Suppression of Combustion Instability in Gas Turbine Combustion Chamber

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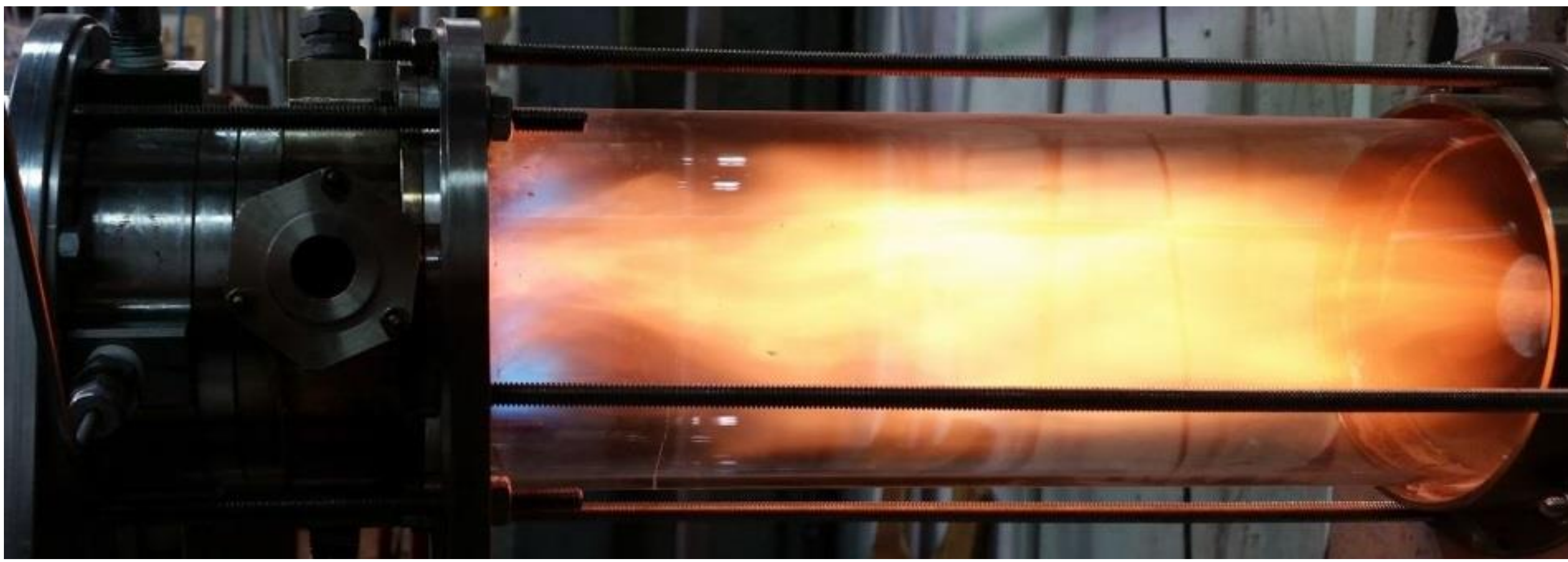

Faculty of Aerospace Engineering, Technion, Haifa, Israel November 17 2016

Turbo & Jet Engine Laboratory

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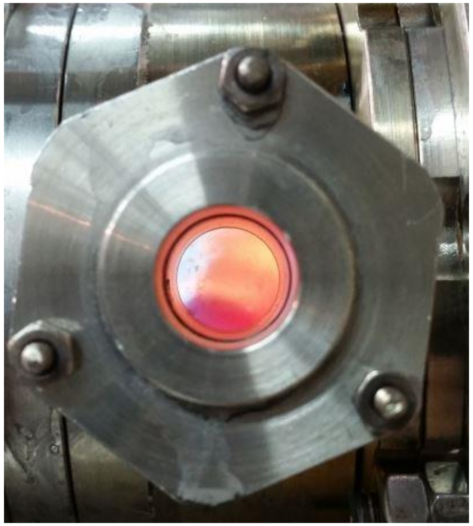
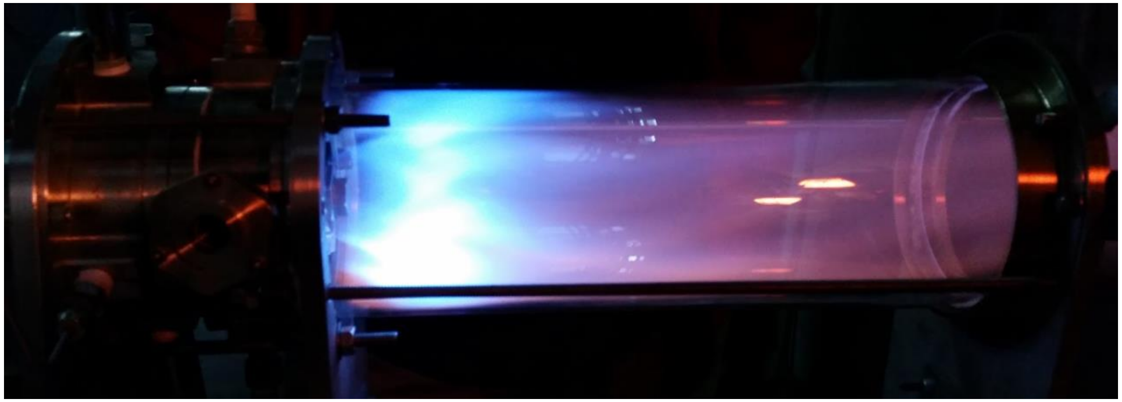
Content of Presentation

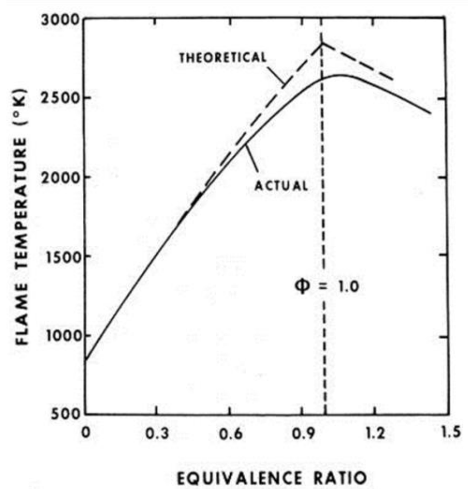
- Introduction
- Free Radicals
- Chemical Kinetics Simulations
- Radicals Generator
- Test Rig Description
- Results
- Conclusions





Introduction

- NOx emission restrictions led to improved combustion methods
- NOx formation requires high activation energy and hence high reaction temperature
- Lean Premixed Combustion method for Ultra NOx combustion (potentially >10ppmv)
- Well premixed mixture → $T_{combustion}$ is a strong function of ϕ
- Low ϕ combustion → Low flame temperature

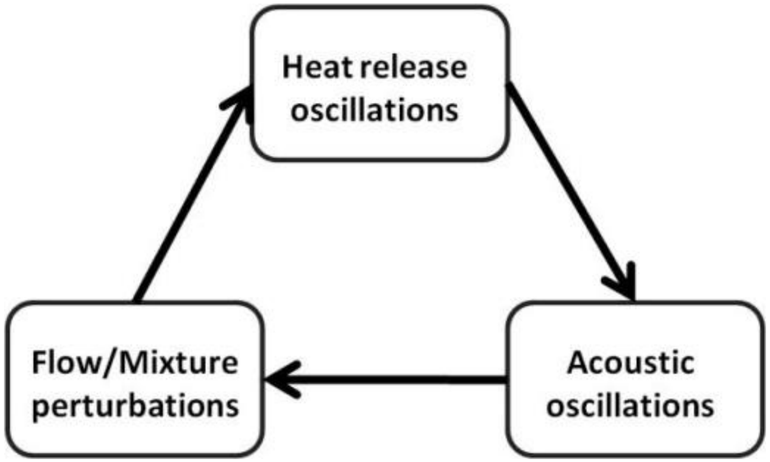


*Oates, Gordon C. *Aerothermodynamics of aircraft engine components*. Aiaa, 1985.

Introduction (cont.)

Drawbacks of Lean Premix Combustion:

- Operation near the Lean Blow Off (LBO) limit causes combustion instability
- Closed Loop: Acoustic Oscillations → Flow and Mixture Perturbations → Heat Release Oscillations → Acoustic Oscillations

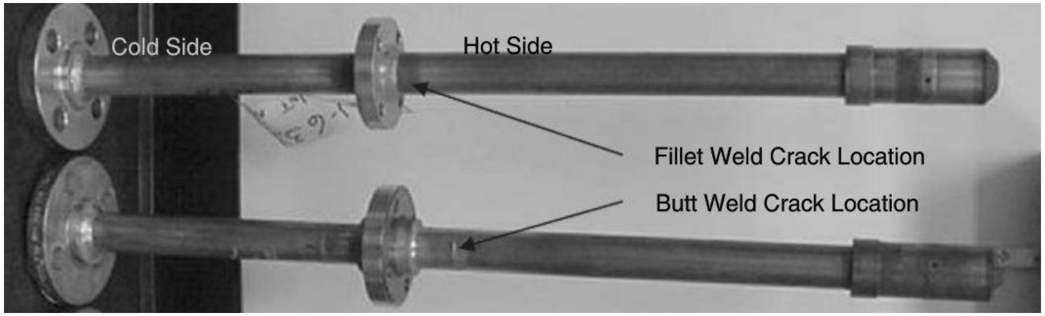


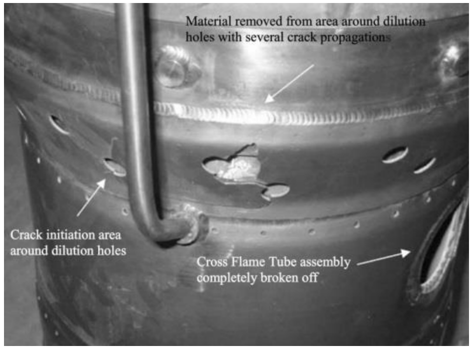
$$\iint_{V\,T} p'(x,t)\cdot q'(x,t)\,dt\,dV \geq \iint_{V\,T} \sum_{i} L_i(x,t)\,dt\,dV$$

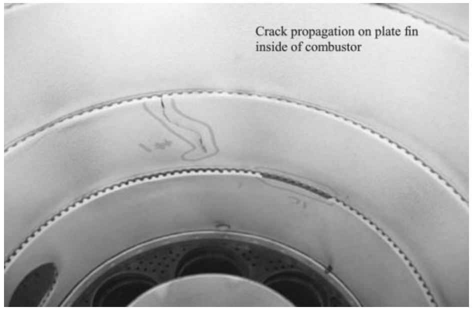
HEAT ADDED DAMPING ENERGY

Introduction (cont.)

- Developed Acoustic Oscillations cause:
  - Combustion Blow Off and Flame Flashback
  - Increased Fatigue Wear
  - Enhanced Heat Transfer to the Liner Wall
  - Control System Interference
  - Components and Engine Failure

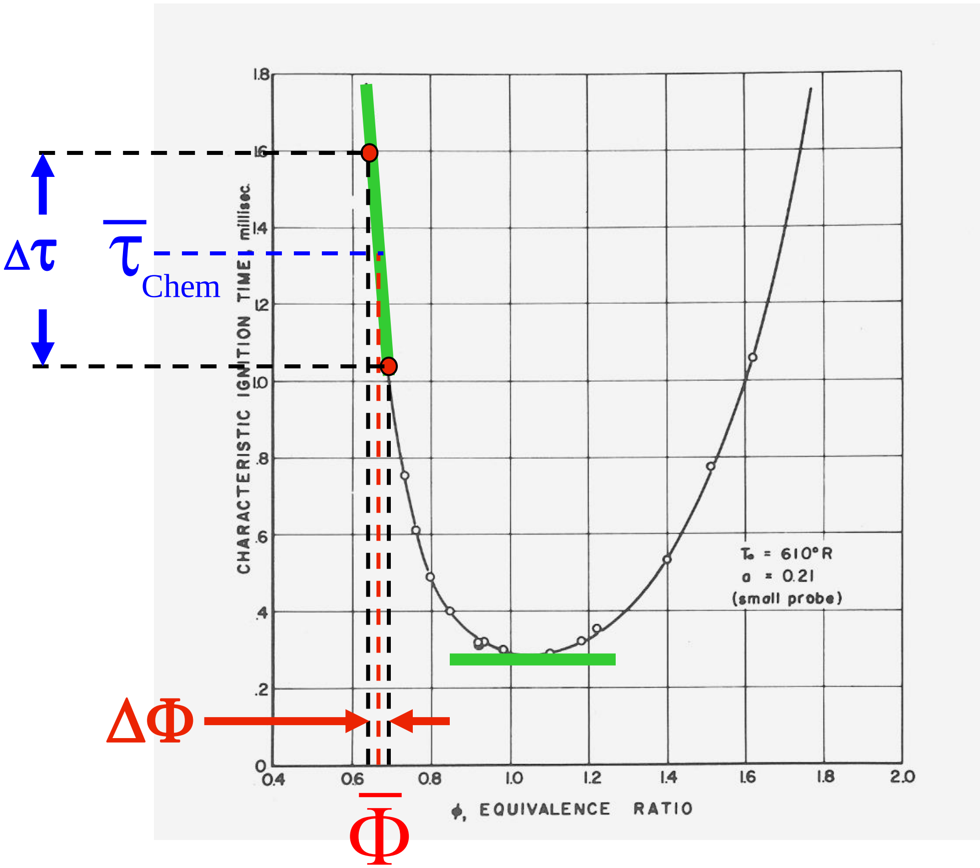






*Sewell, Jesse, Pete Sobieski, and Craig Beers. "Application of continuous combustion dynamics monitoring on large industrial gas turbines." *ASME Turbo Expo 2004: Power for Land, Sea, and Air*. American Society of Mechanical Engineers, 2004

Introduction (cont.)



- Small changes in ϕ → large changes in τ
- Large changes in τ → large changes in q’
- Free radicals have high reaction rate
- Injection of free radicals → small changes in τ

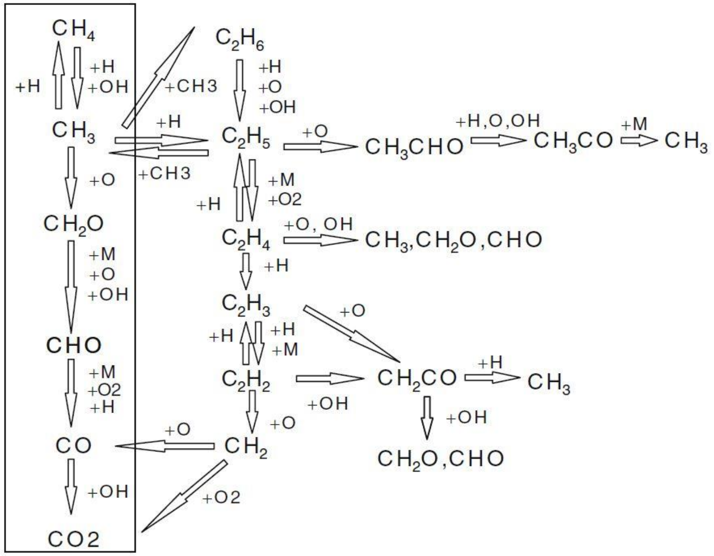
*Oates, Gordon C. *Aerothermodynamics of aircraft engine components*. Aiaa, 1985.

Free Radicals

- Global reaction of combustion:

$$CH_4 + 2\cdot(O_2 + 3.76N_2) \leftrightarrow CO_2 + 2H_2O + 2\cdot 3.76N_2$$

- In real life the reaction of combustion contains tens of thousands of reactions and hundreds of intermediate species



Simplified flow diagram for methane combustion

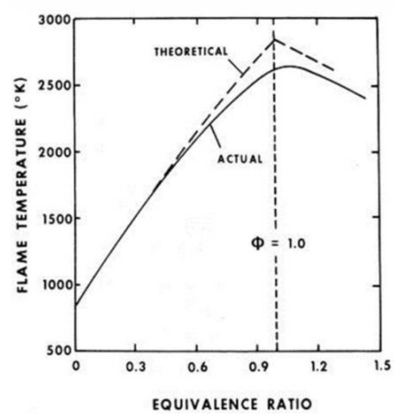
*McAllister, Sara, Jyh-Yuan Chen, and A. Carlos Fernandez-Pello. *Fundamentals of combustion processes*. Springer, 2011

Free Radicals

- These species are called free radicals
- Their main characteristics are:
  - Unstable
  - Very reactive
- Examples of free radicals: H, **OH, CH*,** CH_2, CH_3, C_2H, C_2H_2, C_2H_3, C_2H_4 and more.

Radicals Generator

- Additional small combustion chamber (pilot) is operated at very rich equivalence ratio (non-complete combustion) to generate the radicals
- Pilot's exhaust is connected to the main combustor such that the pilot exhaust gases are injected into the main combustor primary zone
- Products of incomplete combustion contain free radicals and CO (which is also flammable)
- Lack of oxygen (rich ϕ) inside the pilot prevents NOx formation. The resultant CO is burned inside the main combustor

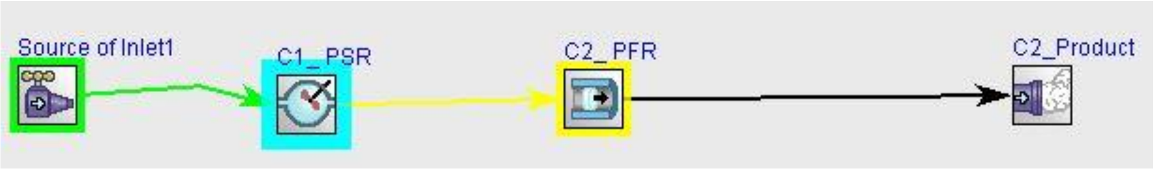


*Oates, Gordon C. *Aerothermodynamics of aircraft engine components*. Aiaa, 1985.

Chemical Kinetics Simulations

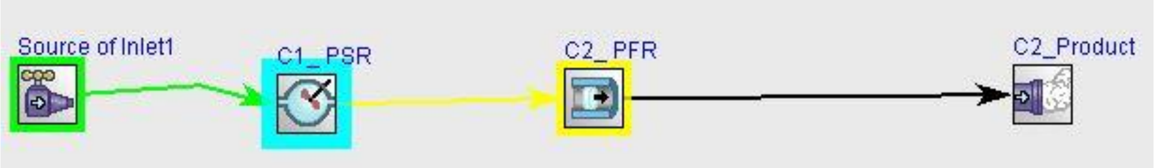
- In order to predict the composition of the pilot's exhaust gases towards appropriate design of the pilot, chemical kinetics simulations were run using CHEMKIN PRO software

- The simulation system:



- Source of Inlet – Initial Conditions
- PSR – Perfectly Stirred Reactor
- PFR – Plug Flow Reactor
- Product – Products of PFR

Chemical Kinetics Simulations



- Summary of the simulation results and conditions:

Operating conditions

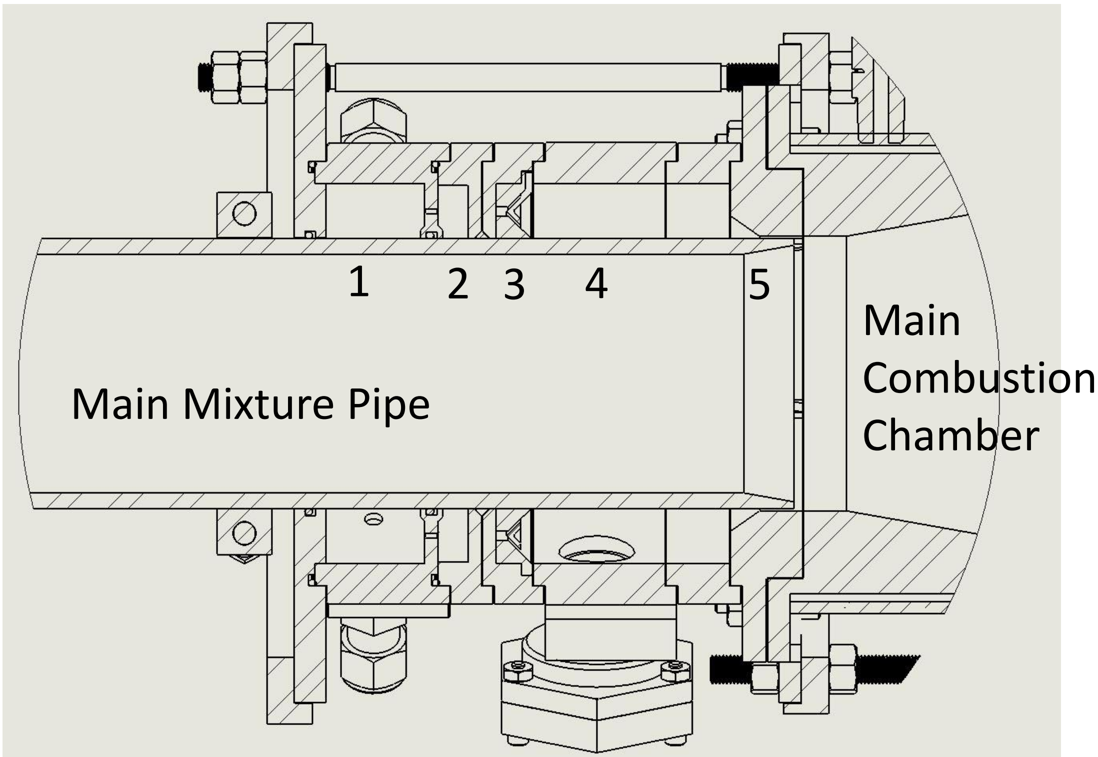
Pressure [atm]	1
PSR Temperature [K]	2000
Residence Time [s]	0.053
Equivalence Ratio	2
Heat Transfer Coeff. [W/m*K]	35
Chemical Mechanism	GRI3.0

Simulation results

Species	LHV [kJ/kg]	Mole Fraction	
		Adiabatic	Heat Loss
CH3	60194.1	0.00033	0.000078
C2H	58988.3	0.00000019	0
C2H3	53595.7	0.0000026	0.0000008
C2H5	51900.3	0.000001	0.0000075
C2H2	48298.1	0.018	0.001
C2H6	47617.4	0.00003	0.00105
C2H4	47249.1	0.0005	0.0137
OH	33085.4	0.0000135	0.000001
CH4	50000	0.0085	0.0195
H	121000	0.000175	0.00001

Radicals Generator (cont.)

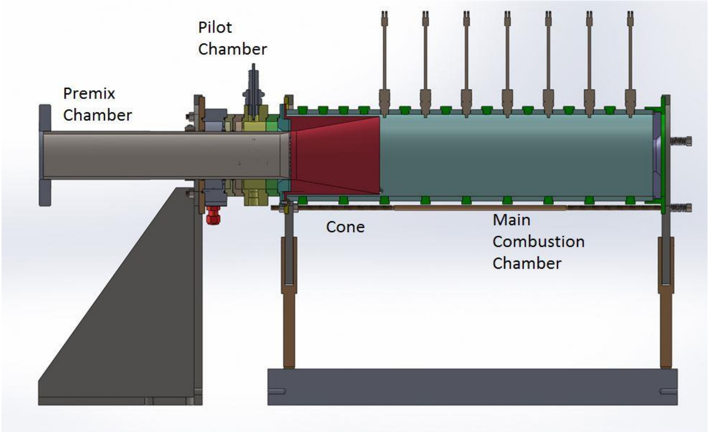
- Radicals generator was designed and operated according to the chemical kinetic simulation results



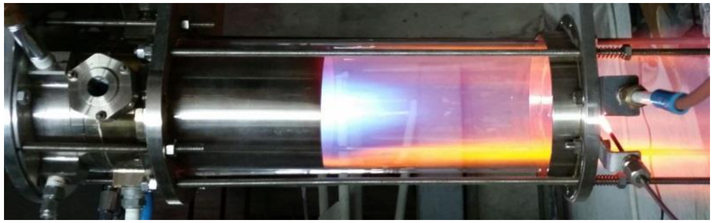
1. Primal chamber
2. Premix chamber
3. Flame holder
4. Combustion chamber
5. Exhaust

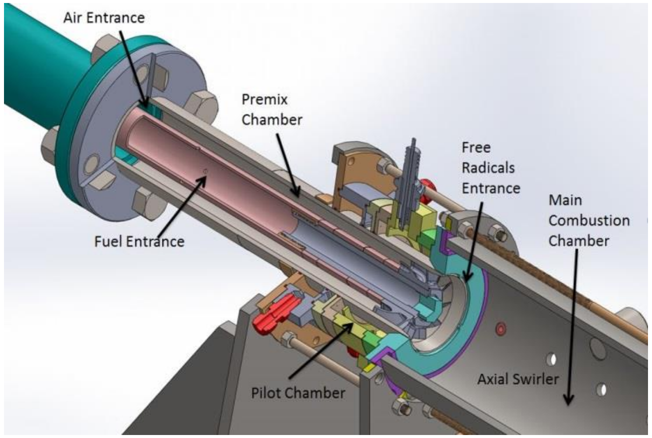
Main Combustion Chamber

- Two configurations of main combustion chamber were tested:
  - Configuration A with gradually diverging cone
  - Configuration B with swirler and sudden flow expansion



Configuration A



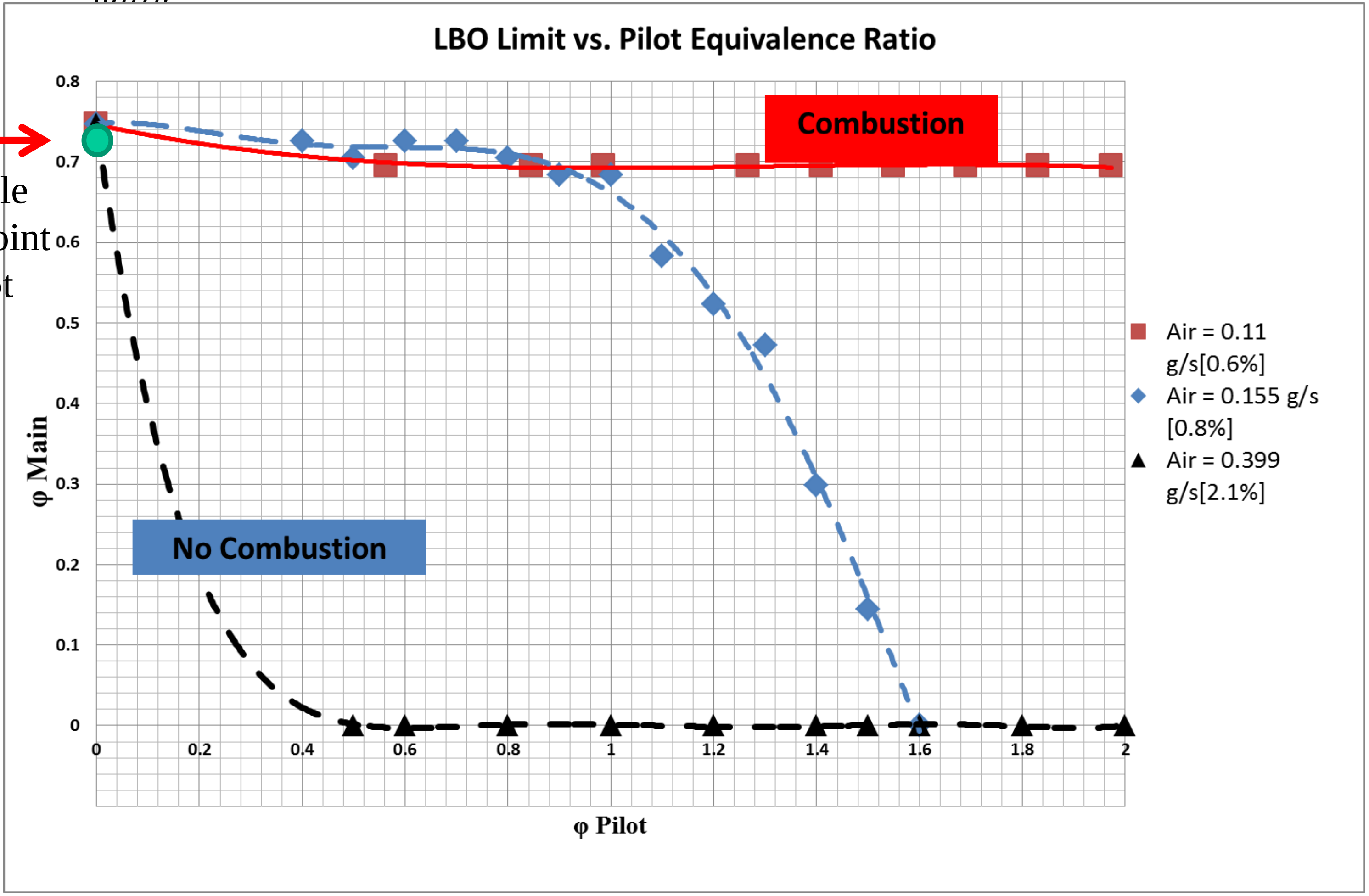


Configuration B

Results – LBO Limit

- The effect of free radicals injection on LBO limit was studied:
  - $\dot{m}_{fuel_{main}}$ – gradually decreased
  - $\dot{m}_{air_{main}}$ – const.

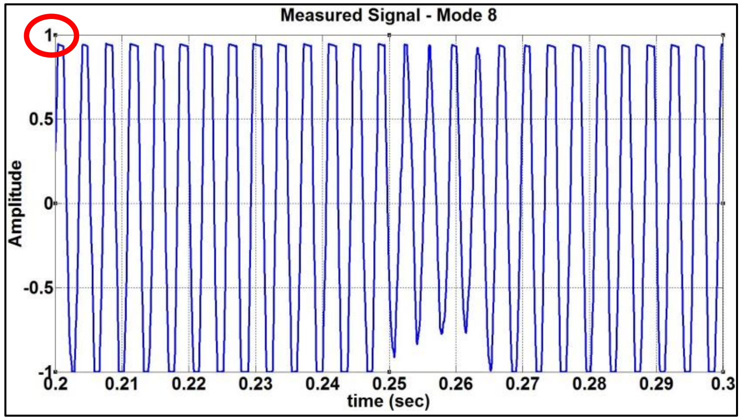
Lowest stable operation point without pilot

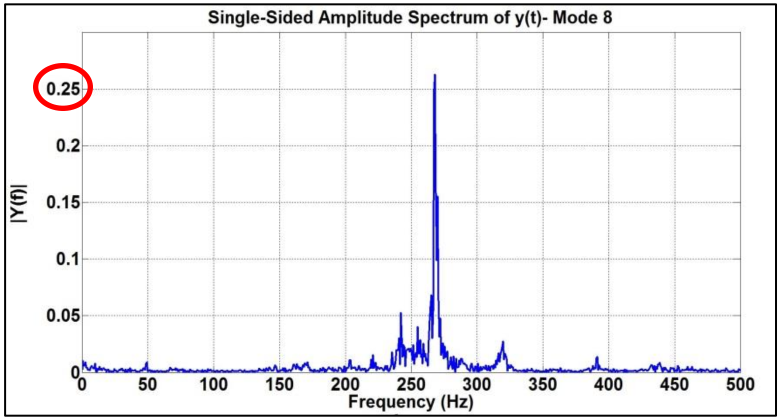


Results – Medium Frequency Oscillations

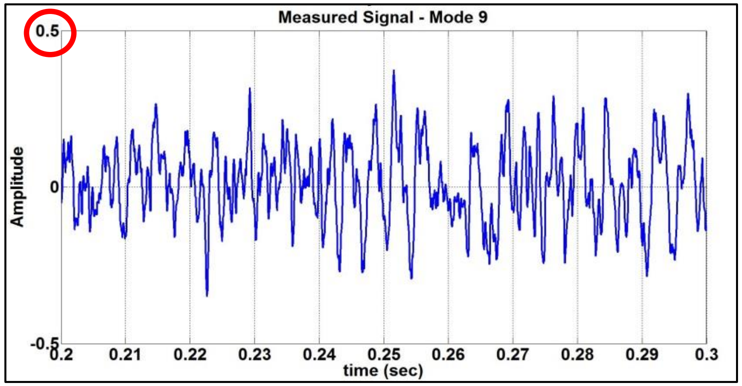
- The medium frequency instability oscillations were suppressed by injection of free radicals into the primary zone of the main combustor. Total amount of fuel was kept constant

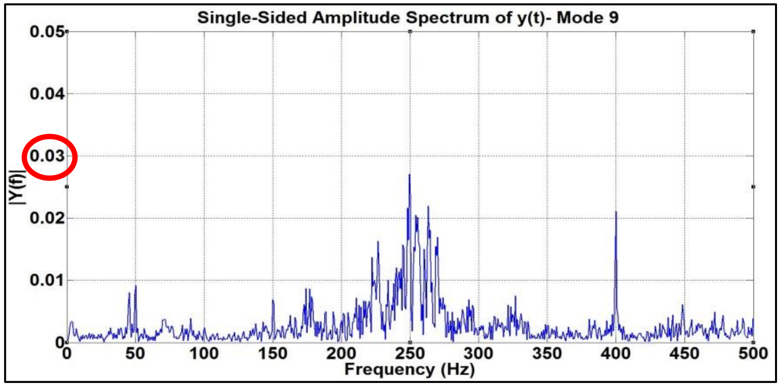
Unstable
No Pilot





Stable
With Pilot





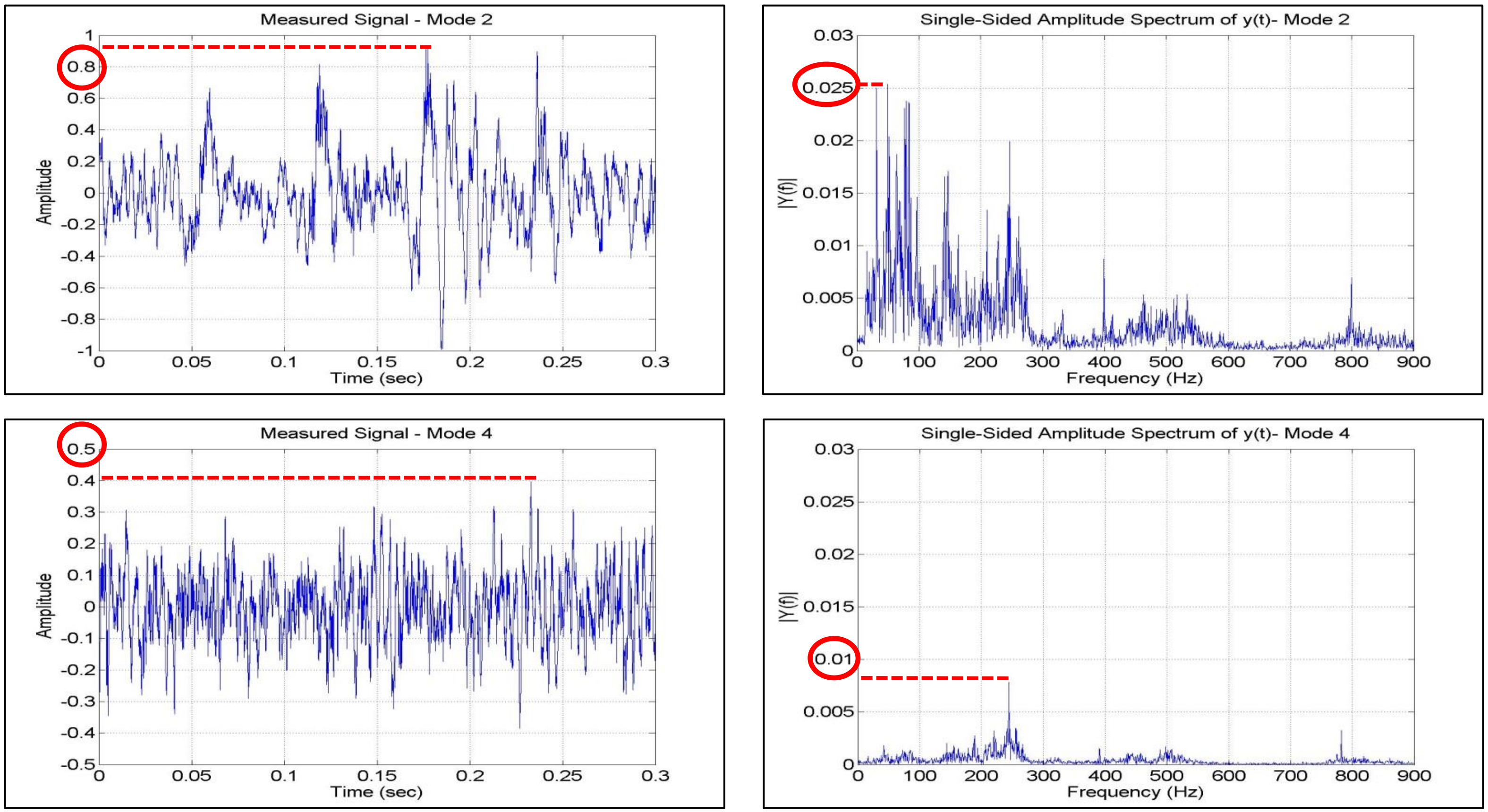
Free radicals suppress the medium frequency instability

Results – Low Frequency Oscillations

- The low frequency instability oscillations were suppressed by injection of free radicals into the primary zone of the main combustor. Total amount of fuel was kept constant

Unstable
No Pilot

Stable
With Pilot



Free radicals suppress the low frequency instability

Conclusions

- The effect of free radicals injection on combustion instability was studied
- Experimental test rig was built based on the chemical kinetics simulations
- LBO limit can be lowered by the injection of the radicals
- Acoustic oscillations (middle and low frequency) caused by the combustion instability could be successfully suppressed by the injection of free radicals

Future Work