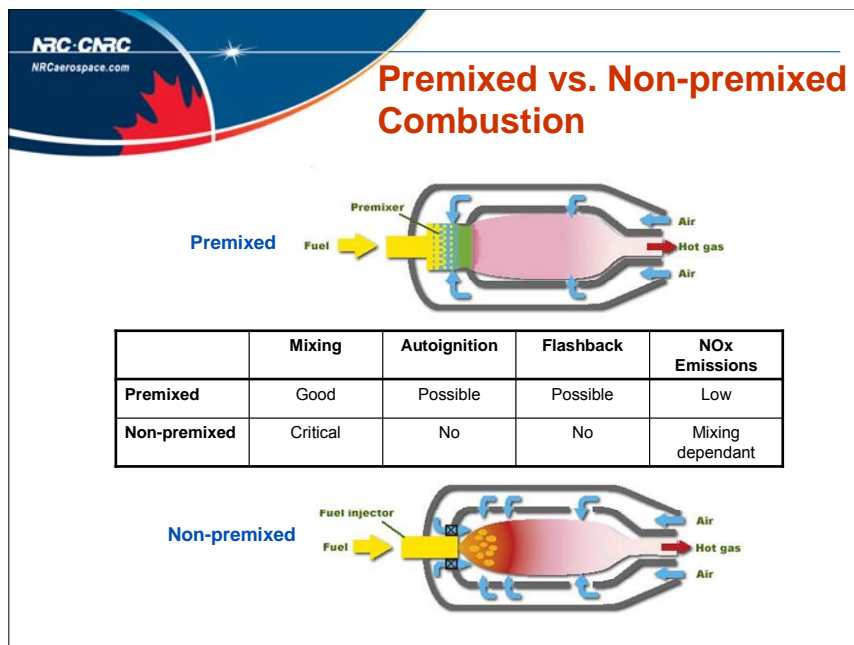
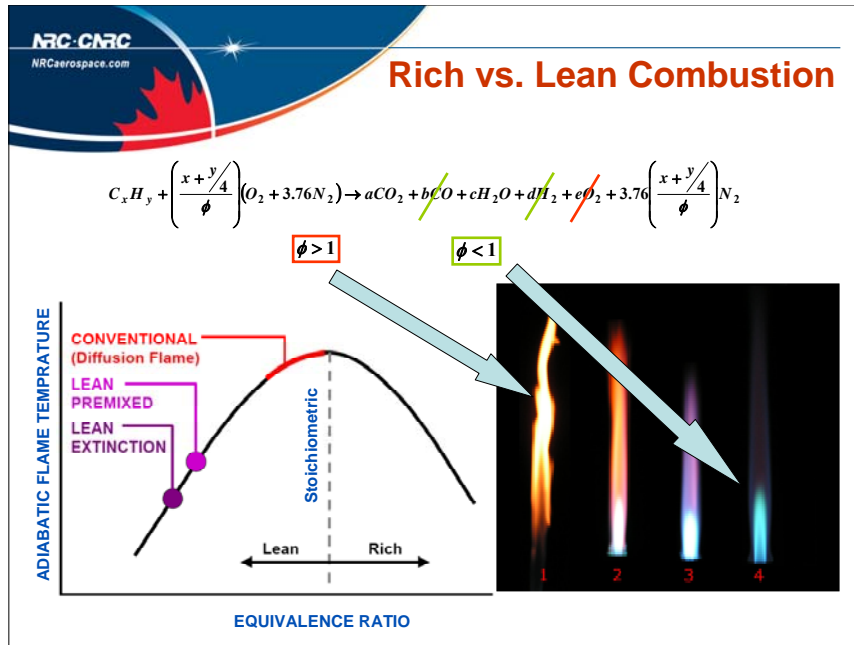
**Ignition Delay:** Time lag between ignition triggering and production of spark. It may also be considered as the time period between start of fuel injection and start of combustion. Ignition delay time is a combination of inert heating time, mixing time and chemical reaction time.

**Flame Speed:** It is also known as flame propagating velocity. It is equal to the velocity of reactants' mixture entering a stationary 1-D flame in a direction normal to the flame. Flame speed is dictated by the physiochemical properties of the combustible mixture and the combustion system configuration.


**Flashback:** Flashback occurs when the flame propagating velocity is more than the velocity of the incoming reactants' mixture. In such a situation the flame enters and propagates through the pre-mixer or the burner tube.

**Lean Blowoff:** The leanest fuel-air mixture limit that will allow steady flame propagation. Flammability limits depend on the physiochemical properties of fuel-air mixture and on the combustion system configuration. Lean blowoff occurs when flame speed is lower than the flow velocity of the unburned combustible mixture.

**Pattern Factor:** Term used to depict the temperature distribution at the combustor outlet. It is determined using Equ (5). A lower value of PF is indicative of a uniform temperature distribution.



The two types of flames, premixed and non-premixed (also called diffusion), are categorized on the basis of the state of the mixedness of the reactants. For a premixed flame, the fuel and oxidizer are mixed at a molecular level prior to their entry into the combustor and prior to the occurrence of any significant chemical reaction. The reactants are required to be in gaseous phase at the time of mixing and therefore in case of liquid fuels, the fuel needs to be pre-vaporized. On the other hand for a diffusion flame, the reactant streams are separated until entry to the combustor. Reaction occurs only at the interface between fuel and oxidizer, where mixing and reaction occur at the same time. In case of liquid fuel, vaporization also occurs simultaneously. For non-premixed flames, achieving good mixing is of critical importance as it influences the combustor performance in terms of efficiency and emissions.



## Chemical Thermodynamics

Absolute enthalpy

Enthalpy of combustion

Adiabatic flame temperature

Combustion efficiency

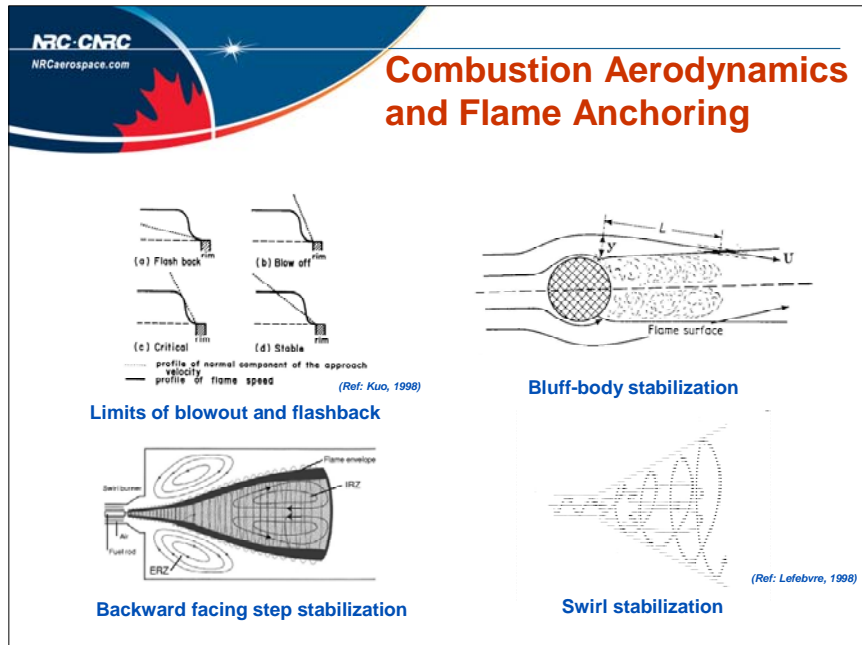
$$\eta_c = \frac{T_4 - T_3}{T_{adia} - T_3} \quad (6)$$

**Absolute Enthalpy** Sum of enthalpy of formation and sensible enthalpy, where enthalpy of formation takes into account the energy associated with chemical bonds while sensible enthalpy is associated with temperature only.

**Enthalpy of Combustion** Also known as enthalpy of reaction or heating value. It is the difference between the absolute enthalpies of the combustion products and the reactants. Typically defined in terms of higher heating value (HHV) or lower heating value (LHV).

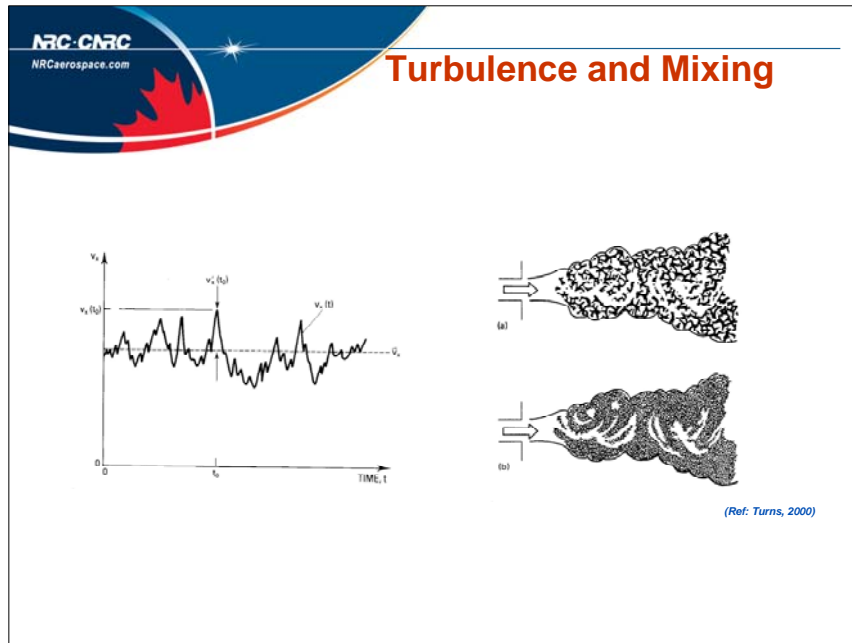
**Adiabatic Flame Temperature** This is the temperature, the flame would attain if the net energy liberated by the chemical reaction was fully utilized in heating the combustion products without losses. In other words it is the theoretical maximum temperature under adiabatic (no heat transfer) conditions. Depends on inlet temperature of fuel and air, fuel properties and fuel-air ratio.

**Combustion Efficiency** Measure of the completeness of combustion and the magnitude of heat loss from the combustion system. Equ (6) may be used as a way to determine the combustion efficiency.



For stable combustion, it is important that the flame be anchored at a desired location and is resistant to flashback, liftoff or blow-off over the complete operating range. Flame stabilization is a balance between the flame speed and flow velocity of unburned combustible mixture.

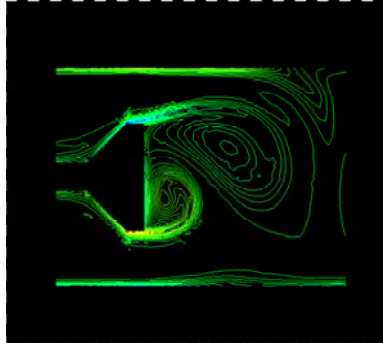
Flame anchoring may be achieved by a variety of methods. The main requirement is the creation of strong recirculation zones. The recirculation zones assist in entraining active species from the combustion products with nearly uniform and adiabatic temperature, and thus help in sustaining a flame. Flames may be stabilized in the wake of an unstreamlined (bluff) body, typically a “vee gutter”. Another method is by a rapid increase in flow area, like a backward step or a dump. Swirl stabilization is yet another technique where the recirculation zone is created by aerodynamic means rather than by mechanical means.



Degree of mixing between fuel and air is of vital importance for combustors, since it influences the level of emissions, the flame temperature and the pattern factor. Mixing is the result of two distinct mechanisms: “micromixing”, which determines the level of mixing on molecular level; and “macromixing”, which is the result of different flow paths, channelling and bypass flows in the combustor. Micromixing affects the rate of reaction through its influence on the local concentration of reactants, while macromixing results from the age distribution difference of packets of combustible mixture.

Turbulent flow results when instabilities in the flow are not sufficiently damped by viscous effects in the fluid. In turbulent flows, the velocity at each point in the flow exhibit random fluctuations. Turbulent flows comprise of random and rapid intertwining of fluid elements and this is what distinguishes it from laminar flow. These fluid elements are called eddies and their motion in a turbulent flows facilitates enhanced transport of momentum, species and energy. An eddy is considered to be a macroscopic fluid element in which the microscopic elements that make up the eddy behave as a unit. Turbulent flows are characterized in terms of turbulence intensity and eddy sizes, where the intensity is the relative magnitude of the fluctuations with respect to the mean flow.

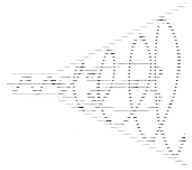
## Vortex Shedding



A flow dynamics phenomenon that is often encountered in bluff body stabilized combustion is that of vortex shedding, which is the occurrence of unsteady flow due to creation of alternating low pressure vortices in the wake of the bluff body. Vortex shedding is one of the leading causes of combustion instabilities. The frequency of shedding depends on the flow characteristics and the geometry of the bluff body.

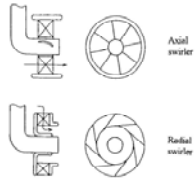
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## Swirling Flows

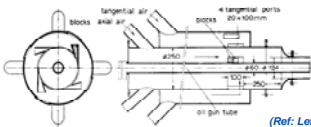


**Swirling flows**

$$S = \frac{G/2}{1-G/2} \quad \text{where } G = \frac{\text{max tanjential velocity}}{\text{max axial velocity}} \quad (7)$$



**Mechanical swirlers**




**Aerodynamic swirlers**

(Ref: Lefebvre, 1998)

One of the most effective ways of inducing flow recirculation is to introduce a rotational or tangential velocity component to the flow. In addition to providing a recirculation zone that aids in flame stabilization, swirl also helps in better mixing of fuel and oxidant. A non-dimensional measure of swirl is the “Swirl Number”, which in the simplest form is defined by Equ (7). For values of  $S < 0.4$ , no flow circulation is obtained and the swirl is described as weak. Most swirlers of practical interest operate under strong swirl conditions i.e.,  $S > 0.6$

Swirl may be generated both by mechanical and aerodynamic means. Mechanical swirling is obtained by employing either fixed or movable vanes, where the configuration of the vanes, in turn may be either axial or radial or a combination of both. On the other hand for aerodynamic swirling the air to the combustor is split into axial and tangential entry ports and the swirl intensity is controlled via variation in the split proportion.



## Chemical Kinetics

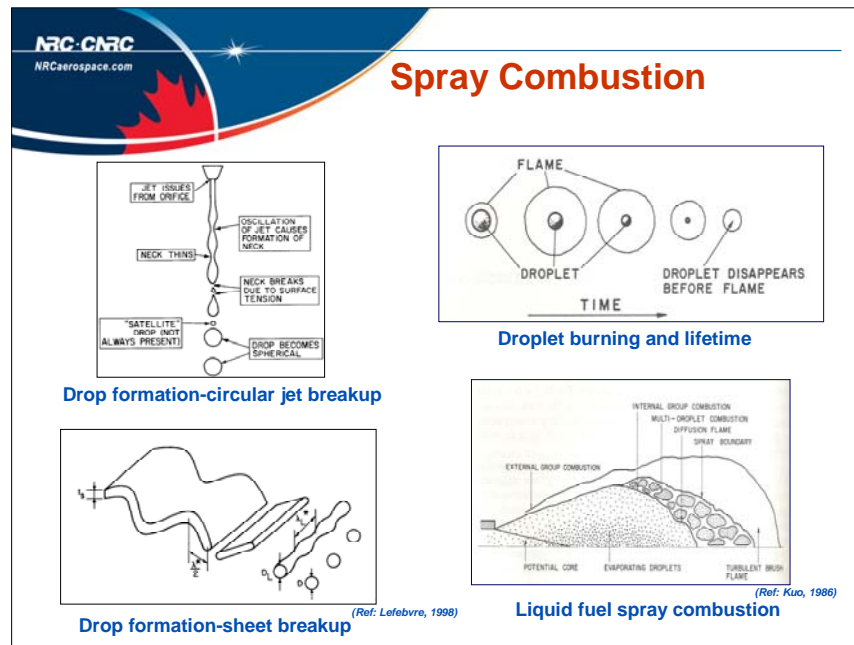
<p><b>Collision Theory</b></p> <p><b>Order of reaction</b></p> <p><b>Activation energy</b></p> <p><b>Global reaction</b></p> $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ <p><b>Quasi-global reaction</b></p> $C_3H_8 \rightarrow \frac{3}{2}C_2H_4 + H_2$ $C_2H_4 + O_2 \rightarrow 2CO + 2H_2$ $CO + \frac{1}{2}O_2 \rightarrow CO_2$ $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$	<p><b>Detailed Chemistry</b></p> <p><b>Chain initiation</b></p> $CH_4 + O_2 \rightarrow \dot{C}H_3 + \dot{O}H$ <p><b>Chain propagation</b></p> $\dot{C}H_3 + O_2 \rightarrow CH_2\dot{O} + \dot{O}H$ <p><b>Chain branching</b></p> $CH_2\dot{O} + O_2 \rightarrow \dot{H}\dot{O}_2 + \dot{H}\dot{C}O$ <p><b>Chain propagation</b></p> $\dot{H}\dot{C}O + O_2 \rightarrow CO + \dot{H}\dot{O}_2$ <p><b>Chain termination</b></p> $CO + \dot{O}H \rightarrow CO_2 + \dot{H}$
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Chemical kinetics is the study of reaction rates in elementary chemical reactions. This knowledge is essential in formulating models that simulate reacting systems. Knowledge of reaction rates is also important to determine the species profiles of the combustion products, which from a gas turbine perspective helps in evaluating combustion efficiency and emission levels. Reaction rates are a function of operating pressure and temperature, and the concentration of reactants (fuel-air ratio).

Important concepts include order of the reaction, Collision Theory and the activation energy. Most elementary reactions of interest in combustion are “bimolecular” i.e., two reactant molecules collide and react to form two product molecules. However, “unimolecular” and “termolecular” reaction are also not uncommon. Unimolecular reactions involve decomposition of a reactant specie into two or more product species, while termolecular reactions involve recombination of three species or reaction of two reactant species with a “third body” specie.

Molecular Collision Theory provides a simplified insight to bimolecular reactions and the influence of operating conditions on the reaction rate. According to the theory the reaction depends on the collision frequency and the probability that the collision will result in a reaction. The reaction probability in turn depends on the activation energy, which is the threshold amount of energy necessary for a reaction; the geometric orientation of the collision; and the structure of the species’ molecules taking part in the collision.

The collection of elementary chemical reactions necessary to describe an overall reaction is called a “reaction mechanism”. The reaction mechanism may involve only a few steps or as many as several hundred. Reaction mechanism may therefore be represented either by a general one-step global reaction or by more complex detailed chemistry models involving several initiation, propagation, branching and termination reactions. Similarly the number of species taking part in the reaction may range from four (two reactants and two products) to several hundred. For example, a very commonly used chemistry model for natural gas-air combustion called GRI-Mech involves 325 reactions with 53 species.



Spray combustion is a combination of premixed and non-premixed combustion. A spray flame will have a wide range of fuel-air ratios and thus temperature distribution across the front. The main physical processes involved in spray combustion are: atomization, fuel vaporization, mixing, ignition and chemical reaction.

Spray characteristics that are of interest are mean droplet diameter, droplet size distribution, cone angle, penetration length, radial volume flux distribution, liquid-air momentum ratio and droplet trajectories. These properties determine the rate and location of burning and heat release in spray combustion.


Atomization is the process of droplet formation and is the most critical process since it influences the mode of spray combustion. Classically, atomization results from flow instabilities, either within or on the surface of a fuel jet or sheet. The instabilities promote the formation of waves that eventually lead to disintegration into ligaments and then drops. For all practical cases atomization is obtained via a different mechanism called prompt breakup. This is possible when fuel is discharged at very high velocity like in the pressure atomizers or when high-velocity air jet impinges on a fuel jet or sheet like in the case of air-assist atomizers.

Before a liquid fuel burns, it needs to be converted into vapour phase. The vaporization process is the rate controlling process in spray combustion and follows the experimentally verified,  $D^2$ -law given by:

$$D^2 = D_0^2 - k t$$

Where  $k$  is the evaporation coefficient,  $D$  is the instantaneous droplet size and  $D_0$  is the initial droplet size. The evaporation coefficient is a function of fuel properties, temperature and flow conditions.


Spray combustion involves both individual droplets burning and burning of vapour clouds. The extent of each mode depends on fuel volatility and mean drop size in the spray. Large drops support individual droplet burning while smaller and more volatile drops favour cloud burning. Other factors that influence the mode of combustion include temperature, oxygen concentration, and relative velocity between drop and surrounding gas.



## Effects of Pressure Ratio

Process	Effect	Reason
Ignition delay	↓	Increase in reaction rate
Flame speed	↑	Increase in reaction rate
Flammability limits	↑	At the rich end of the range
Adiabatic flame temperature	↑	Suppression in dissociation reaction
Combustion efficiency	↑	Higher vaporization, higher mixing
Reaction rate	↑	Increase in frequency of molecular collisions and concentration of reactants
Auto-ignition	↑	Increase in reaction rate
Flashback	↑	Increase in flame speed
Flame anchoring	↓	Increase in flame speed
Atomization	↑	Theoretically only
Vaporization	↑	Increase in reaction rate and flame temperature

The table above shows the effect of increase in gas turbine pressure ratio on various combustion related processes and mechanisms along with the main reasons for this influence. The increases or decreases shown by green arrows are desirable for stable combustion while those shown in red pose combustion challenges.



## Gas Turbine Related Pollutants

Pollutant	Effect	Mechanism
CO	Toxic	Incomplete combustion, dissociation of CO <sub>2</sub> (weak or rich FAR in PZ, low RT, poor mixing, quenching by liner cooling air)
UHC	Toxic	Incomplete combustion, (poor atomization, insufficient flame speed, quenching by liner cooling air)
C (particulates, smoke(95%))	Toxic, visibility	High temperature fuel oxidation under very rich equivalence ratio (very rich FAR in PZ, short intermediate zone, poor atomization)
NO <sub>x</sub> (NO and NO <sub>2</sub> )	Toxic, smog precursor, ozone depletion	Thermal NO (N <sub>2</sub> +O→NO, N+OH→NO) (T <sub>PZ</sub> >1850K) Prompt NO (N <sub>2</sub> +CH→HCN→CN→CNO→NO) Fuel NO (oxidation of fuel bound N <sub>2</sub> mainly heavy distillate fuel)
SO <sub>x</sub> (SO <sub>2</sub> and SO <sub>3</sub> )	Toxic, corrosive	Oxidation of fuel bound sulfur
GHG (CO <sub>2</sub> , H <sub>2</sub> O and N <sub>2</sub> O)	Global warming	Combustion of fossil fuels

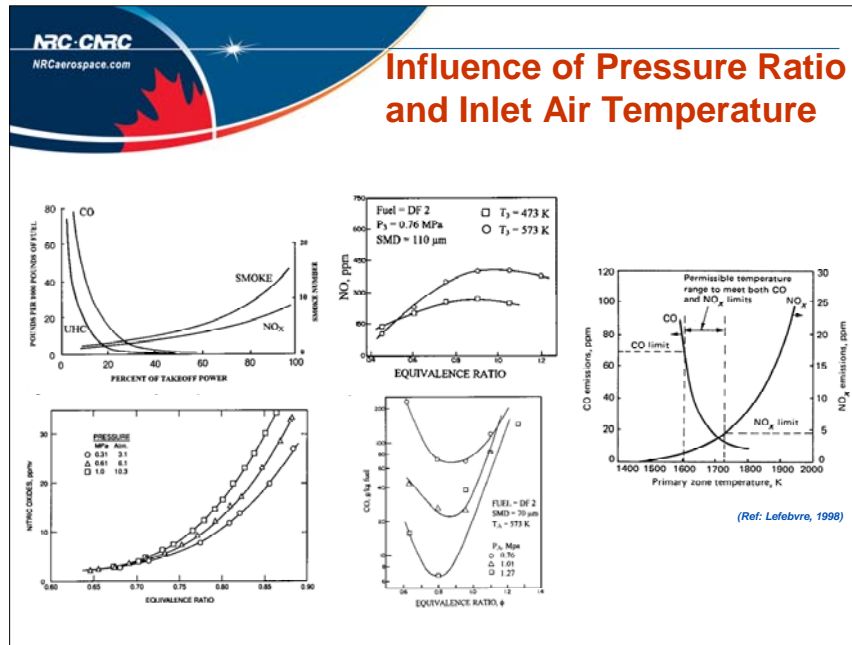
The primary pollutants from gas turbine engines are carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), particulate matter (mainly carbon) and to a lesser extent, unburned hydrocarbons (UHC). Sulfur oxides are also primary pollutants, directly related to the sulfur content of the fuel. NO<sub>x</sub> formation is strongly dependent on the high temperatures encountered in the combustor, while CO, UHC and particulate matter are primarily the result of incomplete combustion. Particulate matter is also a primary pollutant in gas turbines using liquid fuels.

Carbon monoxide arises from incomplete combustion of fuel caused by inadequate burning rates in the primary combustor zone. This may be due to low temperature, very rich or weak fuel-air ratio and/or insufficient mixing between fuel and air. Production of CO may also be elevated due to quenching of post-flame products by entrainment into the liner wall-cooling air.

Unburned hydrocarbons include fuel in the form of drops or vapours, as well as the products of thermal degradation of the parent fuel into species of lower molecular weight. They are caused by poor atomization of fuel, inadequate burning rates and the chilling effects of liner wall-cooling air.

Particulates and smoke mainly in the form of carbon are caused by the production of soot in the fuel-rich zones of the combustor. In practise, the rate of soot formation tends to be influenced more by the physical processes like atomization and mixing rather than chemical kinetics.

The primary NO<sub>x</sub> in combustion systems is Nitric Oxide (NO). It is formed mainly by two different mechanisms: thermal and prompt. Thermal NO production is temperature dependent and is maximum at flame temperatures in excess of 1800 K. On the other hand, the prompt NO mechanism also known as “flame-generated” is the dominant NO formation process in the flame zone. It takes effect as a result of formation of intermediate radicals like HCN, CN or N<sub>2</sub>O. The NO yield from prompt mechanism is consistently always prominent. Studies conducted to determine the effect of equivalence ratio on NO formation, indicate higher prompt mechanism induced production rates near stoichiometric conditions, which is where the temperature is also maximum. Because of the consistency of prompt NO formation, the overall reduction in NO emissions can mainly be achieved by reducing the thermal NO.



The levels of pollutant emissions in gas turbines can be related directly to the pressure, temperature, time and concentration histories of the combustion processes. These may vary from one combustor to another, and from changes in operating conditions for a given combustor. Gas turbines are typically operated at high loads (greater than or equal to 80% of rated capacity) to achieve maximum thermal efficiency and peak combustor zone flame temperatures. With reduced loads (lower than 80%), or during periods of frequent load changes, the combustor zone flame temperatures are expected to be lower than the high load temperatures, yielding lower thermal efficiencies and more incomplete combustion.

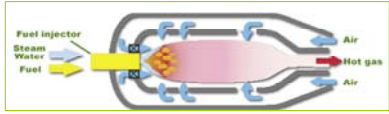
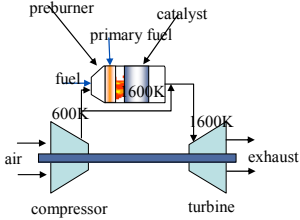
The nature of pollutant formation is such that the levels of CO and UHC are highest at low-power settings and decrease with an increase in power. In contrast NO and smoke are fairly negligible at low powers and attain maximum values at higher power conditions.

Lower CO<sub>2</sub> emissions require higher efficiency, therefore, higher firing temperature and compression ratio. Higher combustor pressures and higher primary zone temperatures also result in lowering the emissions of UHC and CO by speeding the oxidation of fuel. However, these elevated operating conditions result in the formation of higher levels of NO<sub>x</sub>.

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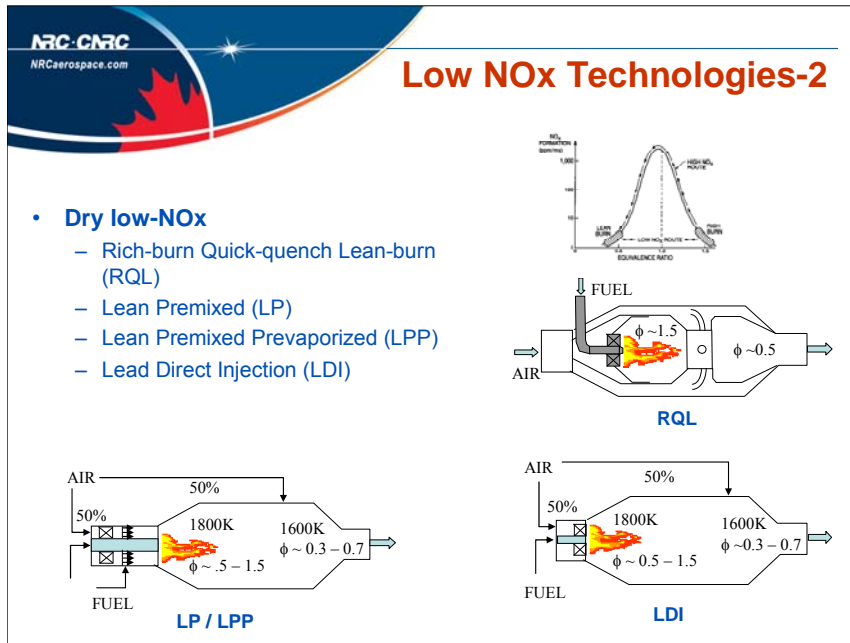
## Low NOx Technologies-1

- **Wet low-NOx**
- **Catalytic combustion**
  - Cool combustion module
  - Selective catalytic reduction (SCR)

The prime objective, in reducing NO<sub>x</sub>, is to lower the reaction temperature together with achieving temperature homogeneity. Wet low NO<sub>x</sub> and catalytic combustion were two NO<sub>x</sub> control strategies that were earlier adopted. In wet method, steam or water is injected in the combustor either directly or via fuel-line or air-line. Up to 60% reduction in NO<sub>x</sub> has been reported with water-fuel ratio of one. However, employment of this method involves high capital and maintenance cost for water treatment. It also results in increased fuel consumption (2-3%) and corrosion to hot parts. It has also been found to result in higher CO and UHC emissions.

Catalytic combustion involves partially reacting a fuel-rich combustible mixture over a catalyst and then rapidly mixing cooling air to produce a fuel-lean reactive mixture. This fuel-lean mixture feeds a catalytic pilot flame that stabilizes the main injector/swirler flame providing reduced NO<sub>x</sub> emissions. Selective Catalytic Reduction (SCR) is another way to reduce gas turbine combustion emission and involves treatment of the flue gases. NO<sub>x</sub> < 3ppm as well as CO < 10ppm have been achieved using catalytic combustion. However, these combustors gradually lose their clean burning efficiency over time and require frequent replacement, thus adding cost to operate and maintain.



Dry low NOx combustion methods are less cost and hardware intensive as compared to the wet and catalytic methods. These techniques include: Rich-burn/Quick-quench/Lean-burn (RQL), Lean Premixed (LP), Lean Pre-mixed Pre-vaporized (LPP), and Lean Direct Injection (LDI).

In RQL combustors, reduction in NOx is achieved by preventing stoichiometric combustion. This is done via a three-stage process, where fuel is burned in controlled fuel-rich and fuel-lean regions separated by air quenching. RQL combustors have excellent operability range. The potential utilization of RQL concept is limited by the ability of the quench process to rapidly and uniformly dilute the fuel-rich mixture and to transport it to the lean zone. The complexity of RQL design is another factor responsible of the not-so-wide use of this concept.

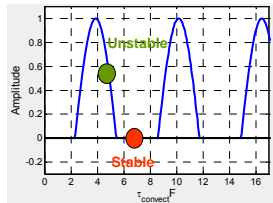
Lean premixed combustors have been found to give the lowest levels of NOx as they are designed to maintain low and uniform flame temperatures. For liquid-fuelled combustors (LPP), the fuel is first atomized and vaporized and then homogeneously mixed with combustion air before introduction in the combustion section. LP and LPP combustors are successfully being used in ground-based power generation application. However, their use in aircraft propulsion applications is limited because of additional hardware required by the pre-mixing chamber and more so because these combustors are prone to auto-ignition and flashback. Another drawback of these combustors is their susceptibility to thermoacoustic instabilities.

The limitations imposed by auto-ignition and flash back and the design complexities encounter in the applications of LPP and RQL concepts have led to the development of LDI combustors. In such combustors, fuel is directly introduced in the combustion section, where it is simultaneously vaporized, mixed and burned with the combustion air. Because of reduced dimensions, simplicity and no unwanted flashback, issues even at elevated pressures and temperatures, LDI concept has a great potential for aircraft applications as well as for land-based power units. Studies conducted to compare LPP and LDI concepts, under same operating conditions, have shown comparable NOx levels when LDI combustor was operated leaner than the LPP combustor. The biggest challenges in LDI combustors are to achieve effective atomization and rapid mixing of fuel and air to avoid formation of local high temperature zones. Thermoacoustic instabilities are also an issue with these combustors.

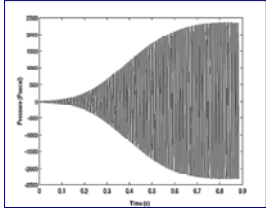
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## Combustion Instabilities

- Unsteady heat release rate in phase with the pressure oscillations
- Acoustic energy gain exceeds energy losses. Limited by non-linear effects
- Susceptibility to Low dry NOx combustors
- Instability criterion
  - $\cos(\tau_{\text{convect}} F) > 0 \rightarrow$  Unstable
  - $\cos(\tau_{\text{convect}} F) < 0 \rightarrow$  Stable

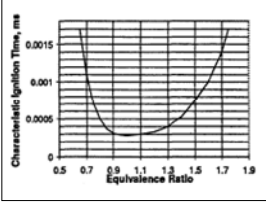


A graph showing Amplitude on the y-axis (ranging from -0.2 to 1.0) versus  $\tau_{\text{convect}} F$  on the x-axis (ranging from 0 to 16). The plot shows a series of peaks and troughs. A green dot is placed at a peak labeled "Unstable", and a red dot is placed at a trough labeled "Stable".



A graph showing Pressure Fluctuation on the y-axis (ranging from -0.05 to 0.05) versus Time on the x-axis (ranging from 0 to 0.9). The plot shows a signal that starts with a small amplitude and grows exponentially over time, indicating instability.

*(Ref: Chatterjee, 2004)*



A graph showing Characteristic Ignition Time, ms on the y-axis (ranging from 0 to 0.0015) versus Equivalence Ratio on the x-axis (ranging from 0.5 to 1.9). The plot shows a U-shaped curve with a minimum around an equivalence ratio of 1.0.

*(Ref: Zukoski, 1978)*

Combustors burning in lean conditions are prone to thermoacoustic instabilities. Thermoacoustic instability is a type of combustor unsteadiness and results because of a coupling between the combustor acoustic modes and the unsteady heat source, where the unsteadiness in the heat release rate is a direct consequence of oscillations in gas medium within the combustion system. Thermoacoustic instabilities may be initiated by perturbations in the mean flow. The geometry of the combustor also has a dominant influence. In spray combustion, the inherent spray dynamics also affect these instabilities.

The significance of thermal-acoustic coupling was documented more than a century ago by Lord Rayleigh, who presented a qualitative explanation of the phenomenon. According to Rayleigh criterion, acoustic wave gains energy when the unsteady rate of heat input is in phase with the pressure oscillations. If the heat is received by the air at the moment of greatest compression, or is rejected at the moment of greatest rarefaction, the oscillations are encouraged. System goes unstable when acoustic energy gain exceeds energy losses. In later research it was shown that the instabilities continue to grow until limited by non-linear mechanisms into a periodic finite-amplitude oscillation.

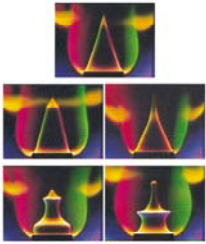
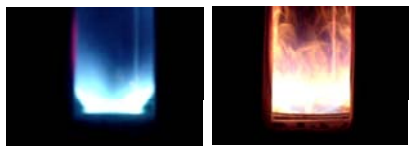
Most practical combustors are susceptible to thermoacoustic instabilities. This is because combustors are high energy density systems with weak acoustically damped geometries. Thus, even small fluctuations in rate controlling processes are sufficient to produce large variations in flame and heat release characteristics leading to oscillations in acoustic pressure field. It has been found that this effect is especially pronounced when the combustors are operated at leaner conditions.

In order for any rate controlling processes to be self-exciting, the characteristic times related to these processes responsible for the heat release disturbance must be of similar magnitude as the acoustic period. Mathematically the criterion for combustion instability can be represented by the equation in the slide above. Here  $\tau_{\text{convect}}$  refers to the time required to transport the fuel-air mixture from the location of fuel injection to the centre of mass of the flame, while  $F$  is the natural frequency of the combustor.

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## Effects of Thermoacoustic Instabilities

### Flame and Combustor Response

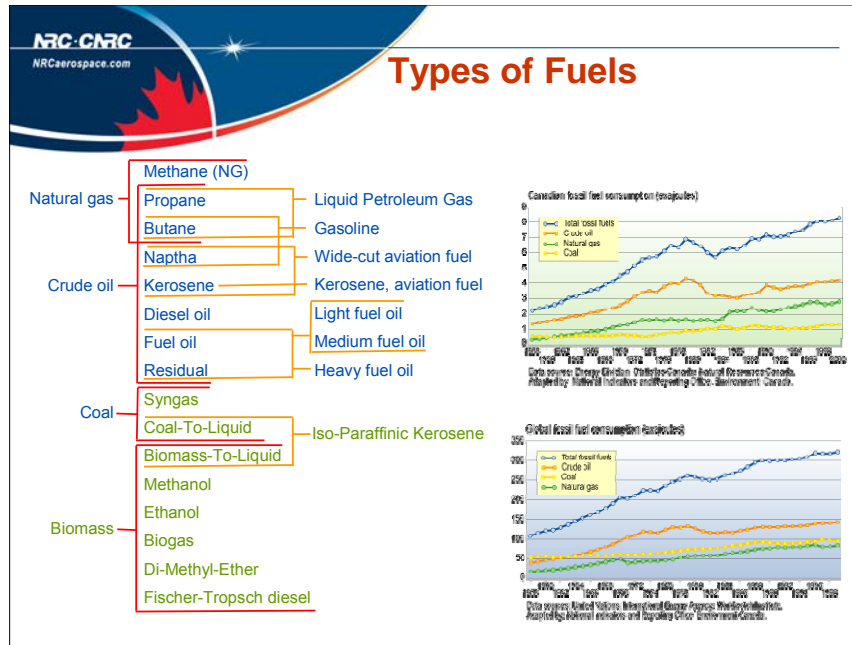
*(Ref: Ducruix et al., 2000)*

### Detrimental Consequences

*(Ref: EPRI-1014465, 2006)*      *(Ref: Rea et al, 2003)*      *(Ref: Lieuwen & McManus, 2002)*

Thermoacoustic instabilities have been a continuous source of concern in the development and operation of high-performance, low-emission gas turbine engines. These instabilities manifest themselves as high amplitude pressure oscillations in the combustion systems resulting in both performance and structural degradation. It has been reported that the cost of repair and replacement of structural components, damaged due to combustion instability related problems alone, exceed US\$ 1 billion annually. In addition, these damages result in costly downtime of the plant.




The performance of combustion systems depends strongly on the physical and chemical properties of the fuels. Choice of a particular fuel depends on the total environment in which a gas turbine operates. For example, fuels for aviation purposes have requirements different from those used in industrial or marine gas turbines.

The majority of gas turbines are currently operated upon conventional fossil fuels like coal or like those derived from natural gas and crude oil. However, due to a rise in the consumption together with the depleting supplies of crude resources, the conventional fuels are being supplemented by alternative fuels. Alternative fuels may be obtained either from crude sources such as coal, tar sands and shale oil or from renewable sources like biomass.

From combustion point of view the gas turbine fuels, both conventional and alternative, and the fuel diluents can be grouped under three headings:

- Hydrogen contents e.g., Synthetic gas, Refinery-off gas.
- Higher hydrocarbon contents e.g., Vaporized liquid fuels, LNG, Associated gas
- Diluents e.g., Water, Carbon dioxide, Nitrogen

For the discussions that will follow, our focus will be on synthetic gas and other gaseous fuels rich in hydrogen contents.



## Syngas Related Issues – Composition Variations

### Feedstock Variation

Composition (Volume %)	Coal-Gas	Bio-Gas	Natural Gas
Hydrogen (H <sub>2</sub> )	14.0%	18.0%	--
Carbon Monoxide (CO)	27.0%	24.0%	--
Carbon Dioxide (CO <sub>2</sub> )	4.5%	6.0%	--
Oxygen (O <sub>2</sub> )	0.6%	0.4%	--
Methane (CH <sub>4</sub> )	3.0%	3.0%	90.0%
Nitrogen (N <sub>2</sub> )	50.9%	48.6%	5.0%
Ethane (C <sub>2</sub> H <sub>6</sub> )	--	--	5.0%
HHV (kJ/m <sup>3</sup> )	6,417	5,315	39,450


### Process Variation

Composition (Volume %)	Min.	Max.	Avg.
Hydrogen (H <sub>2</sub> )	8.6	61.9	31.0
Carbon Monoxide (CO)	22.3	55.4	37.2
Carbon Dioxide (CO <sub>2</sub> )	1.6	30	12
Methane (CH <sub>4</sub> )	0	8.2	2.2
Nitrogen (N <sub>2</sub> )+ Argon (Ar)	0.2	49.3	12.2
Water (H <sub>2</sub> O)	0.1	39.8	7.8
Hydrogen/Carbon Monoxide Ratio	0.33	0.8	0.86

Synthetic gas (Syngas) is produced from gasification of carbon-based feedstock like coal, biomass or solid wastes among many others. Gasification is partial oxidation process at high to ultra high pressures using either air or oxygen as oxidant. Syngas is primarily a mixture of hydrogen, carbon monoxide and nitrogen and may also contain smaller amounts of methane, carbon dioxide, oxygen and other higher hydrocarbons. Depending on the factors given below, syngas can have a significant variation in the relative composition of its constituents:

- Type of gasifier used, e.g., fixed-bed, entrained-flow, fluidized-bed.
- Process temperature e.g., low temperature for non-slugging operation and high temperature for slugging operation
- Feed rate to the gasifier.
- Amount of oxidant introduced during gasification process
- H:C ratio in carbon feedstock. In general the higher hydrocarbon contents in the feedstock result in lower a ratio of hydrogen to carbon monoxide in the produced syngas.


The tables above demonstrate the variations in syngas composition as a function of variations in feedstock and variations in gasification process. Because of this large variation in composition, syngas poses considerable challenges for combustion.



## Characteristic Values

		Flammability Limits (AFR=1/FAR)			Autoignition (°C)	Laminar flame speed (cm/s)
		Stoic.	Lean	Rich		
<b>Methane</b>	CH <sub>4</sub>	17.24	34.26	10.22	537	34
<b>Propane</b>	C <sub>2</sub> H <sub>6</sub>	15.66	32.15	6.25	470	39
<b>Iso-Octane</b>	C <sub>8</sub> H <sub>18</sub>	15.10	26.41	3.97	418	35
<b>Carbon Monoxide</b>	CO	2.47	7.23	0.36	609	39
<b>Acetylene</b>	C <sub>2</sub> H <sub>2</sub>	13.28	43.33	0.28	305	141
<b>Hydrogen</b>	H <sub>2</sub>	34.29	344.40	4.78	400	265
<b>Methanol</b>	CH <sub>3</sub> OH	6.47	12.57	1.61	385	48

The table shows characteristic values of flammability limits in terms of mass-based air-fuel ratio, auto-ignition temperature and laminar flame speed of some of the hydrocarbon fuels as well as hydrogen and carbon monoxide, the latter two being the main constituents of syngas. The table highlights the significant difference in hydrogen flammability range and its burning speed as compared to more conventional fuels like methane (Natural Gas). Also noticeable is the stoichiometric flammability value of carbon monoxide, which is an order of magnitude lower than either methane or hydrogen. Because of these considerable differences in the characteristic values of hydrogen and carbon monoxide, syngas combustion is a challenge for gas turbine designers.

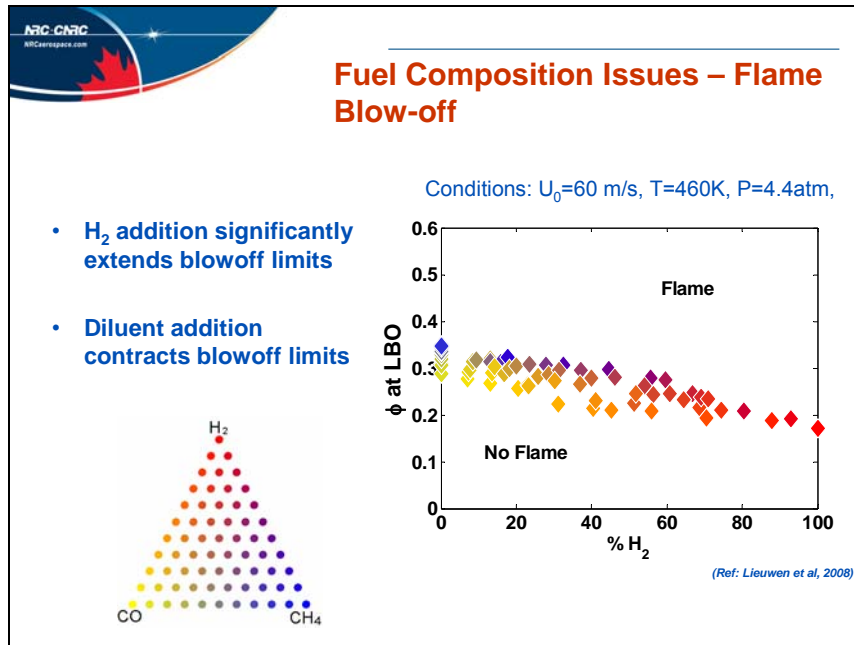


## Important Combustor Performance Parameters

- **Wide operability**
  - Blow-off limits
  - Flashback and auto-ignition limits
  - Static and dynamic stability (flame spatial and temporal anchoring)
- **Low emission**
- **Good turndown**

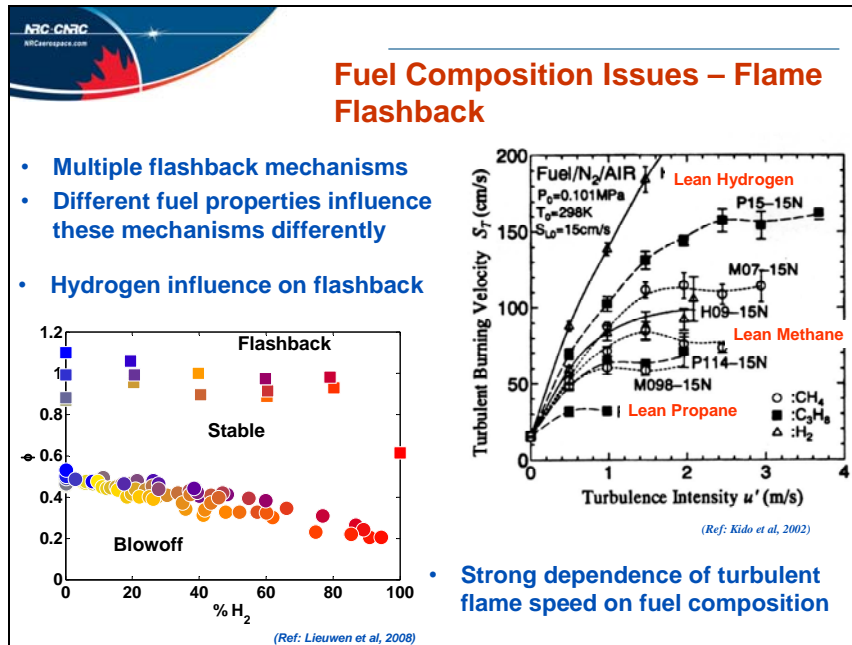
Combustor performance is normally measured in terms of operability, emissions and turndown capabilities. Of course wide operability, low emissions and good turndown is preferred. The operability effectiveness of combustors can be gauged in terms of blow-out, flashback and auto-ignition limits. The operability also depends on the spatial and temporal stability of the flame, i.e., shape and location of the flame and their variation with respect to time. This is generally known as the static and dynamic stability. The static stability sometimes also refers to the flame blow-off.

In the next few pages we will briefly review how the syngas composition and the significant differences in the characteristics of hydrogen and carbon oxide influence combustion operability and emissions. In practice, interdependencies exist within the operability parameters as well as between these parameters and emission/turndown. However, in the discussion that follows, these parameters have been considered independent of each other.



Flame blow-off may occur both at rich as well as lean fuel burn conditions and the limits depend strongly on the physiochemical properties of fuel-air mixture. However, because of the interest in low-emission combustors, the lean blow-off limits are of major concern. This refers to the leanest fuel-air mixture limit that will allow steady flame propagation. Lean blow-off occurs when flame speed is lower than the flow velocity of the unburned combustible mixture. It should also be kept in mind that flame speed is directly related to rate of chemical reaction. The occurrence of flame blow-off in gas turbines results in expensive system shut-down, purge cycles and re-starts.

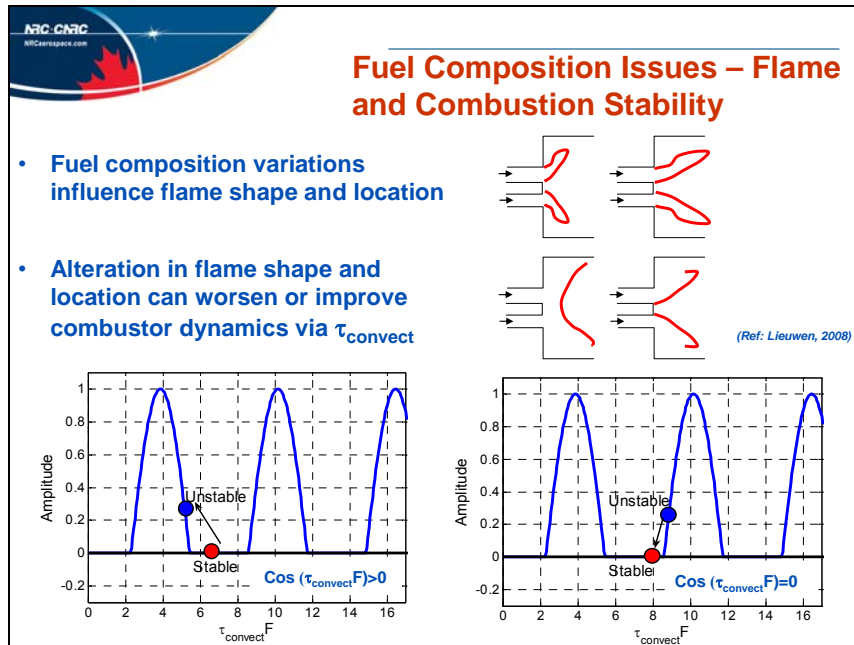
The key factor that influences the flame blow-off characteristics of syngas is the amount of hydrogen content in the syngas. Addition of hydrogen considerable enhances the lean blow-off limits because of its high flame speeds. The figure above highlights this fact for various representative syngas compositions. The lean blow-off limit improves (i.e., equivalence ratio at which blow-off occurs reduces) as a function of increase in hydrogen percentage in the syngas fuel composition. The figure also indicates that addition carbon monoxide and diluents like methane reduces the lean blow-off limit.



Flashback occurs when the flame propagating velocity is more than the velocity of the incoming reactants' mixture. In such a situation the flame enters and propagates through the premixer or the burner tube that are not designed to take high temperatures. Occurrence of flashback leads to overheating and failure of fuel nozzles and premixing section. Flashback in practical combustors can occur via several mechanisms as listed below. Different syngas compositions and thus different characteristic properties affect these mechanisms differently


- In boundary layer
- In core flow
- Strong acoustic pulsations lead to nearly reverse flow
- Combustion induced vortex breakdown

The fuel composition has a strong influence on the burning velocity of the flame as shown in the figure on the right above. The turbulent burning velocity of lean hydrogen-air mixture is roughly double that of lean methane-air mixture and four-times that of lean propane-air mixture. The hydrogen percentage in syngas therefore has a strong effect on the flashback limit. The figure on the left above shows the flashback, blow-off and stable combustion regimes for a variety of syngas compositions. As may be noted, increase in hydrogen percentage lowers the flashback limit to much leaner conditions.



As discussed earlier in the tutorial, combustion instabilities or thermoacoustic instabilities in combustors refer to high-amplitude and damaging pressure oscillations associated with oscillation in heat release rates. It was also shown how these oscillations can cause wear and damage to hot section components. The oscillations may also cause IOD (Internal Object damage) due to release of broken engine pieces in the gas path resulting in damage to turbine section.

Variations in syngas fuel composition influence the flame location and the shape of the flame. These alterations cause the flame center of mass to move thus affecting the time  $\tau_{\text{convect}}$  it takes for the fuel mixture to transport from the point of fuel injection to the flame center of mass. Depending on the integrated value of  $\tau_{\text{convect}}$  a stable combustor may go unstable or an unstable combustor may go stable, as shown in the two bottom figures in the slide above.



## Fuel Composition Issues – Emissions

- Strongly dependant on composition
- In general syngas produce lower emissions for heat/power generation. Benefits better with IGCC
- VOC emissions low
- SO<sub>x</sub> emissions low
- CO emissions dependant on fuel preparation and combustion completeness
- NO<sub>x</sub> emissions function of flame temperature, fuel-air ratio, fuel preparation and CO:H<sub>2</sub> ratio

The strong dependence of gas turbine emissions on the syngas composition is quite evident because of the consequence of syngas composition on combustion characteristics. Overall, the use of syngas in the generation of heat and power produces lower emissions compared to conventional fuels.

In general combustion of gaseous fuels yields lower emissions of volatile organic compounds (VOC) than liquid fuels. Syngas can be even cleaner in terms of VOC emission since they usually contain a smaller amount of hydrocarbon compounds.

Carbon monoxide emissions in syngas combustion primarily come from two sources: unburned syngas CO, resulting from inefficient mixing creating regions with equivalence ratios outside the ignition range; and incomplete combustion of hydrocarbon species in the syngas. Syngas with significant carbon monoxide and hydrogen contents offer a much wider ignition range than those of conventional hydrocarbon fuels. The expanded operational range effectively lowers the probability of unburned gas due to improper mixing, resulting in low emissions of unburned CO.

Nitrogen oxides (NO<sub>x</sub>) are mainly produced via three mechanisms: thermally-generated; flame-generated and fuel-bound. NO<sub>x</sub> emission levels during the syngas combustion are highly variable, and depend on fuel composition, gas turbine operating conditions, level of fixed-nitrogen contaminants in the syngas as well as the particular combustion device. The thermal and flame NO<sub>x</sub> increases with the increase in hydrogen contents of syngas because of the associated rise in flame temperature. On the other hand, higher hydrogen contents allow leaner combustion which tends to lower the NO<sub>x</sub> generation. Fuel-bound NO<sub>x</sub> depends on the presence of ammonia in the combustion and can be reduced by removing ammonia prior to combustion. The fuel-bound NO<sub>x</sub> can also be reduced at richer combustion. The relative amount of carbon monoxide and hydrogen in syngas can have a significant impact on NO<sub>x</sub> emissions. Studies have shown that the NO<sub>x</sub> emissions increase with the increase in CO:H<sub>2</sub> ratio.



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