High Temperature, Low NOx Combustor Concept Development

Kickoff Meeting

Nov 4th, 2015

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David Noble
Matthew Sirignano

Agenda

- Motivation
- Technical background
- Proposed work
  - Task 1: Project management & planning (PMP)
  - Task 2: Kinetic modeling & optimization
  - Task 3: Experimental characterization of distributed combustion concept
  - Task 4: Detailed experimental & computational investigation of mixing & heat release distributions
- Program schedule

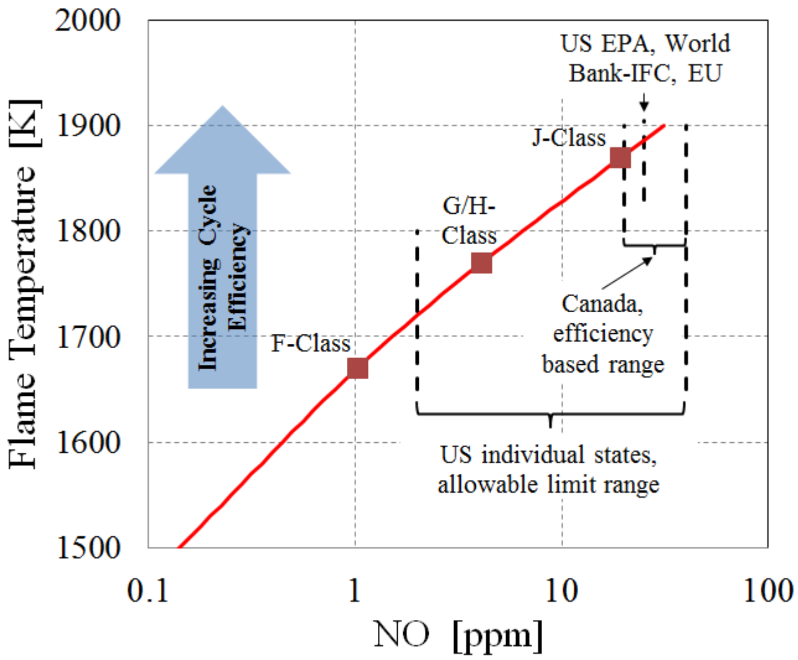
Project Participants

- Contact principal investigator (PI)
  - Prof Tim Lieuwen
- Additional PIs
  - Prof Menon
  - Prof Seitzman
- Collaborators & research engineers
  - Prof Sun
  - Prof German
  - David Noble
- Graduate students
  - Matthew Sirignano
- Undergraduate students

Motivation

Thermal Efficiency

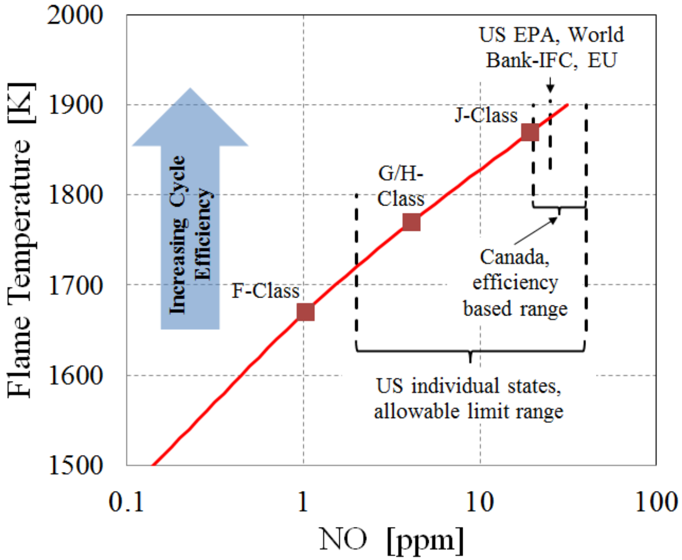
- Thermal efficiency has steadily increased from 47% to 61% over the past 3 decades
  - Success driven by improvements in materials and cooling methods
  - Advanced combustion technologies enabled simultaneous reduction in NOx emissions
- Goal: combined cycle thermal efficiency of 65%
  - Requires turbine inlet temperature ($T_{\text{Turb Inlet}}$) of 1975K
  - New challenge: low NOx at elevated temperatures



Calculations assume methane fuel and a 25ms residence time

Motivation
Emissions

- Current architectures can't meet current emissions standards at elevated $T_{\text{Turb Inlet}}$
  - EPA limit for NO = 30 ppm
  - Current architecture yields 90 ppm NO at $T_{\text{Turb Inlet}} = 1975\text{K}$
- Current NOx reduction techniques are not viable w/o significant residence time reduction



New combustor paradigm is required to meet goal

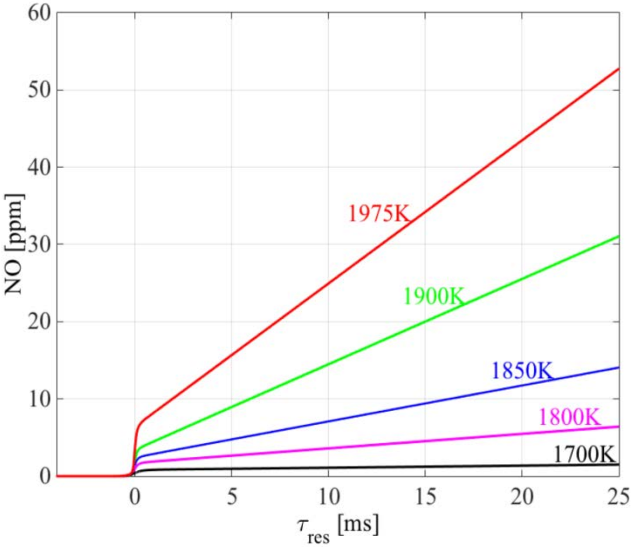
Technical Background

NOx Formation

- Values are generally orders of magnitude below equilibrium

- Significant NOx formation mechanisms
  - Flame generated NOx (Fenimore, N_20, etc.)
  - Thermal (Zeldovich)

- Thermal NOx
  - Approximately linear function of residence time
  - Exponential temperature dependence



$$O + N_2 \Leftrightarrow NO + N$$

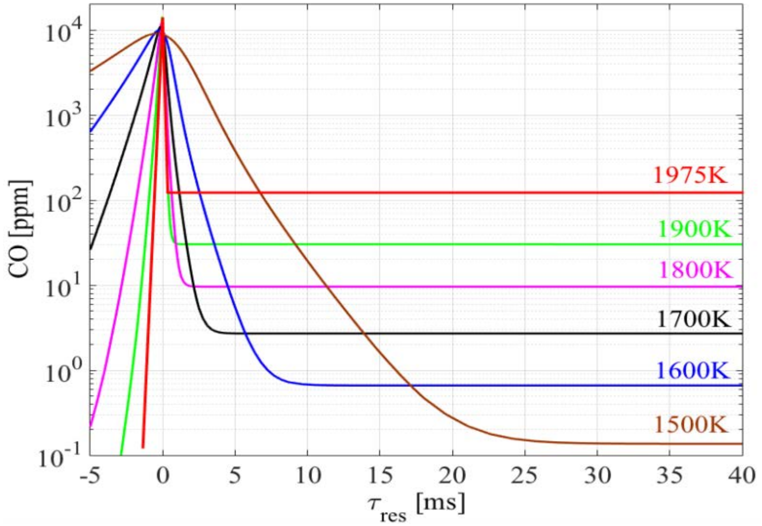
$$N + O_2 \Leftrightarrow NO + O$$

$$N + OH \Leftrightarrow NO + H$$

Technical Background

CO Formation

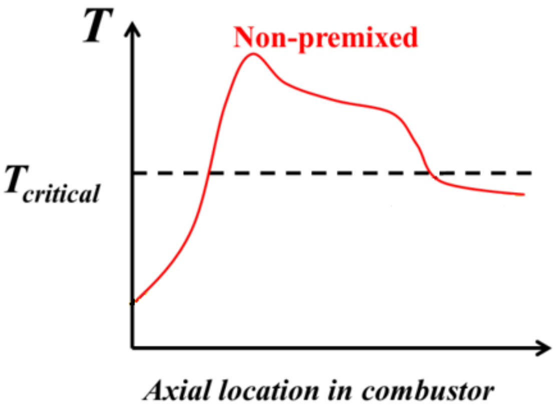
- Values are generally above equilibrium
- Relaxation to equilibrium is exponential function of temperature
- CO emissions generally limit turndown, as relaxation is slow at low temperatures



Technical Background

Current NOx Reduction Techniques

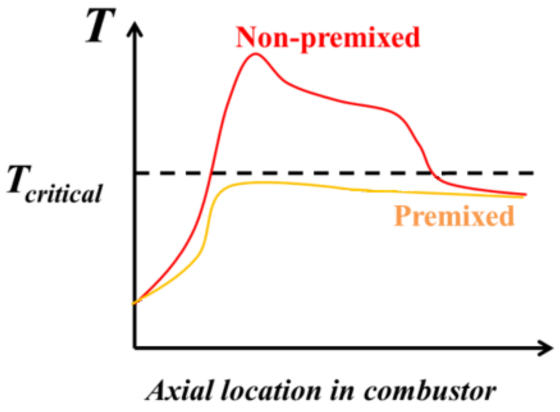
- Current approaches focus on temperature distribution control



Technical Background

Current NOx Reduction Techniques

- Current approaches focus on temperature distribution control
  - Lean, premixed
    - Lean stoichiometry and careful premix



Technical Background

Current NOx Reduction Techniques

- Current approaches focus on temperature distribution control
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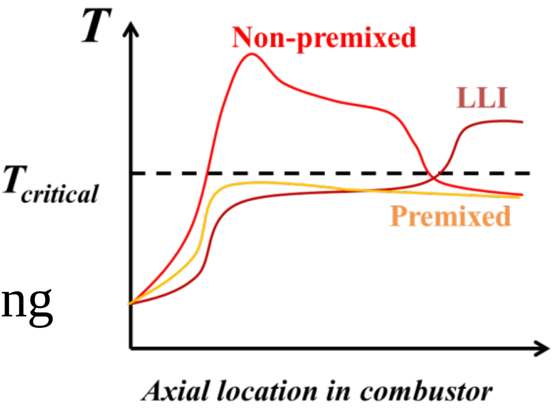
    - Lean stoichiometry and careful premixing
  - Axially staged/Late Lean Injection (LLI)
    - Fuel injection in low residence time, high temp environment



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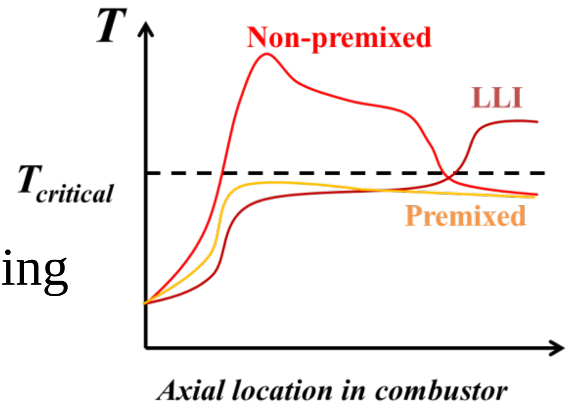
  - Axially staged/Late Lean Injection (LLI)
    - Fuel injection in low residence time, high temp environment
  - Dilution:
    - Lowers temperature at given fuel flow rate
    - Steam/CO_2/N_2



Technical Background

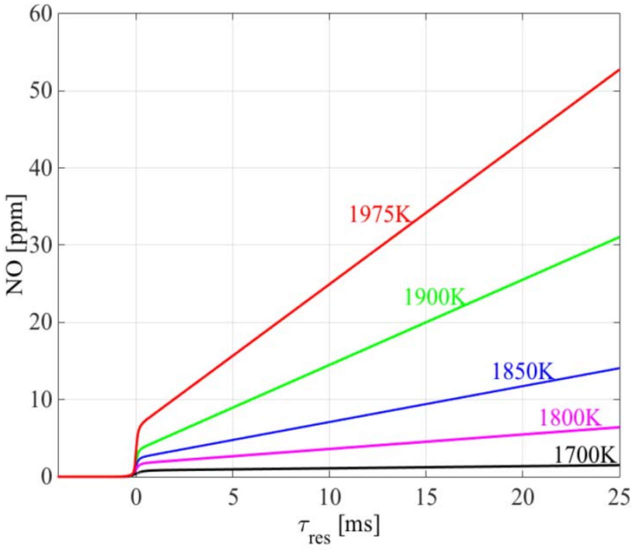
Proposed Approach

- Thermal NO initiating step:

$$O + N_2 \Leftrightarrow NO + N$$

$$[NO] \propto [O][N_2]e^{-38{,}379/T}\tau_{res}$$

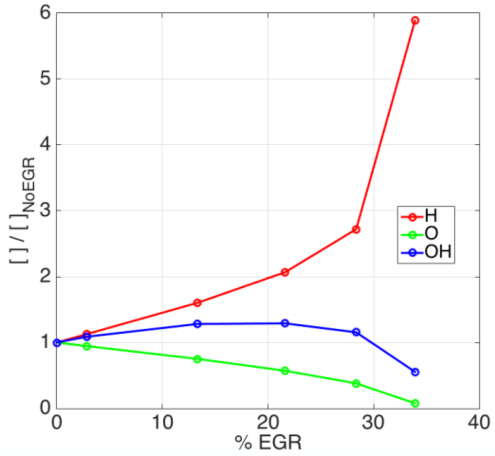
- “Knobs”
  - Temperature
  - Residence time
  - [O] concentration



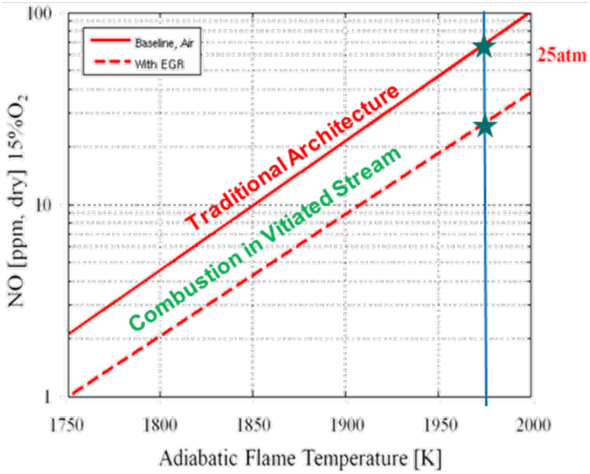
Technical Background

Proposed Approach

- NO formation dependent on residence time and O radical concentration, in addition to temperature
  - Combustion in reduced oxygen atmosphere reduces [O]



- Key approaches:
  - Radical tailoring to minimize [O] concentration
  - Co-optimize with residence time control
  - Advanced manufacturing approaches suggest complete rethinking of combustion – continuous axial distribution of fuel?



Related Work
Axial & Azimuthal Staging

- Axial staging concepts will likely require jet in cross flow (JICF) configuration (to keep the fuel injectors out of hot flow)
  - Georgia Institute of Technology – our group
    - Emissions & stability characteristics of jets of various compositions in vitiated crossflow.
  - Purdue University – Lucht
    - Methane and Hydrogen jets in vitiated crossflow
  - Karlsruhe Institute of Technology – Zarzalis
    - Experimental & computational investigation of methane jet in vitiated cross flow at elevated pressures
  - Technische Universität München – Sattelmayer
    - Experimentally supported reactor model for staged combustor

- In addition to their axially staged work, Technische Universität München , has developed an azimuthally staged approach
  - Focused on operation of ultra-low temperature and equivalence ratio flames to greatly reduce NO emissions

Proposed Work

Key Research Questions

(1) For a given firing temperature and residence time, what are the minimum theoretical NOx limits?

- How much lower is this fundamental limit than the limits achievable with current architectures?

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(2) What does the actual fuel and air distribution patterns look like that attempt to achieve these theoretical values?

- Then, what are the operational behaviors of such a combustion system?

Proposed Work

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(1) For a given firing temperature and residence time, what are the minimum theoretical NOx limits?

- How much lower is this fundamental limit than the limits achievable with current architectures?

(2) What does the actual fuel and air distribution patterns look like that attempt to achieve these theoretical values?

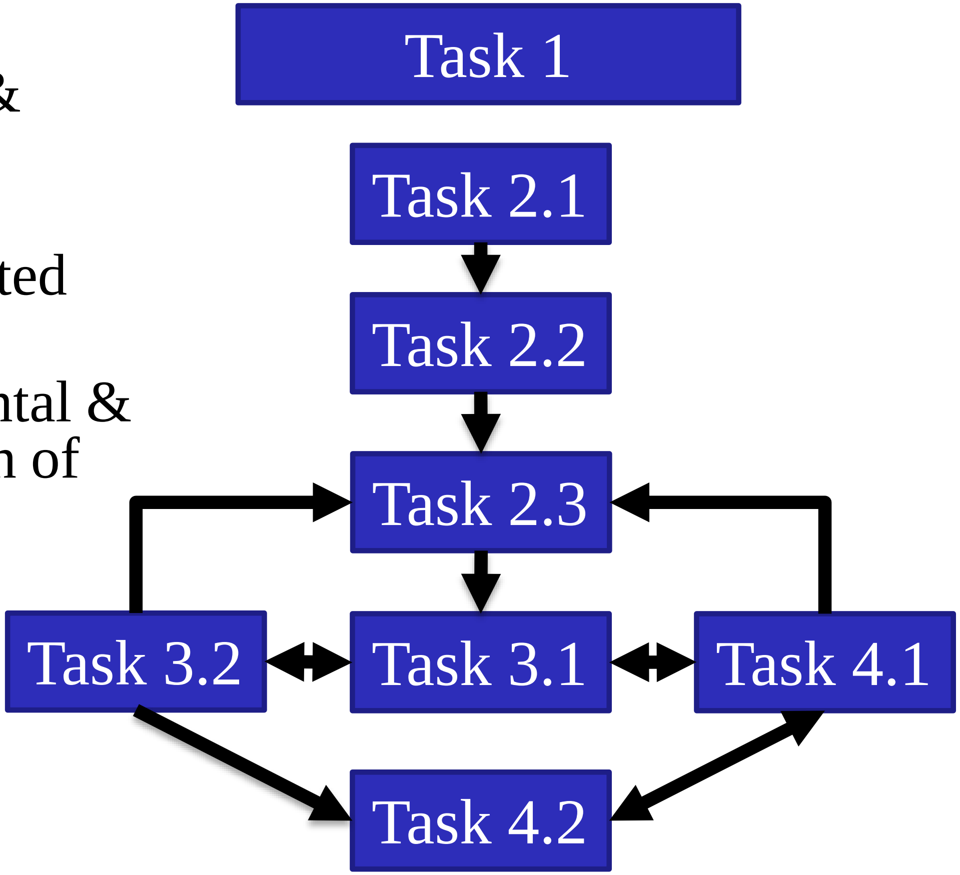
- Then, what are the operational behaviors of such a combustion system?

(3) What do local pre- & post-flame mixing patterns look like and how is the heat release distributed?

Proposed Work

Scope of Work

- Task 1: PMP
- Task 2: Kinetic modeling & optimization
- Task 3: Experimental characterization of distributed combustion concept
- Task 4: Detailed experimental & computational investigation of mixing & heat release distributions



Task 1

Task 2.1

Task 2.2

Task 2.3

Task 3.2

Task 3.1

Task 4.1

Task 4.2

Task 1: PMP

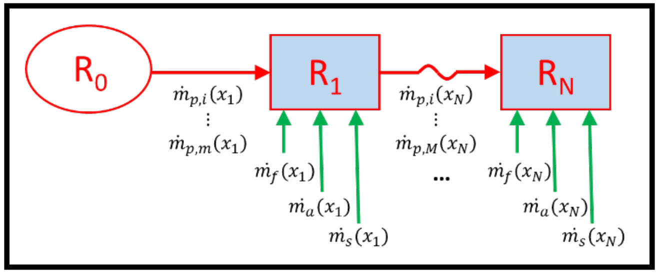
- Project management plan (PMP)
  - – Updated directly following award & every alternate quarter
  - – Key risk management tool
    - Outlines technical, financial, and schedule driven program risks
      - – Highlight risk level at time of PMP update
      - – Include action plan for reduction or rational for acceptance
  - – Tracks milestones/critical decision points
    - Ex: Down-select of experimental concepts

Task 2: Kinetic Modeling & Optimization

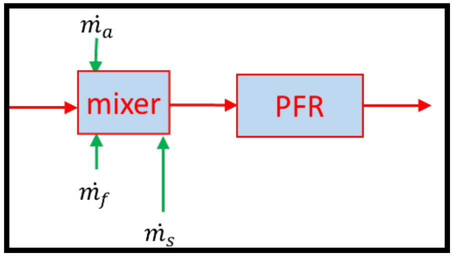
- Task 2.1: Fundamental kinetic studies
  - Utilize detailed mechanisms
  - Develop insight into:
    - Interactions b/w radical profiles
    - NOx formation rates
      - Impact of radical pool tailoring
        - CO_2 & H_2O addition
      - Pressure sensitivity

Task 2: Kinetic Modeling & Optimization (cont)

- Task 2.2: NOx optimization studies
  - Will attempt to answer the first key research question
  - Will develop computational model of an axially staged combustor with multiple injection locations
    - Approach: model a number of "reactor cells"
    - Each reactor cell consists of sub-components such as a mixer and plug flow reactor
  - Optimization study will be conducted on combustor model



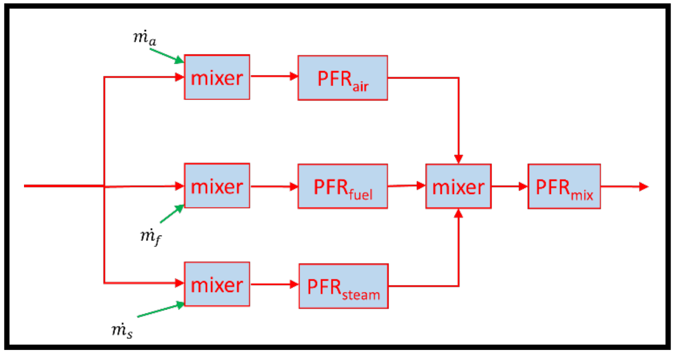
Chain of Reactor Cells



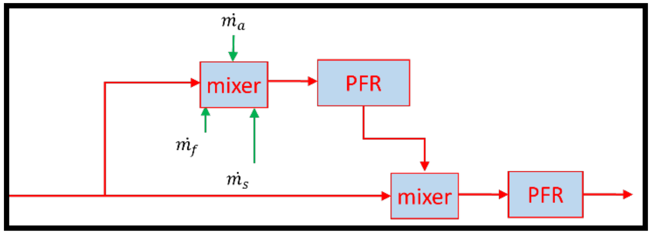
Reactor Cell Model

Task 2: Kinetic Modeling & Optimization (cont)

- Task 2.3: Constrained NOx optimization studies
  - Will refine work conducted in previous task by adding additional physical constraints
    - Mixing
      - Finite mixing times
      - Various schemes for mixing process of injected fluids & main flow
      - Recirculation



Independent Mixing of Injected Fluids & Main Flow



Joint Mixing of Injected Fluids & Main Flow

Task 3.1: Facility Development

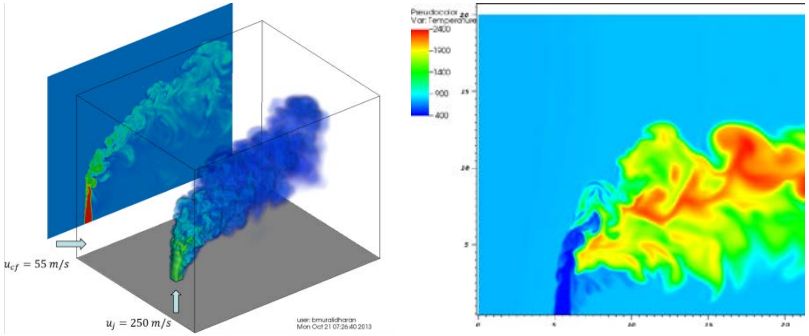
- Design combustion architecture guided by results of Task 2
    - Lean primary burner
    - Distributed secondary injection of fuel/air/steam
        - Premixed & non-premixed
    - Atmospheric
    - Advanced manufacturing techniques
    - Optical access

Task 3.2: Experimental Characterization

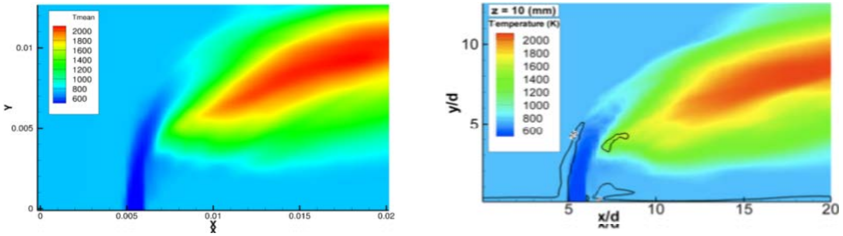
- Observation of operational characteristics of combustor
  - Instability, blow off, limits of operation
- Implementation of fuel/air/steam injection schema developed in Task 2
- Characterization of emissions
  - Local & spatially averaged
    - Traversing probe vs rake
  - Axial profile of key species

Task 4.1: Large Eddy Simulations

- High Fidelity LES
  - Investigate turbulent mixing of staged injection
- LESLIE
  - History of use in combined experimental & computational studies of flame dynamics
- Will conduct full rig simulations matching physical geometry



Velocity & Temperature Isocontours of a Reacting Jet In Cross Flow

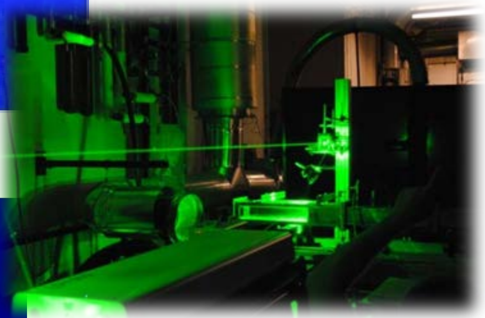


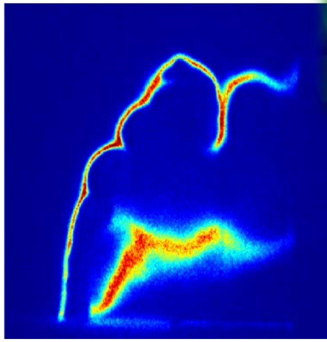
AMRLES and DNS Time-Averaged Temperature (AMR: Adaptive Mesh Refinement)

Task 4.2: Experimental Characterization Using High-Speed Laser Diagnostics

- Velocity field measurement
  - 10 kHz stereo-PIV
- Combustion visualization
  - OH & CH$_2$0 PLIF
  - OH* & CH* chemiluminescence
- Post-processing
  - Full Fourier analysis
  - Proper orthogonal decomposition
  - Dynamic mode decomposition
  - Hybrids

PIV for RJICF





OH PLIF for RJICF

Partnership of Experimental & Computational Investigation

- Interaction of experimental & computational activities crucial for success
  - – PI’s have experience of collaboration in other joint computational & experimental combustion studies

NOx reduction strategies developed in Task 2

→Experimental design of stage injection system

→LES simulation geometry

→Iteration of reduction strategies and/or combustor design

Program Schedule

Summary of Tasks & Deadlines

Tasks	Quarter											
	1	2	3	4	5	6	7	8	9	10	11	12
1.0 – Project Management and Planning												
1.1: Revise PMP after contract is negotiated.	X											
1.2: Update PMP as project progresses			X		X		X		X		X	
2.0 – Kinetic Modeling and Optimization												
2.1: Fundamental kinetic studies	X	X	X	X								
2.2: NO optimization studies		X	X	X	X	X						
2.3: Constrained NO optimization studies					X	X	X	X	X	X		
3.0 – Experimental characterization of concept												
3.1: Facility development	X	X	X	X								
3.2: Experimental characterization				X	X	X	X	X	X	X		
4.0 – Detailed characterization												
4.1: Detailed LES simulations			X	X	X	X	X	X	X	X	X	
4.2: High-speed diagnostics						X	X	X	X	X	X	X
Reporting: Progress reports will be prepared and submitted on a quarterly, semi-annual and annual basis. In addition, a comprehensive final report will be submitted which describes the overall project's objectives, results and conclusions.												
1: Prepare and submit Quarterly Progress Reports	X	X	X	X	X	X	X	X	X	X	X	X
2: Prepare and submit Semi-Annual Report		X		X		X		X		X		X
3: Prepare and submit Annual Report				X				X				X
4: Prepare and submit Final Report												X

Program Schedule

Deliverables

Deliverables	**Quarter**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Revised Project Management Plan.	•											
Updated Project Management Plan.			•		•		•		•		•	
Quarterly Progress Reports	•	•	•	•	•	•	•	•	•	•	•	•
Semi-Annual Reports		•		•		•		•		•		•
Final Report												•

Conclusion

- Increase in turbine inlet temperature would lead to significant efficiency gains
  - NOx formation is important barrier
- New paradigm needed
  - Study will determine fundamental limits to minimum achievable NO levels, as well as provide understanding of architectures associated with realizing these minima
    - Goal is to both develop a roadmap for what improvements are possible, as well as steps toward realization by turbine companies
- Study involves combination of chemical kinetic, experimental, and CFD investigations to fully evaluate the problem