Flameless Combustion Application to Gas Turbine Engines

Ben Zinn and Suresh Menon

School of Aerospace Engineering

Georgia Institute of Technology

Georgia Institute of Technology THE OHIO STATE UNIVERSITY FAMU Florida A&M University CWRU CASE WESTERN RESERVE UNIVERSITY

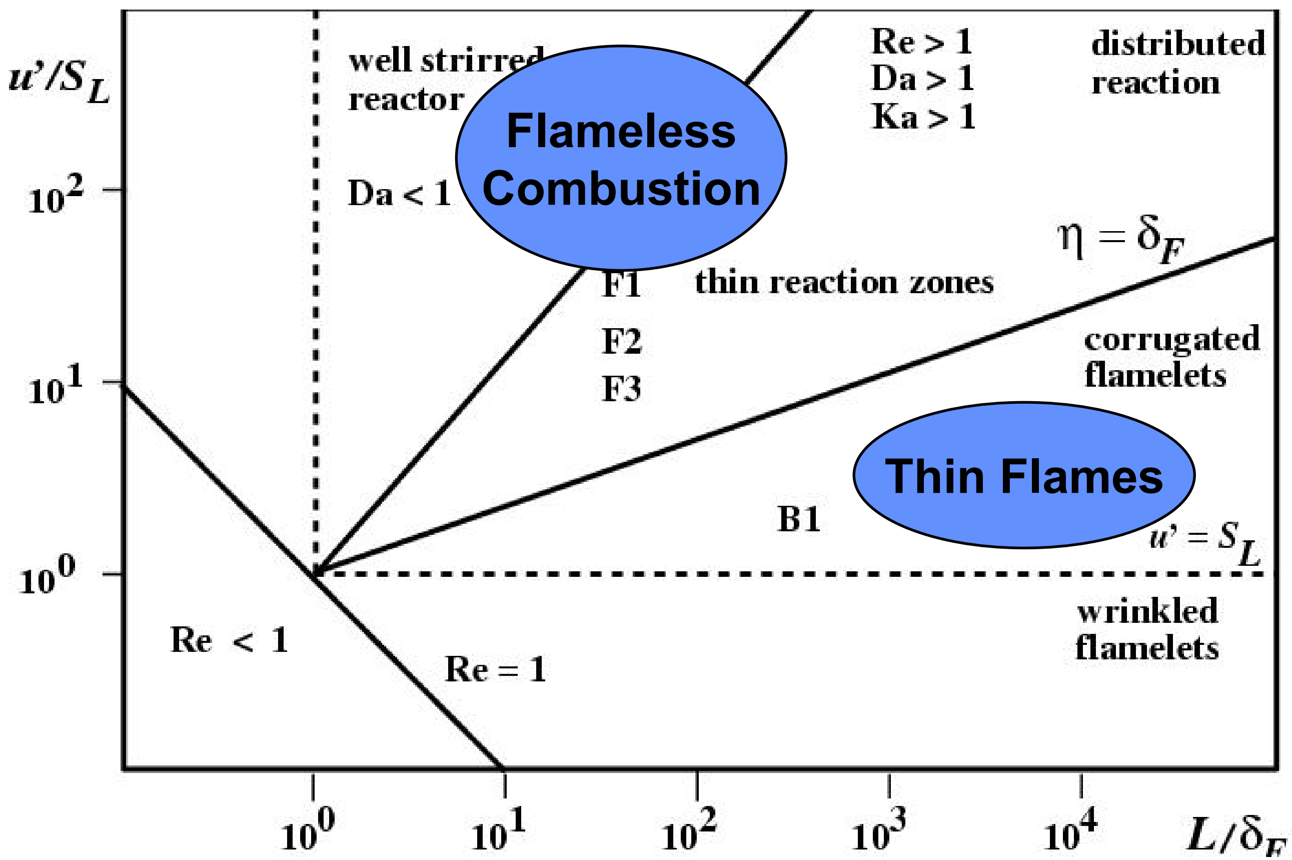
Flameless Combustion

- Combustion without a flame
  - premixing fuel and/or oxidizer **separately** with re-circulated exhaust gases before letting the reactants to mix
- Re-circulation of exhaust gases
  - Increases the inert content of the fresh mixture
  - Raises the temperature of the fresh mixture
- High combustor temperature and large re-circulation rate allows **very lean** fuel-air reaction to occur in a "stable" flameless combustion mode
- Significant reduction in NOx emission (< 10 ppm)
  - Thermal and Prompt NOx production is drastically reduced
- Combustion "noise" almost eliminated

Physics of Flameless Combustion

- Preheating and premixing with inert hot products increase residence time
- Chemical and flow time scales are of similar order
  - Kinetics slow enough to allow prior mixing between reactants and products
- Diffuse reaction zone with no temperature "spike"
- Heat generation is uniform in the entire reaction zone
- Distributed Reaction Zone or (nearly) Well-Stirred reaction zone combustion
  - Turbulence is very high in the mixing region
  - Actual turbulent burning speed is also high
  - Burner size can be reduced

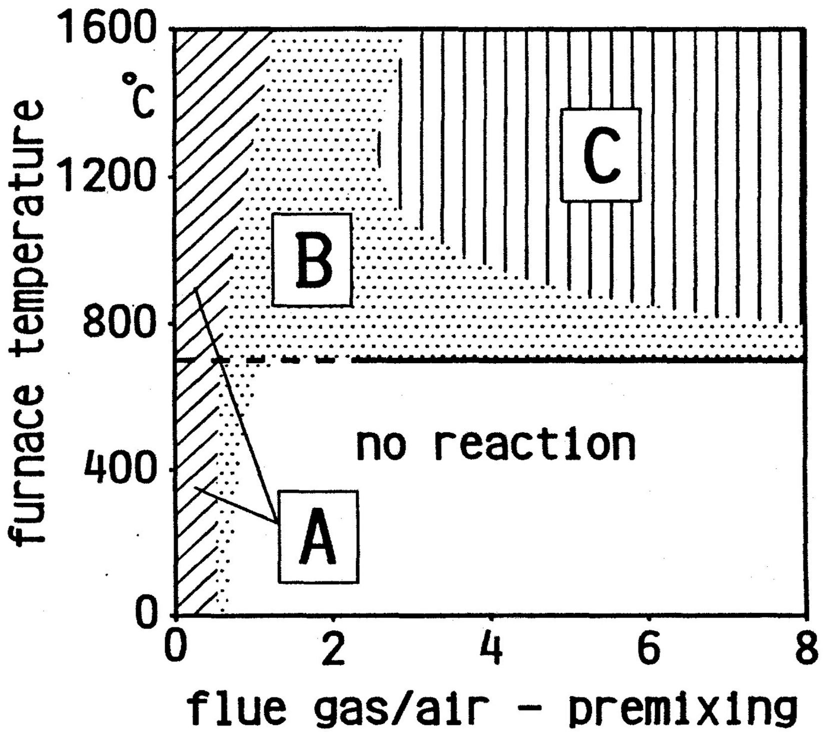
Regimes of Premixed Combustion



Past Studies of Flameless Combustion

- All reported studies are for
  - Furnaces, Regenerative Burners, High velocity Burners, etc.
  - Natural gas, Diesel and heavy fuel oil successfully used
  - Atmospheric pressure combustion
- Significant design issues identified in past studies
  - mixing process is critical to achieving flameless combustion
  - Local Damkohler number must reach O(1) (flow time = chemical time)
  - Fuel and air injection strategies need to be optimized
  - Optimize the amount/method of re-circulation of burnt gases
- Fundamental limitation is that Flameless combustion not possible in a "cold" combustor

Regimes of Flame and Flameless Combustion



$$K_V = \frac{\dot{M}_{St}}{\dot{M}_L + \dot{M}_{Br}} - 1$$

(Wunning et al., 2000)

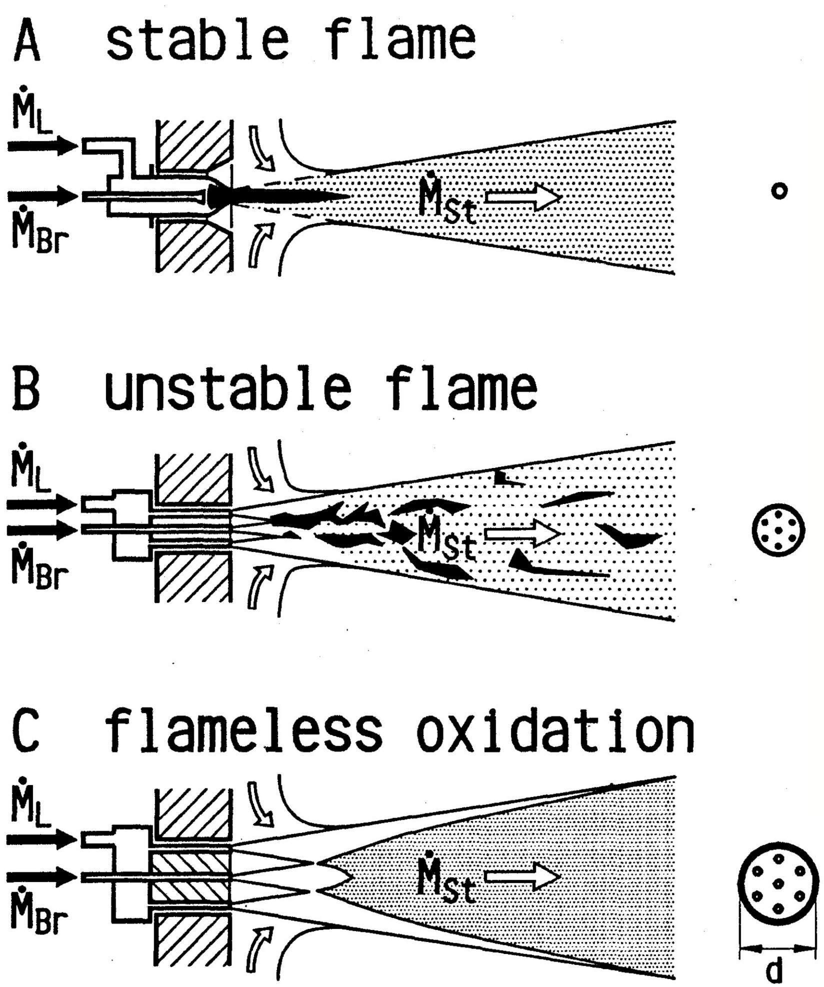
A: Stable Flame Combustion

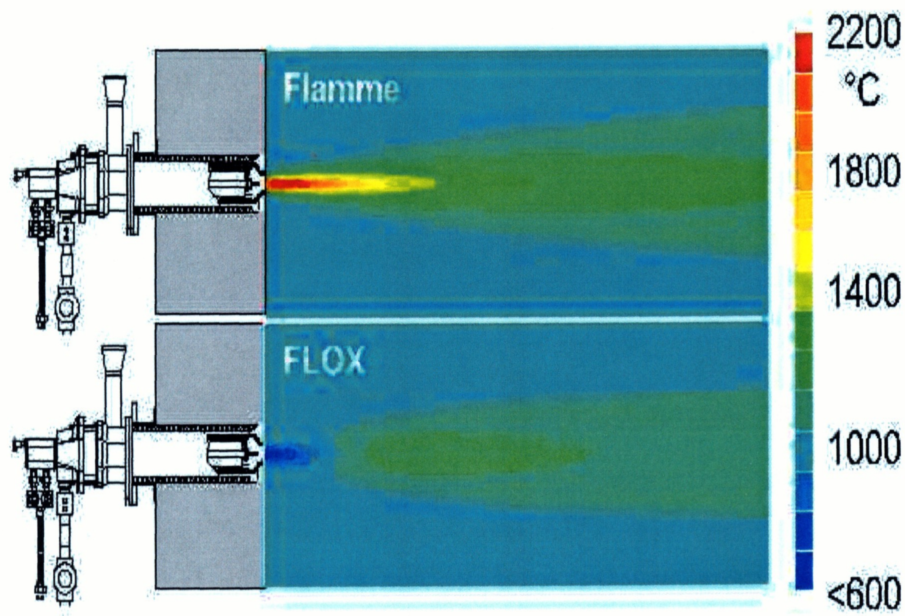
B: Unstable Flame Combustion

C: Flameless Oxidation (FLOX- TM)

Kv: Re-circulation Rate Parameter

Regimes of Flame and Flameless Combustion





(Wunning et al., 2000)

Flameless Combustion in a Furnace

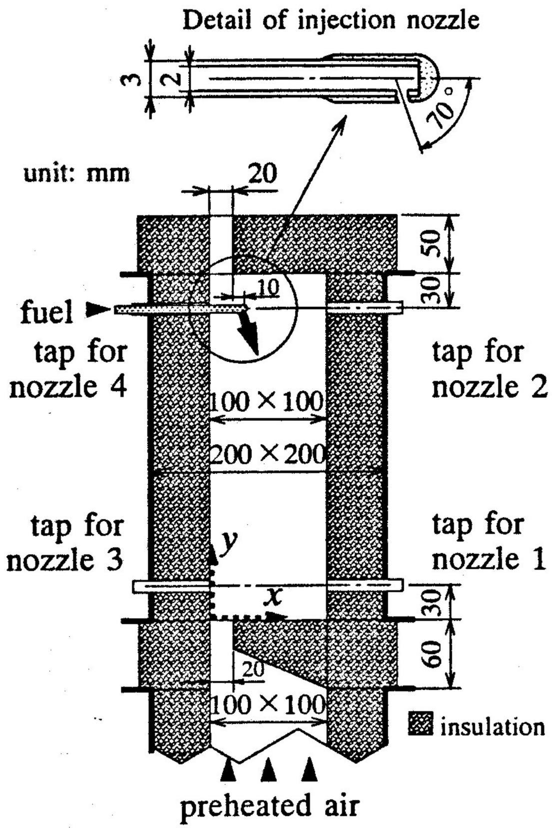
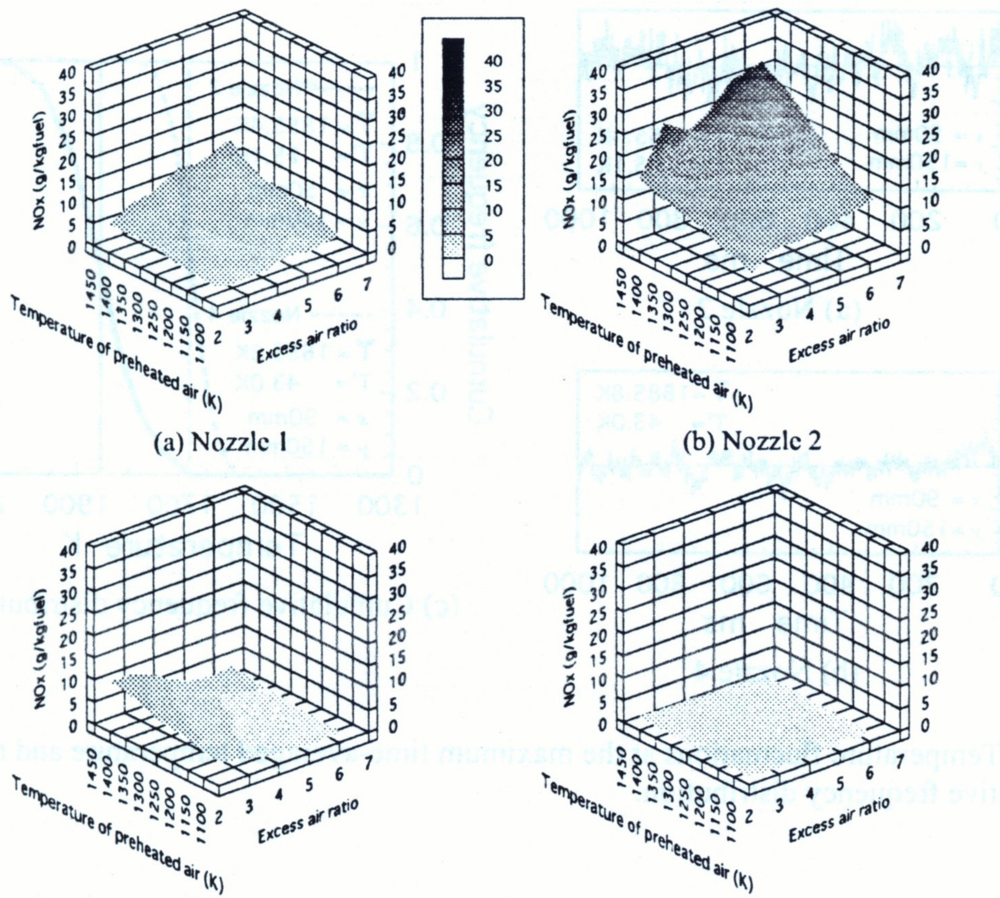


Fig.8 Combustion chamber used in the experiment.

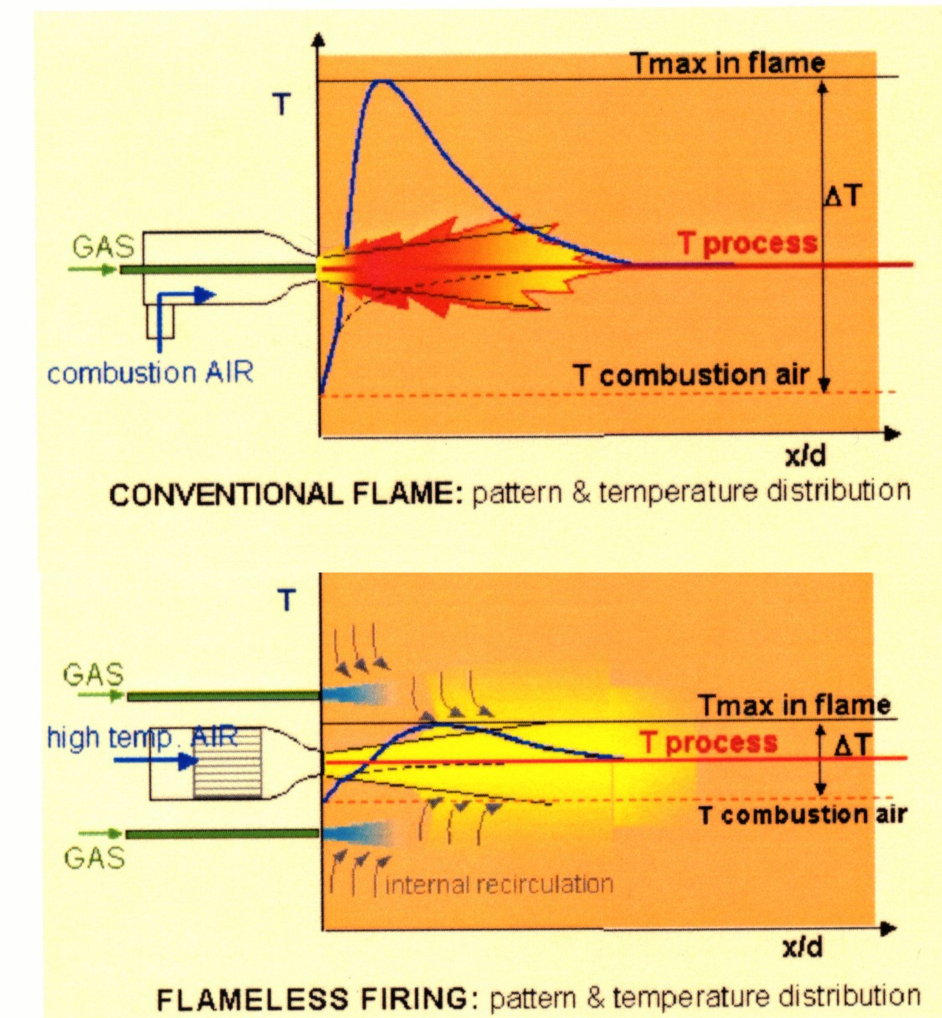
Katsuki et al., 2001



(a) Nozzle 1
(b) Nozzle 2
(c) Nozzle 3
(d) Nozzle 4

Fig.9 Influence of combustion air temperature and global excess air

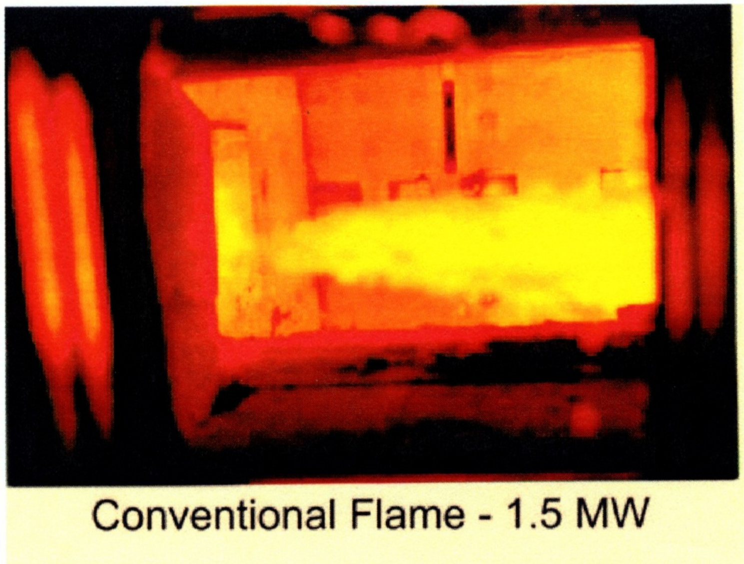
Flameless Combustion in a High-Velocity Burner

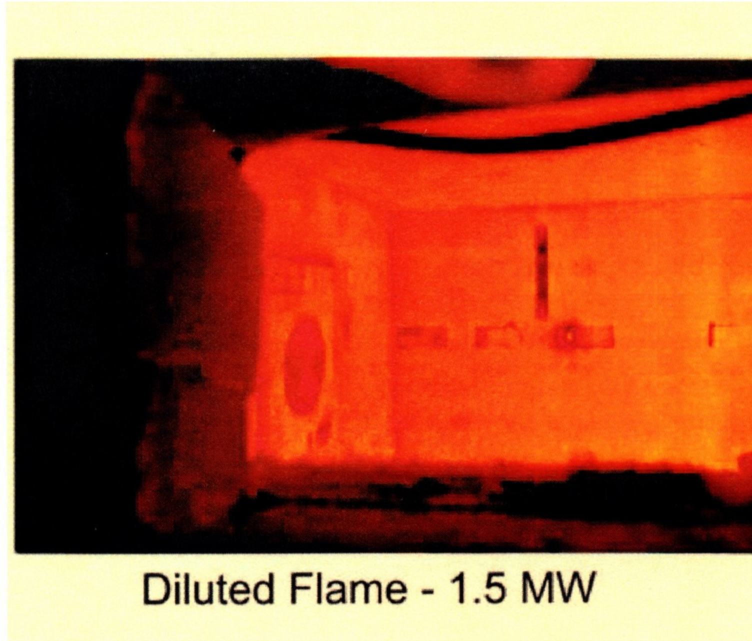


Milani and Sapanaro, 2001

- High velocity burner
- Combustion air is preheated
- High momentum fuel injection
- Entrainment of hot gas is by the kinetic energy of the jet (or jets)
- Fluid Dynamic Entrainment

Flameless Combustion in a Natural Gas Plant





- **Flameless Combustion demonstrated in high power plant**
- **Furnace is transparent during Flameless Combustion**
- **Combustion noise eliminated**

Milani and Saponaro, 2001

LPP v/s Flameless Combustion

- Liquid fuel needs to be pre-vaporized
- Fuel and oxidizer are premixed before reaction
- Very low NOx levels possible
- Flame stability issues (Lean Blowout) are not well understood
- CO and UHC emission increases during LBO
- Vibration and Noise during instability

- Liquid fuel needs to be pre-vaporized
- Fuel and oxidizer are premixed with re-circulating hot products separately before mixing together
- Instability is eliminated
- Vibration and Noise eliminated
- Very low NOx level achieved
- CO and UHC emissions are also minimized

Challenges for Application to Gas Turbines

- Liquid Fuel injection strategy
- High pressure Flameless Combustion issues
  - Turbulent mixing and kinetics time scales
  - spray pre-vaporizing and mixing issues
- How to combine Flameless Combustion mode with "normal" mode of diffusion flame combustion
  - Normal mode is needed for cold start and high power operations
- How much of the "heat" can be recovered for preheating without impacting performance
- What is the impact on Pattern Factor and Turbine Inlet Temperature

Proposed Approach

- Combined experimental-numerical studies planned
- Begin with gas phase studies and then transition to liquid fueled systems
- Extension to high pressure to be considered later
- Experimental studies
  - Systematically evaluate fuel and air injection strategies
  - Methods for optimal re-circulation of burnt products
- Numerical studies: direct and large-eddy simulations
  - Simulate the turbulent mixing process as in the experiments
  - Validate using experimental data and conditions
  - Use simulations to investigate design optimization issues and physics of flameless combustion