I, Erwann GUILLOU,
hereby submit this work as part of the requirements for the degree of:

Master of Science

in:

Aerospace Engineering

It is entitled:

Flame Characteristics and Application of

Flameless Combustion

This work and its defense approved by:

Chair:  Dr. Ephraim Gutmark
        Dr. Shaaban Abdallah
        Dr. Prem Khosla
Flame Characteristics and Application of
Flameless Combustion

A thesis submitted to the
Graduate faculty of University of Cincinnati
in partial fulfillment
of the requirements for the degree of

Master of Science
in the Department of Aerospace Engineering and Engineering Mechanics
of the College of Engineering

December 2nd, 2007

by

Erwann Guillou
Ingénieur de l’Ecole Nationale Supérieure D’Arts et Métiers, Paris, France,
M.S. Mechanical Engineering, July 2005

Committee Chair: Dr. Ephraim Gutmark
Abstract:

Flameless combustion is a technique obtained by operating at high level of turbulence and temperature of oxidizer higher than the autoignition temperature of the air and fuel mixture. Lately, it has received much attention because of its benefits in terms of energy saving and low NOx emission rate.

This thesis aims to collect information, both in theory and practice, which can be useful in understanding the change of combustion regime under typical conditions. An overview of the main motivations to provide new combustion systems until the development of flameless combustion and its interesting characteristics is first presented. An experimental flameless burner, developed from the collaboration between the University of Cincinnati and Goodrich Turbine Fuel Technologies, is then investigated under atmospheric gas turbine engine conditions. The experimental results are subdivided in two parts: first, the characterization of the burner under thermodynamic influences and then, the presentation of qualitative and quantitative results acquired over several gaseous and liquid flames which determines the effect of fuel properties on flame characteristics.

At high preheated air temperature and high pressure drop, it was shown that flameless combustion occurred under very stable conditions. The fuel chemical properties were found to have a subtle effect on the flameless oxidation of fuel with notably an interesting behavior under butane atomization. All the results were finally conclusive on a potential application of such a regime of combustion to gas turbine engine.
Acknowledgments:

I would like to thank in priority my advisor Dr Ephraim Gutmark for different reasons. First, for allowing me to follow my studies in the United States, then for trusting me during my studies on hazardous combustion systems and finally for is guidance along my researches.

Special thanks go to:

Nicholas Overman: for teaching me the basic steps of the low pressure combustor.

Mugam Murugappan: for guiding me at the beginning of my research.

Russell DiMicco: both for his time and answers on design/technical issues and his permanent support.

Michael Cornwell: for is amazing knowledge of combustion and engineering systems in general, for his help during the great part of the tests and is permanent sense of humor.

I finally would like to thank all my lab-mates, both American and international, and my close environment for permitting my research to keep enjoyable.
Table of Contents:

Abstract: ............................................................................................................ 3
Acknowledgments: ............................................................................................ 4
Table of Contents:............................................................................................. 5
List of Tables and Figures: ................................................................................ 7
Nomenclature: .................................................................................................. 10

1 – INTRODUCTION: .......................................................................................... 11

1.1 - History of “Flameless” thru General Combustion: .................................... 11
  1.1.1 - Motivation to New Combustion Systems: ........................................... 13
    a - Production of Carbon Monoxide (CO): ................................................... 14
    b - Production of Carbon Dioxide (CO2): ..................................................... 16
    c - Production of Unburned Hydrocarbon: ................................................... 16
    d - Production of Soot: .................................................................................. 17
    e - Production of Oxide of Nitrogen (NOx): .................................................. 18
  1.1.2 - First Measures to Reduce NOx Emissions: ........................................... 21
    a - Flame Cooling: .......................................................................................... 21
    b - Staging: .................................................................................................... 21
    c - Lean Premixed Combustion: .................................................................... 23
    d - Reburning: ............................................................................................... 24
    e - Usage of Oxygen as Oxidizer: ................................................................. 25
    f - Exhaust Gas Recirculation: ...................................................................... 26
  1.2 - “Flameless” Oxidation Principle: ........................................................... 27
    1.2.1 - Heat Recirculating in “Flameless” Combustion: .................................. 28
      a - Heat Recirculation Combustion Theory: .............................................. 28
      b - Flameless Combustion: Application of Recirculation: ......................... 33
  1.2.2 - Burner Design and Principle: .............................................................. 36
  1.2.3 - Thermodynamic Aspect and Autoignition: .......................................... 39
      a - Thermodynamic Consideration: ............................................................. 39
      b - Autoignition Temperature of Fuel: ....................................................... 41
  1.3 - Flameless Advantages: .......................................................................... 44
    1.3.1 - Flameless Emission: ........................................................................ 44
    1.3.2 - Flameless and Flame Characteristics: .............................................. 50
    1.3.3 - Flameless Stability: .......................................................................... 52
      a - Turbulence in Flameless Combustion: ................................................. 52
      b - Stability Reasons in Flameless Combustion: ........................................ 55
  1.3.4 - Implementation of Flameless Combustion in Gas Turbine Engines: .... 57

2 – EXPERIMENTAL RESULTS with Flameless Combustion: ....................... 61

  2.1 - Facility & Measurements: ....................................................................... 61
    2.1.1 - Description of the Facility: ............................................................... 61
    2.1.2 - Instrumentation: .............................................................................. 63
      a - Plenum Region Conditions: ................................................................. 63
      b - Temperature Measurements of the Combustion Chamber: .................. 64
      c - Pressure & OH* Measurement: ......................................................... 67
      d - Emission: ......................................................................................... 68
      e - OH Spectrometry Measurement: ..................................................... 70
2.1.3 - Data Acquisition: .................................................................................................................. 70
2.1.4 - Measurement Corrections: ..................................................................................................... 74
  a - Temperature: .......................................................................................................................... 74
  b - Emission .................................................................................................................................. 76
2.2 - Characterization of the Combustor at Flameless regime: .................................................. 81
  2.2.1 - Influence of Preheated Air Temperature: ........................................................................ 81
         a - Influence on Exit and Recirculation Temperature: ...................................................... 81
         b - Influence on Emission: .................................................................................................. 83
         c - Heat Release: .................................................................................................................. 88
         d - Pressure Oscillation: ..................................................................................................... 91
  2.2.2 - Influence of Pressure Drop through the Burner: .......................................................... 94
         a - Influence on Exit and Recirculation Temperature: ...................................................... 95
         b - Emission of CO/NOx and CO2/O2: ............................................................................... 96
         c - Heat Release: .................................................................................................................. 98
         d - Pressure Oscillation: ..................................................................................................... 99
  2.2.3 - Temperature profiles: ........................................................................................................ 101
2.3 - Influence of Fuel Properties on Flame Characteristics: ...................................................... 112
  2.3.1 - Previous Results and Presentation of the Experiments: .............................................. 113
         a - Previous Results: .......................................................................................................... 113
         b - Test Procedure: ............................................................................................................. 115
         c - Fuel Presentation: .......................................................................................................... 119
  2.3.2 - Experimental Imaging Results: .................................................................................... 122
         a - OH Chemiluminescence Comparison: .......................................................................... 122
         b - Picture Homogeneity Analysis: ..................................................................................... 139
  2.3.3 - Measurements Related: .................................................................................................. 144
         a - Heat Release: .................................................................................................................. 144
         b - Emission: ....................................................................................................................... 145
         c - Comparison at Low Pressure Drop: ............................................................................. 148

3 - CONCLUSION .................................................................................................................................. 155

REFERENCES: .................................................................................................................................... 159

APPENDIX: .......................................................................................................................................... 161

1 - Test Procedure ............................................................................................................................ 159
2 - Data Acquisition System ............................................................................................................ 163
3 - Emission System Procedure ....................................................................................................... 173
4 - Matlab Code For Data Analysis .................................................................................................. 178
5 - Previous Burner Design .............................................................................................................. 188
6 - New Burner Design ..................................................................................................................... 188
7 - New Combustion Chamber .......................................................................................................... 199
List of Tables and Figures:

Figure 1: Combustion Generates Pollutant Emissions ........................................ 14
Table 1: Influence of combustion parameters on CO production .................... 15
Figure 2: NOx reducing by flame cooling .......................................................... 21
Figure 3: NOx reducing by air staging ............................................................... 21
Figure 4: Staged-combustion burner ................................................................. 22
Figure 5: NOx reducing by lean premixed combustion ..................................... 23
Figure 6: NOx reducing using reburning ......................................................... 24
Figure 7: NOx reducing by exhaust gas recirculation ...................................... 26
Figure 8: NOx reducing by flameless oxidation: (a) nonadiabatic; (b) adiabatic... 28
Figure 9: Temperature history of heat recirculation ....................................... 29
Figure 10: Correlation between combustion air T and NOx emission .............. 31
Figure 11: Schematic structure of heat recirculating furnace .......................... 32
Figure 12: Exhaust gas recirculation Stability limits ....................................... 34
Figure 13: Flame temperature of stoichiometric mixture .............................. 35
Figure 14: Flameless oxidation burner ......................................................... 37
Figure 15: Principle of a burner used in flameless combustion ..................... 38
Figure 16: Autoignition limits and blow-off limits ......................................... 42
Figure 17: NOx concentration expressed as function of Tair ............................ 45
Figure 18: Emission of NOx function of air-preheat temperature and [O2] ....... 46
Figure 19: Emission of NOx function of preheat T in air and [O2] in air .......... 47
Figure 20: NOx emission of conventional, staging and flameless burners ....... 48
Figure 21: Characteristics of the "low emission window" .............................. 48
Figure 22: Propane flame photographs with combustion air temperature ...... 51
Figure 23: Visual comparison between Turbulent premixed and Flameless ..... 54
Figure 24: Instabilities three part cyclic process .......................................... 56
Figure 25: Effect of recirculation on stirred gas temperature and [O] .......... 59
Figure 26: Schematic view and details of the used combustor ....................... 61
Figure 27: Sylvania heater performance curve .......................................... 62
Figure 28: Pannel control of the plenum conditions ................................................. 64
Figure 29: Disposition of the Exit and Recirculation Thermocouples ............. 65
Figure 30: Temperature profiles measurement apparatus ........................................ 66
Figure 31: Microphone and Amplifier for pressure oscillation measurement ...... 67
Figure 32: Temperature, pressure and flow rate measurement of the fuel .......... 67
Figure 33: OH* measurement by optical signal filtered and amplified............... 68
Figure 34: California Analytical Instruments emission sensors: ....................... 68
Figure 35: ICCD Princeton Instruments camera for OH chemiluminescence ..... 70
Figure 36: General Schematic of the acquisition data board .............................. 71
Figure 37: Preheated Air Influence on Exit and Recirculation Temperature .... 81
Figure 38: Preheated Air Influence on CO and NOx Emission ............................ 84
Figure 39: Preheated Air Influence on CO2 and O2 Emission ............................. 88
Figure 40: Preheat Air Influence on Heat Release ................................................. 89
Figure 41: Preheat Air Influence on pressure oscillation ...................................... 92
Figure 42: Pressure Drop Influence on the exit and recirculation temperature... 95
Figure 43: Pressure drop influence on CO and NOx emission.......................... 96
Figure 44: Pressure Drop Influence on CO2 and O2 emission ........................... 98
Figure 45: Pressure Drop Influence on Heat release .......................................... 99
Figure 46: Pressure Drop Influence on Pressure Oscillation ............................ 100
Figure 47: Temperature profile, air preheated at 325°C, ....................................... 105
Figure 48: Temperature profile, air preheated at 425°C, ..................................... 106
Figure 49: Temperature profile, air preheated at 525°C, .................................... 107
Figure 50: Flame structure evolution from flameless to non flameless .......... 113
Figure 51: LBO Limits for different type of fuel injected: ................................. 114
Figure 52: Fuel pressure measurement with different fuels: ............................. 120
Figure 53: Selected OH-LIPF intensity images for various equivalence ............ 122
Figure 54: Selected OH-LIPF intensity images of flameless oxidation .......... 125
Figure 55: Selected OH-LIPF intensity images of flameless oxidation ............ 127
Figure 56: Selected OH-LIPF intensity images of flameless oxidation .......... 128
Figure 57: Selected OH-LIPF intensity images of flameless oxidation .......... 130
Figure 58: Selected OH-LIPF intensity images of flameless oxidation .......... 131
Figure 59: Selected OH-LIPF intensity images of flameless oxidation................. 134
Figure 60: Selected OH-LIPF intensity images of flameless oxidation............... 135
Figure 61: X Cross Section Average Profiles at selected equivalence ratio ...... 139
Figure 62: X Cross Section Average Profiles at selected equivalence ratio ...... 140
Figure 63: Standard Deviation Normalized of the fuel imaging measurements. 142
Figure 64: Heat release measurement function of temperature flame............... 144
Figure 65: CO & NOx emissions function of equivalence ratio en fuel types..... 145
Figure 66: CO2 & O2 emissions function of equivalence ratio and fuel types ... 147
Figure 67: Selected OH-LIPF intensity images of flameless oxidation................. 149
Figure 68: Selected OH-LIPF intensity images of flameless oxidation............... 150
Figure 69: Selected OH-LIPF intensity images of flameless oxidation................. 151
Figure 70: X Cross Section Average Profiles at selected equivalence ratio ...... 153
Figure 71: Standard Deviation Normalized of the fuel imaging measurements. 154
Nomenclature:

**Variables**

- **$CO$** = Carbon Monoxide
- **$CO_{2}$** = Carbon Dioxide
- **$D$** = Geometric Diameter
- **$E$** = Activation Energy
- **$h$** = Coefficient of Convection Heat Transfer
- **$k$** = Coefficient of Conductive Heat Transfer
- **$K_{R}$** = Exhaust Gas Recirculation Rate
- **$\ell_{0}$** = Integral Scale (Turbulence Macroscale)
- **$\ell_{K}$** = Kolmogorov Microscale
- **$H$** = Flame lift-off height
- **$L$** = Geometric Length
- **$LBO$** = Lean Blow Off
- **$NO_{X}$** = Nitrous Oxide / Nitrous Dioxide
- **$Nu$** = Nusselt Number
- **$O_{2}$** = Oxygen
- **$OH^{*}$** = Relative Concentration of OH, measured through fiber optics
- **$P$** = Pressure in Plenum Up-Stream of Burner
- **$Pr$** = Prandtl Number
- **$R$** = Specific Gas Constant
- **$Re$** = Reynolds Number
- **$T_{in}$** = Oxidizer Temperature Up-Stream of Burner
- **$UHC$** = Unburned Hydrocarbons
- **$W$** = Mass Flow Rate
- **$Y$** = Mass Fraction

**Greek Symbols**

- **$\beta$** = Zel’dovich number (non-dimensional activation energy)
- **$\Delta P$, $dP$** = Percent Pressure Drop Across Burner
- **$\delta$** = Flame Thickness
- **$\varepsilon$** = Thermal Emissivity
- **$\phi$** = Fuel Equivalence Ratio
- **$\phi_{st}$** = Fuel Equivalence Ratio at stoichiometric conditions
- **$\gamma$** = Ratio of Specific Heats
- **$\Lambda$** = Diffusion Coefficient
- **$\mu$** = Dynamic Viscosity
- **$\rho$** = Density
- **$\sigma$** = Stephan-Boltzman Constant ($5.669 \times 10^{-8} \frac{W}{m^{2} \cdot K}$)
- **$\tau$** = Characteristic Time
1 – INTRODUCTION:

1.1 - History of “Flameless” thru General Combustion:

By definition, the process of combustion is globally characterized by the sequence of multiple exothermic chemical reactions between a fuel and an oxidant, accompanied by the production of heat and more or less of light in the form of either glow or flame. The initiation of the reaction in a purely thermal point of view is described as following: providing a sufficient amount of heat, which means enough energy to overcome the energy barrier between the unreactive and reactive state of the diradical molecules of dioxide, this heat pyrolyses the molecules of fuel which then produce free radicals (molecular species with unpaired electrons and highly subject to react). Then, the first free radicals produce more radicals thru chain branching mechanisms and this rises in an exponential way.

Parts of the factors describing the combustion reaction are: the induction time and the Air/Fuel equivalence ratio. The induction time is actually the period of time between the chain initiation reactions (fuel pyrolysis) and the chain branching reactions. The Air/Fuel ratio is defined by:

\[ \phi = \frac{\text{Fuel}}{\frac{\text{Air}}{\text{Fuel}_{\text{stoich}}}} = \frac{\text{Air}_{\text{stoich}}}{\frac{\text{Fuel}_{\text{stoich}}}{\text{Air}}} \]

It permits to describe the reaction, being a Rich combustion ($\Phi>1$), a Stoichiometric combustion ($\Phi=1$) or a Lean combustion ($\Phi<1$). It is also related to the gain in temperature.
Flameless combustion is the result from the influence of two phenomena. First, after the energy crisis during the seventies and early eighties, many R&D activities as combustion focused on the improvement of energy efficiency. In term of combustion, thermodynamic considerations suggest that an actual efficient method to improve the energy saving is to use combustion air preheating in order to increase the flame temperature, the combustion intensity/efficiency, and the heat transfer. However, a direct consequence of air preheating is the increase of peak temperature in the flame and therefore, as we will see later, a harmful impact on the thermal NO-formation.

Then, beside energy shortage, which is not perceived by many people, at the same period, the awareness of the negative effects of NOₓ-emissions on human health and more generally on the environment put growing pressure on operators and producers of combustion equipments. Actually, the influence of combustion products into the global climate had become a slogan in the discussion about the combustion of fossil fuels.

Now, although those different arguments about energy resources and environment, we need to keep in mind that the clear task of engineers is to develop efficient combustion systems, that is why the target became to overcome the conflict of interest between energy saving and pollutant emissions.

Thus, while NOₓ-emissions were decreased with secondary measures in some technical sectors, (e.g. catalytic converters in automobiles), the thermal process industry developed and used widely primary measures like staging, utilisation of the energy from high temperature exhaust gases and step after step arrived until the development of “flameless” combustion.
1.1.1 - Motivation to New Combustion Systems:

Fossil fuels have been used by the human society since thousand of years. With the rapid expansion and development of technology, the society rapidly reached a point of over-consumption of any kind of natural resources. Keeping in mind that those resources are not exhaustible, and comparing it to our utilisation, leads to the concern that in a very near future, the fossil fuels will run out. These considerations mainly appeared during the energy crisis of the seventies. Although nuclear and solar energy may provide more promise for the future, fossil fuel can not be quickly replaced for all applications, at least in the near future because of their several advantages including non-radioactivity, safety, mature utilization technologies, high conversion efficiency and cost effectiveness. However, when one considers the negative impact of fossil fuels, besides the limited reserves, concerns over environmental issues turn out to be quite serious. In 1992, the United Nation Conference on Environment and Development provided global efforts to protect our environment. Then, at the Kyoto protocol in 1997, many developed countries discussed the possibility and requirement of reducing the actual carbon emissions by 7% below the 90’s level over the next 10 years. Finally, during the whole end of this last century, more and more attention has been given to the utilization of fossil fuels. Indeed, many problems are directly related to their consumption as motor-fuel and the pollutant that they produce during their combustion. Pollutants such as CO, CO₂, hydrocarbon, soot and NOₓ are the main produced on the priority list.

Taken one after one we can briefly present the main effects of those pollutants on the human body and the global environment.
Figure 1: Combustion generates pollutant emissions

a - Production of Carbon Monoxide (CO):

Carbon monoxide is a significantly toxic gas and is the most common type of fatal poisoning in many countries\textsuperscript{6}. Exposures can lead to significant toxicity of the central nervous system and heart that can be life threatening and cause asphyxia. Following poisoning, long-term sequels often occur and that is why its workplace exposure level has been limited near to 50 ppm\textsuperscript{1}.

The mechanisms by which carbon monoxide produces toxic effects are not yet fully understood. However, its production is basically due to a lack of oxygen in the combustion process which induces incomplete $\text{CO}_2$ formation reaction.

Depending on the temperature of the reaction we have either a fast reaction:

$$\text{CO} + \text{OH} \rightarrow \text{CO}_2 + \text{H} \quad \text{(at high temperature)}$$

Or a slower reaction:

$$\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2 \quad \text{(at low temperature)}$$

Hence, CO is generally found in abundance in low temperature regions.
Different factors can be at the origin of its formation, insufficient residence time, too low or too high equivalence ratios are part of those reasons. Also, inadequate mixing which produces regions too weak to support combustion, excessively fuel rich reaction and quenching of combustion products by entrapment into the wall cooling air can be highlighted. We can summarize in the following table those different origins related to the different combustion parameters on which we play to balance its production.

<table>
<thead>
<tr>
<th>Combustion Parameters:</th>
<th>Equivalence Ratio:</th>
<th>Effect on CO production</th>
<th>Physical affect:</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Increase</em> Inlet temperature</td>
<td>-</td>
<td>CO decreases</td>
<td>Accelerates the production of CO₂ from CO</td>
</tr>
<tr>
<td><em>Increase</em> Combustion pressure</td>
<td>&lt; 0.8</td>
<td>CO decreases</td>
<td>Increase the reaction rate of CO to CO₂</td>
</tr>
<tr>
<td></td>
<td>&gt; 0.8</td>
<td>CO decreases</td>
<td>Prevent dissociation of CO₂</td>
</tr>
<tr>
<td><em>Increase</em> Wall cooling</td>
<td>-</td>
<td>CO increases</td>
<td>More CO is trapped in the film where chemical reactions are frozen</td>
</tr>
<tr>
<td><em>Increase</em> Droplet size</td>
<td>-</td>
<td>CO increases</td>
<td>Less volume and time for CO to react into CO₂ due to more volume to evaporate</td>
</tr>
</tbody>
</table>

**Table 1: Influence of combustion parameters on CO production**

CO has a minimum rate of formation when the equivalence ratio of the combustion reaction is approaching $\Phi \sim 0.8$. At lower equivalence ratio, the rate of oxidation is reduced because of a low temperature, and less CO is converted in CO₂. At higher equivalence ratio, the temperature drops until the point where dissociation of CO₂ takes over". 

- 15 -
b - Production of Carbon Dioxide (CO$_2$):

Carbon dioxide is a greenhouse gas and thus, can influence climate by absorbing outgoing long wave radiations. Indeed, the role of CO$_2$ in global warming phenomena is now widely recognized. The demands for reducing CO$_2$ emission are higher than ever. All fossil fuels generate CO$_2$ as a byproduct so that any efforts to reduce energy consumption will result in a reduction of CO$_2$ emission. Good correlations between fuel consumption and CO$_2$ production suggest that CO$_2$ reduction should be about the same as energy saving. If the combustion takes place using air as the oxygen source, which is almost always the case in industrial combustion, the corresponding equation is:

$$\text{C}_x \text{ H}_y + (x + y/4) \text{ O}_2 + 3.76 (x + y/4) \text{ N}_2 \rightarrow x\text{CO}_2 + (y/2) \text{H}_2\text{O} + 3.76 (x + y/4) \text{N}_2$$

This means that anyhow, we cannot avoid the production of CO$_2$. But, by reducing the consumption of fuel, which is the point to increase the efficiency, we will also decrease the CO$_2$ production.

c - Production of Unburned Hydrocarbon:

Unburned hydrocarbons (UHCs) are the hydrocarbons emitted after petroleum is burned in an engine. Any fuel entering a flame will be reacted. Thus, when unburned fuel is emitted from a combustor, the emission is caused by fuel "avoiding" the flame zones$^1$. Further, some regions of the combustion chamber may have a very weak flame; they have either very fuel-lean or very fuel-rich conditions and consequently have a low combustion temperature. These regions cause intermediate species such as alkenes to be emitted. Sometimes, the term "products of incomplete combustion" is used to describe such species$^1$. 
Unburned hydrocarbons come under different forms such as vapor, drops of fuel, or products of fuel after thermal degradation. Their production can come from fuel atomization, inadequate burning rate, chilling from wall-cooling or high equivalence ratios. If the kinetic reactions related to its formation were as simple as the one for the production of CO, we could analyze them in the same way. Unfortunately, those reactions are much more complex and hard to predict. Nevertheless, it has been shown that the global reaction reacts in the same way as for the formation of CO under the influence of the same parameters.

**d - Production of Soot:**

Soot, also called lampblack or carbon black, is a dark powdery deposit of unburned fuel residues, usually composed mainly of amorphous carbon. It is a major component of the smoke appearing in the combustion of carbon-rich organic fuels in the lack of oxygen\(^1\).

The production of soot in a flame is a complex process consisting of several chemical reactions taking place in series. In the *fuel-pyrolysis zone*, typically clear or blue, the fuel molecules are broken down into various fragments, including “carbon-ring structures”, CH radicals as well as monatomic and diatomic hydrogen. As the combustion process continues, the radicals quickly combine into new structures, giving off heat. These structures polymerize into larger "pre-soot" chains then assemble into formations of hydrogen-rich spheres in the *soot-inception zone*. In the *soot-growth zone*, these spheres give up their hydrogen gas through diffusion, resulting in solids consisting of several of the formerly liquid spheres stuck together into larger chains. It is this portion of the flame that has the bright yellow color\(^8\).
In perfect combustion, the soot would break down into almost pure CO₂ and H₂O, it is only in incomplete combustion that the soot is able to form and escape the flame. The energy being radiated from the soot is an important contributor to the ongoing combustion process, cooling the flame above the soot-growth zone and feeding energy back into the fuel-pyrolysis zone. The separation of flame into zones of different chemical reactions is due to convection forcing the hot reactants upward.

Different parameters influence its production. Unlike CO, the soot formation increases with increasing the pressure (due to an increase of the flammability limits that allows fuel rich regions to form). The fuel type has also its effect on soot, basically its formation increases with the reduction of hydrogen atoms compare to carbon ones. Finally, the rise of pressure droplet size has an impact too because it does not allow it to fully vaporize and burn.

e - Production of Oxide of Nitrogen (NOₓ):

NOₓ is a generic term that refers to mono-nitrogen oxides. They are believed to aggravate asthmatic conditions, and are involved in tropospheric production of ozone. They eventually form nitric acid when dissolved in atmospheric moisture, forming a component of acid rain.

In an internal combustion engine, a mixture of air and fuel is burned. When the mixture is granted to consume every molecule of reactant, we are running at stoichiometry. When this burns, combustion temperatures reach a high enough level to drive endothermic reactions between nitrogen and oxygen in the flame, yielding various oxides of nitrogen, the results of which can be seen over major cities in the form of brown clouds of smog.
There are three primary sources of NO\textsubscript{x} in combustion processes\textsuperscript{5}:

- prompt NO\textsubscript{x}
- fuel NO\textsubscript{x}
- thermal NO\textsubscript{x}

- Prompt NO\textsubscript{x}:
This source is attributed to the reaction of atmospheric nitrogen, N\textsubscript{2}, with fuel radicals such as C, CH, and CH\textsubscript{2}, where it can not be explained by either the thermal or fuel processes. Occurring in the earliest stage of combustion, in fuel-rich flames, it forms via capture of N\textsubscript{2} by hydrocarbon radicals and results in the formation of species of nitrogen. In fuels that contain nitrogen, the incidence of prompt NO\textsubscript{x} is especially minimal.

- Fuel NO\textsubscript{x}
The major source of NO\textsubscript{x} production from fuels such as certain coals and oil is the conversion of fuel bound nitrogen that they contain to NO\textsubscript{x} during combustion. During the process, the nitrogen bounds in the fuel are released as free radicals and ultimately form free N\textsubscript{2}, or NO. Although the complete mechanism is not fully understood, there are two primary paths of formation. The first involves the oxidation of volatile nitrogen species during the initial stages of combustion. During the release and prior to the oxidation of those volatiles, nitrogen reacts to form several intermediaries which are then oxidized into NO. The second path involves the combustion of nitrogen contained in the mixture during the combustion of the char portion of the fuels but this reaction occurs much more slowly than the first one\textsuperscript{1}. 

- 19 -
- Thermal NO$_x$

Thermal NO$_x$ refers to NO$_x$ formed through high temperature oxidation of the diatomic nitrogen found in combustion air. The formation rate is a function of temperature and the residence time of nitrogen at that temperature. It is the most relevant source of NO$_x$, especially if preheated air is used; increasing the combustion temperature. Indeed, at high temperature, considerable NO emission can be found if oxygen containing combustion products is exposed to heat. Usually, above 1600°C (2900°F), molecular nitrogen (N$_2$) and oxygen (O$_2$) in the combustion air disassociate into their atomic states and participate in a series of reactions that occur in a couple of seconds, reaching a couple of milliseconds if the temperature increase above 2000°C (3600°F).

The three principal reactions producing thermal NO$_x$ are: ("Zeldovich Mechanism")

- N$_2$ + O $\rightarrow$ NO + N
- N$^+$ + O$_2$ $\rightarrow$ NO + O  (all 3 reactions are reversible)
- N + OH $\rightarrow$ NO + H

Examination of the chemical reaction paths of nitrogen oxides formation and destruction in flames led to the formulation of guidelines for primary measures of NOx emissions reduction, trying to cut off peak flame temperature and keep the residence time as low as possible to avoid any high concentration of oxygen in high temperature areas.

The following chapter tries to give an overview of the different techniques that have been presented in order to limit NO$_x$ emission. Most of the time, the techniques can not be really separated clearly from one to another. Usually several measures are taken at the same time and that is what permitted the discovery of flameless combustion.
1.1.2 - First Measures to Reduce NO\textsubscript{x} Emissions:

\textbf{a - Flame Cooling:}

As the name indicates, the purpose of flame cooling is to reduce peak temperatures and residence time of combustion products in high temperature areas. It can be achieved by the extraction of energy or by mixing of combustion products with cooler recirculated exhaust gas, water or steam\textsuperscript{3}.

Added to the fresh combustion products, the exhaust gas are cooler than those last ones and therefore, heat release occurs for almost all flames of the combustion process.

![Figure 2: NO\textsubscript{x} reducing by flame cooling](image)

The only main limit with flame cooling stays the problem of incomplete combustion which means emission of carbon monoxide.

\textbf{b - Staging:}

![Figure 3: NO\textsubscript{x} reducing by air staging](image)
The technique of staging is basically used to control nitric oxide formations. In this case, the combustion air is mixed with the fuel at different points. A primary combustion zone with nonstoichiometric conditions is followed by cooling the combustion products in a secondarily combustion zone. The primary zone is used to reach the necessary temperature to run the combustor at low power conditions. To avoid as less as possible the formation of CO and UHC, it is run usually to an equivalence ration near 0.8. Most of the time, air staging is used, which means that the primary combustion occurs under rich conditions and secondary air is injected for the secondary combustion. The cooling can be realized by direct cooling through radiation and convection or through mixing with recirculated zone combustion products from farther downstream (see figure 3 and 4). As heat is released more uniformly throughout the combustion chamber, NOx formation is lowered.

Figure 4 shows a two-stage burner. As the secondary air is injected directly in to the chamber, flue gas is recirculated, increasing the NOx reduction effect.
The staging can actually be achieved directly to the burner design or by fluid injection through separate pipes. The primary combustion then takes place in a combustion chamber where the flame is stabilized by a disk on the gas nozzle. The combustion products enter the furnace with a high velocity (typically 100 m/s), then the jet entrains the exhaust gases from the furnace to cool down the combustion products. Farther downstream secondary combustion takes place with air injected through concentric arranged nozzles. At the highest of power settings, both zones are kept at an equivalence ratio of approximately 0.6 to reduce NOx and soot.

Few disadvantages can be mentioned; first due to fuel staging, the radial temperature profile may vary and lower engine life due to hot sections downstream. Then, it is also difficult to achieve good performances at intermediate power settings because both stages are usually far from their optimum designed operating conditions.

**c - Lean Premixed Combustion:**

This type of combustion has been mainly developed for Gas Turbine Applications (GTA). In this technique, there is no major cooling step involved and the combustion takes place in adiabatic conditions. In lean premixed combustion, the interest is to mix pre-vaporized fuel with the inlet air to achieve a lean fuel/air mixture upstream to the reaction zone.
Then, the combustion zone is therefore kept at a very lean homogeneous state, eliminating hot spots in the combustion region, and thus lowering thermal NO\textsubscript{X}. The adiabatic combustion temperature for premixed air and fuel is controlled by the amount of excess air.

Conventional studies indicate that NO\textsubscript{X} emissions increase with a lack of uniformity in equivalence ratio distribution. This is a main issue when using lean premixed combustors due to the difficult homogeneity downstream the fuel atomizers. That is why it must have uniform fuel distribution to achieve low emission levels. In practice, in order to keep low temperature in the combustion zone, the mixture need to be maintained close to lean blow out conditions, which in term of instabilities is quite hard and usually can lead to flame extinction. In general industrial furnaces, this has not terrible consequences, but knowing that lean premixed combustion has been developed to integrate gas turbine engine, this has a much different impact and can not be in any case acceptable. Another problem with the use of lean premixed combustion is the high probability of flashback with the flame able to propagate upstream of the designed flame holding stagnation point, and consequently damaging the combustor hardware. Finally, due to problem of self ignition, it cannot be applied to very high preheat temperature systems.

**d - Reburning:**

![Figure 6: NO\textsubscript{X} reducing using reburning](image-url)
This technique is applied to reduce the amount of existing nitric oxides rather than reduce the amount of its production. Especially during the use of fuel containing nitrogen, the formation of “fuel NO” cannot be avoided. In this case, a reburning fuel can be injected to the combustion products to reduce the NO to N₂. The reburning fuel can be the same or another fuel than the main fuel. To achieve good results, the process has to take place in a specific temperature range and a good homogeneous mixture has to be provided. Depending on the process conditions, reburning could be named either a primary or a secondary measure.

**e - Usage of Oxygen as Oxidizer:**

This technique is considered to be as a measure to reduce fuel consumption and NOₓ emissions. This last assumption is based on withdrawing all nitrogen from the combustion process. To realize this, all the following conditions must be guaranteed:

- the oxygen must be pure
- the fuel should not contain any nitrogen
- the combustion has to be light to avoid inleakage of air

It is actually hard to achieve all those prerequisites, knowing that pure oxygen is really expensive and not available in large amount for combustion and that natural gases contain usually 1 to 14% of nitrogen. If there is any nitrogen available in the combustion chamber, the high temperature of combustion with oxygen can lead to extremely high production of NO if no special precautions are taken. Indeed, to get any advantage of the use of pure oxygen, the energy consumption and the emission of pollutants for oxygen production have to be considered.
f - Exhaust Gas Recirculation:

Here again, the point is to lower peak flame temperature, which as we saw is a technique to lower thermal NO-formation. When we talk about exhaust gas recirculation, we do not mean to mix those gases in the flame, but upstream the combustion with air and fuel (see figure 7). Two types of exhaust gas need to be separated. First there is external recirculation where the exhaust gas is taken from the stack and then added to the air (using a blower or a jet pump to bring them at the required pressure)\(^3\). Then there is internal exhaust gas recirculation which is achieved by special burner design. A benefit of this technique is that no additional equipment and piping are required and that there is no negative influence on the efficiency.

![Figure 7: NO\(_x\) reducing by exhaust gas recirculation](image)

In 1989, a surprising phenomenon was observed during experiments with a self recuperative burner. At furnace temperatures of 1000°C and about 650°C air preheat temperature, no flame could be seen and no UV-signal could be detected. Despite that, the fuel was completely burnt, the CO content in the exhaust was below 1ppm, the NO\(_x\) emissions were close to a few ppm and the combustion was stable, smooth, without lifted flame\(^3\).

This condition has been called flameless combustion because of its lack of luminosity and we are now going to enter more in detail in this process by making a review of its working and biggest characteristics in term of emission and stability.
1.2 - “Flameless” Oxidation Principle:

Combustion processes are generally controlled by three different types of variables: fluid dynamic, thermodynamic and composition. Most commonly used to classify a type of combustion is its temperature rate. In this sense, a rough classification of combustion processes divides them as occurring either at low, high or intermediate temperature. This is, actually, a loose way of classifying such complex processes, and it usually needs at least additional specification of the stage of the process considered. There is further complexity when there is more than one temperature relevant to the combustion process and it could seem an incongruity to refer to a process as developing at low temperature when the reactants are preheated at relatively high value. Nevertheless, there are processes which satisfy such conditions.20

From an historical point of view, systems with a so high reactant temperature were introduced by researchers who focused their interest on preheating regenerative systems applied to air system. Therefore, the most used acronym to classify flameless combustion is related to air. Indeed, we will say High Temperature Air Combustion (HiTAC) and it appears in several review lectures as well as in the title of several symposia. HiTAC, previously known as highly preheated air combustion, refers to a rigorous definition reported the first time by Katsuki et al originated from the concept of the “large excess enthalpy combustion” introduced by Weinberg. In the literature we can also find it under a couple of other different names depending on the origin of the process such as Flameless Oxidation, Low NOX injection, Moderate and Intense Low oxygen Dilution (MILD) or Heat Recirculating Combustion.
It has first been developed with high turbulence level and exhaust gas recirculation in order to produce low NO\textsubscript{X} emissions. The systems were developed to recycle the energy in the hot flue gas back to the inlet air in order to increase energy. To occur, flameless combustion requires low oxygen concentration that is also why it uses recirculated exhaust gas to dilute its concentration, allowing flameless operation with lower turbulence levels than what would be required with 21 % oxygen concentration.

Also, are required distributed temperature field, reduced flame temperature and intense turbulent flow until reaching a supposedly well stirred reaction. It is a process in which air temperature is such high that the inlet temperature of reactants is higher than autoignition temperature of the mixture\textsuperscript{13}.

1.2.1 - Heat Recirculating in “Flameless” Combustion:

a - Heat Recirculation Combustion Theory:

As we saw previously, preheating of a combustible mixture by recycled heat from exhaust gases has been considered as an effective method for combustion of low caloric fuel or ultra-lean mixtures. In the past, many researches have been performed on this system of combustion and the concept itself has been clearly demonstrated by Weinberg.

![Diagram of heat recirculating in "flameless" combustion](image)

**Figure 8:** NO\textsubscript{X} reducing by flameless oxidation: (a) nonadiabatic; (b) adiabatic
In the case of a completely adiabatic system (figure 8 b), the outlet temperature of the burned gas would be the same regardless of the heat recirculation. So, knowing this, we can see that the maximum temperature level in heat recirculating combustion is determined by the temperature and the quantity of recycled heat, and therefore, it is independent of the equivalence ratio of the mixture or the caloric value of the fuel used.

![Figure 9: a) Temperature history of heat recirculation b) Schematic diagram of flammability](image)

In figure 9-a, we can see the temperature history of premixed combustion with and without heat recirculation in an adiabatic system. Accordingly, it has been agreed\textsuperscript{14} that the temperature rise in the case of heat recirculating combustion is proportional to the amount of recycled heat. This aspect is true for premixed combustion, however, not always in the case of non-premixed combustion or diffusion combustion. This is actually a really important point when we consider highly preheated air combustion in practical systems. In the past, flameless combustion has often tried to sustain stable combustion in the mixture of low caloric fuel (not flammable at atmospheric temperature), and therefore the combustion followed the temperature rise of the mixture to an elevated level by heat recirculation and by the use of radiative heat transfer, as well as heat convection or heat conduction\textsuperscript{15}.
Figure 9-b shows the combustible domain expressed by equivalence ratio, caloric value of fuel and mixture temperature. At normal ambient temperature, an ordinary hydrocarbon gaseous fuel mixed with atmospheric air exhibits a combustible domain around the stoichiometric composition that increases significantly when increasing the temperature of the mixture. A large increase of the temperature, actually, as we will see later, may cause autoignition of the mixture.

With low caloric fuel, on the other hand, the combustible domain disappears at ambient temperature and starts to reappear when the mixture is preheated to a certain temperature level (see the dot profile in figure 9-b). Thus, we can understand that with an excess of enthalpy, we bring the mixture from outside of the combustible domain into the inside by heat recirculation, allowing combustion with low caloric value fuel or ultra-lean.

In actual furnaces, diffusion or non-premixed combustion is more common because of its safety and controllability. Recycled heat from the exhaust gas is utilized for heating the combustion air instead of the mixture. In the past, this technology was first applied to the glass and cement industries, where high temperatures were essentially required, and preheated air of 873°C was utilized by a recuperative burner. In this case, preheat resulted in a reduction of fuel input rate by 30%. Subsequent improvement in materials has permitted higher preheat, and glass melting regenerative furnaces have been working with preheated air exceeding 1273°C. The reduction of fuel consumption in this case reached 50%15.
It has been held that the combustion reaction takes place near-stoichiometric during the mixing process of fuel and air in non-premixed combustion, even if the excess air ratio is quite high, and the near-stoichiometric flame temperature produces large amounts of nitric oxides when it is preheated. Therefore, as seen in figure 10, we cannot help but stop preheating the air so that the nitric oxide emission does not violate air quality regulations, even though more energy saving is expected by higher preheating.

Many research and efforts have been done to satisfy these two incompatible requirements simultaneously. Among them, a high frequency alternating flow regenerative furnace, the basic concept of which is shown in the following figure 11, is one of the most successful systems in which remarkable energy saving can be achieved without emitting high concentrations of nitric oxides.
Figure 11: Schematic structure of heat recirculating furnace

The system consists of two sets of a ceramic honeycomb regenerator and a burner. Since they are operated alternately every minute or so, an extremely high heat exchange coefficient is achieved by the effect of unsteady heat transfer in the honeycomb regenerator, where the flow direction of the exhaust gas and fresh air alternates against each other. In practice, we can preheat the combustion air up to almost the exhaust gas temperature resulting in a sufficiently low temperature of the outgoing exhaust gas. Therefore, preheated air higher than 1000°C can be easily obtained compared to other types of heat recovery devices, and this fact suppresses the heat loss in the exhaust. It was not considered in the past that the utilization of such high temperature combustion air was consistent with low nitric oxide emission technology. However, the experimental facts were reported that the combination of direct injection of fuel into the furnace and the high momentum ejection of staging air resulted in unexpected low nitric oxide emission\(^{15}\).
b - Flameless Combustion: Application of Recirculation:

In contrast to combustion in stabilized flames, flameless oxidation is a nonstabilized but mixing controlled combustion and is achieved by specific flow and temperature conditions. It is primarily based on dilution of the unburnt gases as a very effective method to lower peak flame temperatures, resulting in lowered NOx emissions. Exhaust gases are recirculated internally in three stages. Mixing of air and exhaust gases is followed by addition of fuel to the diluted air. Finally, a non-burner-stabilized combustion, referred to as flameless oxidation, takes place, in which exhaust gases are again internally recirculated. Preheating of air is not a necessary requirement for flameless oxidation because exhaust gas recirculation dominates the process of heating up unburnt gases.

The most important difference to conventional flames is the very high exhaust gas recirculation. The recirculation rate is defined as

\[ K_v = \frac{E}{(F + A)} \]

where \( E \) is recirculated exhaust gas, \( F \) is fuel, and \( A \) is combustion air.

To provide reliable operating conditions in conventional systems, exhaust gas recirculation rates of \( K_v < 0.3 \) are used as a NOx-reducing technique. As stated earlier, flue gas recirculation is efficient in NOx reduction but limited by the maximal quantity of recirculated gas since in normal ambient air vitiation it may lead rapidly to blow-off. However, under special conditions, as shown by Wunning, a stable form of combustion is also possible for much higher recirculation rates of exhaust gases.
Figure 12 shows a schematic diagram of the stability limits for different combustion modes\textsuperscript{16}.

Stable flames (A) are possible over the whole range of combustion chamber temperatures if air is not vitiated, providing sufficient amount of combustion products recirculated to stabilize the flame. At ambient temperature, this combustion regime is limited for low exhaust recirculation rates up to 30\% (somewhat increased at higher temperatures). For higher recirculation rates, the flame becomes unstable (B), as already observed in many experimental works, the flame lifts off, and finally blows out (for temperatures below self-ignition). If, however, the furnace temperature and the exhaust gas recirculation are sufficiently high (Kv > 3), the fuel can react in the very steady, stable regime of flameless oxidation (C). As can be seen from the diagram, it is not possible to operate a burner with flameless oxidation in a cold combustion chamber. Therefore, the combustion chamber must be heated up with undiluted burner-stabilized flames before it can be switched to flameless oxidation. In theory, flameless combustion has a little temperature rise in the reaction zone and comes very close to the model of a well-stirred reactor\textsuperscript{17}. 
This is due to the fact that turbulent timescales are much smaller than chemical timescales because of the very strong dilution of the pre-mixture.

In a well-stirred reactor, the temperature for ignition and extinction can be described as:

\[
T^* = \frac{(2 + Q^*) \pm \sqrt{4(1 + Q^*)/E^*Q^*}}{2(1 + Q^*)/E^*}
\]

\(T^*\) denotes a nondimensional temperature \(T^*/T_u\), \(Q^*\) a nondimensional heat of combustion \(Q^*=(T_b-T_u)/T_u\), and \(E^*\) a nondimensional activation energy \(E^*/RT_u\). \(T_b\) is the temperature in the burnt (equilibrium adiabatic flame temperature) and \(T_u\) in the unburnt gases. For large values of \(E^*\), the quadratic equation has two solutions, one for ignition and one for quenching, that coincide when \(E^*/4(1+Q^*)/Q^*.\) From this value, the well-known S-shaped curve solution develops into a monotonous transition between burnt and unburnt gases for \(E^*/4(1+Q^*)/Q^*.\) For this case, the temperature rise in the reaction zone can be solved iteratively and leads to the solid line shown in figure 13-a describing the temperature rise in the combustion zone of a well-stirred reactor as function of the preheat temperatures18.

**Figure 13: Flame temperature of stoichiometric mixture**

- 35 -
Figure 13-b shows different contours of maximum flame temperature on the combination map of preheated air temperature and recycling rate of combustion products, where $R$ is gas recirculation ratio, $\alpha$, the ratio of the recirculated heat to the total heat contained in the recirculated gas flow, $\xi_h$, the heat exchange coefficient, and $\xi_m$, an empirical constant defined by the convective heat transfer coefficient in a parallel flow heat exchanger$^{14}$. Adding highly preheated air and high recycling rate of burnt products generates a relatively low maximum flame temperature. We actually understand that the stoichiometric flame temperature in highly diluted air, where the mass fraction of oxygen is far below the value in normal atmospheric air, is not as high as we usually expect. This is the key for highly preheated air combustion when it is applied to practical combustion systems. Keeping the global equivalence ratio constant, the flame temperature in the furnace can be varied or regulated by a combination of control of the preheated air temperature and the recycling rate of burnt gases. Because the incoming airflow entrains surrounding burnt gases in the furnace, a high rate of recycling of burnt gas can be induced by the high momentum ejection of combustion air as well as by the furnace configuration.

1.2.2 - Burner Design and Principle:

Generally, flameless combustion can be realized by internal or external circulation or by their combination. Most designs of internal heat circulation have involved bluff body, porous media or swirling flow. Most of these have been aimed at flame stabilization and are very effective. However, with the increased concern on pollutants reduction and energy conservation, advanced methods are being sought.
Internal heat circulation relies on heat convection and species circulation so that a big group of hot and active radicals can be maintained in the reaction zone which subsequently assists in flame stabilization. In contrast, external circulation methods use heat exchanger to transfer the thermal energy via conduction between combustion products and solid media so that heat can be exchanged to the cool reactant. Most of the enthalpy contained in hot combustion products can be then recirculated back into the combustion process. This then allows one to utilize the energy for flame stabilization, control the reaction process and achieve desirable composition in addition to conserving energy.

A Flameless oxidation burner is shown in figure 14. Unlike staged combustion, flameless oxidation features no primary zone\(^\text{19}\). The energy required for ignition is provided by the recirculating flue gas from the exhaust back to upstream near the air injection. For this reason, the furnace chamber temperature must be at least 800-900°C to avoid any instability due to the temperature gradient between the relatively hot flue gas and the cool air injected. We can also take a more detailed example (figure 15) and better understand the process involved to reach flameless combustion.
Figure 15: Principle of a burner used in flameless combustion

When heating up the furnace, the fuel (1) is injected into the burner (2) and mixed with air (3). The mixture is then ignited, and burner-stabilized flames are formed. The exhaust gases stream, due to the furnace geometry in a reverse flow, are guided upstream of the furnace along the heat-exchanging fins of the burner (5). The exhaust gases heat up the air and accelerate its flow velocity. Once the chamber has reached a temperature above 800°C, flameless mode is possible, and a control valve (8) switches the fuel flow to the center nozzle (9). The stable flames extinguish, and the air with its high momentum is diluted with the recirculating flue gases. A mixture between exhaust gases, air, and fuel is then formed and heated up continuously by the hot gases with a reaction taking place further downstream in the furnace. Unlike stabilized mode, at that point, the temperature of the flameless oxidation mode gets lower at the burner and increases continuously to temperatures of about 1200°K\textsuperscript{20}. 

- 38 -
1.2.3 - Thermodynamic Aspect and Autoignition:

a - Thermodynamic Consideration:

When considering combustion efficiency and energy conversion efficiency, as we saw before, the important factor is flame temperature. Weinberg provided initial concept of Excess Enthalpy Combustion in 1971\textsuperscript{21}. In his study, he introduces the discussion about temperature limitations and refers to different factors, either positive or negative. Heat circulation is used for energy savings. However, combustion engineers have to pay attention to the upper limit of combustion temperature because of materials constraints used in the equipment and pollutants formation. From the economic point of view, it is of course better to use thermal energy generated by the combustion process itself to heat-up the oxidant or fuel, which is often of low thermal energy, than via the use of electrical or mechanical energy. The amount of energy circulated into the combustion process is given as:

\[ \int C_p \, dT = Q_c + Q_a = H_f - H_0 \]

The summation is restricted by \( T_f \), the final temperature and \( T_0 \), the initial temperature, \( Q_c \) is the heat release by chemical energy conversion, \( Q_a \) is the energy added and \( H_f / H_0 \) are the enthalpy at the two earlier mentioned states.

The circulation part of thermal energy from the generated products increases the combustion temperature so that enthalpy of the reaction zone is above the conventional combustion level. Actually, this has resulted in the use of the term “Excess Enthalpy Combustion”. Now, the increase in thermodynamic efficiency must be coupled with other desirable characteristics of low NO\textsubscript{x} formation, reliability of the refractory material, distribution of temperature, and other associated factors.
Thermodynamic considerations suggest that preheating the oxidant (and not fuel due to possible fuel decomposition and safety aspects) to very high temperatures will increase thermal cycle efficiency.

Thus, enthalpy is added into the flame with air preheat without any other changes. From the point of pollutants formation, especially NO$_x$, high temperature of combustion has been recognized to be one of the most important parameter. Therefore, the combustion temperatures and chemistry must be controlled so that NO$_x$ formation and emission is acceptable. One method of maintaining the same temperature in the combustion zone, as we saw in the previous paragraph, is to dilute the incoming combustion air with hot combustion products. The recirculation of some amount of hot products into the reaction zone dilutes the inlet concentration of oxygen in the air. Therefore, oxidation of N2 is lowered by both diluted air and low peak flame temperatures in the flame. In the implementation of excess enthalpy technology, low oxygen concentration air at high temperatures is usually used for the combustion air. When in conventional burners increasing the preheat air temperature increases NOx emission levels, in that case, in high temperature air combustion, the temperature of combustion gases in the furnace or reactor is small (only about 50 to 100°C above the incoming combustion air at high temperature). The oxygen concentration in the combustion air is very low (only about 2 to 5%, depending on the application). So, under these conditions, the hot spot zones are eliminated to provide uniform thermal field distribution in the combustion zone with high temperature combustion air and low emission rate.
b - Autoignition Temperature of Fuel:

Autoignition (not to be confused with spontaneous combustion) is the phenomenon by which a combustible mixture of fuel and oxidizer reacts in a self-accelerating manner, leading towards fully fledged combustion without use of sparks. Experiments show that autoignition allows initiating combustion in a gas mixture that will not burn otherwise, which means that it will not burn in the usual mode where fuel is consumed in a thin high-temperature sheet of flame. It was suggested by Wunning that if the diluted air temperature exceeds the fuel auto-ignition temperature, the fuel ignites automatically and continuous combustion is sustained. Premixed or homogeneous autoignition occurs when the fuel and oxidizer have been previously mixed, down to the molecular level. On the other hand, non-premixed or inhomogeneous autoignition occurs when the colder fuel and hot oxidizer mix and react simultaneously, either in a stagnant field, or in a flow field that can be laminar or in most applications turbulent. Ultimately, inhomogeneous autoignition is a result of both chemical reactions, the fluid mechanical processes that bring the reactants and the “radical pool” necessary for reaction together, and the thermodynamical destiny of the heat that is released from this reaction. By definition, the overall autoignition chemistry is exothermic, with most of the important elementary reactions also being exothermic. However, some key elementary reactions can be endothermic depending on the fuel-oxidizer system and conditions. Indeed, autoignition temperatures of gaseous fuels are dependent on kinds of fuel and concentration of oxygen of the diluted air. It therefore appears experimentally that a stable combustion domain exists for high ratio of exhaust gas recycling and that under ideal conditions, such combustion takes place without any visible or audible flame.
To explain the observation of Wunning, it is interesting to consider the combined effect of high temperature air and increased inert content of a mixture on flame stability. Katsuki and Hasegawa\textsuperscript{23} observed that for a diffusion flame, the conditions for flame stabilization are such that the temperature of the inlet gases has to be increased if the oxygen concentration is lowered. Actually, highly diluted air with oxygen content as low as 3\% can sustain combustion when it is preheated up to 1200 K°.

In fact, when a fuel mixes with combustion air, some heat is required to initiate the combustion. Therefore, a recirculating flow of combustion products behind a pilot flame is frequently utilized in furnace combustion to stabilize flames.

However, if the combustion air is sufficiently preheated, combustion follows instantly upon the mixing of the two reactants anywhere in the furnace. Considering combustion of natural gas with atmospheric air, auto-ignition will occur when the preheating temperature of air exceeds approximately 1100 K, and for lower preheating temperatures, a forced ignition and a flame stabilizer will be necessary for stable combustion.

![Figure 16: Autoignition limits and blow-off limits](image)
Looking at figure 16, when decreasing the oxygen content by dilution with inert gases, like carbon dioxide or nitrogen, the autoignition limit in terms of air preheating temperature rises slightly, but the forced-ignition limit rises significantly. In other words, as the air preheating temperature goes down, it becomes more difficult to stabilize the flame in low oxygen circumstances. For oxygen content lower than 15% in the diluted air, the combustible region for forced ignition disappears and only autoignition occurs when the diluted air is extremely preheated. The point is that we can burn a gaseous fuel even in quite low oxygen content condition, such as vitiated or diluted air, if its temperature is sufficiently high.

Although too large an amount of exhaust gas recirculation may cause flame extinction when we apply ambient air as an oxidizer, preheating of the combustion air above the autoignition temperature of the fuel ensures complete combustion, even with an intense exhaust gas recirculation.

A key hope in the combustion community is a better understanding and control of autoignition. For now, present understanding of autoignition is primarily from experimental data and simulations limited to zero or one-dimensional studies (such as in shock tubes, rapid compression machines, and, recently, in steady laminar one-dimensional experiments and simulations\textsuperscript{24}). Most of these works assume perfectly mixed gases with no spatial variations. However, in reality, autoignition in normal environments is a more random chemical process involving many short-lived molecular species within a three-dimensional spatial structure that dynamically evolves. It is the details of this transient chemical and dynamical structure that would need further investigation.
1.3 - Flameless Advantages:

The main characteristic of flameless oxidation mode is the uniform thermal field obtained. The presence of exhaust gas recirculation, at high recirculation rates, reduces the temperature rise during the reaction by a few hundred degrees. In addition, we will see, the influence of air preheating on NO\textsubscript{x} emissions become small with increased dilution. Steep gradients, large temperature and concentration differences are characteristic of flame combustion whereas flameless oxidation mode is much more homogeneous. The heat release due to combustion reaction is distributed, yielding a dispersed and moderate temperature rise. In contrast to the diffusion flame, no high gradients of temperature and species concentration are observed. The temperature profiles of flameless oxidation are lower than in non-diluted diffusion flames and uniformly distributed. The principal advantage is that by avoiding peak temperatures, the thermal NO\textsubscript{x} formation can be largely suppressed, even at the highest air temperatures. Following are some different results encountered in the literature that gives some direct values to describe the effect of flameless combustion in comparison with conventional burners or even staging burners.

1.3.1 - Flameless Emission:

During the last quarter of century, a lot of experiments and detailed chemical kinetic calculations have been done to elucidate the formation mechanisms of nitric oxides. As we could see, an increase in combustion air temperature has been recognized as one of the influencing factors because it generally causes higher flame temperatures.
Consider, however, what will happen when we use air preheated to a temperature higher than the auto-ignition temperature of a gaseous fuel as suggested by Wunning. If fuel and air react with each other at a near-stoichiometric ratio in a non-premixed flame, the flame temperature would vary depending on the initial temperature of the reactants. Almost the same quantity of nitric oxides should be emitted every time when the same quantity of fuel is burned in non-premixed flames with the same air preheat. This is a conjecture based on the assumption that a similar flow structure occurs with highly preheated air as with ambient temperature air. However, experimental results showed that the NOx emission changes significantly by only changing the mixing process between the fuel and air, keeping the flow rates and temperatures of the fuel and air constant\textsuperscript{25}.

In order to see the direct influence of the burner design, tests have been performed with different burners that are conventional burner, staged burner and flameless burner. For these tests, the furnace chamber temperature averaged 1200°C and the NOx emission was taken for each of them.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig17.png}
\caption{NOx concentration expressed as function of Tair}
\end{figure}
Figure 17 compares the results obtained in terms of NO\textsubscript{x} emissions from those three different types of burners at different combustion air temperature. As the graph demonstrates, staged combustion and flameless oxidation (FLOX burner) reduce NO\textsubscript{x} output remarkably. Indeed, for a combustion air temperature of 1000°C, for instance, the maximum NO\textsubscript{x} concentration is well below 180 mg/m\textsuperscript{3} for flameless oxidation, when it easily reaches 1400 mg/m\textsuperscript{3} for the conventional burner.

Now, in order to determine whether high temperature air combustion would adversely affect the emission of NO\textsubscript{x} and other greenhouse gas, measurements were made on the emission of various gaseous species. Figure 18 shows the NO\textsubscript{x} emission levels for propane flame as a function of air preheat temperature at 15%, 8% and 2% O\textsubscript{2} in air. The emission of NO\textsubscript{x} increases with air-preheat temperature. However, at high air preheat temperatures and low oxygen concentration very low NO\textsubscript{x} emission is observed. NO\textsubscript{x} emissions at 1150°C air preheat temperature actually decreased from 2800 ppm at 21% O\textsubscript{2} to 40 ppm at 2% O\textsubscript{2}.

![Figure 18: Emission of NO\textsubscript{x} function of air-preheat temperature and [O2]](image-url)
Similarly the emission of NO\textsubscript{x} was found to be low with CO as the fuel (see figure 19). The emission of NO\textsubscript{x} was low under flameless conditions of low oxygen concentration and high preheat air temperature.

![Figure 19: Emission of NO\textsubscript{x} function of preheat T\textsubscript{∞}air and [O\textsubscript{2}] in air using Carbon monoxide as the fuel (N\textsubscript{2} as the dilution)](image)

The different chemistry in the flameless burner results in different pollutant emissions. The most impressive difference concerns NO\textsubscript{x} emissions, which is expected because of the reduction of the gas temperature peaks and the absence of a flame front rich in active radicals. The abatement in NO\textsubscript{x} emissions can be clearly seen in figure 20 from accumulated data and assuming efficient air preheat (order of 60-75% of flue gas temperature)\textsuperscript{26}. NO\textsubscript{x} is decreased by one order of magnitude with respect to the best staging design. It should be kept in mind that the development of flameless techniques were first driven by low NO\textsubscript{x} investigations and that practical application of high air temperature (for energy saving purposes) has been hindered for a long time because of high NO\textsubscript{x} emissions.
The pollutant formation processes in a gas turbine are associated with the combustor design and operational conditions. The nature of pollutant formation is such that the concentrations of carbon monoxide and unburned hydrocarbons are highest at low-power conditions and diminish with increased power. In contrast, oxides of nitrogen and smoke are fairly insignificant at lower power settings and attain maximum values at the highest power conditions.
Characteristic trends are summarized and sketched in figure 21 for conventional gas turbines. The thermal NO is exponentially dependent on temperature. Thus, the reduction in temperature emerged as the main strategy for controlling thermal NO\textsubscript{x} emission from gas turbines. The second objective is to eliminate the hot spots from the reaction zone. Indeed, there is little point in achieving a satisfactory low average temperature if the reaction zone contains localized regions of high temperatures in which the rate of NO\textsubscript{x} formation remains high. Finally, the time available for the formation of NO\textsubscript{x} should be kept to a minimum. Reduction of thermal NO by both the flame temperature and residence time reduction is accomplished by increasing the flow of air. However, the reduction of the NO\textsubscript{x} emissions by reducing the reaction temperature and/or residence time can have an adverse effect on the combustion stability, the production of CO and UHC or even thermal efficiency. The presence of fuel bound nitrogen results in the formation of substantial quantities of fuel NO. The process is less temperature dependent than the thermal route and reduction of flame temperature does not markedly reduce nitric oxide formed in this way. Control of fuel NO is thus directed toward either utilization of fuel rich conditions that reduce fuel nitrogen components to molecular nitrogen or removal at the exhaust. The requirement to simultaneously minimize all three NO\textsubscript{x} formation rates without producing unacceptable levels of other pollutants still remains as a huge task. The effort in previous works, are mainly concentrated on reducing the main NO formation route, i.e. thermal NO emissions, and flameless combustion as been shown to have good effects on this way.
1.3.2 - Flameless and Flame Characteristics:

In the literature, flame characteristics have been examined with high temperature combustion air using several advanced diagnostics. A main trend is that the flame stability limits increases significantly at high temperatures and low oxygen concentration. Under flameless conditions, the flame stability is very wide as compared to any other combustion method. The flame structure depends in fact on fuel properties, preheated air temperature and oxygen concentration in the air.

In experiments made by A.K. Gupta, fuel was injected via a nozzle in a direction normal to the heated airflow so that the initial mixing between the fuel and air was in the form of a jet in a cross-flow (this form of jet mixing being known to be very efficient). The momentum of the gas jet was then maintained constant when examining other gaseous fuels, providing similarity in mixing between the fuel and air. Oxygen concentration in the air was varied from 21% (normal air) to below 2%. Thus the equivalence ratio was varied from $\phi = 0.83$ (with 2% O$_2$) to $\phi = 0.079$ (with 21% O$_2$) for the propane-air flames examined. The equivalence ratio was therefore different between fuels for the same oxygen concentration. As an example, changing the fuel from propane to methane and maintaining the same momentum of the fuel jet changed the equivalence ratio from 0.3 (for 2% O$_2$ in air) to 0.03 (for 21% O$_2$). The combustion air supplied to the test section of the furnace was preheated to temperatures ranging from 900°C to 1200°C with oxygen concentration ranging from 21% to 2%. Finally, flame photographs were obtained with air preheated temperature of 1100°C and oxygen concentration of 21, 8 and 2% in combustion air and are shown in figures 22.
Figure 22: Propane flame photographs with combustion air temperature of 1100°C and O₂ conc. (from left to right) of 21, 8 and 2% (Nitrogen as the dilution gas)

The flames show four distinct colors of yellow, blue, bluish-green, and green. Under certain conditions it was reported that colorless flame was also observed. It has also been seen that varying the fuel influence the flame color that suggests significant role of fuel property on the flame thermal signatures and heat transfer characteristics of flames. The size and color of the flame depends on air preheat temperature and oxygen concentration (obtained by changing the amount of gas recirculation) in the combustion air. The flame volume typically increases with increase in air temperature and decrease with O₂ concentration in the combustion air. The size of blue color region in the flame decreased with increase in oxygen concentration (up to about 15%) and temperature. It could be experimented that for very fuel-lean mixtures and at high air preheat temperatures (1100°C), the luminosity of the flame (and hence the heat flux) was found to be very low. At high air preheat temperatures and low oxygen concentration, e.g., around 2 - 5 % oxygen concentration in air, the flame was found to be of greenish color. The greenish flame color pronounces at higher air preheat temperatures and low oxygen concentration in the air, suggested high levels of C₂ species.
It has also been reported that the flame volume in a whole dramatically increases under conditions of low oxygen concentration and high temperature combustion air. No flame color can be observed with very low O₂ concentration in air (less than 2%). These conditions actually well describe flameless oxidation and determination of pertinent species present under those conditions will allow one to suggest its mechanistic pathways. Indeed, it could be seen that the fuel chemical property has a significant effect on the flameless oxidation of fuel, but because of a lack of information concerning the exact chemical path that govern the phenomenon, this domain of flameless oxidation still requires further examination.

1.3.3 - Flameless Stability:

a - Turbulence in Flameless Combustion:

There are three main combustion regimes for turbulent flow: wrinkled laminar flames, flamelets-in-eddy and distributed reaction. Flameless is not really part of those regimes and can actually be considered as a fourth one.

- The wrinkled laminar flame is where chemical reactions occur in thin sheets. In this regime, flame propagation can be viewed as a one-dimensional laminar flame with planar velocity in which turbulence “wrinkles” the flame, increasing the area of the flame in which the ratio between turbulent and laminar flame speeds is equivalent to the ratio between the area of the wrinkled flame and the time-averaged flame area.

- The flamelets-in-eddies flame regime lies between wrinkled-laminar-flame and distributed reaction regimes. This regime occurs for some turbulent premixed combustors, and is based upon eddy breakup.
The distributed-reaction regime is the most difficult to achieve and requires fast mixing with lower chemical reaction rates. This regime typically requires small flow passages with high velocities in which pressure drops are large and flame stability is uncertain. For this reason this mode of combustion is generally viewed as impractical, even though is the closest to the flameless combustion one.

Several parameters affect these combustion regimes including characteristic lengths, turbulent Reynolds number, and Damköhler number.  

Physically, the Damköhler number is the ratio between the fuel/air mixing time and the chemical reaction time, and is commonly used in describing turbulent premixed combustion. Specifically, it is the ratio between the characteristic flow time and characteristic chemical reaction time. For premixed turbulent flames, Turns uses the mixing parameter as the dissipation time of large eddies and the reaction time based on laminar flame speed such that

\[
\tau_{\text{flow}} = \frac{\ell_0}{V_{\text{rms}}} \quad \text{and} \quad \tau_{\text{chem}} = \frac{\delta_L}{S_L}
\]

The Damköhler number then becomes

\[
Da = \left( \frac{\ell_0}{\delta_L} \right) \left( \frac{S_L}{V_{\text{rms}}} \right)
\]

, with \( \delta_L \) (flame thickness), \( \ell_0 \) (turbulence macro-scale), which represents the average size of large eddies in turbulent flow. The Kolmogorov micro-scale (\( \ell_K \)) is a length over which the turbulent kinetic energy dissipates to fluid internal energy. This is the smallest scale considered in turbulent flow, and in which kinematic viscosity effects are large.
When the turbulence becomes sufficiently high to diffuse the chemical gradients and to make the reactions distributed (well stirred reactor) any momentum gradients that may exist are also diffused by the same turbulent mixing. In this randomly diffusive turbulent process, the coherent unsteady flow structures such as shedded vortices are dissipated quickly.

For the analysis of the structure of flameless oxidation, we can make a comparison to premixed combustion. Measurements were done in a wrinkled, high-turbulent premixed methane Bunsen flame, and compared with experiments in a flameless oxidation chamber. Figure 23 shows simultaneous measurements of OHLIPF (right side), temperatures (left side) and representative horizontal sections of the reaction zones at the indicated height (middle)³.
In the wrinkled premixed flame, a sharp rise of temperature and OH in the reaction zone can be usually observed, which is typical for the flamelet structure, the maximum of OH occurs near the thin reaction zone and in the oxidation zone downstream, the OH signal decreases continuously. The highly turbulent premixed flame (upper images in figure 23) shows a very sharp temperature rise of about 1500°K within the reaction zone, similar to that in a wrinkled flame. However, the OH distribution becomes more uniform in the burnt side, because turbulence is affecting the oxidation zone. In the case of flameless oxidation, there is only a small temperature rise, temperatures stay below 1650°K, and the OH intensity is significantly lower. The OH intensity shows a homogeneous distribution on the burnt side similar to the structure of highly turbulent premixed flames, although less wrinkling of the reaction zone indicates a less turbulent state. The dilution with exhaust gases increases the chemical timescales compared with the turbulent timescales. A further detailed investigation of the turbulent parameters is needed for a complete analysis and classification of flameless oxidation.

b - Stability Reasons in Flameless Combustion:

In term of premixed flames, an important concern that we have already mentioned is the stability of the process. Indeed, a variety of different instabilities including large scale interactions of flows in different parts of the combustion chamber can impact turbulence. Acoustic instabilities can also couple with the combustion process, but it is of little concern. However, it can become significant when coupled with turbulent or fluid mechanical instabilities.
Actually, it is common to characterize combustion instabilities by sketching a three part cyclic process (see figure 24). Hence, we get fluid mechanics process that results in a fluctuation in heat release rate that itself couples and reinforces an acoustic mode that trips the unstable fluid dynamic structure\textsuperscript{28}.

In the case of flameless combustion, we obtain a stable process for two reasons.

The first reason and maybe the most commonly understood explaining the fact that we get a stable flame in flameless combustion is that the reactions are distributed. This property involves the heat release to be uniform and though, the size of its region to get close to the entire combustion chamber. Helping the heat release to get more distributed decreases the risk of combustion heat release perturbation and therefore stabilizes the acoustic instabilities by the same occasion, at the origin of the poor decibel level characterizing the process. A distributed flame over a large area is less likely to be affected by a coherent fluid dynamic instability such as vortex shedding than a thin flame. The strong turbulence intensity required to dissipate coherent flow structure should normally tend to extinguish the flame due to high flame strain and excessive dissipation of heat and radicals.
However, because of the oxidizer temperature above the auto ignition temperature, this does not occur. Actually, when the oxidizer temperatures are very high, the low Damköhler number of “Flameless” reactions permits the process to evolve at a very stable rate, with even low NOₓ production\textsuperscript{28}.

The second reason that flameless combustion is more stable is that: “there is no single point of combustion initiation”. In other words, the flame is initiated at many locations simultaneously and randomly and not at a single region near a stagnation point. Typical diffusion flame and lean premixed combustion requires hot combustion produces to be recirculated back upstream to initiate and stabilize the flame near the forward stagnation point. Having the entire flame initiated and stabilized at a small region leaves the entire flame vulnerable to coherent fluid dynamic fluctuations that affect this region.

When the turbulence is very high and the oxidizer temperature is above the auto ignition temperature, the flame is initiated in many locations simultaneously, making no single region of the flame dependent upon any other region of the flame. This lack of interdependence of the flame is part of the highly desirable characteristics of flameless combustion.

1.3.4 - Implementation of Flameless Combustion in Gas Turbine Engines:

Aero gas turbine engines are designed to operate has leaner has possible, this with aim to decrease the specific fuel consumption and reduce NOₓ emissions. The application of flameless combustion to such a field is interesting. Indeed, flameless combustion has been proved to operate at very lean conditions with high stability and low emission. As we could see in the previous chapter, operating at very lean conditions has also been proved to increase instabilities in the combustion process.
Therefore, flameless oxidation is commonly not well seen as a solution for aircraft gas turbine engine, even if its behavior is highly required in term of emission and efficiency. To reach such a regime of combustion, different parameters need to be regulated. Flameless oxidation occurs at high turbulent level in order to dissipate coherent flow structures and reach a point where the flame is completely distributed over the maximum volume of the combustion chamber. However, operating at this rate and adding lean combustion conditions increase the risk of instabilities. To avoid this case of unexpected blow off, high temperature oxidizer is the solution. As we could see previously, it has been demonstrated that flameless combustion occurs with an oxidizer temperature in the range of 650°C and a combustion temperature of 850°C.

In the case of aero gas turbine, the air entering the combustor is coming from the compressor and therefore already has a high temperature due to the gas compression. Hence, increasing the pressure ratio would increase the resulting discharge temperature (T3) and thus reduce the amount of energy needed to reach the flameless regime.

But, as a fact, we can see in table 2 that at any conditions, the compressor discharge temperature stays lower than the 850°C (1100°K) required.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Engine Condition</th>
<th>Takeoff</th>
<th>Climb</th>
<th>Approach</th>
<th>Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>T3 (°K)</td>
<td>822</td>
<td>786</td>
<td>639</td>
<td>511</td>
<td></td>
</tr>
<tr>
<td>P3 (MPa)</td>
<td>3.23</td>
<td>2.81</td>
<td>1.25</td>
<td>0.52</td>
<td></td>
</tr>
<tr>
<td>T4 (°K)</td>
<td>1914</td>
<td>1811</td>
<td>1467</td>
<td>1153</td>
<td></td>
</tr>
<tr>
<td>Equivalence Ratio</td>
<td>0.498</td>
<td>0.460</td>
<td>0.343</td>
<td>0.250</td>
<td></td>
</tr>
<tr>
<td>O₂ %</td>
<td>9.8</td>
<td>10.5</td>
<td>13.2</td>
<td>15.4</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Typical engine conditions for a 32:1 compression ratio engine
As the power output of the engine decreases from takeoff to idle, the inlet air temperature at the entrance of the combustor also decreases from 822°K to 511°K. This tells us that gas turbine engines need an energy supply varying regarding to the engine power output. Moreover, we can even conclude, having a look at figure 25 that flameless combustion may not operate at idle conditions. In this figure, the recirculated exhaust gas mass ratio corresponds to the ratio between the mass of recirculated gas and the mass of the air/fuel mixture. Effectively, even with infinite gas recirculation, the gas oxidizer temperature at idle condition would be just around the expected temperature of 1100°K to make flameless combustion occur. Actually, those two graphs permit us to conclude that flameless combustion could be reached at take-off, climb and approach conditions with a variation in the amount of gas recirculated to increase the preheated temperature. Then, to compensate the low discharge temperature at idle condition, we would have to flip the flameless combustion mode to another combustion mode with ignition and low power settings such as turbulent diffusion flame.

![Figure 25: Effect of recirculation on stirred gas temperature and [O] oxygen concentration for a 32:1 compression ratio engine.](image-url)
The good point in gas turbine engine is that the combustion is adiabatic and thus, the amount of oxygen in the exhaust gases is only a function of the equivalence ratio. Hence, the highest engine conditions produce the lowest oxygen concentration, highly beneficial on NOx emissions. Looking at the X-axis in figure 25, we can see that the amount of combustion gases needed to mix with the compressor discharge air would be of 2 to 2.5 for this type of engine and would produce a concentration of oxygen part of exhaust gases not higher than 16%.

Obviously those are values needed for such an engine but that would change with another one. The compressor discharge temperature is function of the compression ratio so with a higher pressure ratio we would have to furnish less energy to achieve flameless, or evenly no energy at all. This is really important because the recirculation of gases requires heat exchangers that are practically not applicable in gas turbine engine in terms of weight and size. Therefore the main goal in application of flameless combustion in gas turbine engine is to design a combustor sufficiently efficient to provide enough gas recirculation by its own and be able to run at the required temperature.

That is actually one of the main purposes of all the experiments that we have been processing and that are presented all along the rest of this thesis. We looked for a supposedly perfect burner that would allow application of flameless combustion and thus specific condition of air preheat, turbulence level and pressure drop but with parameters in the range of the ones used in the gas turbine community. Then, another issue was to better understand the chemical process itself and improve the energy/pollutant rate of efficiency when running under gas turbine environment.
2 – EXPERIMENTAL RESULTS with Flameless Combustion:

2.1 - Facility & Measurements:

2.1.1 - Description of the Facility:

The facility used is an atmospheric vertical combustor from the Gas Dynamics and Propulsion Laboratory at the University of Cincinnati. A picture of this combustor is presented above and accompanied by a global explanation of its different parts. The rig is composed of 3 general parts that are:

- the heater
- the conditioning chamber
- the combustion chamber
The heater is a 72 kW heater which is used to preheat the air entering the combustion chamber. The air is supplied by a 2 inches pipe with a maximum pressure upstream of 100 psig. This permits to obtain a maximum air mass flow rate of 355g/s. The performances of the heater are shown in figure 27. As we can see, the maximum temperature allowed is 760°C (1400°F), but this value is limited by the mass flow rate of air passing through the heater. Actually, during the tests, we have never used an air flow rate higher than 80g/s, which according to the heater performances should have given us an air temperature close to 700°C (1300°F). However, because of low heater inlet pressures (far from the maximum allowed of 150psi); the actual maximum temperature reached during the experiments was around 540°C (1000°F).

![Figure 27: Sylvania heater performance curve](image)

The conditioning chamber is, as we can see in figure 26, composed of an inner flow conditioning segment (L=610mm=24in, D=133mm=5.25in). Inside this segment, the chamber is first (from the air entering) composed of a 16 gauge stainless perforated cone (40% open space), then follow a spacer and a honeycomb straightener.
The rest of the segment is divided by five different screens (from bottom to top): 14, 20, 35, 40, and 165 Mesh screen, respectively corresponding to an open air section of 48, 46, 45, 42, 38% and used for flame uniformity.

On top of the conditioning chamber is the plenum section (L=149mm=5.88in, inner D=154mm=6.07in) which makes the link with the chamber of combustion (L=457mm=18in, D=203mm=8in, round quartz combustion chamber or cylinder stainless steel combustion chamber depending on the tests run) and permits to implant the flameless combustion burner (see further description).

2.1.2 - Instrumentation:

During the tests, a lot of different values have been measured, either to characterize the burner when running at flameless combustion, or to study the regime of combustion itself and look for a better understanding. The main elements on which we focused our attention were the evolution of critical parameters such as temperature and emission. However, running a combustor also requires a perfect master of the facility and therefore, the set of instrumentation was chosen in order to answer both the safety control question of the device and the description of the flame characteristics.

a - Plenum Region Conditions:

First, we need to mention the instrumentation directly related to the heater. Indeed, near the exit of the flow conditioner that we saw in the previous paragraph, we can notice 8 different ports. In fact, only 3 of them are used. They permit to measure the plenum region conditions and directly indicate the values on the plenum panel control (see figure 28).
Hence, 2 of those ports are used to install sheathed-junction type K thermocouples. One is used for the feedback control of the heater, the other one for data acquisition. The last port is used for a single Druck pressure transducer that measures the plenum pressure and evaluates the pressure drop across the burner (0-5 psig pressure range, gain of 1.0psig/V and a 2.5 kHz response).

![Figure 28: Pannel control of the plenum conditions](image)

The control panel displays the pressure drop and the air mass flow rate, allowing control and quantification of the air supply.

**b - Temperature Measurements of the Combustion Chamber:**

- **Exit of the chamber and recirculation:**

  A set of thermocouples is used to determine the range where flameless operates (see figure 29). This set is composed of 3 type B thermocouples positioned at the combustor exit at a radius of approximately 50mm (2in) from the combustor and burner axial centerline, and spaced one from another by 120°. One of them is directly hung on the emission torch and the two others are fixed using a stainless semi circle system. A fourth type B thermocouple is placed through the bottom of the flameless burner along the burner centerline 38mm (1.5in) upstream of the burner face (**recirculation zone**).
Figure 29: Disposition of the Exit and Recirculation Thermocouples

Those 4 thermocouples are type B ones from OMEGA with 0.010in diameter wires composed of platinium at 70% and rhodium at 30% for the negative terminal when for the positive terminal we have platinium at 94% and rhodium at 6%. The connection of those thermocouples is made using a 16 channel thermocouple reader from Stanford Research System. Actually the thermocouples are connected to 4 analog output channels and then linked to an acquisition card for collecting temperature data. (The reader has a 12Hz conversion rate, ±1 of least significant displayed digit resolution with automatic range select, ±0.1°C for temperatures up to 999.9°C and ±1.0°C for temperatures 1000°C and higher).
- Inside the chamber:

To determine the temperature mapping of the combustor, we performed some specific tests in which thermocouples were traversed across the diameter of the chamber. This permitted us to obtain for different conditions (18 cases varying in term of equivalence ratio, preheated air temperature and pressure drop) the evolution of the temperature map inside the combustor. These tests have been performed using a stainless steel chamber (in opposition to the rest of the tests using a quartz chamber). The chamber is a cylinder of 450mm (18in) long with a diameter of 203mm (12in). We used this chamber because it features instrument ports on one side of the wall spaced of 50.8mm (2in) apart along the whole height. Because we could not take some measurements all over the combustor at the same time, two sets of test have been realized to characterize one condition of combustion. Indeed, we used a rake of four thermocouples (see figure 30) at position 50.8mm, 101.6mm, 152.4mm, 203.2mm downstream from the burner face in a first set of measurement across the combustor. Then, we repeated the operation at locations 254mm, 304.8mm, 355.6mm and 406.4mm to get the upper part of the combustor.

Figure 30: Temperature profiles measurement apparatus
c - Pressure & OH* Measurement:

The apparatus used to measure the pressure oscillations at the exhaust of the combustion chamber is presented below (figure 31). A Brüel & Kjaer® low-noise high-sensitivity microphone was connected to a signal conditioner/variable amplifier set to a dynamic range of 0.1-10kHz and with a resolution of 31.6mV. The microphone was positioned pointing along a diameter of the combustor, around 25.4mm (1in) downstream of the combustor exit plane, and 203mm (8in) from the combustor axial centerline.

Figure 31: Microphone and Amplifier for pressure oscillation measurement

The measurements of the fuel pressure were done using a Druck pressure transducer with a range of 0-500psig because of the high pressures occurring during the test and a gain of 100psig/V (as seen in figure 32). The fuel flow rate was measured using a Micro Motion Elite coriolis mass flow meter (model CMF010 with a range of 0 to 22.7g/s) as seen below and used as a guideline tool for the whole set of experiments.

Figure 32: Temperature, pressure and flow rate measurement of the fuel
Figure 33 shows the connection used for the measurement of OH*. We used three different points near the injectors to install the optical fibers centered around 50mm (2in) from the centerline of the burner, flush with the burner face and equally positioned (120° apart). The optical signal was filtered by an OH* (310nm) optic filter, then amplified and converted to an electrical signal with a photo multiplier tube.

Figure 33: OH* measurement by optical signal filtered and amplified

**d - Emission:**

Also part of the set-up is the emission measurement which is primordial to demonstrate the interest of flameless combustion results.

We have been doing some measurements covering four different types of pollutants that are: CO₂ (%), CO (ppm), O₂ (%) and NOₓ (ppm)

Figure 34: California Analytical Instruments emission sensors:
The emission sampling probe is placed along the combustor exit plane (see figure 34), along a diameter at a radius of 50.8mm (2in) from the combustor axial centerline. To measure all those pollutants, we used California Analytical Instruments emission sensors, using model 601NDIR to measure CO, CO\(_2\), O\(_2\), and model 600CLD for NO\(_x\). The NO\(_x\) are measured via NO\(_x\) chemiluminescence analyzer thermally stabilized with Peltier Cooler, CO and CO\(_2\) by NDIR analyzer when O\(_2\) is measured by paramagnetic analyzer. The model 300HFID for UHC was not used because of faintness reasons.

The calibrated ranges for the emissions are: NO\(_x\) – 300ppm, CO – 500ppm, CO\(_2\) – 20%, and O\(_2\) – 21%. The NO\(_x\) sensor has a maximum resolution of 10ppb with repeatability better than 0.5% full scale with a response time of 90% full scale in less than 1sec. The CO/CO\(_2\)/O\(_2\) has repeatability better than 1% full scale and a response time of 90% full scale in less than 2sec. Actually, due to the length of the heated sampling line between the probe and the sensors, there is a 15 second delay between the time we collect the sample and the time of its measurement. This delay is accounted for in post processing of the data so that emission concentrations correspond to the proper conditions recorded by the other instrumentation.

It is also important to highlight the accuracy of the measurement, most of the thermal sensors provide a good measure of the actual temperature, such does the pressure dynamic sensors and the flow-meters. The pressure oscillation measurements and heat release measure are used more as trends than exact value. However it is important to note that in the emission system, when CO2 and O2 have an accurate stable value, the CO and NOx measurements are quite oscillating and vary with +/- 1ppm and +/-5ppm respectively. The emission system should need some company calibration even if it still gives interesting trends. The results are quite close to the reality and this problem only matters in term of exactitude. The point here being more focused on qualitative measure with a good order of magnitude, we can consider those measures as highly satisfying.
OH Spectrometry Measurement:

![ICCD Princeton Instruments camera for OH chemiluminescence](image)

**Figure 35: ICCD Princeton Instruments camera for OH chemiluminescence**

In order to have an idea of chemistry effects related to flameless combustion regime, we have been processing some tests using different types of fuel (liquid or gas). Those tests involved all the same instrumentation as above but also required the use of a spectroscopy camera to get OH chemiluminescence measurements. The system used was a PI-MAX (from Princeton Instruments) Intensified CCD Camera model 1k that has an imaging array of 1024x1024 with 19x19μm as pixel size and a wavelength range of 200 to 1050 nm. The camera was placed to a distance of approximately 5 feet from the combustor, fixed on a tripod and mounted with a 307/310 nm filter (OH particles wavelength filtration). All the measurements were then taken with the camera associated WinView32 software.

### 2.1.3 - Data Acquisition:

As represented in figure 36, the experimental set-up is separated in three different parts, two of them are physically visible and already described; the facility and its instrumentation, the last part is the acquisition part which allowed us to collect all the data necessary to characterize and analyze the flameless regime under typical conditions.
All the instrumentation (measuring the exit temperature T1, T2, T3; the pressure oscillation by microphone; the fuel flow rate Wf; the OH* optical signals; the emission and the plenum conditions: temperature Tpl, pressure Ppl, air flow rate Wa) is somehow connected to a system of acquisition related to a computing terminal.

Figure 36: General Schematic of the acquisition data board and instrumentation
The data acquisition is collected using National Instrument hardware and software. We actually used three different acquisition boards connected to two computers

- A National Instruments PCI-6031E A/D board was used to perform time-averaged acquisition and connected to one computer. This board has an input resolution of 16 bits, capable of 32 differential analog input channels with maximum scan rate of 100 kHz. An input range of ±10V is used with absolute accuracy of 1.147 mV at full scale with temperature drift of 0.0001%/°C and an offset of 479.2 µV. It also has an average noise of 54.9 µV. The time-averaged data is then recorded from all the instrumentation with an averaging interval of 0.25 sec. High speed simultaneous data is taken for plenum, combustion pressure and OH* fiber optic signals at a frequency of 6000 Hz.

- The second computer was used to acquire dynamic acquisition and was linked to two National Instruments PCI-6143 A/D boards. Each board has an input resolution of 16 bits, capable of 8 differential analog input channels with maximum scan rate of 250 kHz. An input range of ±5V is used with absolute accuracy of 3.613 mV at full scale with temperature drift of 0.0003%/°C and an offset of 104 µV. The average noise is of 122 µVrms. Additionally, there is a ±5° phase mismatch at 100 kHz with -90 dB crosstalk at 50 kHz, and a bandwidth of 490 kHz.

We used programs written with National Instruments programming language LabVIEW as interface and control of the acquisition process. For both of the computers, the main purpose of the programs was to facilitate as much as possible the process of acquisition. One of these programs is called “combustion avg data acquisition”, and as its name indicates, it is used to obtain an average value of all the measurement during the time of acquisition.
It is basically divided in six different windows (see appendix) which permit:

- To load the starting data that we want in case that special conditions of departure are required (or to keep always the same initial values). With the click of a button, the user can command the software to tare all desired channels to zero. This zero point is saved for each channel and added to the calculations.
- To load the different channels linked to the sensors and the test conditions required (offset and scale factors are available).
- To acquire all the values which are needed during the unfolding of the tests as well in term of security as in term of research.
- To create a proper file corresponding to each test and allowing to select the necessary variables.
- To show a time trace of each desired signal and to plot the Fast Fourier Transformed (FFT) associated.
- To save all the data in an identified file (text file) consisting of the date, time descriptions and comments allowing to classify it. A time stamp is included in the header to inform the user of the time at which data started writing to the output file. The time of each data point is also recorded in seconds/milliseconds from the start of the file recording.

During the actual test, according to the type of test that you perform, you can directly, implementing the fuel type, calculate the stoichiometric equivalence air/fuel ratio associated and the time average system also performs calculations such as pressure drop. Both programs display numerical and graphical on-screen values of input data. Additionally, the user also has the option of using a single button to control the start and stop of data written to an output file, or to trigger output file writing from a single digital input channel. The user can choose either single or multiple channels for the mass flow rate measure of the fuel and air in the case that multiple flow meters are needed to record a single flow rate.
The user can also specify an effective area for a pilot if there is one for a given burner; an
equivalence ratio will be calculated for both the pilot and the total fuel/air mass flow rate.
Additionally, these settings can be saved or loaded from a configuration file. Fuel type
and hardware sample rate and size are also automatically included in the file header so
that all information pertinent to each test is included for later review.

2.1.4 - Measurement Corrections:

a - Temperature:

Thermocouples have become widely used as simple and reliable tools for
measuring temperature of solids and fluids. Unfortunately, errors in measurement can
occur in fluids of high temperature and very low Reynolds Numbers; in such cases,
convective heat transfer is low, and radiant heat transfer reduces the measured
temperature from that of the actual fluid. Radiant heat transfer is proportional to
temperature to the fourth power.\(^30\).

Significant error in thermocouple readings can occur when the walls to which the
thermocouple radiates energy are of a significant temperature difference relative to the
low Reynolds number fluid being measured. Correction for the radiation loss is offered
by Shaddix in the following corrective equation:

\[
T_g = T_w + \frac{e_w \sigma (T_w^4 - T_t^4)}{kNu} D
\]

where,

\[
Nu = Nu_{\text{sp}} = 2.0 + 0.60 \text{Re}_D^{1/3} \text{Pr}^{1/3}
\]
In the current case, the wire bead at the exposed thermocouple junction is sufficiently large, such that effects of radiant heat transfer from the wire are insignificant compared to those of the junction bead. Therefore, the temperature correction equation becomes dependent upon the thermal conductivity, the diameter, the emissivity of the junction bead, the Nusselt number of the flow, and the difference between the thermocouple and wall temperatures. The major difficulty lies in calculating the Prandtl and Reynolds numbers.

\[
Re_D = \frac{\rho V_D D}{\mu} \quad \text{Pr} = \frac{c_p \mu}{k}
\]

Both equations depend on the properties of the fluid being measured. Physical properties of reacting flow are very difficult to determine experimentally because the exact composition of the flow is required along with the individual properties of each component within the fluid. On top of this, reacting flow can contain literally hundreds of constituent substances. Compounding the problem is the fact that thermal properties of substances vary with pressure and temperature. The current experiments also vary equivalence ratio, which affects the equilibrium composition of the reacting fluid. Governing the complexity of determining fluid thermal properties, due to the mixture of reactants and combustion products, the NASA CEA (Chemical Equilibrium with Applications) program was used to numerically approximate the characteristics of the reacting flow, including dynamic viscosity, density, and Prandtl number. For use in the previous equation, an average bead diameter was measured to be 0.50mm. To perform correction factors, polynomial curve-fits of the needed fluid parameters were made for a temperature range of 800°C – 1600°C and equivalence ratios between 0.20 and 0.80. The polynomials were then evaluated for the mean exit and recirculation temperature at each equivalence ratio to numerically attain the reacting fluid properties.
**b - Emission:**

Standard practice in the aerospace industry is to relate emissions concentrations of CO and NO\textsubscript{x} to a reference of 15% O\textsubscript{2}\textsuperscript{30}. The corrective equations are based upon the measured oxygen concentration and that at standard atmospheric conditions. Therefore the equations for emission concentration in parts per million at the reference condition of 15% O\textsubscript{2} become the one presented as following:

\[
\left( NO_x \right)_{\text{ref}15\%\text{oxygen}} = \frac{5.9 NO_{X,\text{meas}}}{20.9 - O_{2,\text{meas}}}
\]

\[
\left( CO \right)_{\text{ref}15\%\text{oxygen}} = \frac{5.9 CO_{\text{meas}}}{20.9 - O_{2,\text{meas}}}
\]

Those two equations are thus the one that we used to correct the data acquire during the test of the combustor. Those corrections were actually directly done by implementing them inside the LabVIEW acquisition program to simplify further process of the data.
At this point, we have been able to better understand what is flameless combustion, first among combustion in general, and then in its process itself. We enumerated a number of parameters that have been recognized as main elements in its formation and we also described which elements could be useful in term of gas turbine engine application. Staying focused in this field of research and using the experimental set-up described in the last paragraph, now, let us describe the approach of the tests that we realized in order to study the flameless regime of combustion.

The tests performed follow a series of experiments started a few years ago when studying the SIEMENS flameless research burner (Appendix5: modified version of the FLOX burner manufactured under EU program and on the basis of the burner concept provided by Wünning). The burner was actually composed of a circle of 12 premixed fuel and air jets mixed with the combustion products and tested under pressure drop, preheated air and flame temperature influences. The results were globally unsuccessful, the burner demonstrating the usual premixed flame instabilities when combustion transits out of steady flameless mode and having troubles to create the necessary high turbulence rate required in flameless combustion. Because of the poor recirculation zone created by the geometry and the injection, unlike the jet velocities were increased, the entrainment kept weak, the temperature dropped excessively and the combustion rapidly became unstable.

The point was then to overcome those weaknesses and look for a new concept. This has been achieved when testing new methods such as using swirl method combustion. Indeed, a good way to obtain a well defined recirculation zone can be realized using a high swirl number and injecting the fuel directly in this zone. The burner illustrated in figure 37 results from this technique and was designed at the University of Cincinnati.
Starting from the combustor, the above burner and all the acquisition set-up available, studding all the previous works that have been performed on the burner and mainly illustrated in the master thesis of Nicholas R. Overman, it appeared useless to spend more time looking for the best chamber of combustion configuration. Indeed, Nicholas’s work has been quite laborious and definitely efficient and relevant in this way, comparing all different sort of configuration, changing the length of the chamber; its diameter and testing different fuels. This permitted him to state that the best chamber was the largest and the longest, which dimensions are of 457mm (18 inches) high and a diameter of 203mm (8 inches). It is therefore the one we have been using during all our experiments.

The first step of the analysis was conducted with the main aim to determine the operation range of the burner and identify the regions of flameless combustion. All this part was realized with the help of Nicholas. Testing included evaluation of the performances of the flameless burner for steady–state conditions at different pressure drops (3%, 4% and 5%) and air inlet temperatures between 325°C and 525°C, which are temperatures in the range of preheat temperatures at which current industrial gas turbines operate.
Then, for each configuration, the equivalence ratio was modified between approximately 0.3 and 0.65 by controlling the fuel mass flow rate while the air mass flow rate was kept constant. The designed experimental program has concentrated on the sensitivity study. Actually, because the most influential burner/combustor parameters which influence the performance of the flameless combustion system were reported in the literature to be air preheat temperature, pressure drop and equivalence ratio for the same composition of the fuel, we started with this first set of measurement. This allowed us to quantify the influence of those parameters on our specific burner. The influence was mainly studied on temperature values (exit temperature, recirculation temperature and a set of experiment specially to map the temperature profiles in the chamber), emission behavior (CO₂, CO, NOₓ, O₂) and combustion parameters evolution such as heat release and pressure oscillation.

In a second set of measurements, when the flameless mode regions were identified, we focused our attention in more restrictive tests. An element that still stays unclear in the flameless mode is the chemistry evolution implicated during the reaction. As any other type of combustion, the flameless mode involves a reaction between an oxidant and a fuel, but although the oxidant is usually constant as air, the fuel chemistry may change. Does this have an impact on the flameless characteristics, on its emission rate or flame structure? Can we, using different fuels, but staying with fuel types from a same family and close enough in their composition, understand the reactions involved in the process or identify some general trends?
Those are the type of question that we have been asking ourselves during this second set of measurement which consisted in OH* chemiluminescence imaging and emission measurements for different fuel that were: propane, butane, nonane, hexane, pentane, toluene and jet A (to have a actual aero fuel point of view). The evolution of the combustion status, from a diffusion flame combustion to the flameless mode was then depicted by instantaneous pictures filtering the OH* particles. Those images were then processed and analyzed to make relations between state of combustion and flame characteristics. This was directly done by scaling the pictures and then quantifying their disparities while put side by side to the associated emission measurements.

The results of those measurements are presented in the following chapter.
2.2 - Characterization of the Combustor at Flameless regime:

2.2.1 - Influence of Preheated Air Temperature:

In this part, we kept the value of pressure drop constant at an average value of 4% and then we realized three different sets of measurement at 325°C, 425°C and 525°C for a same type of fuel. The fuel tested at that point was, for simplicity and financial reasons, propane. Indeed, this fuel is the easiest to manage during the tests and also the most available in the laboratory.

a - Influence on Exit and Recirculation Temperature:

Figure 37: Preheated Air Influence on Exit and Recirculation Temperature
(description p64, dp=4%, Fuel=Propane in Cross-Flow Injection)
Temperature measurements were taken for different range of operating conditions, from discrete flame, distributed reaction regime to near lean blow out. Figure 37 presents the behavior of the exit and recirculation temperatures for the following range of equivalence ratio: 0.7 to 0.3 (near LBO) for the three different preheat air temperatures tested. The exit temperature data corresponds to the average value of the corrected measurements compensating for thermal radiation effects of the three thermocouples placed on top of the combustion chamber (the three values being almost identical) whereas the recirculation data corresponds to the unique thermocouple positioned near the injectors (description p64). Actually, the recirculation temperature is the one upstream the burner face and the fuel injection. It is the result of the mix between the hot combustion products and the cooler inlet air. As we could see in the literature, the recirculation zone is a main element in flameless combustion, thus it is interesting to quantify its evolution along the different combustion regimes and especially compared to the exit temperature.

What can be first seen is that the recirculation temperature and the exit temperature have a same behavior regardless the preheat temperature. Indeed, both of them present same trends at either 325°C or 425°C or 525°C. However, it is important to highlight the fact that despite the poor influence on the temperature values, the flameless regime itself was encountered only for a small range of equivalence ratios which varies with the temperature of the preheat air. We also notice that comparing the recirculation temperature to the exit temperature at same equivalence ratio, the recirculation one is always higher than the exit one but with a difference of temperature decreasing from 400°C at an equivalence of 0.7 to 50°C near LBO.
Finally, we can also see that the temperatures are affected primarily by the flame temperature itself, which varies with the equivalence ratio. For both the recirculation temperature and the exit temperature, their values decrease practically linearly from 1650°C at phi=0.7 to 1000°C at phi 0.3 and 1450°C at phi=0.7 to 950°C at phi=0.3 respectively. This highly suggests, especially for the recirculation temperature, that there is a great mixing of the exhaust gases with the inlet air down in the burner diffuser section since the preheated air value does not affect the results but the amount of fuel does. These results actually indicate that both the flow field and the inlet temperature do not have a big impact in the characteristic of the flameless regime itself but highly influence its range of formation. Indeed, even if the inlet temperature is really high, it does not mean that flameless combustion is going to occur. It may actually need a good recirculation zone, highly important to achieve a great mixing and thus reach the perfect conditions under which flameless regime develops.

b - Influence on Emission:

We previously saw that combustion was sustained even in an extremely low concentration of oxygen, if the combustion air was preheated higher than the autoignition temperature of the fuel. In our case, we are using propane and heating the air around its temperature of autoignition (which is around 490°C), then we try to lower the amount of oxygen as much as we can by dilution of the combustion air with recirculated burned gas in the chamber of combustion. Indeed, a direct application of the principle of making the oxygen content of the oxidizer low is to decrease, as we could see, the temperature fluctuations in the flame as well as the mean temperature.
CO and NOx emissions are plotted in figure 38 and give us an idea of the preheat air temperature effect on their production. This one is seen to be from poor to no effect since preheating at 325°C, 425°C or 525°C leads to approximately the same trends and values at same equivalence ratios.

![CO Emission](image)

![NOx Emission](image)

**Figure 38: Preheated Air Influence on CO and NOx Emission**
*(Description p69, dp=4%, Fuel= Propane in Cross-Flow injection)*

However, as expected, at the highest preheat air temperature; the widest operating range and turndown ratio are achieved for the burner. This range decreases until the lowest air preheat temperature of 325 °C resulting in the lowest turndown ratio with a LBO limit at a relatively high equivalence ratio of 0.42. At air preheat temperature of 525°C, the LBO limits are much more extended and reduced to an equivalence ratio of 0.28.
What we can understand from these results is that the addition of heat, using higher preheat air temperatures, reduces the radical concentration required from recirculated gases to sustain the combustion. Operating the burner around or above the autoignition temperature of the fuel results in a diminution of the induction time, allowing spontaneous ignition to occur without necessity to provide fluid mechanically induced stagnation point/region in the flow to stabilize the combustion.

What we can also notice if we go deeper in the analysis of CO emissions is that, part of the flameless burner characteristics is the fact that CO production is very low for equivalence ratios reaching near LBO to LBO. Compare to the actual gas turbine engines burner that we usually encounter in the literature with an emission rate of the order of hundreds of ppm, here we barely reach, at the worst case, the dozen of ppm. In fact, this can be explained taking in consideration that we have a high concentration of OH radicals at conditions near LBO which promotes the CO oxidation in CO2.

The NOX emission gives the feeling that at lower preheated temperature, its amount is lowered. This is an expected trend knowing that high preheat air temperature results in higher flame temperature and as a consequence higher level of NOX.

On the other hand, what were not expected are rather the general trends of the curves. Indeed, typical emission trends yield the lowest CO and NOX emissions just below an equivalence ratio of 0.40-0.50. From that point, NOX emissions usually increase exponentially with increasing the equivalence ratio until its production reaches a maximum near phi=1.0 and in the other way decreases until LBO when CO increases exponentially for decreasing equivalence ratios until LBO. Here, those trends do not appear.
Instead, there is a minimum in CO concentration around an equivalence ratio of 0.40 to 0.55 and unlike the expected exponential decay of NO\textsubscript{X} with respect to equivalence ratio; this one is sort of flipped about the horizontal. The concentrations are extra low at flameless regime (under 1ppm at \(\phi=0.3\) except for a peak of CO measured when the flame blow out), quickly increase with equivalence ratio but start to level off at an equivalence ratio of 0.60 with a value not higher than 80 ppm.

Finally, we can see the typical behavior that is expected in flameless combustion. When lower temperatures tend to produce more carbon monoxide and higher temperatures lead to more nitrous oxides, flameless combustion leads to this paradoxical phenomenon where simultaneously low concentrations of both CO and NO\textsubscript{X} are encountered. In usual combustion methods, there is a trade-off between high concentrations of either CO or NO\textsubscript{X} but flameless combustion, being well distributed, allows no single point of ignition or flame front and permits the OH particles produced to easily react with CO.

In term of NO\textsubscript{X} oxidation, if we link the temperature response to the emission product, an easy explanation can be given on the results. Indeed, the primary production path of NO\textsubscript{X} is through thermal NOx and yields an exponential dependence on temperature. As seen in the temperature profiles measurement, the temperature distribution through the combustion chamber seems to be more homogeneous during the flameless regime compared to non-flameless mode producing large temperature gradients leading to temperature hot spots far above the mean bulk temperature. That is the lack of those hot spots that is at the origin of thermal NO\textsubscript{X} production reduction. The recirculation zone has also its impact if we think that recirculating the NO\textsubscript{X} particles among the oxidizer ones makes its dilution easier and allows the consumption of NO\textsubscript{X} as an oxidizer.
What could then be guessed is the evolution of CO$_2$. As a matter of fact, both the diminution in CO and NO$_X$ emission imply the formation of CO$_2$ by chain reaction and thus a great amount of CO$_2$ near LBO should be expected at first view. Nevertheless, if we look at the range of CO and NO$_X$ produced, we have values oscillating around hundred of ppm at the most. Not to say that this has no effect on CO$_2$ emission but it is still far from the usual CO$_2$ measured concentrations and we should thus obtain a “normal” behavior on the CO$_2$ formation.

CO$_2$ curves are actually of an order of a few percents (figure 39) at flameless regime and we can not, by consequence, see the influence of the CO and NO$_X$ drop off in its formation. That is why we rather find a linear trend increasing with increasing the equivalence ratio with some values between 3 to 8%. The O$_2$ is also behaving “a priori normally” with an opposite linear decreasing progression with rise of equivalence ratios and some values between 15 and 7%. At higher temperature, the operating range of equivalence ratio increases in the same way, allowing combustion at very low equivalence ratio like 0.3. At same equivalence ratio, the air preheat as absolutely no influence, we can actually see all the three curves (in figure 39) for the three air preheat temperatures superposing each other for both CO$_2$ and O$_2$. 

- 87 -
Figure 39: Preheated Air Influence on CO$_2$ and O$_2$ Emission (measure description p69, dp=4%, Fuel=Propane in Cross-Flow Injection)

c - Heat Release:

Described in the experimental acquisition set-up are three optical fibers that measure the amount of OH* particles, the result being converted then in Volt. After processing the data with a Fast Fourier Transfer Matlab program (see appendix 4) and noting the frequencies at which we measured a magnitude peak (see selected examples in figure 40-a,b) for each equivalence ratio, we then plotted the average graphs corresponding to those three optical measurements (see figure 40). One of those graphs corresponds to the magnitude of the peaks when the other one corresponds to the value of the associated frequency, both of them function of the equivalence ratio.
Figure 40: Preheat Air Influence on Heat Release (description p68, dp=4%, Fuel=Propane in Cross Flow Injection), a),b) Selected Spectra, c) Frequency(Hz), d) Magnitude(V)
This measure of OH* concentration permits us to quantify the heat release during the different mode of combustion. The point is that in combustion, an important parameter is the flame appearance; defined by its color, its size, its stability and its homogeneity, and directly linked with the heat release. Therefore, the OH* measure is an easy way to describe or better understand the flame structure.

The main trends are described as following: first, for the higher temperature cases, the heat release oscillations are the lowest in term of frequency. The magnitude are, regardless of any preheat temperature, very low and decreasing steadily with equivalence ratio. This agrees with the fact that flameless combustion only occurs when heat release oscillations are below a certain magnitude, characterizing flameless combustion as combustion occurring uniformly with no single ignition point or stagnation point. Another element that those graphs show is the actual dominant frequency at which heat release occurs, which is also function of equivalence ratio. Some cases show variation in frequency at which heat release occurs for equivalence ratios above the flameless combustion regime, but the peak frequencies for the different cases seem coalesce in the flameless regime. The magnitude of the peak rises with the raise of equivalence ratio when we are in or close to the flameless regime, while out of it, the magnitude trends to stabilize or evolve slightly linear but dropping down. It also seems that phi=0.5 (comparing the three different preheated air responses) is an intermediate value between the two main regimes of flameless and non-flameless combustion even if rising the preheat temperature seems to faintly displace this value in the lean fuel direction.
d - Pressure Oscillation:

Unlike current combustion methods, flameless combustion has no single ignition point or stagnation point. This, in term of instabilities, is really interesting because having no single ignition point, it is unlikely that heat release has a part in driving acoustic instabilities and for that reason, flameless usually occurs at very low acoustic ranges. However, the other interest in flameless combustion is to occur at very lean conditions to reduce emissions while improving the combustion efficiency and this may have consequences on the global instabilities and thus, the acoustic part.

Using the microphone set-up (description p67), we have been able to plot the pressure oscillations in the same way as we did for the OH* concentration by first using an FFT filter and then identifying the frequencies for which the pressure oscillations were maximum (selected sample in figure 41-a,b). The results are presented in figure 41.

Temperature air preheat has a direct impact on pressure oscillation. The exhaust gases at high temperature are recirculated back to the intake to mix with the preheated air of a much cooler temperature. The presence of these exhaust gases in the mixture alters both the composition and the thermodynamic state of the intake charge, thereby influences the combustion process and this also and specially in term of “combustion noise”.

The combustion noise arises inside the combustion chamber due to temporal fluctuations of heat release processes. The exhaust gases and the air preheat meet each other in the chamber of combustion at two different temperature fluid streams mixing and create shear layers at the origin of the pressure oscillations at the exit of the combustor. Decreasing the preheat air temperature increases the difference of temperature compared to the exhaust gas recirculated.
Figure 41: Preheat Air Influence on pressure oscillation (description p67, \(\Delta p=4\%\), Fuel=Propane in Cross Flow Injection), a),b) Selected Spectra, c) Frequency(Hz), d) Magnitude(Pa)
This rise allows stronger shear layers and thus greater oscillation. Figure 41 well illustrate this behavior with the three curves dissociated one from another and average amplitude increasing with decrease of the inlet air temperature. The frequencies at which the oscillations occur are essentially the same at each preheat air values, fluctuating around 300Hz. with a minor attenuation proportional to the flame temperature.

However, for a same preheat temperature and different equivalence ratios, the progression of the oscillation amplitudes is quite interesting. At high equivalent ratio, the mean temperature in the chamber is at its maximum and regardless to the thermal mixing fluctuation, the pressure magnitude stays globally constant at an average value of 2 to 3 Pascal. Decreasing the equivalence ratio rapidly increases the magnitude until a peak at phi=0.4 were the combustion regime flips from non-flameless to flameless. After this, the magnitude rapidly starts to decrease back during the flameless regime until its minimum near LBO. As a qualitative result, we can mention our direct experience as an operator during the flame temperature variation of each test by separating the noise statements in three stages that well correspond to the equivalence ratio states described above.

Starting the test at high equivalence ratio, the noise is quite tolerable wearing hear protection until a point where instabilities appear and sound peaks occurs (but still tolerable). In the flameless regime, the oscillations stabilize and we could at a time, barely identify audible noise level at the lowest phi. Globally, the combustion noise is measured and perceived as being at its best level during the flameless combustion regime. This permitted to believe that such a regime of combustion is highly recommended in gas turbine engine, not only in term of efficiency and particle emission pollution effects, but also because of noise pollution and safety considerations.
2.2.2 - Influence of Pressure Drop through the Burner:

In the next part of the experiments, a second main parameter influencing the regime of flameless combustion is studied. This parameter is the pressure drop through the burner and it has different effects. First, it is expected that increasing its value, a uniform and distributed flame should occur because, as it has been seen in the literature, increasing the air flow rate permits the formation of a larger and stronger recirculation zone downstream the burner face. Then, another effect is the impact on combustion instabilities. High pressure drops tend to facilitate the chemical reaction by allowing a better mix of the air associated with exhaust gases and the fuel. The reaction is then more distributed and by therefore more stable.

Using a preheated temperature of an average value of 425°C to not influence the results too much with temperature effects, we have been performing different tests on the combustor for three values of pressure drops that are: 3%, 4% and 5%. For each of them, we acquired the evolution of main parameters in function of the equivalence ratio in the same way as we did with the preheated air temperature influence.

The results are presented as following with respectively in order the impact on exit and recirculation temperatures, the emissions associated, heat release and acoustic oscillations.
a - Influence on Exit and Recirculation Temperature:

As seen for the different preheat temperature tests, we obtain a recirculation temperature with a maximum around 1600°C when the exit temperature does not even reach 1400°C. Over the whole set of equivalence ratios we can see a similar behavior as previously with the recirculation temperature higher than the exit one.

Actually, increasing the pressure drop, we increase the amount of air in the combustion chamber. Therefore, we expect at same equivalence ratio configuration, because of a better mixing and a bigger reaction zone, an increase of the recirculation temperature from dp=3% to dp=5%. However, nothing seems to change from one value to another and it looks like for our configuration of burner, as previously, the only parameter that influences the exit temperature and the recirculation one, is the flame temperature itself.

Figure 42: Pressure Drop Influence on the exit and recirculation temperature (measure description p64, Tair=425°C, Fuel=Propane in Cross Flow Injection)
b - Emission of CO/NO\textsubscript{X} and CO\textsubscript{2}/O\textsubscript{2}:

![Graph showing CO emission](image)

![Graph showing NO\textsubscript{X} emission](image)

Figure 43: Pressure drop influence on CO and NO\textsubscript{X} emission (measure description p68, T\textsubscript{air}=425°C, Fuel=Propane in Cross Flow Injection)

The results in figure 43 show the effect of the increase in pressure drop on CO and NO\textsubscript{X} emissions as a function of equivalence ratio and at the average air preheat temperature of T\textsubscript{air} = 425°C. It is interesting to note that for all pressure drop rates tested, recorded CO and NO\textsubscript{X} emissions exhibit similar trends. At low equivalence ratios and close to LBO limits, the emissions are very low with only a peak at LBO. Actually, we can observe emissions under 1 ppm and this for all pressure drops. In the case of CO emission, we can observe that until phi=0.55, the emission stays constant and very low (except a peak at LBO), then increases rapidly to reach a value still reasonable.
This looks similar to the results obtained when changing the temperature of the preheat air. The NO\textsubscript{X} emission is more likely to increase from near lean blow off until a maximum around 100 ppm after an increase of equivalence ratio above \(\phi=0.6\). If we come back to the results collected when changing the air preheat temperature, we can actually conclude that both the inlet temperature and the pressure drop have low to no influence on the CO and NO\textsubscript{X} emission measurements. Only the inlet temperature permits a better utilization of the burner, allowing it to operate in a bigger range and higher turndown ratio. Their influence is more likely in the mixture itself, the reaction reaching a better behavior when increasing both of those parameters.

Similar to the temperature and NO\textsubscript{X} emission results, the \(O_2\) and \(CO_2\) concentrations seem independent of pressure drop, but only a function of equivalence ratio/flame temperature, and mixing quality. Here again, the curves plotted are exactly the same that the ones we can observe after changing the air inlet temperature. The results are presented in figure 44 and demonstrate the poor impact of the pressure drop on the burner response.
c - Heat Release:

Dependence of OH* signal for different pressure drop is presented in figure 45. We can see that for all mass flow rates, the signals have two distinct regimes. For lower fuel equivalence ratios, dependence of OH* on fuel equivalence ratio is quickly increasing and then stabilizes after a value of \( \phi = 0.45 \). This is close to what we saw previously in our study of the temperature influence with a more stable average tendency from one value to another. The curves are the same with similar behavior in frequencies until \( \phi = 0.5 \) and then variations for richer ratios traduce a change of behavior in the combustion process and flame parameters.
d - Pressure Oscillation:

In figure 46 we present the effect of pressure drop across the combustor on combustion noise stability. We can thus now draw conclusions from the variation of pressure drop. Strength of the jets added to the high swirl number is having stabilizing effect on combustion but act in the opposite way on the pressure oscillation near Lean Blow Out and thus acoustic instabilities. For high pressure drop (5%), low to no combustion instabilities are observed while a variation in the noise could be noticed. As we reduce the amount of injected air, peak of pressure magnitude is picked up with the microphone around the fuel equivalence ratio of 0.4 and globally decreasing.
The recirculation zone is getting stronger at very low equivalence ratios with increase in pressure drop and this has consequences in keeping the combustion stable. Actually, measurements at equivalence ratio lower than 0.4 present a huge drop off that corresponds to the transition from diffusion type of combustion to flameless.

![Pressure Oscillation Graph](image1)

**Figure 46: Pressure Drop Influence on Pressure Oscillation (measure description p67, Tair=425°C, Fuel=Propane in Cross Flow Injection) a),b) Selected Spectra, c) Frequency(Hz), d) Magnitude(Pa)**

Finally, we can see that the frequency at which pressure oscillation occurs is around a value of 250Hz which is one hundred hertz less than for the OH emissions. Thus, it is quite important to notice that both pressure oscillation and heat release seem to be decoupled and not interact on each other to favorite instabilities. This is in fact an important characteristic of flameless combustion that has been recognized in the literature and that we can highlight in our tests.
2.2.3 - Temperature profiles:

Flameless combustion is easily recognizable by the flame that it produces, having the property of being well distributed over almost the whole chamber and supposed to produce a homogeneous temperature spread all over the combustion chamber. The temperature measurements that we saw previously were going on this direction, the recirculation temperature tending to reach the value of the exit temperature and vice versa when we approach Lean Blow Off. The recirculation is actually one of the main features that allow flameless combustion to occur. The high turbulence effect permits the recirculation of exhaust gases added to the combustion mixture and by cause and effect, heating the whole reduces the Damkoler number and stabilizes the combustion. An interesting part of the tests was to look deeper in the combustion chamber and map the temperature profiles during the evolution of the parameters at the origin of the phenomenon. As we described in the experimental set-up, a set of measurements has been processed using a 457mm (18in) high and 203mm (8in) wide steel combustion chamber to measure the temperature inside the chamber. Actually, because of the apparatus used, two set of measurements were done, one for the temperature downstream the chamber and a second upstream the chamber. This was due to the fact that only four thermocouples at a time could be traversed through the chamber. Temperature distributions for preheat temperature of 325°C, 425°C and 525°C were measured and for each of those temperatures we also looked at the influence of the pressure drop making it vary from 3% to 4% and finally 5%. This represented nine cases in term of pressure drop and preheated temperature influence, multiplied by two due to the fact that for each of those nine conditions we also changed the flame temperature.
We took a measurement at phi=0.55 where we were sure that no flameless combustion occurred and a second at phi around 0.35 to have an idea of the temperature mapping under flameless combustion. Those results are presented in figure 47 to 49 and finally form a grid of eighteen temperature mappings (qualitative results are presented when selected quantitative results can be found in figure 46). The r/D and z/D coordinates that we used on the Tecplot tracing represent the normalized radial and axial directions respectively and are both normalized by the burner diameter D. To better understand the temperature presentation we need to keep in mind the relation between coordinates and physical region of the chamber, r = 0 being at the wall of the chamber and evolving until r = 0.5 at the centerline of the combustion chamber. On the other direction, z = 0 is at the dump plane. The measurements where taken, adding the two sets, at eight different latitudes separated of 2 inches apart and moved from the wall position every 0.5 inches. That is why we do not have a mappings starting exactly at r=0 and z =0.

The results can be divided in three different influences, one being the preheated temperature part, the second one the pressure drop effect and finally and the most important one, the equivalence ratio weight. The results of each case indicate diverse behavior but a general trend can be immediately seen for all of them, combustion being more intense downstream the burner, near the centerline, which is actually the position of the recirculation zone that we were expecting. This last one is positioned from r/D=0.4 to the centerline at the burner level and is spread conically until r/D=0.3 at z/D=0.6 to 0.8 depending on the equivalence ratio.
The recirculation zone is bounded by the lowest temperature zone on its left with a quick temperature drop of 400 to 800°C depending on the combustion regime. The lowest region corresponds to the zone where fresh mixture is injected.

Penetration of jets can be well defined as the region where the temperature is at a transition value from the hottest recirculation zone and the downstream injection zone at the lowest temperature. This region is well seen on the bottom left of each temperature maps by its blue color and seems to present no combustion affect. On the upper part of those two regions, which describe the trend down in the chamber, we have a more homogeneous zone spread outward that corresponds to the reaction zone at an average temperature of 1200°C.

Now, from one profile to another, a couple of differences can be examined. The three/four different zones that we just described present some disparities. Increasing the preheated temperature, basically and as expected, increases the average temperature over the chamber of combustion as we can see comparing each same equivalence ratio and pressure drop conditions for different preheated temperatures. For instance, comparing all f) maps that correspond to a pressure drop of 5% and an equivalence ratio of 0.55 indicates an increase of almost 200°C from the lowest preheated temperature to the highest. The big impact of the preheat air can also be seen on the homogeneity of the whole temperature that we immediately see on the following figures.
Figure 46: Selected Temperature Profiles at Both Dp=3% and Dp=5% for the cases when Tair=325°C and Tair=525°C with Propane Fuel in Cross Flow Injection at \( \Phi = 0.35 \) and \( \Phi = 0.55 \)
Figure 47: Temperature profile, air preheated at 325°C.
(measure description p66, Fuel=Propane in Cross Flow Injection)

φ=0.35  a)dp=3%, b)dp=4%, c)dp=5%
φ=0.55  d)dp=3%, e)dp=4%, f)dp=5%
Figure 48: Temperature profile, air preheated at 425°C,
(measure description p66, Fuel=Propane in Cross Flow Injection)
θ=0.35  a)dp=3%, b)dp=4%, c)dp=5%
θ=0.55  d)dp=3%, e)dp=4%, f)dp=5%
Figure 49: Temperature profile, air preheated at 525°C,
(measure description p66, Fuel=Propane in Cross Flow Injection)
φ=0.35 a)dp=3%, b)dp=4%, c)dp=5%
φ=0.55 d)dp=3%, e)dp=4%, f)dp=5%
The different figures well show the variations on homogeneity from one preheat air value to another one. When we have at $T=325\,^\circ C$ a big gradient of temperature from one zone to another, and even inside the zone itself for the reaction zone that seems to present peak temperature spots within its formation, the regions at higher preheated air temperature are also well described but with a gradient of temperature much smaller and an increase in their homogeneity. Indeed, the reaction zone almost stays at the same temperature whatever preheated temperature we impose. But the lowest temperature zone downstream to the fuel injection trends to get much hotter and homogenous, such as the reaction zone does at higher air preheat temperature.

The pressure drop influence can be estimated comparing each a), b), c) or d), e), f) profiles. Looking at the recirculation zone, we can feel a slight increase on its temperature and its spread by raising the pressure drop. The main influence is better seen on the non reaction and the reaction zones. Both of them clearly trend to get more homogeneous by raising the pressure drop and this can be easily explained due to the fact that increasing the air mass flow rate enhances the mixing between the recirculated gases and the fresh combustion mixture and yields a stronger homogeneity in temperature among the whole chamber. Putting side by side all the pressure drop cases, we can definitely see the importance of pressure drop control while the preheated temperature is increased, allowing at the highest temperature to well distribute the temperature all over the chamber and not form concentrated reaction zone that would be dramatic in term of combustion emission.
The last and most influencing parameter is the equivalence ratio. At lower flame temperature, the profile itself is seen to be comparable in its shape to the one at high equivalence ratio but with an overall lower temperature. However, there is a strong difference on the temperature distribution. At high equivalence ratio, we can notice a temperature gradient of about 200°C from the wall to the centerline, whereas at phi=0.35, this gradient is lower than 50°C. Both values demonstrate sharper central peaks near the recirculation zone inside the injectors place but for low equivalence ratio, we can notice a flattening of the profile spreading the temperature of the recirculation zone in the reaction one and allowing the non reaction zone to get closer to the average value.

To conclude on those figures, it is really interesting to see the behavior that we can attain at optimized flameless regime. The best illustration of this is the figure 49 c) that shows the combustor under flameless combustion at phi=0.35, T=525°C and Dp=5%, and presents almost the same temperature overall the combustion chamber. This well demonstrates that the reaction at that time is distributed throughout the whole volume of combustion and that the mixing is at that point the most uniform (taking in consideration that the bottom left zone corresponds to a non reaction zone that could be eliminated by a better injection direction).
To finalize this first part of tests studying the characteristics and behavior of our actual burner under variation of temperature, pressure drop and equivalence ratio, we can say that its comportment is actually highly encouraging to a potential use in gas turbine engine.

Indeed, at some points and under typical conditions, the burner could reach highly interesting performances that well represented the flameless regime sought after. What we could actually see under those several sets of measurement is summarized below:

The last part of the measurements which was the temperature profiles can be added to the results that we obtained on the exit temperature and the recirculation one varying the air temperature and its injection. Both of them are actually converging to the best performances that flameless combustion can provide compare to usual combustion. We could appreciate the contrast between those two modes of combustion, seeing that at flameless combustion, we were having a uniform temperature all over the combustor with a slight peak near the centerline downstream the injector face that corresponds to the recirculation zone when at the opposite for the turbulent flame regime we could feel a strong bell shaped temperature distribution even close to the exit. The bulk temperature was maintained between those two modes expect that for flameless combustion, hot spots were suppressed and this could be well illustrated looking at the emissions measurements. Indeed, both the NOx and CO emissions were little (under 10 ppm at flameless regime) and demonstrated the importance of using such a regime of combustion in gas turbine engine. By the way, the best configuration for flameless to occur in our tests was at air temperature of 525°C, which is not far from the discharge temperature achievable in some aircraft compressors.
The main concern in its utilization remains in the instabilities that it may produce, but looking at the pressure results under pressure drop and air temperature influence, both showed weak instabilities. Near LBO, we could reach a few Pascal and this decoupled from the heat release. Those two parameters actually showed that the flameless burner was running safely with great stability in fluid mechanics structure. The heat release itself could show us that great mixing was achieved near LBO and that only a few particles were detected at flameless combustion.

Now, this gives us a characterization of the burner running with propane and does not really correspond to what we would run in the reality if applied in gas turbine engine or any other type of furnace. Thus, the next part of the study turns its attention on the fuel characterization, comparing fuels, characteristics, composition and results on flameless combustion. This is a way to reach both practice and understanding on high temperature oxidation combustion
2.3 - Influence of Fuel Properties on Flame Characteristics:

This second part of the experiments corresponds to a deeper analysis of the fuel injection effect on flameless combustion. The previous part allowed us to demonstrate under which conditions the burner was running at flameless regime and actually also illustrated and confirmed our first literature part. Flameless combustion was seen to occur at high preheated air temperature and high pressure drop when the fuel injection was near Lean Blow Off. Those characteristics are the one we took in consideration to move on to the second step of our experiments. What follows is a research on the injection itself and more precisely a study of the link between chemical composition of the fuel and flameless formation. As we could notice along our literature review, there is a main point that stays indeterminate about flameless combustion which is the mechanistic pathways during and after the transition between normal turbulent flame and flameless combustion. Looking at the flame itself, there is a great disparity between those two modes; both of them showing a globally blue flame or even glow but with structures quite dissimilar. As we can see in figure 50 which is a sample of pictures obtained when running propane with a preheat air of 525°C and a pressure drop of 5%, at Lean Blow Off, we have the extinction of the flame (a) when just before, the flameless flame (b) presents a wide distributed almost colorless flame with a characteristic flow over the wall chamber. The two other pictures show the transition when increasing the flame temperature. First, a drop in the luminosity (c), the flame becoming much brighter and confined near the burner and finally (d) the flame spreading in length with the apparition of orange/yellow on its top part. The flame is at this time the brightest and its flow is well defined by a big pitch helix, swirl that is roughly perceptible at flameless, the flame getting “stabilized”.
2.3.1 - Previous Results and Presentation of the Experiments:

a - Previous Results:

As we could see, it has been experienced that with different types of fuel the flame structure and actually also the Lean Blow Off limits were different. Figure 51 represents the variations in LBO limits that could be listed in previous tests\textsuperscript{30} with different types of fuel (both gaseous and liquid) for the present burner. Regardless to the fuel, increasing the preheated temperature lower the Lean Blow Off limits. The pressure drop has a tendency to work in the opposite way but what is interesting is that the fuels are reacting differently and affect more or less the range of use of the combustor, allowing or not to run at lean to very lean conditions.

Quite surprising is the similarities of the two fuels propane (gas) and Vulcan (liquid close to Jet A) that permitted us to construct a set of experience essentially based on fuel variation and study of those variations on the flame behavior and its colorless formation at flameless regime.
Indeed, the fuel chemical properties have a significant effect on flameless oxidation and it appeared to us that both thermal and chemical behavior of flameless combustion required further examination. With this in mind, we prepared a grid of experiments allowing the comparison of different fuels at flameless and non flameless modes. Because the chemical pathways which conduct to flameless combustion still stay unknown, we decided to study a couple of different fuels and tried to find a link between their compositions, their properties, associated to the regime of combustion.
Actually, seven types of fuel were studied with all of them different lengths of hydrocarbon chains. They were propane (that we have been using until here), butane, pentane, hexane, toluene, nonane and because we kept in mind that the final interest of all those tests is to demonstrate the potential use of flameless combustion under aero gas turbine combustion conditions, we also realized some tests with Jet A.

b - Test Procedure:

The procedure of the tests themselves was globally the same as previously using the same apparatus composed of the combustor, the thermocouples (three at the exit and a middle burner one for the recirculation temperature), the plenum conditions (temperature and pressure), the fuel conditions (flow rate, temperature, pressure) and the heat release measured by OH optical fiber measurements. Added to this equipment, knowing that OH* formation is quite relevant at flameless condition, we also imaged the OH* chemiluminescence by using an Intensified CCD (ICCD) camera with a narrow band pass filtered centered at 310 nm.

The camera used was a PI-MAX Princeton Instruments designed for general macro-imaging and microscopy imaging applications. It uses a proximity-focused microchannel plate (MCP) image intensifier fiber-optically coupled to a CCD array. Then, during the acquisition, the computer controlled both the system configuration and data acquisition via WinView/32 software.

In order to capture the phase-locked flame images within one cycle of combustion, we realized approximately three different sets of measurement for every cases of fuel and flame temperature.
The ICCD camera was set in the shutter image capturing mode with a manual trigger and the use of the OH filter permitted us to run both at dark and normal room illumination. Each final picture within a same cycle is the average of three different pictures comparing the trend of the flame at same conditions. Those three pictures are themselves the average of 10 images at the same phase with exposure time of 25µs. The signature of the picture was then realized by calculating the equivalence ratio associated having the air flow rate constant and the fuel flow rate varying from high flow rate until Lean Blow Off. At the same time, we also noted the emission and have been able, as we will see later, to well identify flameless regime for all the fuel tested.

Although the procedure of the tests was the same as previously, it appears that whereas the injection of propane could be done with no trouble, in the case of liquid fuels, the ability to get coherent values at low pressure drop was compromised. In the case of propane, the fuel is already pressurized at 200 psig and allows it to be injected under high flow rate without any problem. First, in the case of n-butane, the fuel is pressurized at low pressure (50 psig). This limits its mass flow rate and did not allow us to obtain stabilized injection at high flow rate. For this reason, we decided to run the butane as a liquid by liquefying it and then measure the influence of this transfer of phase on the fuel properties via flameless combustion. We also ran tests with propane as a liquid.

We started our first set of measurement with an experimental set-up sheet at a temperature of preheat air of 525°C and a pressure drop of 3%. This permitted us to realize some measurements with propane (both at gaseous and liquid state), approximately with nonane and toluene but here again we have been confronted with a new dilemma.
We could not reach any stable flame at low pressure drop; the fuel temperature was too high and did not allow a good injection. Because of the temperature and the necessary pressure in the manifold, the fuel tended to phase change; we could not achieve a good stabilization of the fuel pressure tank and constantly had the fuel pump to shut down. We thus realized three different improvements in our test system and procedure, one for the fuel temperature, one for the pressure drop and the last one to get a constant injection pressure.

- The easiest way to lower the fuel temperature at its injection was to insulate the fuel injection tubes with a high temperature protective layer that avoids any contacts between them and the mounting flange, and also limits warming of the tubes by combustion heat induction. Then, because of hot spots in the manifold design, we also redesigned it adding a water cooling system all around that permitted to inject a constant amount of cold water flow around the manifold tube and cool the fuel before it reaches the injector tips.

- Because of the relatively low fuel viscosity (see further fuel presentation) and high compressibility, we could noticed that the flow number of the fuels was not low enough to generate a sufficient pressure drop across the nozzle for the tested mass flow rates. Actually we can understand this in a way in which the upstream fuel pressure required to produce the necessary flow rates was not the appropriate one that would stiffen the bulk modulus of the tested fuels and dampen its modulation. Therefore, we rapidly reached the point where our current installation and injection could not allow us to run relevant tests and measurement at pressure drop as low as 3%.
Looking about the results comparing the propane at different pressure drops and being aware of its poor impact on the overall measurements, we then decided to run our tests at higher pressure drop and did all the fuel comparison at a pressure drop of 12%.

- The fact that we increased the pressure drop through the combustor helped us to reduce the fuel injection fluctuations but did not completely solve the problem. In one hand, both of the last improvements permitted the fuel to get injected in a better state but in the other hand, we still could feel some oscillation in the fuel pumping due to the heating of the fuel in the pump. The use of a turbine pump was first selected because of low viscosity consideration but because of the fuel temperature, we still had thermal problem with the pump and decided to use another type of pumping by using an accumulator type of injection. Indeed, we used a 5 gallons bladder accumulator that we filled with the same amount of fuel and then redirected the fuel in the other way to use the accumulator as a constant pressurized source. This technique was quite successful and permitted use, with a little knowledge of hydraulic schematic, to attain a sufficient pressure and supply the high fuel flow rate needed due to high air flow rate.

We can notice that in our case a gear pump would have been efficient but because of the relatively low viscosity of the fuel, it could not be chosen. The best solution here would have been to use a multiple stage pump that well behaves when using low viscosity fuel at high pressure. But unfortunately we did not have one available at that time and we can also guess that its use would have required a cooler anyhow because of the fuel warming. Thus, the accumulator solution seemed to be the only efficient and accurate solution.
c - Fuel Presentation:

The following table presents the overall characteristics of the fuel tested ranked by their boiling point value:

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Boiling Point (°C)</th>
<th>Flash Point (°C)</th>
<th>Autoignition Temp. (°C)</th>
<th>Viscosity (nP) at 25 °C</th>
<th>Flame Temp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propane</td>
<td>-42.09</td>
<td>-104</td>
<td>490</td>
<td>0.186</td>
<td>1280</td>
</tr>
<tr>
<td>Butane</td>
<td>-0.5</td>
<td>-60</td>
<td>405</td>
<td>0.258</td>
<td>1340</td>
</tr>
<tr>
<td>Pentane</td>
<td>36.1</td>
<td>-49</td>
<td>290</td>
<td>0.240</td>
<td>1290</td>
</tr>
<tr>
<td>Hexane</td>
<td>69</td>
<td>-23.3</td>
<td>225</td>
<td>0.294</td>
<td>-</td>
</tr>
<tr>
<td>Toluene</td>
<td>110.6</td>
<td>4</td>
<td>480</td>
<td>0.590</td>
<td>-</td>
</tr>
<tr>
<td>Nonane</td>
<td>151</td>
<td>31</td>
<td>205</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Jet A</td>
<td>175-300</td>
<td>38</td>
<td>210</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3: General Characteristics of the tested fuels at Stoichiometric Conditions (Φ=1)

Those values permit us to have a first overview on the differences that the fuels originally present. We can verify that effectively, all the used fuels have a relatively low viscosity and well agree with the problems recorded in the previous paragraph. We can also notice that all the autoignition temperatures relative to the fuels are lower than the preheated air temperature of 525°C during the test and thus, all of them are supposedly in good conditions to run at flameless combustion.

One other characteristic is the boiling point temperature that is for all of them relatively low and explains the main problem that we had in the fuel injection. Regardless propane at gaseous conditions, we can notice that inject it as a liquid would have been really hard to achieve due to its boiling point at -42°C.
Hopefully this one was well pressurized in its tank and we did not have any problem, but the low boiling point of the butane explains well the first problems encountered. Analyzing the liquid fuel boiling point, it is easy to understand that running with preheated air at 525°C when the maximum boiling point temperature of those fuels is around 150°C necessitates high constant pressure in order to stabilize the fuel in its state and avoid any sort of instabilities.

Actually, looking at figure 52 that corresponds to the fuel pressure measurements during the whole set of data for all the fuels, we can directly see the effect of the boiling point on the necessary fuel pressure value.

![Figure 52: Fuel pressure measurement with different fuels: (Tair=525C, dp=12%)](image)

The curves show the same ranking as the one listed above comparing the boiling point temperatures and basically illustrate the fuel from the easiest to inject (gaseous propane at the lowest pressure, curve below) to the hardest (propane liquid at the highest pressure).
Although the values stay approximately constant among the whole range of equivalence ratio, we can feel a slight increase with the flame temperature which seems understandable with increasing the fuel flow rate.

For a couple of fuel (toluene, nonane, jet A) we can also notice an increase at some point (actually around 0.42 and 0.45) which corresponds to a change back and forth in the equivalence value, increasing and then decreasing to finally increase again its value. This phenomenon is remarkable in all the data processed that are presented in the next chapter.
2.3.2 - Experimental Imaging Results:

a - OH Chumiluminecence Comparison:

Figure 53: Selected OH-LIPF intensity images for various equivalence ratios and propane as fuel (Tair=525°C, dp=12%, Cross-Flow Injection)
The first set of pictures was realized using propane fuel which is a three-carbon alkane with molecular formula: \( \text{C}_3\text{H}_8 \), normally a gas, but compressible to a liquid that is transportable. Propane undergoes combustion reactions like all other alkanes. In the presence of excess oxygen, it burns to form water and carbon dioxide under the following reaction:

\[
\text{C}_3\text{H}_8 + 5\text{O}_2 \rightarrow 3\text{CO}_2 + 4\text{H}_2\text{O} + \text{heat}
\]

The OH chemiluminescence measurements for propane injected as a gas are presented in figure 53 with a variation of equivalence ratio between \( \phi = 0.35 \) and \( \phi = 0.57 \). Those equivalence ratios were calculated using the values of air and fuel mass flow rate measurement from the data acquisition and a stoichiometric air/fuel equivalence ratio of 15.67 estimated from the equation above. The OH intensity value as we would see later varies from a maximum value of 6070 at \( \phi = 0.57 \) and 363 at \( \phi = 0.35 \) near Lean Blow Off. The tests with propane showed a good behavior at flameless combustion with a net transition around \( \phi = 0.4 \) with the usual turbulent flame regime. The pictures are all rescaled in term of color with a max/min range and are not really demonstrative at high flame temperature because of the difference of scale. However, for small equivalence ratio we can easily see the great distribution of the flame and a small variation in color (and thus OH mixing) with a light blue and green color spread allover the picture. Increasing the fuel flow rate creates a bigger variation between the region near the injectors and the one downstream the burner. The display of OH particles tends to rapidly decrease with two clear regions of high intensity detaching step by step from one to another when increasing the flame temperature.
In figure 54 we can compare those measurements with the pictures realized for propane but this time injected as a liquid (by preheating the tank and filling the bladder). We then replaced the fuel pressure transducer for a higher range type one, allowing some measurements up to 500psig and changed the fuel injection, from gaseous atomizer to no use of tips. Only changing the injection process already changed the results. When we had a flameless limit at 0.4 with gaseous propane, the range of measurement was lowered and the limit was shift to 0.42. The behavior is mainly the same even if with liquid injection, the propane seems to demonstrate a better application near flameless regime. The flame shape is slightly more homogeneous for any same equivalence ratio and never describes two distinct separated OH spots. We can also noticed three states of OH particles emission that are well separated for the liquid injection type compare to its analog at gaseous state, this would be confirmed later on by the plot of average profiles of the pictures for similar equivalence ratios.

For both of the tests, the heat release due to combustion reaction is distributed, yielding as we will later see to a dispersed and moderate temperature rise. In contrast to the diffusion flame, no high gradients of temperature and species concentration are observed at flameless regime. The principal advantage is that by avoiding peak temperatures, the thermal NO formation can be largely suppressed, even at the highest air temperatures. Fuel injection can be seen to even more spread the recirculation and reaction zones, especially in the radial direction. This permits to believe that propane injected as a liquid is more likely to run at flameless combustion because of the better mixing achieved without use of injector tips.
Figure 54: Selected OH-LIPF intensity images of flameless oxidation for various equivalence ratios and propane injected as a liquid as fuel (Tair=525°C, dp=12%, Cross-Flow Injection)
After testing propane, we moved on the second gaseous fuel we wanted to compare which is Butane. As we mentioned earlier, the tests were done using butane injected as a liquid because of the low pressure tank (50psig) that could not permit us to run at stable state. Butane, also called n-butane, is the unbranched alkane with four carbon atoms and a general molecular formula: \( \text{C}_4\text{H}_{10} \). The n-butane name refers to the butane and its only isomer, isobutene (“\( \text{CH} (\text{CH}_3)_3 \)”). The butane has some characteristics globally close to the propane and burns under the following reaction:

\[
2\text{C}_4\text{H}_{10} + 13\text{O}_2 \rightarrow 8\text{CO}_2 + 10\text{H}_2\text{O} + \text{heat} \quad (\Phi_{\text{Air/Fuel stoic}}=15.46)
\]

Because of its familiarity with the propane, it is quite interesting to compare both of the fuels in term of combustion behavior and notably at the specific regime of flameless combustion. Looking at the figure\text{55} that represents the OH chemiluminescence pictured when running the butane, we can see that the results are far from what we were expecting. Of course, because of the injection itself, the flame shape looks similar with the one found with propane when injected as a liquid. However a couple of details can be noticed and need to be highlighted. First, the behavior of the fuel regard to flameless regime is really interesting. We have been able to run the fuel at flameless combustion under almost all the range of measurements. Even if the fuel did not allow us to get a wide range of operational combustion, the flameless part was huge compare to the propane and all the other fuels as we will see later. We believe that not only the injection but also the fuel itself has good characteristics to run at flameless. From \( \phi_i=0.4 \) until almost \( \phi_i=0.48 \), the fuel was presenting flameless combustion characteristics, with at all the equivalence ratios, a flame well distributed over the \( x \)-axis and spreading in length vertically while decreasing the flame temperature.
Near lean blow off, the flame was practically colorless and the OH visualization permitted us to conclude that not only the OH particles were few but also completely dispersed all over the chamber. Even at high fuel flow rate, the flame never presented any yellow or orange color and kept being far-lifted. Both the mixing patterns and the fuel properties affected the flame features and the combustion mechanism to provide the best efficiency of the burner (as we will see in further examination of the temperature and emission signature) and the best characteristics to run at flameless combustion.

**Figure 55:** Selected OH-LIPF intensity images of flameless oxidation for various equivalence ratios and butane injected as a Liquid as fuel (T<sub>air</sub>=525°C, dp=12%, Cross-Flow Injection)
Then, after running some originally gaseous fuels, we directly used liquid fuel that we injected in a bladder accumulator and ran several tests.

Figure 56: Selected OH-LIPF intensity images of flameless oxidation for various equivalence ratios and Pentane as fuel (Tair=525°C, dp=12%, Cross-Flow Injection)
Figure 56 details the pictures performed when running pentane as fuel. Also known as amyl hydride, pentane is also part of the alkane hydrocarbon family and presents the following molecular formula: $C_5H_{12}$. As the most volatile hydrocarbon that is liquid at room temperature, pentane is often used in the laboratory as a solvent that can be conveniently evaporated or can also be used as a fuel, burning to form carbon dioxide and water such as:

$$C_5H_{12} + 8 \text{O}_2 \rightarrow 5 \text{CO}_2 + 6 \text{H}_2\text{O}$$

From this combustion equation we can pull out the stoichiometric air/fuel equivalence ratio of 15.36 that we used to determine the equivalence ratio related to the taken pictures. Unfortunately the fuel injection during the tests was not as good as for propane or butane, the fuel jets being a bit asymmetric with the right injectors more accurate than the left ones, but still we can deduce a general trend from the measurements. While operating at flameless conditions for a $\Phi$ around 0.37, the flameless window decreased rapidly with increasing the flame temperature with a common turbulent flame structure appearing at $\Phi=0.4$. Considering that at this value, we just start the flameless process with butane, it is quite surprising that changing the fuel, actually increasing the carbon part of its composition from one atom and decreasing the autoignition temperature, results in such a different behavior. The fuel rapidly split in two concentrated zone downstream the injectors (in fact one bigger right zone due to the injection) and does not present any flameless shape upper $\Phi=0.45$. At high equivalence ratio, the flame structure is once again different as previously with a lift off much lower than for the previous tests and a notable increase in the gradient of OH distribution between the location near the fuel injectors and the exit of the region more downstream the recirculation zone. This is a characteristic that we found for all the next proceeded tests.
In our two next experiments we continue to examine different fuels by increasing the number of carbon atoms one by one, first testing hexane and then toluene.

Figure 57: Selected OH-LIPF intensity images of flameless oxidation for various equivalence ratios and Hexane as fuel (Tair=525°C, dp=12%, Cross-Flow Injection)
Figure 58: Selected OH-LIPF intensity images of flameless oxidation for various equivalence ratios and Toluene as fuel (Tair=525°C, dp=12%, Cross-Flow Injection)
Both hexane and toluene present a behavior similar and close to the one acquired with pentane. The range of equivalence ratio under which flameless combustion could be felt is slightly different though.

Hexane, as its prefix indicates it, is composed of six carbon atoms and has the general chemical formula: \( C_6H_{14} \). Similar to propane, butane and pentane, its carbons are connected by single bonds. Toluene, with the molecular formula \( C_7H_8 \) presents one more carbon than hexane and a different structure. Unlike hexane, toluene is not constituted of single bonds that form a linear structure but contains a six-membered ring of carbon atoms with alternating single and double bonds. The last carbon differentiates it from benzene with the presence of a methyl group. This is quite interesting in terms of chemical reaction because it procures it a better trend to react. That is actually why during the tests, we actually diluted the Toluene with Nonane at 50% to reduce the too bright infrared radiation on the combustion chamber walls due to a high rate of reaction.

Both of them undergo combustion reaction by respectively:

\[
2C_6H_{14} + 19O_2 \rightarrow 12CO_2 + 14H_2O + \text{heat} \\
C_7H_8 + 9O_2 \rightarrow 7CO_2 + 4H_2O + \text{heat}
\]

The difference in term of stoichiometric Air/Fuel equivalence ratio is thus more important with the toluene with an order of 13.47, when for the hexane; the value stays around 15 with a calculated value of 15.2. This was important to keep in mind when using toluene because whereas the air mass flow rate was maintained constant around a similar value, the fuel mass flow rate had to be switched in order to achieve the same range of equivalence ratio.
The results are reported on the above two figures 57 and 58. We can notice the similarity in the flame distribution under flameless combustion, describing a conical flame shape from the injectors that ends up well distributed as well horizontally as vertically.

The particular point highlighted here is the high concentration of OH particles at high flame temperature that brings the flame to become rapidly unchanged in appearance while increasing the equivalence ratio. We can actually well see three different steps with a homogenous flame at low $\Phi$, then a structure starting to fluctuate in its lift-off, flow and brightness, and finally a high turbulent structure flame which increases in brightness while going away from lean blow off.

Both of them are presenting poor capacities to react at flameless combustion. The regime is actually transiting to turbulent flame really quickly and for both of them presents bad characteristics in term of homogeneity. Particularly the toluene that not only demonstrates two individual spots of flame at high flame temperature, but also a confinement of the OH particles spread near the injectors. It definitely seems that for both of them, the injection is made less uniform and this impacts the global mélange present in the chamber. The methyl part of the toluene may be highly involve in this behavior, actually especially on the poor display of the flame out of flameless regime while for the hexane it is clear that the increase in its boiling point plays an important role in keeping its injection constant. Unless this consideration, the hexane flame is quite long in term of lift-off in the same way as for the previous one bounded alkanes tested.
Figure 59: Selected OH-LIPF intensity images of flameless oxidation for various equivalence ratios and Nonane as fuel (Tair=525°C, dp=12%, Cross-Flow Injection)
Figure 60: Selected OH-LIF intensity images of flameless oxidation for various equivalence ratios and Jet A as fuel (T_{\text{air}}=525°C, \text{dp}=12\%, \text{Cross-Flow Injection})
The two last fuels that we ran under a pressure drop of 12% and a preheated temperature of 525°C were nonane and Jet A. We depict them at the same time because they demonstrate same characteristic on the injection and have close composition even if they are differently structured. During the tests, we either run from lean bow off limits to non flameless mode or decreased the fuel flow rate in such a way that blow off would end up the set of measurement. However we also, at some points, increased and decreased the fuel flow rate in a same set. This is quite visible in those two last measurements with a change of injection, more fuel being injected by some atomizers than others and resulting in a variation of the OH concentration localization, (flipped from right to left in figures 59 and 60).

Nonane is the following hydrocarbon of the “ane” family (characterized by single bounds) and possesses nine carbons atoms part of its C₉H₂₀ formula. It reacts following the equation:

\[
C₉H₂₀ + 14O₂ → 9CO₂ + 10H₂O + \text{heat}
\]

Jet fuel is a type of aviation fuel designed for use in jet-engined aircraft and permits us to build a direct link between the fuel tests that we ran and the potential application of flameless combustion in gas turbine engine. Jet A is actually the standard jet fuel type in the US since the 1950s and is only available there. Its composition is in grand part made of a long chain of polymers with many secondary hydrogen bonds and close to nonane it has a low autoignition temperature. The nonane response in term of OH chemiluminescence is presented in figure 59 when the Jet A appears on figure 60.
The equivalence ratio was calculated using an Air/Fuel stoichiometric equivalence ratio of 15.18 and 14.66 respectively. The set of pictures follows the results encountered previously with the other liquid fuel.

Near lean blow off, the area of chemiluminescence is slightly confined at the center of the downstream injector zone for the nonane, letting us think that the behavior is not as great as for other first fuels. Still, the OH response keeps on staying low at that point but is far from being as efficient as with butane for instance. The flameless window is actually rapidly transiting to a less stable state when increasing the flame temperature at a higher level than \( \Phi = 0.4 \). On the other hand, with Jet A, we have been able to reach a point highly similar to the one attained with propane or butane, the flame being completely spread around the injector area. The shape of the flame was similar as previously at high equivalence ratio with a Y shape signature: poor OH particles just near the nozzles forming the leg of the Y and two well defined individual zones downstream the nozzles that describe the branches of the Y. This behavior was characterizing generally all the tests with fluctuation on the size of the zones. A general trend was remarkable near phi=0.4 for all of them, the individual injectors flame spread until a point where they all join together and merge to form a single flame that continue to spread itself within the chamber of combustion until a complete distributed flame that was recognized to be the signature of flameless combustion occurring.

If we compare all the pictures within a single fuel, the behavior can be well compared from one picture to another but because the pictures are auto-scaled from their max/min intensity values for better visualization of the flame shape; the comparison from one fuel to the next one is not as accurate.
To solve this dilemma, we plotted picture profiles permitting to better understand the evolution of the fuel flame shape when increasing the flame temperature and put side by side the results for each fuel tested.

The results are shown in figure 61 and figure 62. For a better understanding and characterization, we focused our study on the X-axis by calculating the average Y-axis intensity value for each 1024 X-axis pixels. We then plot the 1024-point curves describing the average shape of the flame for each equivalence ratio. Because the results are more relevant over the radial direction than the axial one, only those curves are shown here. Then, conscious of the fuel and range of equivalence ratio disparities, all the curves were plotted at the same scale of OH intensity and each range of equivalence ratio was color-scaled to better identify curves of same configuration from one graph to another.

The color scale was done as following: for values of Φ<0.4, the color pink was chosen with a gradient of pink thru purple when approaching 0.4. From 0.4 to 0.45, the gradient was blue with a green color when reaching Φ=0.45. The green gradient was used for equivalence ratio from 0.45 to 0.5 with 0.5 values yellow. Finally, an orange gradient was used for values higher than 0.5 and the color red for any curves plotted at high equivalence ratio, i.e. Φ>0.55.
b - Picture Homogeneity Analysis:

![Propane (12%) X Cross Section](image1)

![Propane as a Liquid (12%) X Cross Section](image2)

![Butane (12%) X Cross Section](image3)

![Pentane (12%) X Cross Section](image4)

Figure 61: X Cross Section Average Profiles at selected equivalence ratio for Propane, Propane as a Liquid, Butane and Pentane (Φ color scale: Pink: Φ<0.4, Blue:0.4<Φ<0.45, Green:0.45<Φ<0.5, Orange:0.5<Φ<0.55, Red:Φ>0.55)
Figure 62: X Cross Section Average Profiles at selected equivalence ratio for Hexane, Toluene, Nonane and Jet A (Φ color scale: Pink: Φ<0.4, Blue:0.4<Φ<0.45, Green:0.45<Φ<0.5, Orange:0.5<Φ<0.55, Red:Φ>0.55)
Looking at the results presented in figure 61 and 62, it is quite interesting that the first four fuels tested present big similarities when the four last fuels are similar to each others but quite different from the first ones. Indeed, butane, propane (injected as a liquid or not) and pentane, when ran at low equivalence ratio, showed a good behavior converging to flameless combustion. Each of them allowed a wide range of equivalence ratio to operate at flameless combustion compare to the four last ones. Except butane, they are all basically described by a three-step flame shape with first a well distributed flame characterized by a low flat curve near lean blow off. Then increasing the flame temperature influences the injection with a nozzle presenting a higher flow rate than the others. At that point, the flame transits to a less stable state and presents a drop of the intensity near the injectors. Finally at high equivalence ratio, represented by a redder color, all the nozzles present a well defined individual flame that affect the average intensity curve in a way in which the curve transit to an M-shaped one. The trend transits from flat to one peak and ends up with two peaks. Only the butane seems to not adhere to this transition with a behavior almost all the time describing flameless combustion. Indeed, even at high equivalence ratio, compare to the other fuels, the curves stays quite flat and seems to present only two steps. One at flameless combustion with a constant radial average value and step by step reaching a M-shaped curve characterizing the passage from flameless to non flameless.

For the four last liquid fuels, the trend is similar except that flameless combustion could be seen at only very low equivalence ratio and then the curves rapidly modulated and agreed with the transition to a different state of combustion.
A last analyze of the pictures was performed to quantify their homogeneity. We thus analyzed statistically the spread of the intensity over the whole picture by comparing each pixel values. Actually, the derivation consisted in determining the average intensity value for the whole picture. Then we calculated the spread of each pixel value by evaluation of the standard deviation of the distribution. This calculation was made keeping in mind that the deviation corresponds to the square root of the variance, defined by the squared differences between data points and the mean. Basically, we can formulate our calculus as being the root mean square deviation of the intensity pixels from their arithmetic mean. This calculation has been done for each radial profile to obtain one number characterizing one picture at one state for a particular fuel. The value was finally normalized by dividing the obtained result by the mean. The results of this calculation are presented in figure 63.

![Standard Radial Deviation Normalized](image)

**Figure 63: Standard Deviation Normalized of the fuel imaging measurements**
This last analysis of the pictures permits us to enforce the pertinence of our previous conclusions. Indeed, the graph well agrees with the fact that propane, butane and pentane have similar behaviors near lean blow off with a very low value of deviation at lean combustion that demonstrates the high homogeneity of OH spread with flameless oxidation. Compared to the above pictures, we can remark that flameless combustion could be reached each time the deviation was inferior to 0.2, which for the butane case corresponds almost to the whole set of measurement. The propane had a similar behavior regardless to the injection which actually just switched the curve to higher equivalence ratio when injected as a liquid. All the fuels present a first point (or set of point for the 4 first fuel tested) in or near the flameless combustion zone that well corresponds to the type of combustion observed during the tests at those levels. Unless butane, the low deviation (around 0.1) value at low equivalence ratio then rapidly drops linearly with a relatively high slope that corresponds to the transition to non flameless mode, then finally keeps on increasing when running out of flameless mode but with a break down in the slope. The low equivalence ratio values show us that improving the fuel constitution by adding carbon atoms generally decreased the homogeneity of the flame at which flameless combustion occurs. Comparably, the use of toluene permits us to guess by imaging comparison that the restriction of hydrogen atoms compared to the number of carbon, decreases the ability of the fuel to react at flameless regime even at high autoignition temperature.
2.3.3 - Measurements Related:

a - Heat Release:

The results in figure 64 suggest that recorded OH* fiber optic signal as a function of equivalence ratios for the different fuels exhibits two distinctly different regimes. At lower equivalence ratios, OH is approximately exponential function and then gradually the dependence is becoming linear approximately around an equivalence ratio of the order of 0.45. This trend is almost independent of the fuel investigated. The transition point corresponds to a region where combustion instability occurred and where the visually distributed combustion changed to discrete flames corresponding to individual jets. This is actually exactly in accordance to our previous analysis. We can also notice the change in the nonane and Jet A trends with a drop around the transition point that corresponds to the change in the injection, the fuel being injected back and forth increasing and decreasing its amount.
**b - Emission:**

![CO Emission graph](image1)

![NOx Emission graph](image2)

Figure 65: CO & NO\textsubscript{x} emissions function of equivalence ratio on fuel types

NO\textsubscript{x} and CO emissions are presented in figure 65. As expected at flameless combustion mode, the amount of both CO and NO\textsubscript{x} are quite low.
Fuels effect on NOx production seems to be following the results in term of OH formation and distribution. Both, butane and propane injected as a liquid present very low amount of NOx emission and evolve at the same rate. As we saw in the burner characterization tests, here again, we did not notice an exponential evolution of NOx emission as function of the equivalence ratio. The curves all present a start practically exponential that gradually evolves linearly at high coefficient. Comparing the fuel emissions permit us to conclude that NOx emission is “a priori” function of fuel composition with a general similar trend. This means that NOx emission evolves in the same way from near lean blow off to diffusion flame but do not start at the same value in term of equivalence ratio. Thus, we basically have eight similar curves translated and shifted from each other. We notice that increasing the number of carbon in the fuel molecular formula and actually decreasing the autoignition temperature tends to spread the range of operating combustion equivalence ratio and allows flameless to occur leaner. The injection, looking at the different curves, seems to have an important impact too because for both butane and propane, that were gas injected as liquid, the emissions are lower than all the different liquid fuels. The toluene, probably due to its chemical structure varying from the others, presents higher rate than all the fuel tested and attest the fact that the chemical composition of the fuel and its structure influence the combustion process. The surprising part is that for all the fuel, CO production is similar and does not seem to be influenced by any type of composition.

Figure 66 presents both CO2 and O2 emission and concords with CO in the way in which fuel composition barely affect their production. This let us think that the reaction itself is the same but that the pathways are quite different.
Hence, by changing the fuel composition, we change its ability to react; actually we influence the rapidity of the reaction and thus the capacity to get a complete or not combustion. The composition of the fuel and actually its properties in term of temperature rates highly suggest that the texture and chemical structure, notably by increasing the autoignition temperature and the number of hydrogen atoms compare to the number of carbon atoms and limiting the number of carbons, are key parameters at which importance need to be paid under flameless oxidation.

Figure 66: CO2 & O2 emissions function of equivalence ratio and fuel types
e - Comparison at Low Pressure Drop:

In gas turbine engine, the typical value of pressure drop is very low, usually it hardly goes higher than 5% and 6% is actually not even tolerable. Because our tests have been realized running the combustor at a pressure drop of 12%, we also tried to get some results when using a lower pressure drop. As we could see previously, the fact that all our tests were done at Dp=12% is due to the low fuel viscosity and problems encounters when running the fuel at high air preheated temperature. The relatively high temperatures of oxidizer stream in flameless combustion leads to a faster heating of the liquid fuel. Thus, the increase of liquid/gas interface temperature makes the surface tension decrease leading to a better atomization compare to a similar process without preheating. This effect is stronger when pressure increases. In this case, surface tension decreases, approaching zero when the critical pressure is reached. In this pressure range fuel droplet fragments are formed with no resistance and no further coalescence occurs, as the minimization of surface free energy suggests. The process is actually similar to the one encounter in diesel or gas turbine engine and lead to the fuel evaporation or gasification that leads to pump instabilities, both the pressure and the temperature starting to get to high in comparison of the turbine pump limits. The only solution remained to run at high pressure drop. This actually favors the process of flameless combustion and it is thus interesting to study the actual dependence of the flame characteristics when changing the pressure drop. In the first part of the experiment, we could feel low to no influence from the pressure drop value to flameless combustion parameters. However, we did not study the impact of both pressure drop and change of state of the fuel on the flame itself.
Figure 67 to 69 show the only OH chemiluminescence obtained when running at Dp=3% and using propane, propane as a liquid and nonane as fuel.

Figure 67: Selected OH-LIPF intensity images of flameless oxidation for various equivalence ratio and propane as fuel (Dp=3%)
Figure 68: Selected OH-LIPF intensity images of flameless oxidation for various equivalence ratio and propane as a liquid as fuel (Tair=525°C, Dp=3%, Cross-Flow Injection)
Figure 69: Selected OH-LIPF intensity images of flameless oxidation for various equivalence ratio and nonane as fuel (Tair=525°C, Dp=3%, Cross-Flow Injection)
The three last set of OH intensified images presented in figure 67, 68 and 69 permit us to better understand the impact of the pressure drop on the burner tested at flameless combustion. Because we already made some tests showing the poor influence of the liner pressure drop on emission and temperature mapping, those figures add a new glance by showing the flame evolution. The main conclusion of those tests is obviously that the flame characteristics sensitivity to pressure drop is minimal. Indeed, except for the shape of the flame at high equivalence ratio for propane injected as a gas that describes much more singular jets spot than at higher liner pressure drop, the results are slightly the same and the trend is definitely similar. We find again the fact that the flame shows flameless characteristics at low equivalence ratio, typically under 0.35 which is actually leaner than at higher pressure drop, the results being sort of shift to leaner combustion. Looking at the results obtained in the same way as previously (description p138) in figure 70 and 71, we can recognize similar trends as previously. We can remark that the curves describing the nonane results in figure 70 show a single peak that is typical to poor mixing and weak atomization that we then encountered in all the other fuels tested and did not permit us to obtain stabilized results. Those three compared results act more as qualitative results and permit us to believe that the results described at higher liner pressure drop are actually the one that we can expect at lower pressure drop such as 3%. Indeed, because a gas turbine engine will lose efficiency for each additional air pressure drop taken across the combustion liner, those results are of a big interest and suggest us to look in the future in favoring higher pressure fuel rates than pressure drops to favor flameless combustion at reasonable gas turbine engine conditions.
Figure 70: X Cross Section Average Profiles at varied equivalence ratio for Propane, Propane as a Liquid and Nonane (Tair=525°C, dp=3%) (Φ color scale: Pink: Φ<0.4, Blue:0.4<Φ<0.45, Green:0.45<Φ<0.5, Orange:0.5<Φ<0.55, Red:Φ>0.55)
In this second part of experiment, the main purpose was to obtain further information concerning the development of flameless combustion. Because of a lack of information and a real difficulty in understanding its mechanism, we realized both a test at high and low pressure drop (for the one we could obtain) for different type of fuels having in mind the effect of chemistry influences such as structure, autoignition temperature and type of injection. At the end, the results were quite relevant even if not quantitative enough and permitted us to conclude in a great potential utilization of flameless combustion in such a difficult type of system that are gas turbine engine. Except for the n-butane that particularly showed good behavior and quite surprising data, all the other fuels globally presented similar trends with a preference for high autoignition temperature ones and concurred in the existence of common intermediate reaction that are rate limiting instead of having the rate reaction sensitive to the fuel.
3 - CONCLUSION

This thesis has been investigating on combustion and actually a particular type of combustion that one would call particular regime of combustion but which has been commonly called “Flameless combustion”.

After a quite exhaustive literature review on the subject, we could recognize the characteristics of “flameless combustion” to be its low emission level of CO and NOx even when running very lean with very stable limits in term of instabilities and uniformity. The particularity of occurring with a well distributed flame similar to the well stirred combustion type is due to the fact that recirculation exhaust gases into the reaction zone and using preheated gases at high turbulence level allow the fuel and gas to mix faster than the necessary time for the reaction to be completed. Therefore the reaction rate is reduced when the mixing of the reaction improves. This behavior is well understood and has been well studied over the last decade but an important point that could also be noticed in our literature review is the poor amount of explanation on the mechanism itself. Indeed, a lot of experiments could demonstrate under which conditions flameless combustion occurs but none of them could clearly define the mechanism itself. It is actually still unexplained from a chemical point of view and that is why the main purpose of this thesis was to obtain more information, both quantitative and qualitative, that could permit a better understanding of the pathway involved and then in the future adapt such a type of combustion to gas turbine engines.

The next step was thus to realize tests in an actual burner. That is what has been done using the Goodrich Aerospace/UC burner mounted on the low pressure combustor facility available at the University of Cincinnati.
The task was then divided in two parts, first the characterization of the burner itself and then a deeper research on its flameless domain.

The burner was studied evaluating the influence of two main elements in flameless combustion that are the preheated temperature of the oxidizer and the pressure drop value of the combustor that for a typical gas turbine engine can not exceed 5 to 6%. Tests at preheated temperature of 325°C, 425°C and 525°C and pressure drop of 3%, 4% and 5% were then run while measuring the emission, the heat release, the temperature and the acoustic answers. The results demonstrated a poor effect of both the preheated temperature and the pressure drop value with curves approximately the same at similar temperature of combustion. However it could be well seen that for lean value of equivalence ratio, the higher the preheated temperature and the pressure drop were, the better flameless combustion occurred. Indeed, at 5% of pressure drop and a preheated temperature of 525°C the combustion was found to be well distributed over the whole volume of the chamber of combustion and demonstrated very low values in terms of CO and NOx emission as well as thermoacoustic instabilities.

Curious to understand more about the phenomenon itself, we then started a second set of experiments comparing different types of fuel that were propane (injected as a gas and a liquid) butane (injected as a liquid), pentane, hexane, toluene, nonane and Jet A. The conclusion was similar for all the fuel tested with slight differences between each other except for the n-butane that demonstrated a surprisingly good behavior with a wider range of operational flameless combustion. Because the reaction seemed (from OH chemiluminescence images) to be in general the same but with different pathways it appears that only intermediate reaction common to all the fuel tested are rate limiting.
Comparing all the different results for every fuel at flameless regime, it seems clear that the mixing characteristics under which flameless occurs have a main impact on the particular production of CO and NOx typical to that type of combustion. As we could see, the best results encountered were the one when using high autoignition temperature fuel. Indeed, flameless occurs when the oxidizer is preheated at a temperature higher than the autoignition temperature of the fuel, which was the case for all of our case. Increasing the autoignition temperature however decreases the tendency of the fuel to initiate faster and thus the main element to control is the rate of reaction to allow a great mixing while initiating quickly. That is why looking for fuel with high autoignition temperature may be a good start to operate flameless combustion in gas turbine engine to both influence the ignition and at the same time limiting the time of the reaction for mixing considerations.

Because the reaction seemed to be much different with toluene and propane, having both of them high autoignition temperature, it would be interesting to elaborate a new grid of experiments that would permit a better understanding of this behavior (comparing toluene and octane for example). Actually both the number of hydrogen atoms while compared to the number of carbon atoms and the autoignition temperature seem to mainly influence the results and acting in the same way. That is why a great step for future testing resides in identifying the chemical species at the origin of the process. This requires performing tests using a planar laser induced fluorescence system (PLIF) which is available at the University of Cincinnati. This would allow quantifying the concentration of different species such as OH at each step of the reaction and giving better information on the localization of those species.
Adding a particle image velocimetry test (3D stereoscopic PIV) would permit to visualize the reacting flow and identify the flow field.

Both of those tests, PLIF and PIV, require the construction of a special chamber of combustion that would allow a fast cleaning of the chamber walls. Indeed, during the combustion tests, if no measures are taken, the burnt particles would quickly form a layer on the quartz chamber and yield erroneous results. That is why in the last annexes are presented the potential drawings of the required chamber, squared with detachable windows (for easy cleaning) that should be used with the same system to realize PLIF and PIV experiments. The addition of those tests would probably give a much bigger identification and understanding of flameless combustion and allow a sharper optimization for its future use in potential system such as gas turbine engines. This would need further investigations but for sure yield evolution.
REFERENCES:


APPENDIX:

1-Procedure for the Flameless test:

The first step would be to check all the connections which correspond to the different variables measured. Also we take in consideration that at this point of the test (just before starting it up) all the combustor is assembly and every circuits are well screwed.

Then, the procedure of test is split on different parts, which are the following ones:

0) **Pressure supply:**

Before starting any test you need to turn on the pressure which aliments several test supplies (which means that you need to be awarded of the eventual tests running at the same time).

Hence in case that it has not been done, turn on the alimentation valve which controls the Low Pressure system of the laboratory.

(Normally the pressure doesn’t have to be more than 175 psig and usually its value turns around 150 psig)

1) **Air supply:**

Start up the wind tunnel (turn on the pump which ventilates the top of the combustor).

---

---
2) **Water supply:**
Turn on the on/off valves that control the water supply (used for cooling the facility).

![Image](image.png)
(if the valve is perpendicular to the water pipe, it means that the valve is off, otherwise it is on)

3) **Fuel supply:**

The fuel supply is turned on only during the real test (before it’s needed to start the acquisition programs, turn on also the emission system (and calibrate it if necessary) and check everything on the rig (aluminum on every wires to avoid them to burn, check that the facility is safe and **plug the security valve**).

4) **Test procedure:**

For each test we have a specific matrix. In the case of a flameless test we will have different inlet/outlet on the matrix. Most of the time the parameters which will change during the test would be the nature of the fuel, the preheated air temperature, the size of the quartz cylinder (chamber of combustion), and finally the pressure drop.

- Hence, first we decide the nature of the fuel and then we print the sheet test associated with this fuel, which will give you some information about the rate of flow you need to start your test and how make it evolve in order to reach near the lean blow off limits (the temperature of the test and the pressure drop are some elements that will influence it).

- Then you take in consideration the temperature parameter of the test and you configure it at the one you want (For example 325, 425 or 525 C)
Test procedure:

- Use the Air supply cupboard to put the value of the pressure drop that you want (for example 3%, 4%, 5%)

Turn the temperature system ON

Enter the temperature that you want and wait until the top value of the temperature (which is the actual one on the supply) is the same than the one above (the wished one)

Select the value of the pressure drop (which opens more or less the air valve above the cupboard) using the sheet that give you the proportionality between the value that you want and the displayed value.
- Then you open the fuel valve and you use the valve of regulation to regulate the value of the flow rate that you’re looking for (you find the value on the test sheet corresponding to the fuel, temperature and pressure drop, then you read it on the flowmeter).

At this time you can start the data acquisition and acquire, hence all the values are saved on an excel file that you named in function of the test that you are doing (date, fuel, pressure drop and temperature).

- Then using the test sheet you decrease the value of the fuel flow rate step by step until you reach the state of lean blow out (characterized by the fact that you almost don’t have a flame anymore and you hear less and less of noise).

- When the flame disappears you turn off the On/Off valve and you go to see the time trace of the variables on the acquisition program. You wait a moment until stabilization and then you stop acquire. You will reach at this time on a page of the program that will propose you to start a new test.
If you want to make a new test you change the name of the file by the parameters corresponding to the next test and then you can wait until you want to start acquire.
Finally you configure the facility another time (change the temperature if necessary, change the pressure drop or even the fuel or the quartz chamber)

- When everything has been set up again you can restart acquire and redo everything until you have finished your test matrix.

⇒ Finally you just have to do the reverse way and turn off everything.

2-Data Acquisition:

Before each test it’s advised to print the “Set up sheet” corresponding to the wished test and check that all the channels correspond to what we want.
(For instance a ‘Flameless test’)

Then check the feedback of the channels to know if they are on the good position on the data acquisition board (DC or AC). For example, during the “flameless test” all the channels must be connected as DC because they vary from 0 to 10V except one channel, the #10 which correspond to the Pressure Mic and needs to be connected on AC (because it varies around 0). Thus, it is advised in case that we are not sure of the connections, to check that every parameter is on the good position.

After this we can start the acquisition computers: (knowing the password *********)

- On the right computer we open the program: “combustion Avg data acquisition”
- On the left computer we open the program called: “Combustion simul IV”
(knowing that as a preliminary all the channels are created on the National Instrument system and directly linked to the Lab VIEW programs)

Use of the data acquisition program:

- First of all start the program by pushing the running button (on the two programs, knowing that the second one is directly connected to the values of the first one)

- Then, the first step of the program is to load the data corresponding to the desired test, in the case that it’s the first run, one does not have to load anything, just continue on the next page and regulate the different parameters (offset and factor) in order to obtain a satisfactory trace of the different channels. However if it is not the first run, one usually load the last data saved during some previous test to ensure a continuity along the tests.
- The file loaded, we arrive on the channel set up page on which we check that they are all identified and correspond with the one on the data sheet.

- The third page corresponds to the loading of the fuel parameters following the test that you are running.

- Then you configure the file set up by creating a file path in which you will save the specific data that you want to keep during the test (cf the explanations of the writing acquisition farther) and describe the particularities of the test.

- Finally before arriving on the proper acquisition page you can make the choice to save or not all the values of the test, usually to not save some real big files it’s chosen to avoid the safeguard of the entire test and just keep its appropriate testing parts using the writing path.

- The last page is the acquisition one and aims to show a time trace as well as the average value of the whole recorded channels.
During the test you can also choose to acquire some specific parts by pressing the acquire button. This will directly send a signal to the other program informing you that the current values are saved and you can then carry out a real test (for instance the research of the Lean Blow Out moment during a flameless test)
• **Load set-up:**

  - Available windows
  - Ability to load previous conditions
  - Load them
  - Or keep the default case and go directly to the **next step**

Front Panel
• **Channel set-up:**

Scan rate and number of samples to regulate the acquisition speed and accuracy.

**Set-up all the channels** corresponding to the sensors and linked by the acquisition card (NI).

Enter values’ name, unities and some eventual corrective factor or offset.

Go to the next step.
• **Fuel and Air set-up:**

  - Set-up the **Fuel** conditions with the appropriate stochiometric ratio.
  - Same thing for the **Air**.
  - And finally the **Pilot** parameters.

  Go to the **next step**.
• **File set-up:**

![Diagram showing file setup](image)

- Test and choice of the variables required during the acquisition.
- Creation of a path with a description for each test and with the possibility to save it in the future.
• **Data acquisition: (left side)**

Front Panel

![Diagram of data acquisition interface]

- **Time trace** of the selected variables
- Control of the acquisition
- Variables choice

(See right side)
(See low part)
• Data acquisition: (right side)

Stop
the acquisition in any case

Instantaneous value of the selected channels

Choice operating channels

Research of the zero values
• Data acquisition: (low part)

**FFT trace** (amplitude and phase) of the selected channels with peak cursor

**Peak detector**: number, position, value

Parameter setting of the peak detector and the FFT averaging

---

High Pressure Combustor 13
• **Save Set-up:**

Save the file choosing the appropriate path

Make the final choice to save or do not save the corresponding data statement

→ At this state, one is actually at the end of the test, you clear it and are ready for some new samples statement restarting (or resetting) the program.
3-Procedure for the emission system calibration:

The emission system needs to warm up during 30 minutes before any handling so the first thing to do will be to start it up turning all the switches on (on the front of the device for the NOX one and on the back for all the other ones).

After, in order to calibrate it you need to follow the following steps:

(Keep in mind that a brochure exists for this device explaining everything about the behavior of the machine and how to calibrate it. Thus the purpose of this procedure is to get familiar with the different elements of the machine and not an accurate description that you can find in the Gas Analyzer brochure).

1) Start Up
2) Turn ON the bottles
3) NOX calibration
4) CO, CO2, O2 calibration
5) HC calibration
1) Start up the machine: (wait 30 mn)

2) Turn ON the Bottles:

⇒ Turn ON the Air compressed (bottles on the left) until 24 psig

⇒ Turn ON the gas compressed (40%hydrogen, 60%helium) bottle (on the right) until 20 psig and let the Nitrogen one at Zero (which is going to be use for the Zero calibration).

At this time of the procedure we have all the elements regulated to start the calibration of the emission system.
3) NOX calibration:

(this one fluctuates so the manipulation needs to be done a few times until we arrive to a steady value).
For the calibration we use the screen and the keyboard that we find on the analyzer.

- We go on the main menu (clicking Main)

→ We need to save the calibration and use a password each time one calibrates:
  • set up (F5)
  • password (F5)
  • system operator (F4)
  • enter
  • password (F4 F4 F4)

- Back to the main menu (Main)

→ Check the sample tank:
  • set up (F5)
  • calibration setting (F2)
  • span gas calibration (F1)
Then you check the value of the sample bottle that you’re going to use

- Back to the main menu (Main)

→ Calibrate:
  • calibration (F4)
  • manual calibration (F2)
Disconnected the sample pipe on the back of the NOX analyzer and connect the one of the Nitrogen bottle instead (that you take from the tri valve connection. Turn ON the nitrogen until 5 psig.
  • zero gas calibration (F1) wait until stabilization then (F1) to come back in the previous menu
Turn the Nitrogen OFF and disconnect its sample pipe to connect the NOX sample bottle instead. Turn ON the bottle.
  • span gas calibration (F2) wait until stabilization then (F1)

→ Redo it a few times (zero and sample bottle calibration until a steady value then you are done for the NOX calibration
4) CO, CO2, O2 calibration:

For this calibrations, you follow exactly the same steps than previously knowing that for the CO and the CO2 gas value are pretty stable hence the handling need to be done only one time (on the opposite the O2 gas need to be done at least 2 times)

→ To change the gas analyzed you use the arrows of the keyboard (watch the principal screen) and choose the gas that you want to calibrate between CO CO2 and O2.

ATTENTION: after those two part calibrated, do not forget to screw back the Nitrogen pipe on the tri valve connection and the sample tube on the sample gas inlet either.

5) HC calibration:

This calibration is different (because it does not need the use of the nitrogen to calibrate the zero) and usually much more sable than the others:
- Turn the switch button on ZERO
- Use the ZERO button to regulate the value at zero
On the back of the analyzer you connect the HC sample bottle on the span inlet
- Turn the switch button on SPAN
- If the value is different than 500 then regulate it until you get 500 (it corresponds to the value that you find on the sample bottle)
- Turn the switch button on SAMPLE
4-MATLAB code for Data Analysis:

clear all
close all
format compact
format short e

% ***** input variable for performing fourier transform *****
fs = 6000; % frequency data was taken at (Hz)
tavg = 1;  % time for individual fft to be averaged (sec)
tover = 0.5; % time to overlap averages (sec)
tset = 60;  % time over which to perform each fft (sec)
tstep1 = tavg*fs; % converts time interval to average over into number of data points
tstep2 = tover*fs; % converts time interval to overlap into number of data points
tsetstep = tset*fs; % converts time interval for sets into number of data points
dynChan = 5;

% ***** Plotting variables for Averaged ************************************
xmina1 = 0.20;
xmaxa1 = 0.70;
ymina1 = 0.010;
ymaxa1 = 1500.0;

xmina2 = 800;
xmaxa2 = 1400;
ymina2 = 0;
ymaxa2 = 300;
ymina3 = 0;
ymaxa3 = 5;

% ***** Plotting variables for Dynamic ************************************
xmind = 0.20;
xmaxd = 0.70;
ymind = 0;
ymaxd = 3000;
zmind = 0.0001; %0.001; %0.00001;
zmxd = 0.10;  %10.0;  %1000;
xtxt = -900; % -900 for 0-2500Hz range, -450 for 0-1000Hz range, -150 for 0-400Hz range
ytxt = 1;

% ***** input variables for average data files *****
RowStart = 12;  % row to start reading in from average data file (in order to skip header)
ColStart = 0; % column to start reading in from average data file

afs = 1000; % frequency at which data was recorded for averaging file
samp = 250; % number of samples for which data was recorded for averaging
avgtime = samp/afs; % time interval for which data was averaged

style = 1; % data processing style: 1 - averages by equivalence ratio and processes
dynamic file
  % 2 - averages by traverse position (for temperature traverse)
if style == 1
  Accur = 0.025; % change in phi or traverse position from first set value that is
considered a different ratio
else
  Accur = 0.25;
end

SRUN = 1; % start run - run number to start analysis
ERUN = 9; % end run - run to end analysis

% *** Dynamic data file
%PcCOL = 10; % column of data that is the combustor pressure for dynamic
data file
%OHCOL = 11; % column of data that is OH* for dynamic data file

% *** Averaged data file
% **** Column positions of parameters ****
timePos = 1;
WaPos = 2;
PplPos = 3;
TplPos = 4;
WftPos = 5;
PfPos = 6;
TfPos = 7;
TcmbPos = 8;
Tex2 = 9;
Tex3 = 10;
TrecPos = 11; %11;
PcmicPos = 12; %12;
OH1Pos = 13; %13;
OH2Pos = 14; %14;
OH3Pos = 15; %15;
CO2Pos = 16; %n/a;
COPos = 17; %n/a;
O2Pos = 18; %n/a;
NOPos = 19; %n/a;
UHCPos = 20; %n/a;

PhiPos = 21; %17;
dpPos = 22; %18;
travPos = 17; %16

OHPos = OH1Pos;

if style == 1
    StepPos = PhiPos;
else
    StepPos = travPos;
end

%OHPos = 11;
%PplkisPos = 15;
%FuelSplitPos = 17;
%dpPos = 19;
%PhiPos = 20;

EmissionStart = CO2Pos;
EmissionStop = UHCPos;
DataColumns = dpPos; %17; %20; %22

Wfmin = 0.005;
Phimin = 0.05;
OHLBO = 0.001;
timeshift = 15; % delay time (sec) in emission reading

% *** Number of Runs to Process determination ****
NUMRUNS = (ERUN - SRUN)+1; % number od runs to analyze
count = 2; % variable for plotting - tracks number of figures
k = 1; % variable for plotting - tracks number of plots per figure

DPHILBO = zeros(NUMRUNS,3);
n = 1;

% filepath to read raw data from
filepath1 = 'C:\Documents and Settings\racine\My Documents\01 RESEARCH
DATA\RAW DATA\Flameless\tests 2006-08-24\';
% filepath to write processed data to
filepath2 = 'C:\Documents and Settings\racine\My Documents\01 RESEARCH
DATA\PROCESSED DATA\Flameless\tests 2006-08-24\';
% file prefix for raw data file to read in
fileprefix = 'test 20060824';
for i = SRUN:1:ERUN
    if count > 1
        clear DATAA DATAPhiAVG DATAD DATAP1 DATAF Fp phiRng;
    end
    disp(['Run ', num2str((i-SRUN)+1), ' of ', num2str(NUMRUNS)])
end

% **** generates filenames for files to be opened ****
if i < 10
    filename1 = [filepath1,fileprefix,'-00',num2str(i),'.dat'];
    filename2 = [filepath1,fileprefix,'-00',num2str(i),'.dyn'];
    filename3 = [filepath2,'Processed Phi Avg test ',fileprefix,'-00',num2str(i),'.dat'];
elseif (i < 99 & i >= 10)
    filename1 = [filepath1,fileprefix,'-0', num2str(i),'.dat'];
    filename2 = [filepath1,fileprefix,'-0', num2str(i),'.dyn'];
    filename3 = [filepath2,'Processed Phi Avg test ',fileprefix,'-0',num2str(i),'.dat'];
else
    filename1 = [filepath1,fileprefix,'-', num2str(i),'.dat'];
    filename2 = [filepath1,fileprefix,'-', num2str(i),'.dyn'];
    filename3 = [filepath2,'Processed Phi Avg test ',fileprefix,'-',num2str(i),'.dat'];
end

filename4 = [filepath2,'Processed Phi LBO Limit ',fileprefix,'.dat'];

% !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
% AVERAGED DATA FILE PROCESSING !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
% !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
% **** opens averaged data file and locates point where fuel is turned
% this point is then determined for the dynamic file data of later use

DATA0 = dlmread(filename1,'t',RowStart,ColStart);
[DROW0 DCOL0] = size(DATA0);

if style == 1
    datashift = timeshift/avgtime;
    % shifts data to account for emission time delay
    DATA1(1:(DROW0-datashift),1:(EmissionStart-1)) = DATA0(1:(DROW0-
    datashift),1:(EmissionStart-1));
    DATA1(1:(DROW0-datashift),EmissionStart:EmissionStop) =
    DATA0((datashift+1):DROW0,EmissionStart:EmissionStop);
DATA1(1:(DROW0-datashift),(EmissionStop+1):DCOL0) = DATA0(1:(DROW0-
datashift),(EmissionStop+1):DCOL0);
    [DROW1 DCOL1] = size(DATA1);
    % *** determined fuel shut-off point ****
else
    DATA1 = DATA0;
    DROW1 = DROW0;
    DCOL1 = DCOL0;
end

if style == 1
    for j = (1:DROW1)
        if (DATA1(j,WftPos) <= Wfmin)
            ShutOff = j-1;
            break
        end
    end
else
    ShutOff = DROW1;
end

% Creates final data set for averaged data that compensates for time
% offset of emissions and stops when fuel is shut off
DATAA = DATA1(1:ShutOff,:);
[DROWA DCOLA] = size(DATAA);
clear DATA0, DATA1;

pk = 1;
phiRng(pk) = 1;

Sphi = DATAA(phiRng(pk),StepPos); % starting phi
Uphi = Sphi + Accur; % upper phi limit (deviation from start)
Lphi = Sphi - Accur; % lower phi limit (deviation from start)

Navg = 1;
numphii = 1;
phiAvg(numphii,1) = Sphi;
phiAvg(numphii,2) = 0;
DATAPhiAVG(numphii,:) = DATAA(1,2:DCOLA);
phiLBO = 0;
for jj = 2:DROWA
    Cphi = DATAA(jj,StepPos);
    if Cphi > phiLBO %Cphi > Phimin % if DATAA(jj,OHPos) > OHLBO
        if ((Cphi < Lphi) | (Cphi > Uphi))
            pk = pk + 1;
            phiRng(pk) = jj; % sets position in matrix of each new phi set
        end
    end
end
\[ S\phi_i = \text{DATAA}(\phi_i\text{Rng}(pk),\text{StepPos}); \quad \% \ \text{starting } \phi \\
U\phi_i = S\phi_i + \text{Accur}; \quad \% \ \text{upper } \phi \ \text{limit (deviation from start)} \\
L\phi_i = S\phi_i - \text{Accur}; \quad \% \ \text{lower } \phi \ \text{limit (deviation from start)} \]

\[
\text{DATAPhiAVG}(\text{numphi},:) = \text{DATAPhiAVG}(\text{numphi}, :) / \text{Navg}; \quad \% \ \text{averages all values for given } \phi \\
\phi\text{Avg}(\text{numphi}, 1) = \phi\text{Avg}(\text{numphi}, 1) / \text{Navg}; \quad \% \ \text{average } \phi \ \text{values together} \\
\text{phiAvg}(\text{numphi}, 2) = \text{Navg}; \quad \% \ \text{increments } \text{numphi} \\
\phi\text{Avg}(\text{numphi}, 1) = S\phi_i; \quad \% \ \text{initializes next } \phi\text{AVG} \\
\%\phi\text{Avg}(\text{numphi}, 2) = \text{Navg}; \quad \% \ \text{number of points averaged for eqv ratio} \\
\text{DATAPhiAVG}(\text{numphi}, :) = \text{DATAA}(jj,2:\text{DCOLA}); \quad \% \ \text{initializes next } \text{DATAPhiAVG} \\
\text{Navg} = 1; \quad \% \ \text{resets number of points to average} \\
\text{else} \\
\text{DATAPhiAVG}(\text{numphi}, :) = \text{DATAPhiAVG}(\text{numphi}, :) + \\
\text{DATAA}(jj,2:\text{DCOLA}); \\
\phi\text{Avg}(\text{numphi}, 1) = C\phi_i + \phi\text{Avg}(\text{numphi}, 1); \\
\text{Navg} = \text{Navg} + 1; \\
\text{end} \quad \% \ \text{end if} \\
\text{end} \quad \% \ \text{end loop } jj \\
\text{if } \text{numphi} > 1 \\
\text{numphi} = \text{numphi} - 1; \\
\text{end} \\
\quad \% \ \text{Determines LBO point} \\
\text{if } \text{style} == 1 \\
\text{if } ((\text{DATAA}(jj, \text{OHPos}) <= \text{OHLBO}) \& (\phi_i\text{LBO} == 0)) \\
\phi_i\text{LBO} = \text{DATAA}(jj,\text{PhiPos}); \\
\phi_i\text{LBO}(n,1) = \phi_i\text{LBO}; \\
\phi_i\text{LBO}(n,2) = \text{round}(\text{mean}(\text{DATAA}(:,\text{dpPos}))); \\
\phi_i\text{LBO}(n,3) = \text{round}(\text{mean}(\text{DATAA}(:,\text{TplPos}))); \\
\text{end} \\
\text{end} \\
\text{end} \quad \% \ \text{end loop } jj \\
\text{end} \quad \% \ \text{Determine LBO point} \\
\text{if } \text{numphi} > 1 \\
\text{numphi} = \text{numphi} - 1; \\
\text{end} \\
\text{[dummy numrng]} = \text{size}(\phi\text{Rng}); \\
\text{pk} = \text{pk} + 1; \quad \% \ \text{increments counter } pk \\
\phi\text{Rng}(pk) = \text{DROWA}; \quad \% \ \text{sets end of data set for } \phi\text{Rng} \\
\phi\text{Rng}(2:\text{numrng}) = \phi\text{Rng}(2:\text{numrng}).*(fs*\text{avgt ime}); \\
\quad \% \ \text{plotting purposes} \\
\% \ \text{for } kk = 1:\text{numphi} \\
\% \quad \phi\text{Avg}(2(1:(\text{tstep1/2})+1),kk) = \phi\text{Avg}(kk);
if numphi > 1
    for m = 2:numphi
        phiMax(m-1) = phiRng(m) - phiRng(m-1);
        end % end loop m
    MaxRngPhi = max(phiMax());
else
    MaxRngPhi = mean(DATAA(:,PhiPos));
end

% *** Writes data out to file ********
dlmwrite(filename3,DATAphiAVG(1:numphi,:),'	');

% !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
% DYNAMIC DATA FILE PROCESSING !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
% !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
if style == 1
    % **** loads dynamic data file ****
    DATAD = dlmread(filename2,'	',RowStart,ColStart);
    [DROW2 DCOL2] = size(DATAD);

    % **** determines frequency range for FFT ****
    f1 = (fs*(0:(tstep1/2))/tstep1)';
    [Nrow Ncol] = size(f1);

    % **** creates new matrix of perturbations from the mean value over
    % desired interval ***
    DATAP1 = zeros(DROW2,DCOL2);
    for j = 1:DCOL2
        DATAP1(:,j) = DATAD(:,j) - mean(DATAD(:,j));
        end % end loop j
    [DROW3 DCOL3] = size(DATAP1);
    DATAF = zeros(Nrow,dynChan,numphi);

    % **** loop that cycles through dynamic data channels ****
    for numCh = 1:dynChan
        switch numCh
            case 1
                chan = 2;
            case 2
                chan = 3;
            case 3

chan = 4;
case 4
  chan = 5;
case 5
  chan = 6;
otherwise
  break;
end % end switch
disp(['     chan ',num2str(numCh), ' of ', num2str(dynChan)])

% **** averages the data by the specified averaging interval ('tavg')
% overlapping the time intervals by which to average by 'tover' by
% running through each discrete equivalence ratio and finds fft for
% that phi
for r = 1:numphi % loop through equivalence ratios
  Navg = 1;   % number of averaged intervals
  % averages together short interval fft's (given by small specified time)
  startPhiLim = phiRng(r);
  stopPhiLim = phiRng(r+1);
  for s = startPhiLim:tstep2:stopPhiLim % loop to average each point of
    equivalence ratio
      nextstep = s + tstep1;
      if nextstep > DROW3
        nextstep = DROW3;
      end
      % *** performs FFT ***
      fftx = fft(DATAPI1(s:nextstep,chan));
      Fp = fftx(1:Nrow)/tstep1;
      if Navg == 1
        DATAF(:,numCh,r) = 2*abs(Fp);  % creates a new matrix for each phi
       data set
      else
        DATAF(:,numCh,r) = DATAF(:,numCh,r) + 2*abs(Fp);  % adds values
       for average time interval together
      end % end if
      Navg = Navg + 1;
    end % end loop s
    DATAF(:,numCh,r) = DATAF(:,numCh,r)./Navg;  % divides the data by the
       number of intervals that have been added together
  end % end loop r

  n = n + 1;

disp('   Writting FFT Files . . .')
% writes data file for each equivalvence ratio containing FFT
% results for each dynamic channel
for p = 1:numphi
    if i < 10
        filename5 = [filepath2,'Processed FFT ',fileprefix,'-00',num2str(i),' phi ',num2str(phiAvg(p,1),'.2f'),' N ',num2str(phiAvg(p,2),'.1f'),'.dat'];
    elseif (i < 99 & i >= 10)
        filename5 = [filepath2,'Processed FFT ',fileprefix,'-0',num2str(i),' phi ',num2str(phiAvg(p,1),'.2f'),' N ',num2str(phiAvg(p,2),'.1f'),'.dat'];
    else
        filename5 = [filepath2,'Processed FFT ',fileprefix,'-',num2str(i),' phi ',num2str(phiAvg(p,1),'.2f'),' N ',num2str(phiAvg(p,2),'.1f'),'.dat'];
    end % end if
    dlmwrite(filename5, [f1 DATAF(:,1:dynChan,p)],'	');
end % *** end of main loop (number of runs)

disp('     Calculating LBO Limit . . .')
numtemp = 1;
tempindex(numtemp,1) = 1;
[LBOcount, dummy] = size(DPHILBO);
Tstart = DPHILBO(1,3);
TU = Tstart + 25;
TL = Tstart - 25;
for gg = 2:LBOcount
    Tcur = DPHILBO(gg,3);
    if ((Tcur < TL) | (Tcur > TU))
        numtemp = numtemp + 1;
        tempindex(numtemp,1) = gg-1;
        numtemp = numtemp + 1;
        tempindex(numtemp,1) = gg;
        Tstart = Tcur;
        TU = Tcur + 25;
        TL = Tcur - 25;
    end
end
numtemp = numtemp + 1;
tempindex(numtemp) = LBOcount;

m = 1;
TEMPS = zeros(numtemp,1);
for hh = 2:numtemp
    if (tempindex(hh) - tempindex(hh-1)) > 1
        TEMPS(m,1) = round(mean(DPHILBO(tempindex(hh-1):tempindex(hh),3)));
        m = m + 1;
    end
end

-188-
end

% *** Writes data out to file ********
dlmwrite(filename4,DPHILBO,"\t");
end

disp('PROCESSING COMPLETE !)
5-Previous Burner Design

**Previous Burner Design:** Siemens Flameless Injector Derived from Winning EU Program

- Rig of 12 Fuel Injectors
- Burner Face
- Injection Tip: 4 Gaseous Fuel Jet at 45°

6-New Burner Design and Drawings:

A new flameless burner design was implemented, utilizing high swirling flow in conjunction with circumferential fuel jets to obtain intense mixing with swirling flow (patent impending).

6 Fuel injectors in tube with Jet into the Recirculation Zone

- 0.8 Flow Number Pressure Atomizer
- Air Swirl Holes
- Fuel Manifold

Swirl chamber and Injectors
NOTES:
1. USE 1/8" OD STAINLESS STEEL SEAMLESS TUBING WITH 0.049" WALL THICKNESS (MEAN DIAMETER 0.785 +0.003 / -0.000"
2. START WITH TUBE OF LENGTH 12.5" AND ROLL TUBE TO INNER DIAMETER OF 3.75 +0.002 / -0.000"
AND WELD SEAM
3. RAMP TUBE BEFORE ROLLING- ENDS TO OVERLAP WHEN ROLLED

DRILL #38 THRU HOLE ON ONE SIDE (6 PLACES EQUALLY SPACED)

DRILL #34 THRU HOLE ON ONE SIDE (2 PLACES EQUALLY SPACED)

<table>
<thead>
<tr>
<th>PART</th>
<th>DESCRIPTION</th>
<th>FEEDBACK</th>
<th>MATERIAL</th>
<th>TOLERANCE</th>
<th>NOTE</th>
<th>DRAWN BY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

University of Cincinnati

Fuel Manifold Ring
Straight Section

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>FINISH</th>
<th>QUANTITY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

Angled Injection Fuel Line Assembly Weldment

<table>
<thead>
<tr>
<th>PART</th>
<th>DESCRIPTION</th>
<th>FEEDBACK</th>
<th>MATERIAL</th>
<th>TOLERANCE</th>
<th>NOTE</th>
<th>DRAWN BY</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

-194-
NOTES:
1. Use 7/16"-12 X 36 Stainless Steel Rod
   (McMaster 0954X0203)
NOTES:
1. USE 1/4" 303 STAINLESS STEEL ROD
   (McMaster 90644232)
NOTES
1. USE 1/4-20 THREADED 3/4" STAINLESS STEEL ROD
7-NEW CHAMBER OF COMBUSTION

Following are the drawings for the chamber of combustion required to realize PLIF and PIV test in good conditions.
1 - Drill and Tap 0.25" deep Hole for 1/4"-20 threaded fastener (2 places)

2 - Drill and Tap 0.15" deep hole for 1/4"-20 threaded fastener
Use ........

1. Machine 9.70 x 9.70 square hole 0.25 deep
2. Drill clearance thru hole for 7/8" threaded fastener (4 places)
3. Drill thru 10" diameter hole
4. Drill clearance thru hole for 1/4" threaded fastener including head (4 places)
1. Drill and tap 0.2" deep hole for #10-24 threaded fastener (2 places)

2. Drill and tap 0.2" deep hole for #4-40 threaded fastener (8 places)
1 - Drill clearance thru hole for 4-40 Threaded fastener (8 places)
1 - Drill Clearance thru hole for 1/4" threaded fastener
1 - Drill and tap thru hole for 1/2" threaded fastener (Swagelok fitting) (20 places)

University of Cincinnati

Plug Wall

Title:

Diagram:

Dimensions:

18.00

7.50

0.25

Comments:

See DWG. NO. R14-BFG-810

Rev. A

Sheet 1 of 1
View of the window (scale: 1:3)