Experimental and Computational Investigations of Boundary Condition Effects on Simulations of Thermo-Acoustic Instabilities

Reacting Flows Lab
Combustion Systems Dynamics Lab

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Outline

- Motivation for the Study
- Goals, Scope of the Project
- Work Breakdown-Tasks
- Facilities
- Modification of Rijke Tube => Testbed
- Instrumentation
- CFD/FEA Simulations
- Issues associated with Boundary Conditions
- Future Work Plan

Industry Needs - “Clean Coal Technology”

- Environmentally <u>responsible</u>, <u>sustainable</u>, <u>independent</u>, energy source for power generation.
- Increased use of synthetic fuels, coal-derived syngas:
  - greater fuel variation, higher H_2 content leading to ...
  - additional issues associated with thermo-acoustic instabilities.
- Improved simulation of combustion dynamics needed to address gas turbine combustor design. Reduced-Order Model-Based design
- Hierarchical framework to systematically validate CFD simulations against scaled combustor data.
- Educate students in combustion fundamentals to become leaders in clean sustainable energy generation for the future.

Project Goals and Objectives

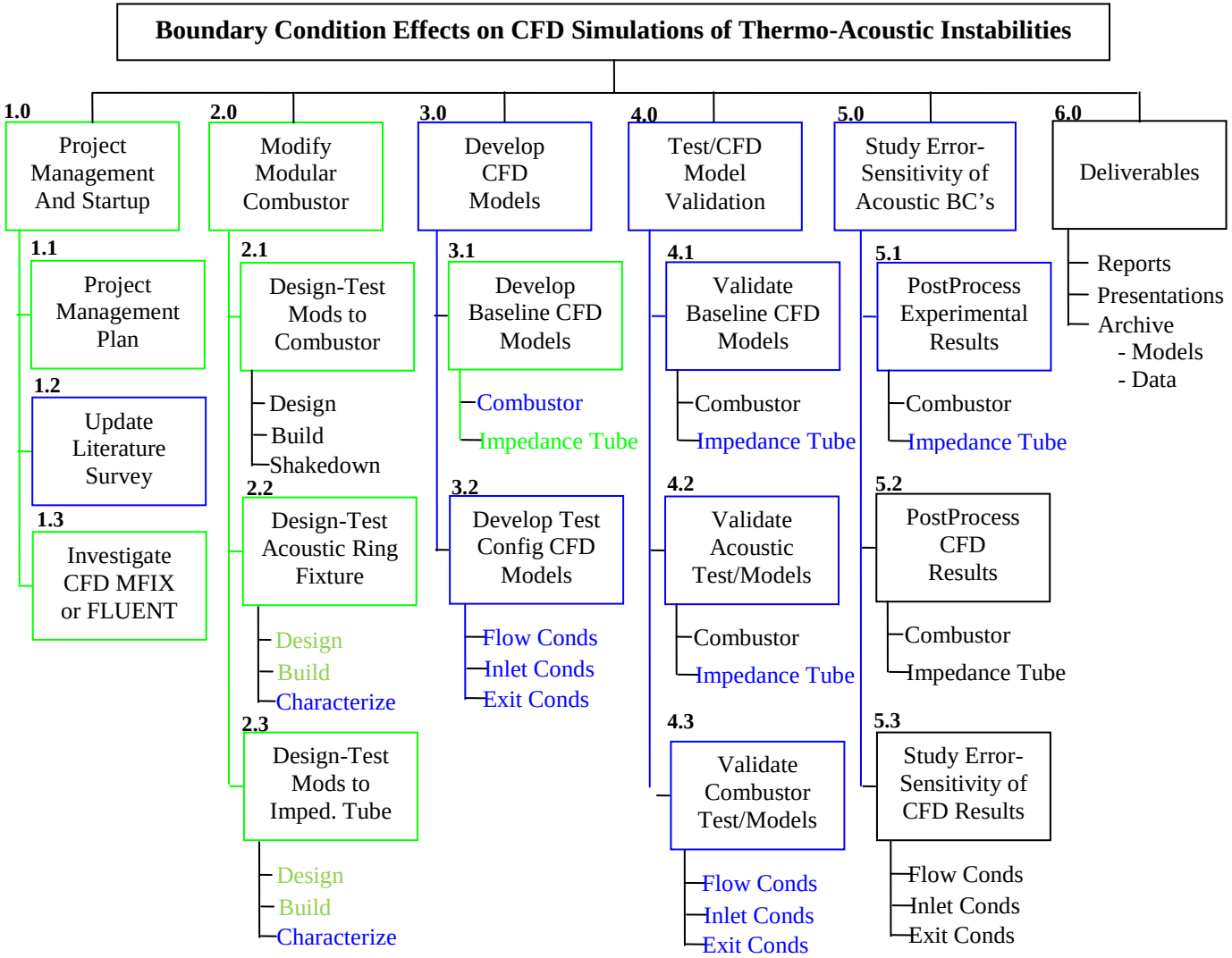
Goal:

Determine the sensitivity of transient thermo-acoustic CFD simulations to time-domain boundary conditions.

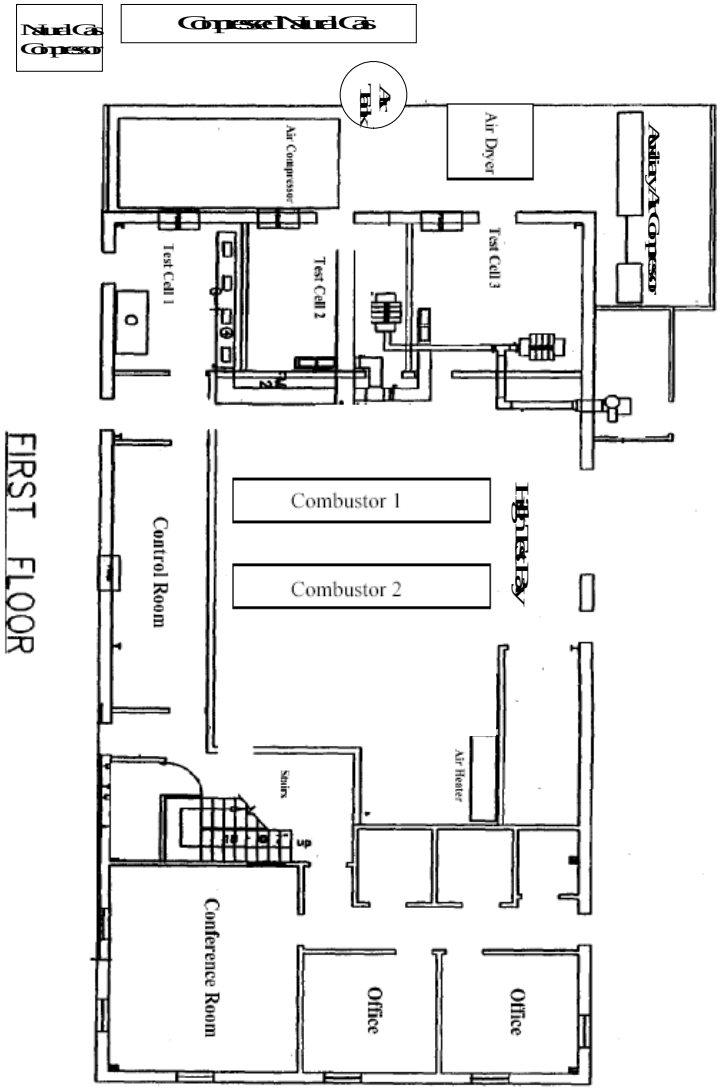
Objectives:

- Develop flow-impedance tube testbed for acoustic BC characterization and CFD simulation
- Modify combustors to measure and quantify acoustic BCs
- Develop transient CFD combustor models
- Validate transient CFD models against combustor testbed.
- Demonstrate sensitivity of CFD thermo-acoustic instability predictions to simulation BCs.

Work Breakdown-Tasks

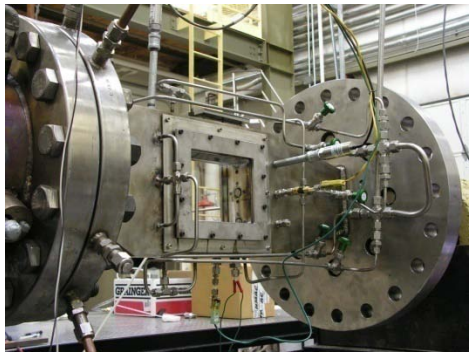


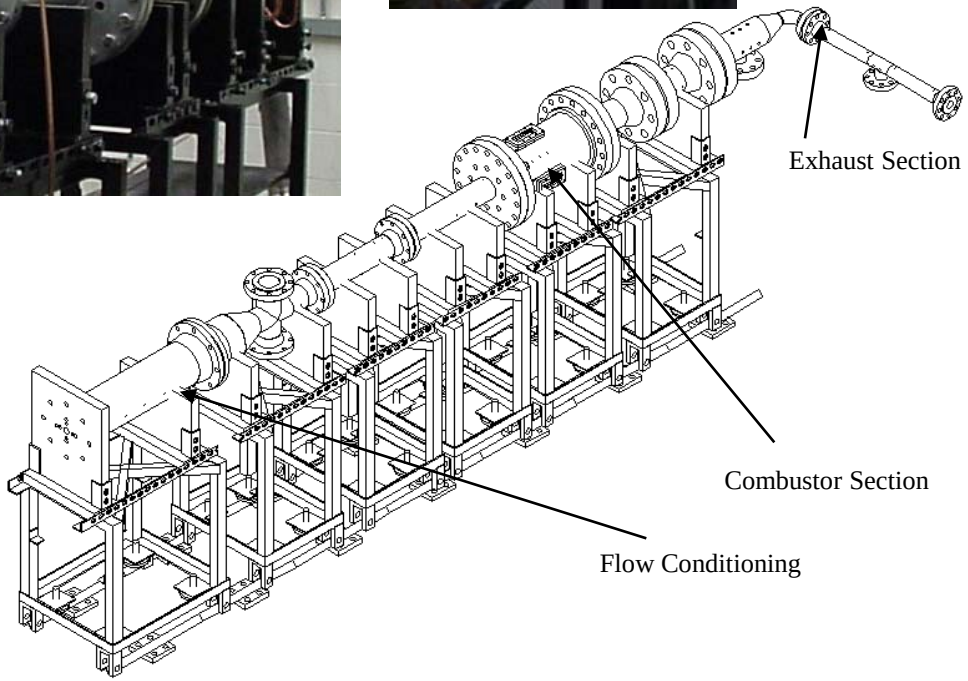
CSDL-Combustion Systems Dynamics Lab



2000 sq. ft. experimental area including high-bay

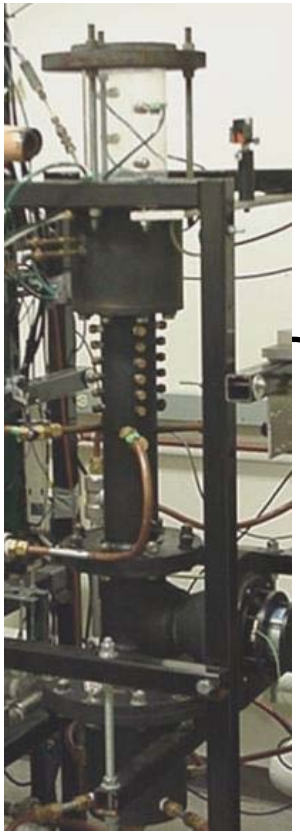
CSDL Modular Combustion Rig



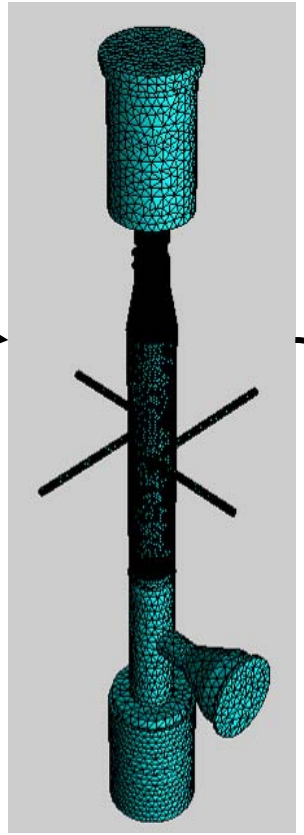


CSDL Lean Premixed Turbulent Flame Swirl Stabilized Combustor Rig

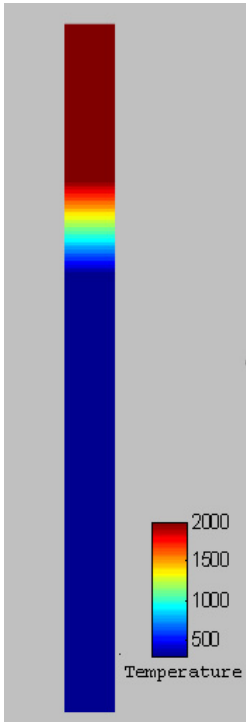
Simplify combustor geometry appropriately



Build finite element model

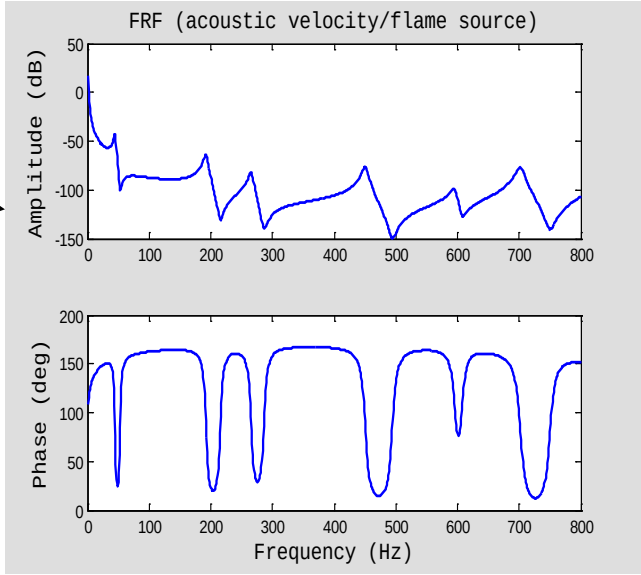


Map hot temperatures

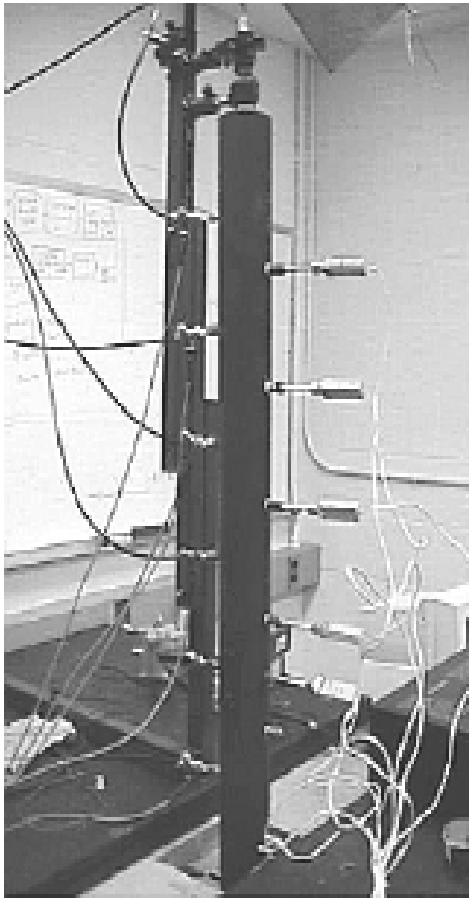


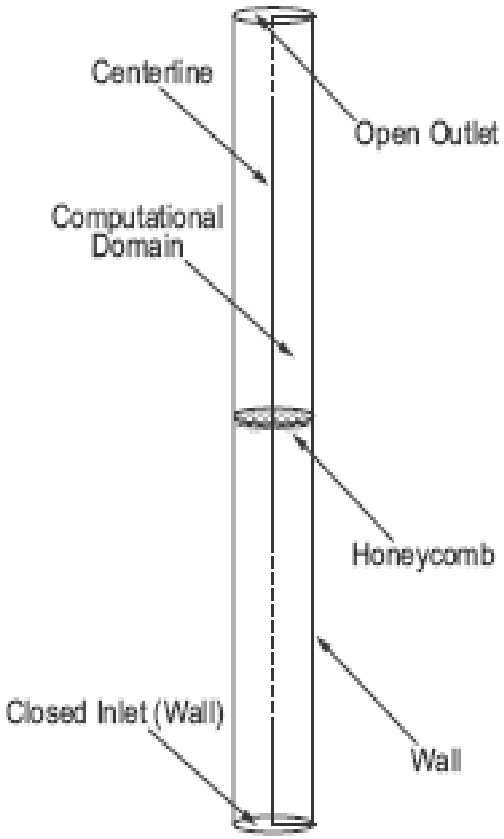
Finite element modeling was used to accurately predict the acoustic response in combustors

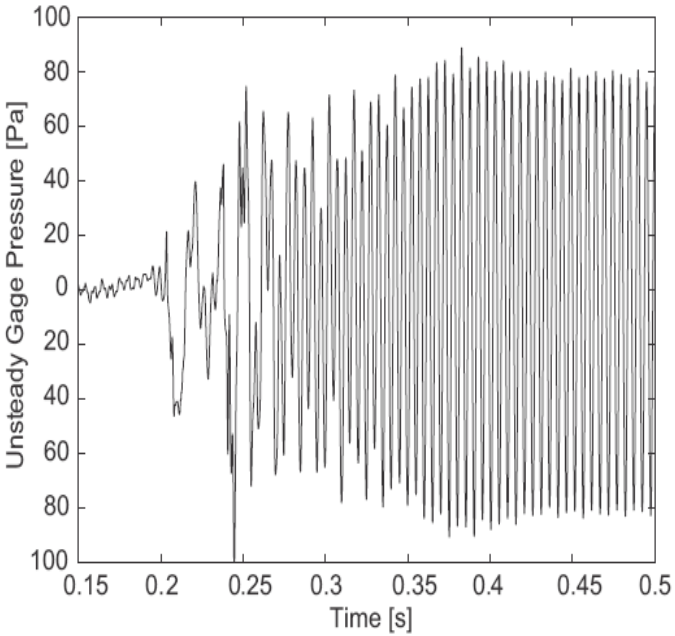
Obtain acoustic frequency response at desired locations



RFL Modified Rijke Tube



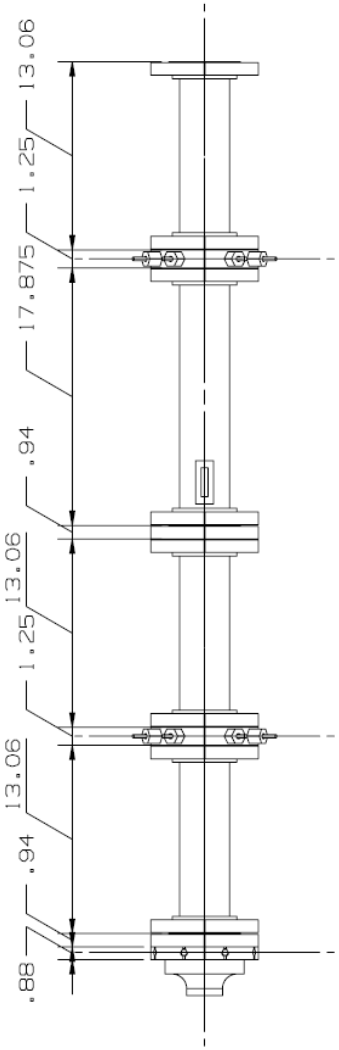


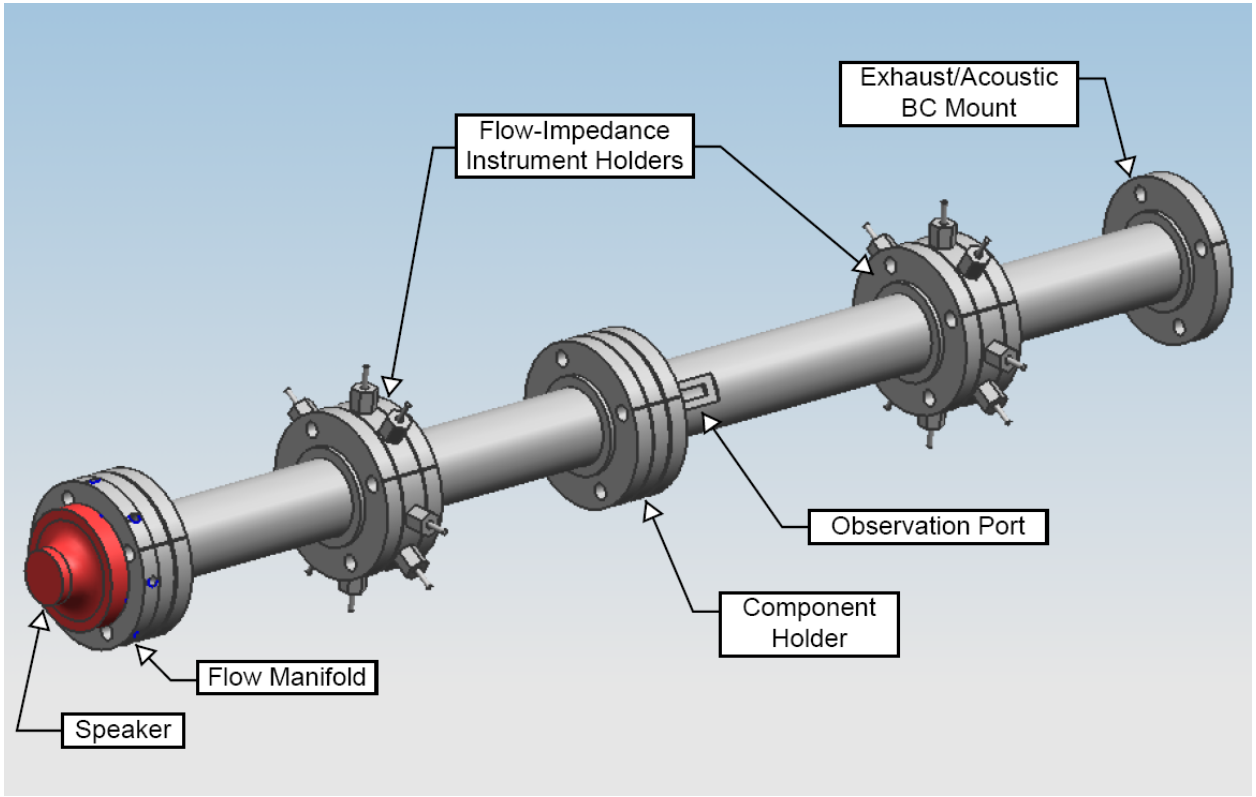


- Premixed Laminar flame
- CFD limit cycle prediction consistent with experiment

Chatterjee, Prateep, "A Computational Fluid Dynamics Investigation of Thermoacoustic Instabilities in Premixed Laminar and Turbulent Combustion Systems," PhD, Dissertation Virginia Tech Mechanical Engineering, 2004.

Rijke Tube Modifications, Testing and Simulation



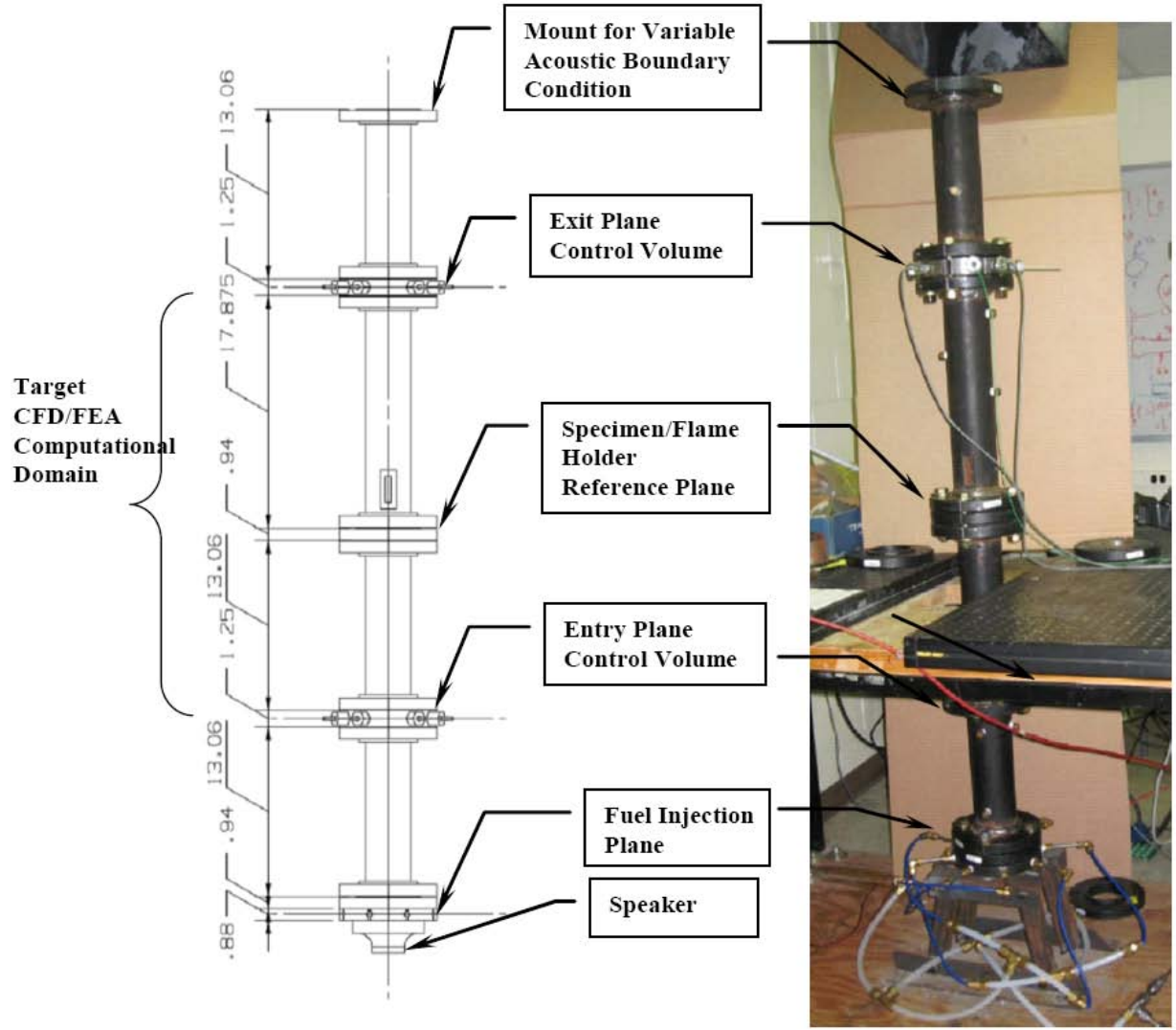


Modify Rijke Tube to a Flow-Impedance Tube

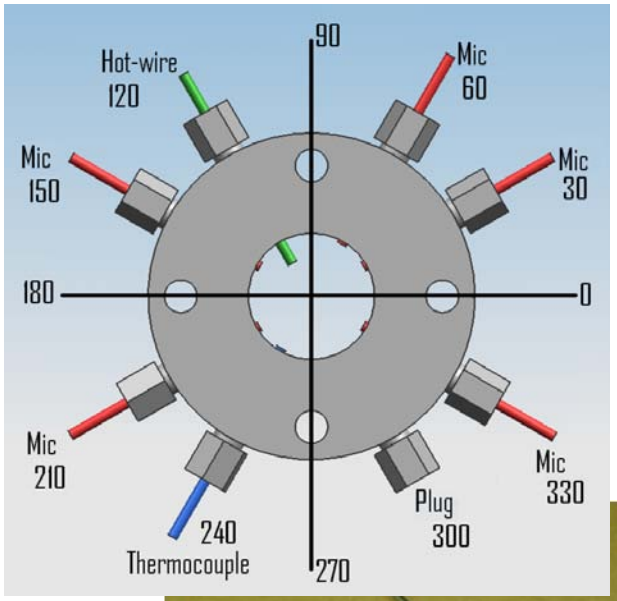
- "Instrumentation Holder"; measurements on entry & exit planes
- "Component Holder", acoustic, flow impedance characterization

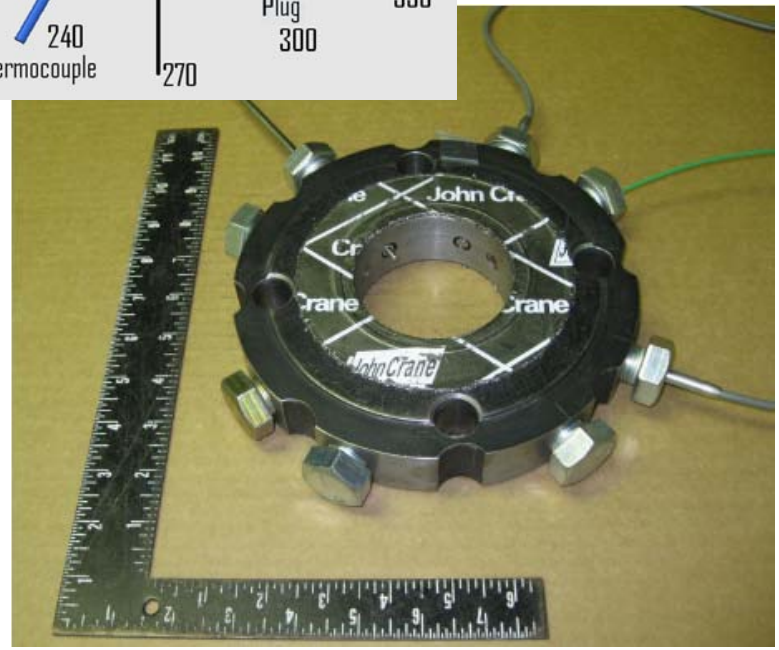
Rijke Tube Modifications, Testing and Simulation

- Entry/Exit Plane:
  - Flow
  - Thermal
  - Mean Pressure
  - Acoustic Pressure
- Axial Sensors:
  - Temperature
  - Acoustics
- Tunable Flow
  - Equiv. Ratio
  - Flow Rates
- Acoustic BC's



Instrument Ring



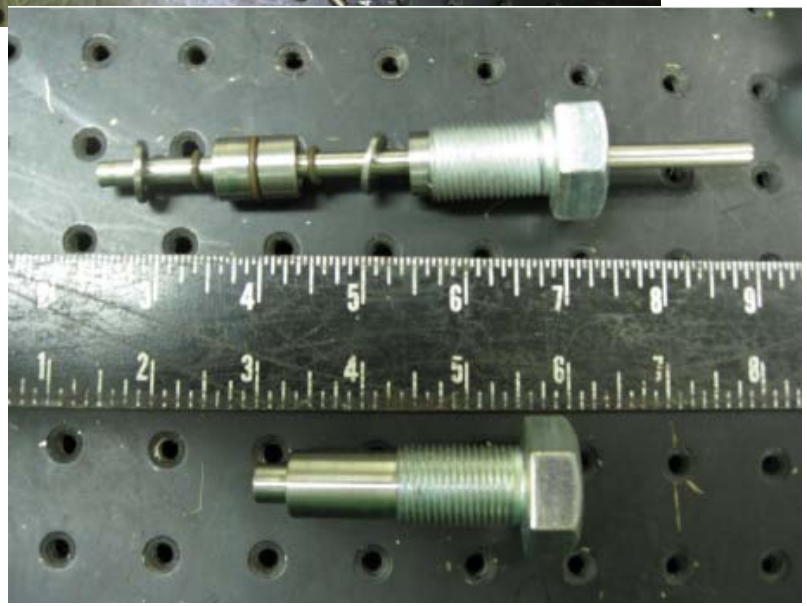


- Planar Measurements
  - Flow
  - Thermal
  - Dynamic Fluid Pressure
  - Acoustic Pressure

Configurable sensors:
  - Circumferential
  - Radial

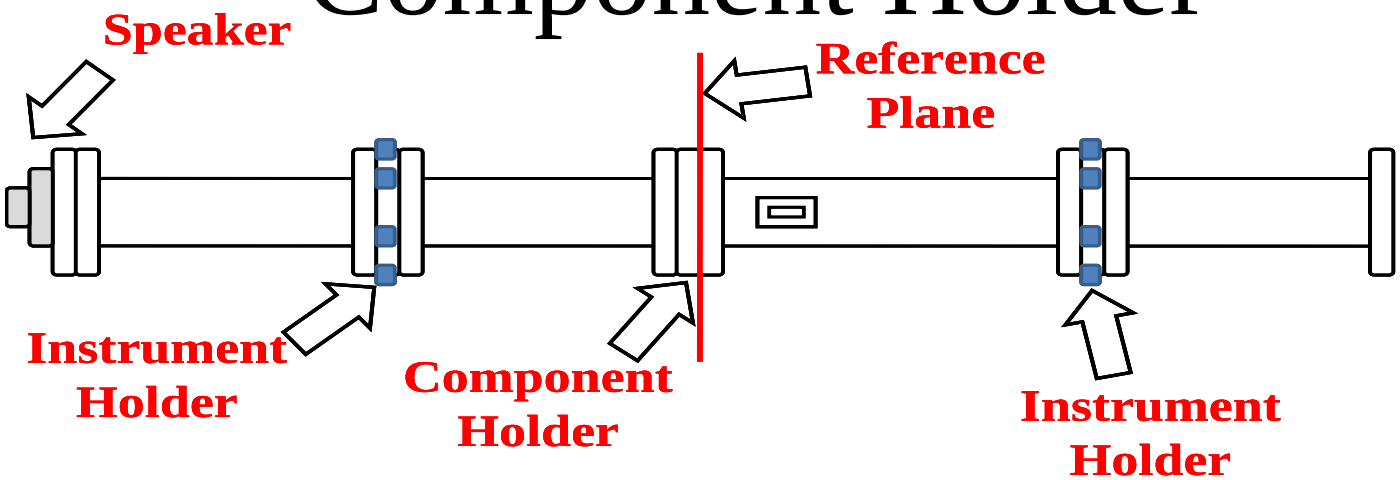
Acoustic Characterization
  - Source identification
  - Acoustic impedance

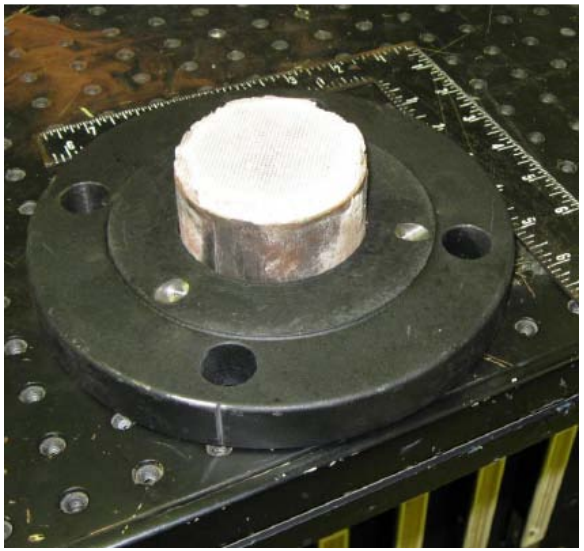
Instrument Holder

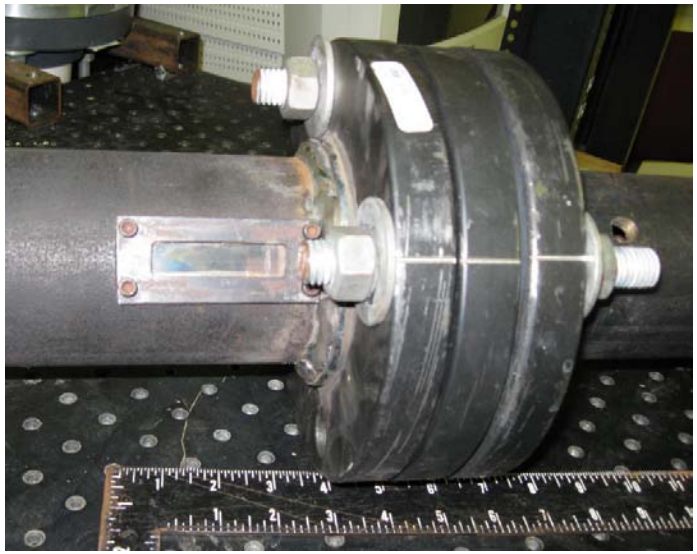


- Radial/Circumferential Measurements
  - Sealed, Adjustable
  - Locked, No Rattle!
- Axial Measurements:
  - Acoustics Pressure
  - Thermal, Flow
- Configurable
- Stubs Fit Flush to Inside Wall of Tube

Component Holder

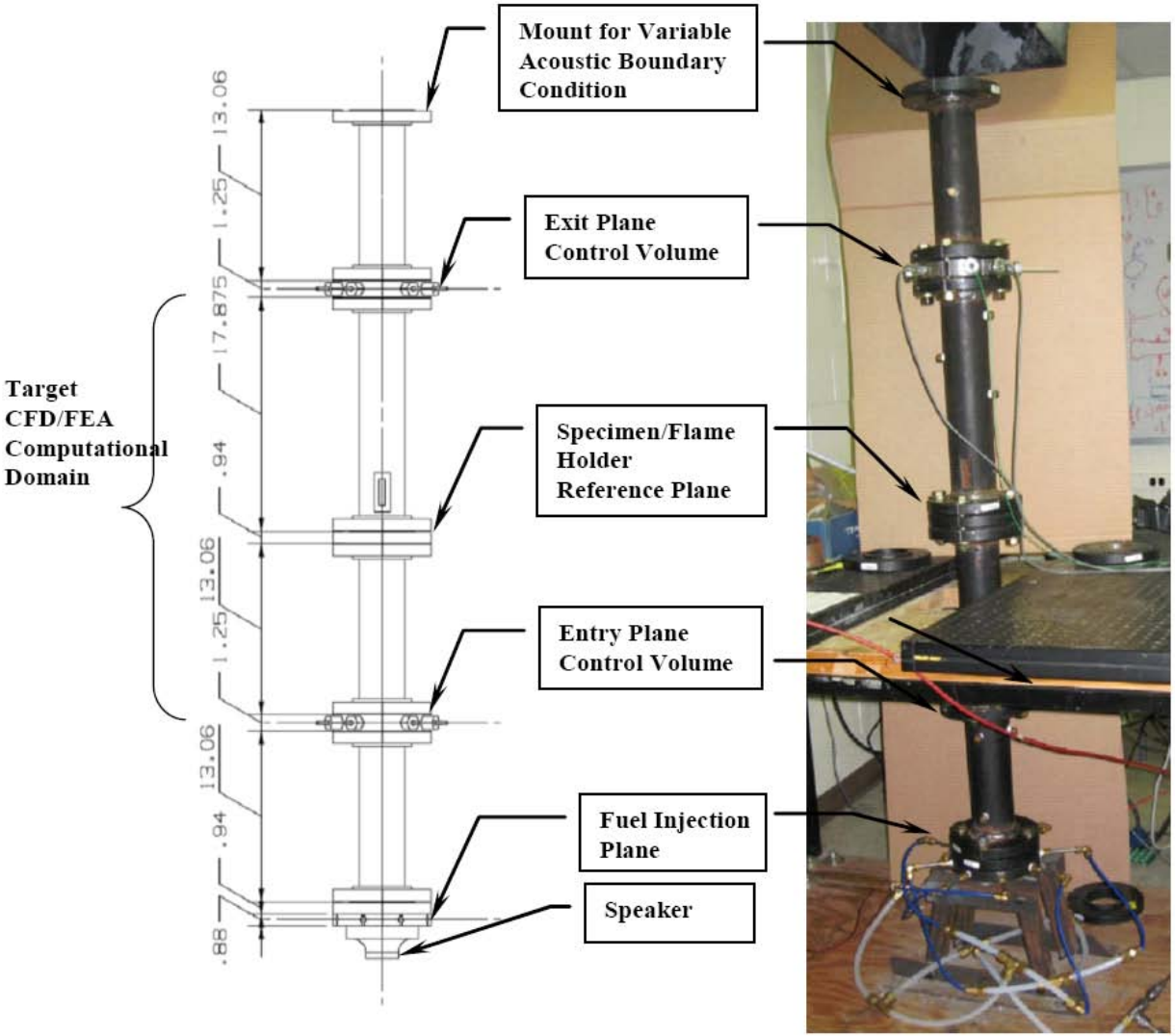






- Design allows for in-place characterization and operation

Variable Acoustic Boundary Conditions



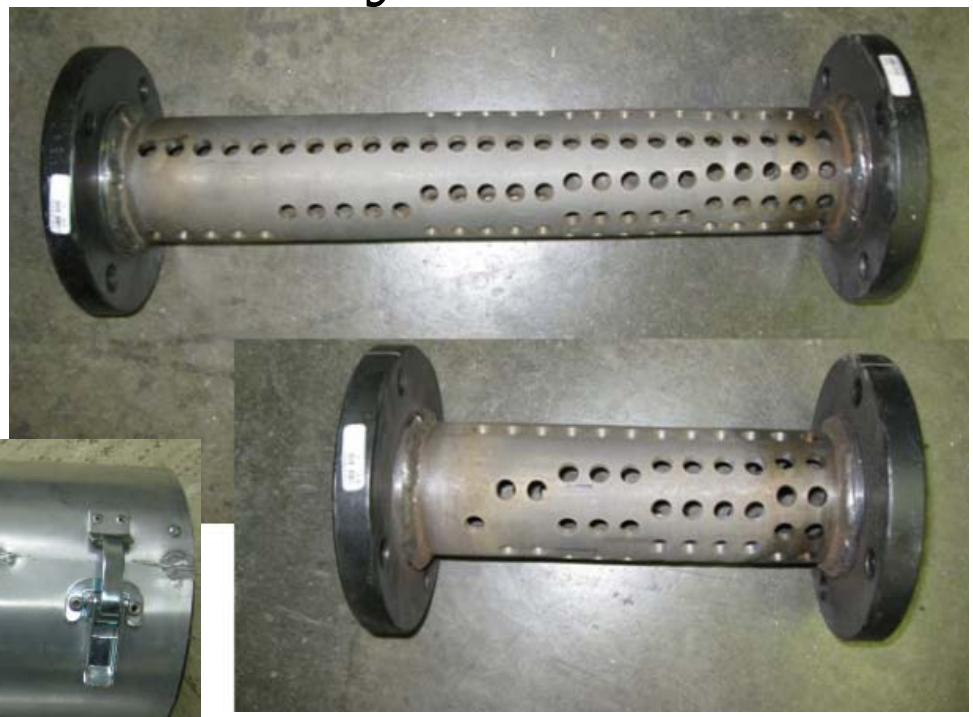
- Acoustic BC's
  - Length Variation
  - Impedance
- Investigate Flow Condition Effects on Acoustics
  - Mach Number ~ 0.2
- Investigate Variation on Instability Conditions
  - Downstream conditions

Variable Acoustic Boundary Conditions

- Acoustic characterization requires changing acoustic BC's
  - Anechoic End – no acoustic energy reflected, problematic for flow
  - Open End – some energy reflected, accommodates all flow conditions
  - Rigid End – "all" acoustic energy reflected, no flow condition
  - Speaker Impedance
- Breakdown of linear acoustics theory with flow coupling

Damped Acoustic Boundary Conditions

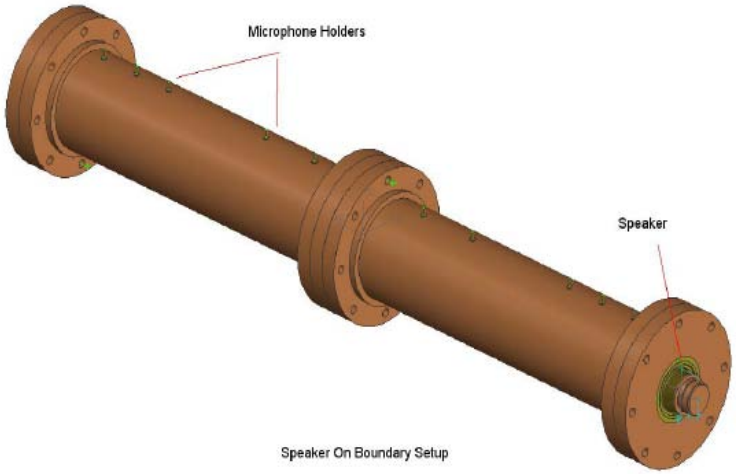
- "Muffler" design
  - Perforated tube
  - Acoustic/Thermal insulation
  - Steel outside sheet



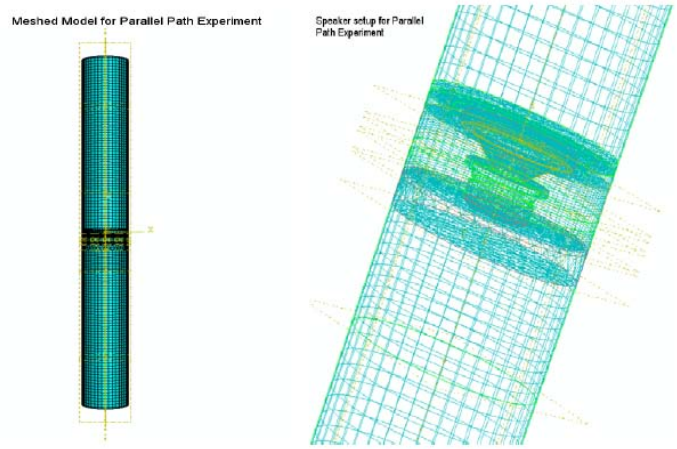
Flow-Impedance Tube Testbed Testing/Simulations

Establish known flow and acoustics in impedance tube.

- Experimental characterization from fully instrumented testbed
  - Known reproducible conditions-develop experimental technique
  - Establish experimental noise floor
- Computational characterization-reconcile models and experimental results
  - Simpler model cases with dominant mechanics: model exploration
  - Establish computational noise floor

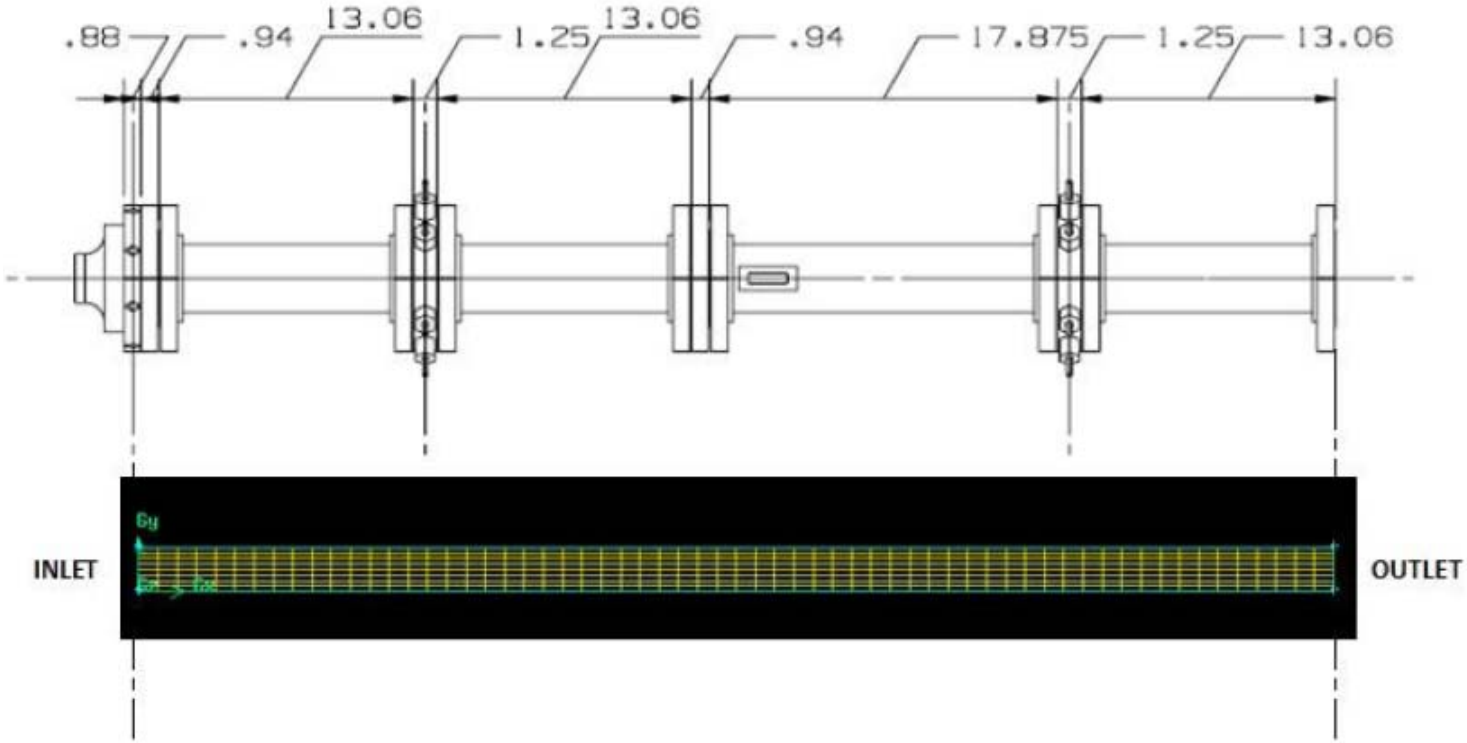


Flow-Impedance Tube



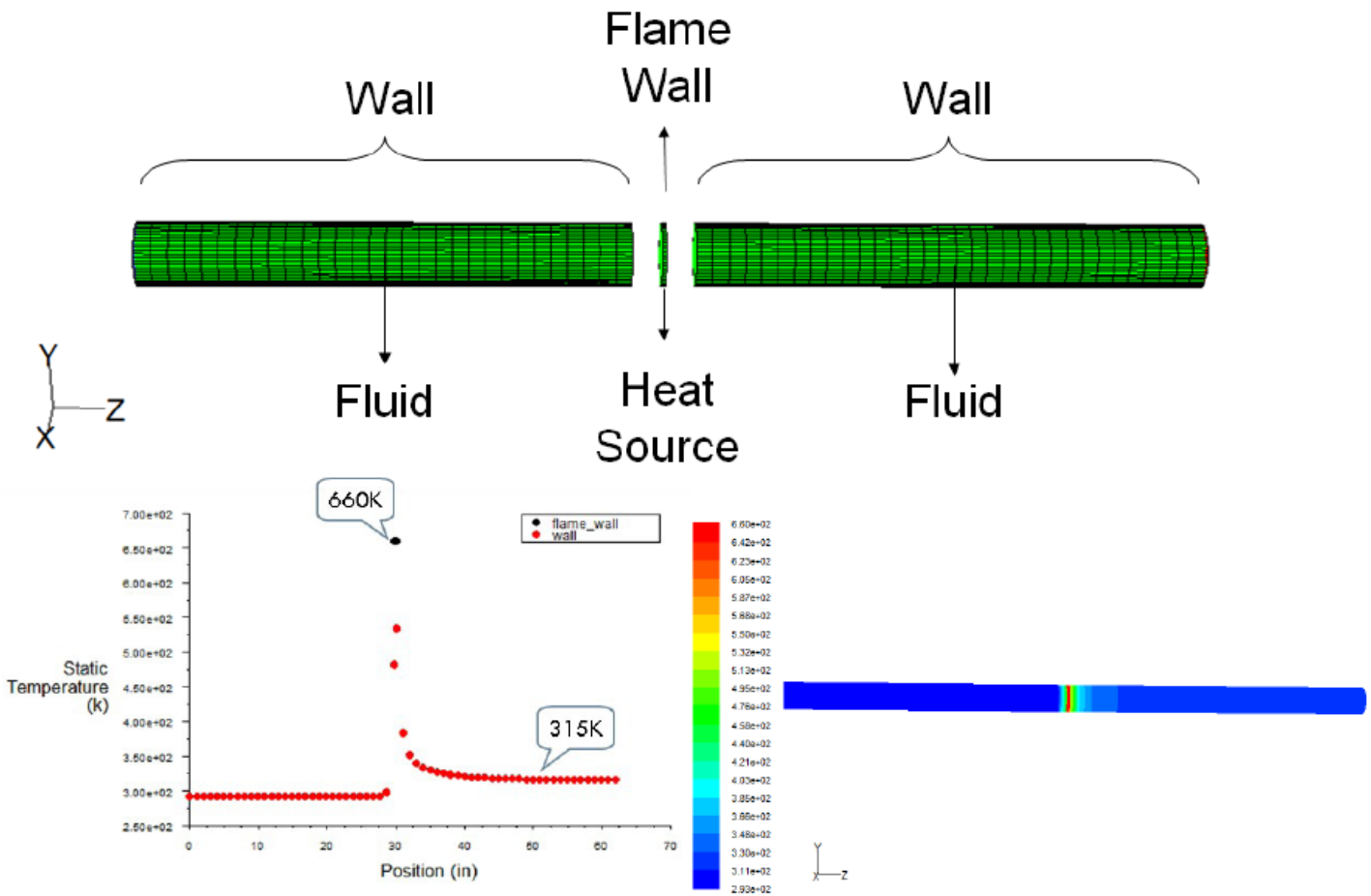
FEA Model of Flow-Impedance Tube

CFD Control Volume Approach to Combustor Modeling



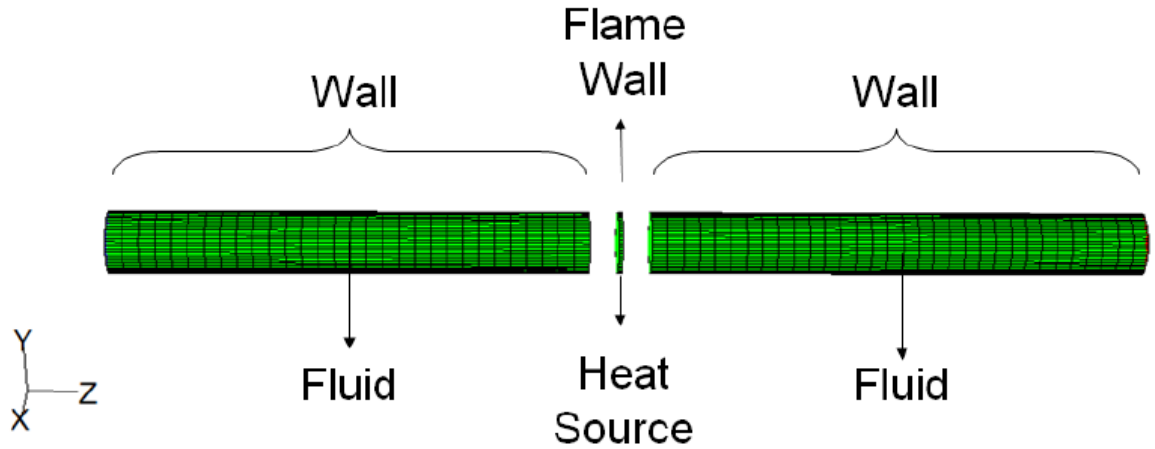
- CFD models of the baseline flow-impedance tube
  - Axisymmetric, 3-D geometry, Steady-State and Transient mechanics
- Reconcile models against experimental results
  - Fluid centerline temperature profile, flow velocities and pressure

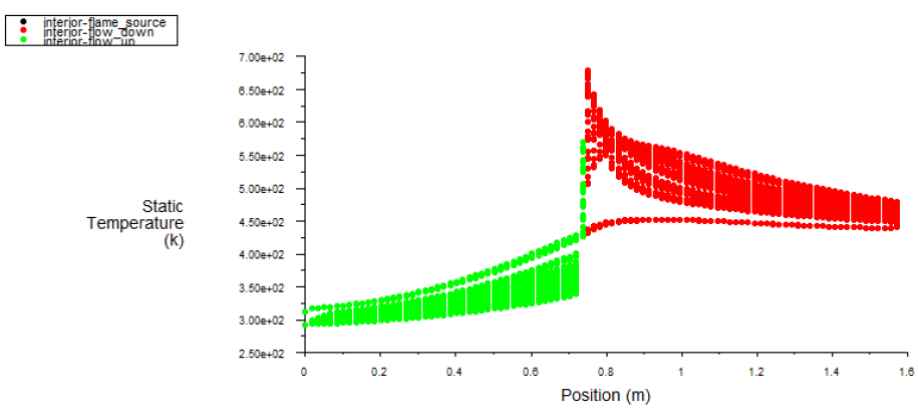
CFD Baseline Model Thermal-Fluid Model

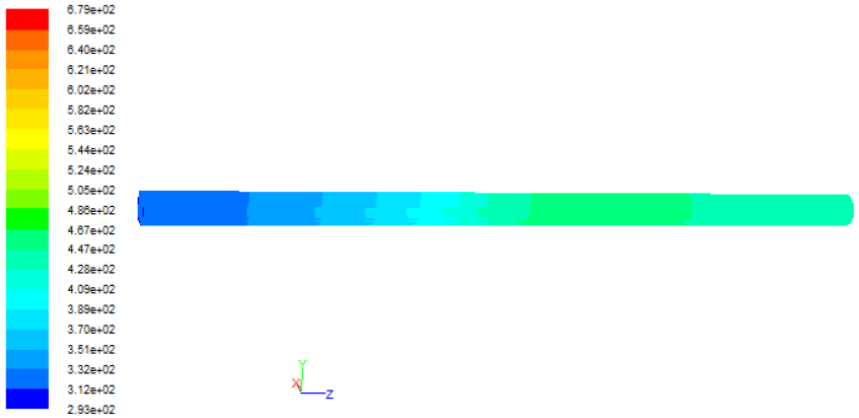


- Captures fluid centerline temperature and axial distribution

CFD Baseline Model Thermal-Fluid-Solid Model

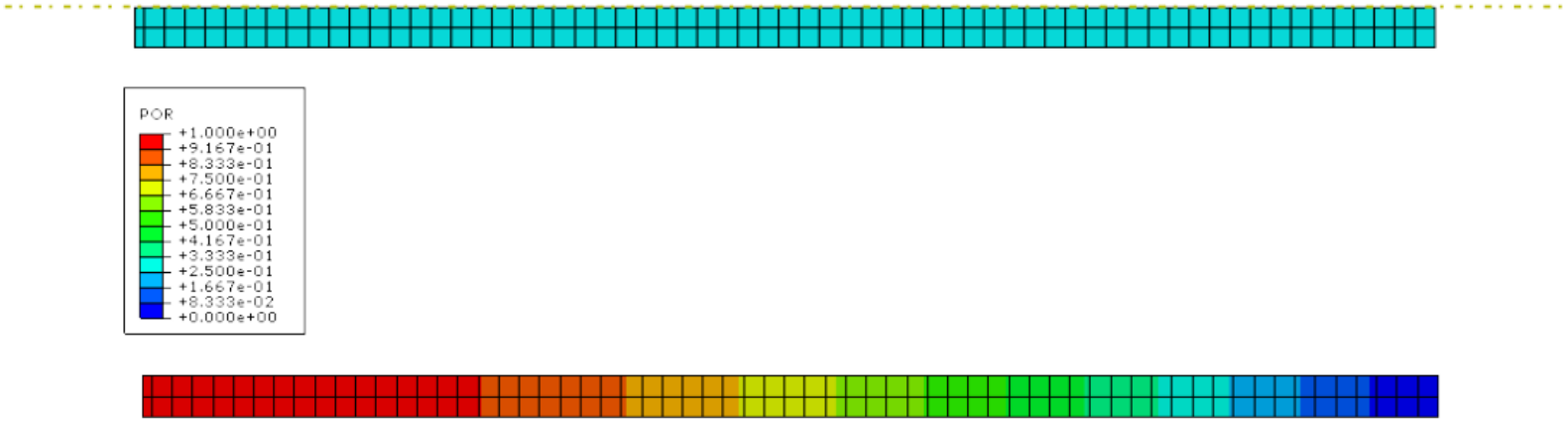




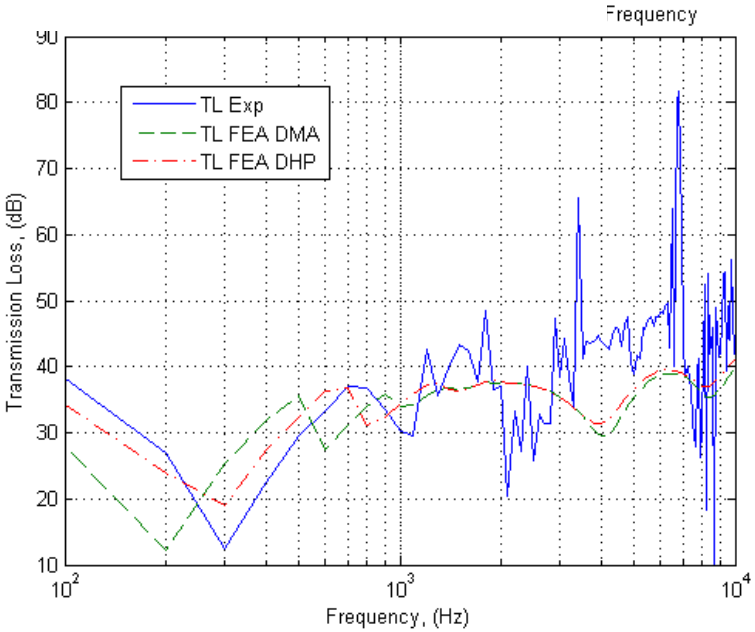


- Fluid radial temperatures and distribution compared with Exp.
  - Centerline and wall temperatures represented with less than 5 % error.

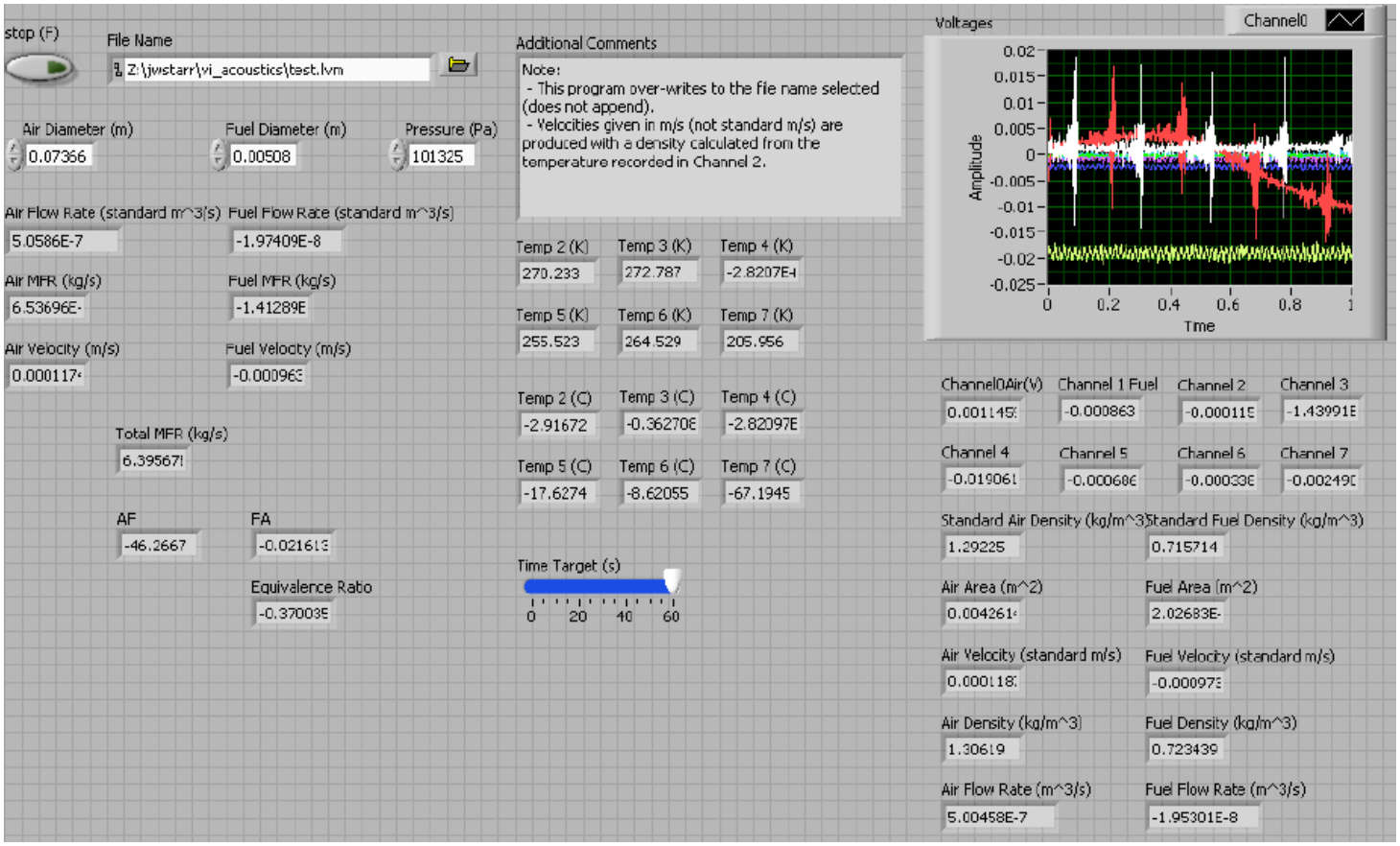
FE-Based Acoustic Baseline Modeling



- Validate Baseline Acoustics Model
  - Open-, Anechoic- and Rigid-End BC
  - Speaker impedance characterization
- Quarter wave: 54 Hz
- Lowest Frequency: 40 Hz
- Plane Wave Cutoff: 2030 Hz
- Flow Impedance Extracted from Exp.

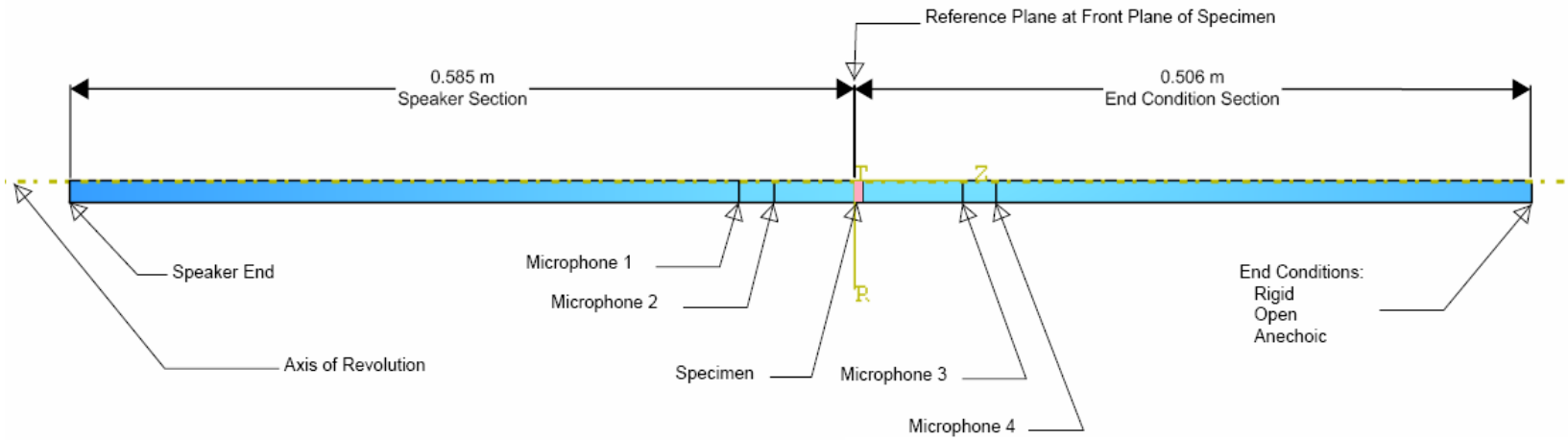


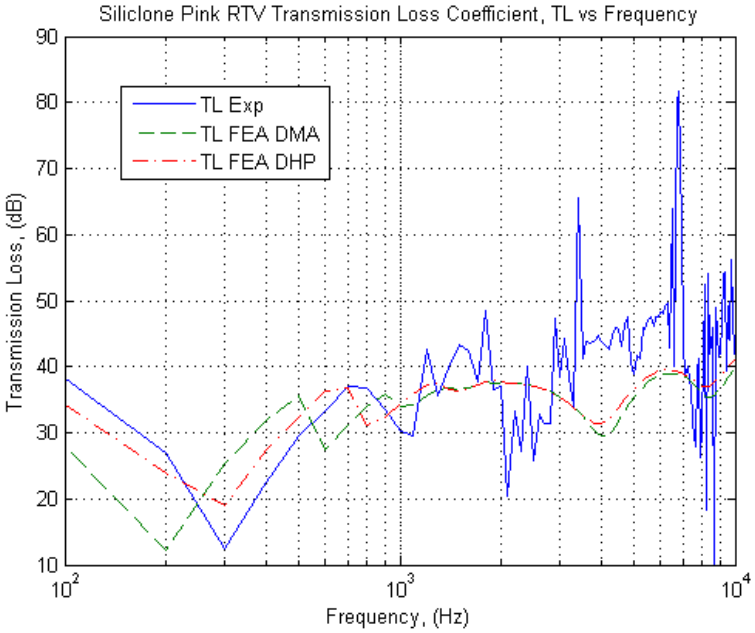
Data Acquisition Software



- 24 channel data acq. panel to control, acquire and display data
  - Time-series data posted to comma separated archive for post-processing

Pre- Post-Signal Processing

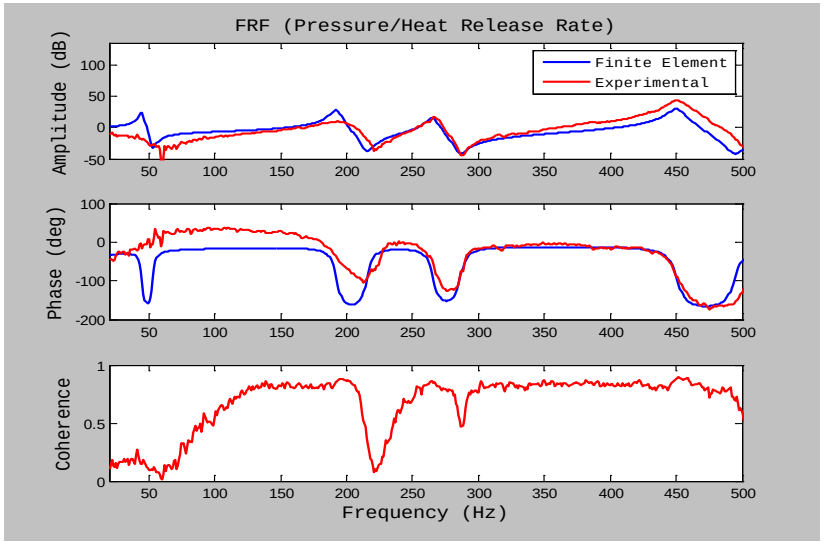




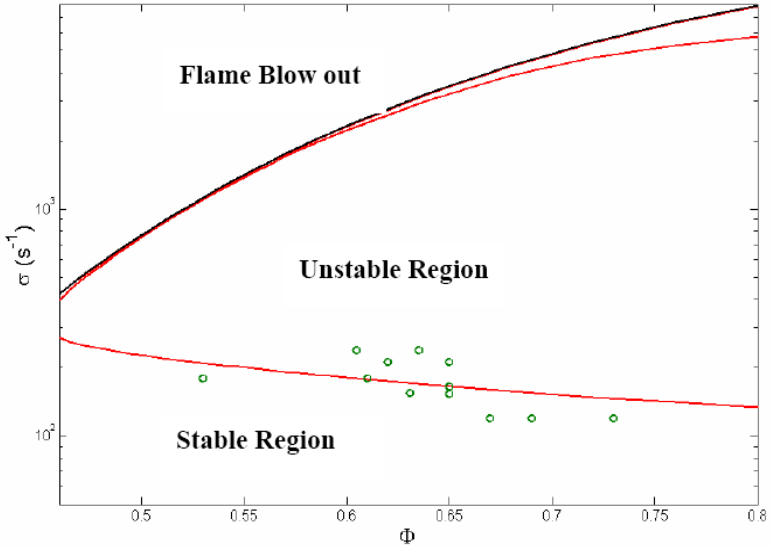
- MATLAB post-processing of data
- Refine Frequency-Domain Impedance Tube Acoustics Methods
  - Four-Load Method for impedance
  - Multi-port methods for sources
- Frequency-Domain to Time-Domain Transformation Methods

Sensitivity Analysis

- Establish impact of acoustic BC misrepresentation/errors.
  - Experimental sensitivity analysis baseline for test
  - Define errors and uncertainty in measurements, propagation of error.
- Reconcile models against experimental results
  - Establish sensitivity of FRFs relative to acoustic impedance BCs
  - Ultimately predict the impact on thermo-acoustic stability prediction



FRF Acoustic Pressure relative to Heat Release Rate



Combustion Stability Map

Acoustic Boundary Condition Representation Issues

- Time-Dependent Acoustic BC Issues
  - Frequency-Domain frequency resolution artifacts
  - Improper transformation of Impedance BCs from Frequency-Domain to Time Domain, causality effects. Temporal Error.
  - Impact of Spatial Error, experimental/computational
  - Proper utilization of time-domain acoustic BCs.
- Proposed Elements of Sensitivity Study
  - Dimensional representation, spatial error
  - Inlet/outlet effects
  - Laminar/turbulent effects
  - Frequency resolution and FRF shifts
  - Steady-State vs. time-dependent BCs

Work Plan

- Flow-Impedance Tube-Experimental
  - Shakedown of experimental configuration
  - Execute test program
- Flow-Impedance Tube-Computational
  - FEA models: acoustics, steady/transient flow,
  - CFD simulations: acoustics, steady/transient flow
- Frequency-Domain to Time-Domain Signal Processing
- Educational Mission/Efforts
  - Senior Undergraduate ME student
  - ME Ph.D. student in combustion CFD, Applied Math
- Coordinate Efforts with NETL Staff
  - CFD Simulations, Test Program

Acknowledgments

- DoE UCR DE-FG26-08NT43326
- Dr. Ron Breault, Technical Program Manager,
- Kenneth David Lyons, Technical Program Manager

- NETL Combustion Group Staff

Questions?

Thank you

Project Time Table

		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
1.0 Project Management Plan and Startup														
1.1 Formalize Project Management Plan	■													
1.2 Update Literature Search		■												
1.3 Investigate CFD Codes, FLUENT, MFIX		■	■											
2.0 Experimental Setup for Modular Combustor Facility														
2.1 Design, Build and Test Mods to the Modular Combustor														
2.1.1 Design/Build/Install Modifications to Modular Combustor		■	■	■										
2.1.2 Shakedown Updated Configuration for Combustor				■	■	■								
2.2 Design, Build and Test Acoustic Test Fixtures														
2.2.1 Design/Build Acoustic Ring Fixture for Modular Combustor		■	■	■										
2.2.2 Modify/Install/Test Existing Impedance Tube for Acoustic Ring			■	■										
2.2.3 Install/Test Acoustic Ring in Modular Combustor				■	■	■								
3.0 CFD Model Development														
3.1 Develop Baseline CFD Models for Combustor				■	■	■	■							
3.2 Develop Baseline CFD Models for Impedance Tube			■	■	■	■								
3.3 Develop Test Configuration CFD Models					■	■	■	■	■					
4.0 Test/CFD Model Validation/Correlation														
4.1 Validate Baseline Test/Model Matrix														
4.1.1 Refine Baseline Test/Model Matrix				■	■	■								
4.1.2 Validate Baseline CFD Combustor Models							■	■	■					
4.1.3 Validate Baseline CFD Impedance Tube Models						■	■	■						
4.2 Validate Test/Model Matrix for Combustor Configurations														
4.2.1 Refine Test Configuration CFD Models							■	■	■					
4.2.2 Validate Test/Model for Combustor Configurations								■	■	■				
5.0 Sensitivity Analysis of Acoustic Boundary Condition Effects														
5.1 Postprocessing of Experimental Test Results					■	■	■	■	■	■	■			
5.2 Postprocessing of CFD Sumulation Results					■	■	■	■	■	■	■			
5.3 Sensitivity Analysis							■	■	■	■	■	■	■	
6.0 Deliverables and Reports														
6.1 Quarterly Reports	■	■	■	■	■	■	■	■	■	■	■	■	■	
6.2 Yearly Presentation						■				■				■
6.3 Final Report														■

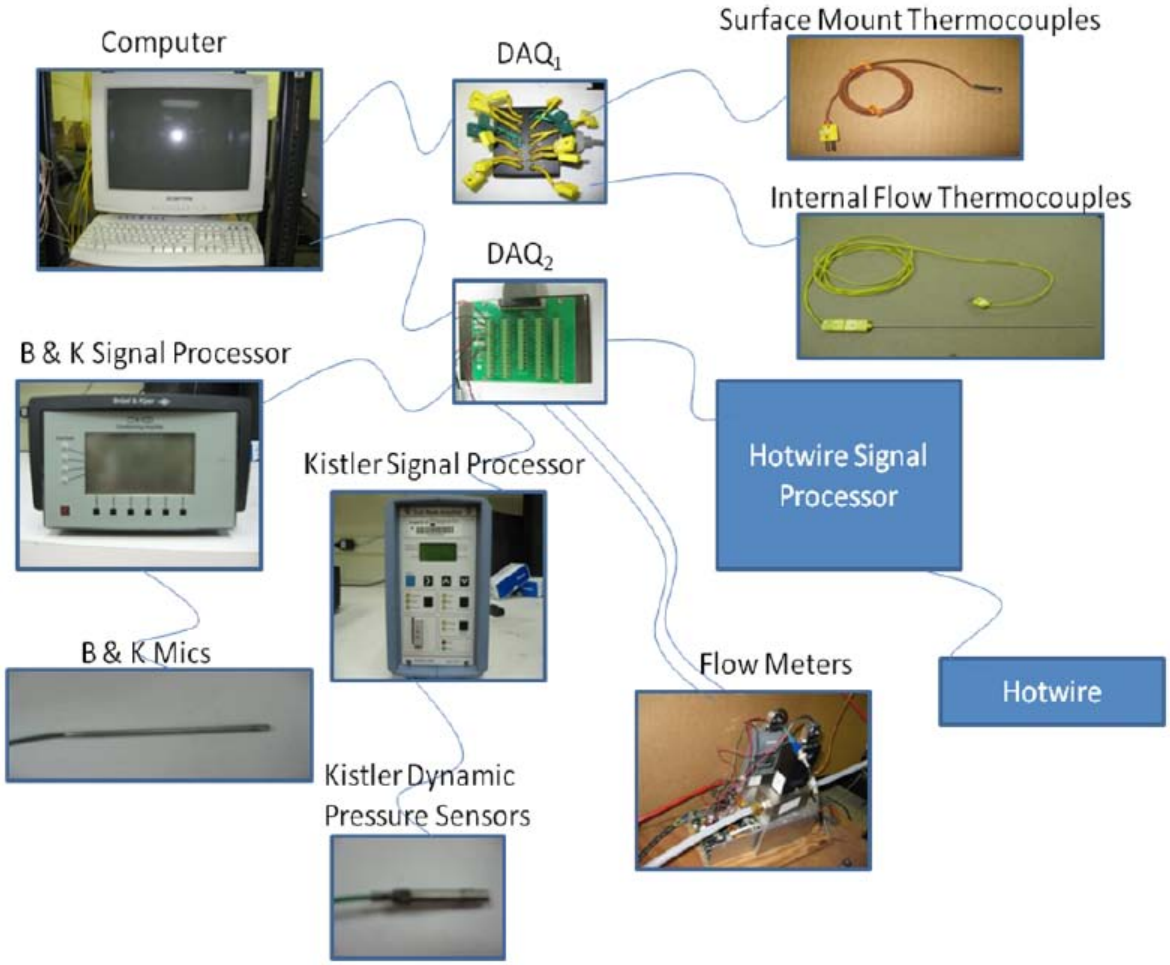
Instrument Holder Sensors

- Acoustic Microphones: B&K 4944 field microphones, 1/4” diameter
  - Asymmetric circumferential sensor array, impedance and source identification
- Dynamic Pressure Sensors, Kistler 211B5 similar footprint
  - Mean flow pressure, mounted in pairs for redundant velocity
- Velocity Measurement: Hot-Wire Anemometer
  - Single- or three-component measurement
- Temperature Measurement: Thermocouple
  - Types “K” non-reacting flow region, Type “B” reacting flow region

B&K Array Microphone

Kistler Dynamic Pressure Probe

Data Acquisition Hardware Components



- Components in data acquisition system
  - 24 Channels, simultaneously acquired to capture dynamic response

Summary of Available Experimental Apparatus

Small-Scale:

- Laminar flat-flame burner
- Self-excited laminar flat flame Rijke tube combustor

Mid-Scale:

- Gaseous fueled turbulent swirl stabilized combustor
- Liquid fueled turbulent swirl stabilized combustor
- Cold flow spray injector rig

Full-Scale:

- Modular rig
  - Bluff body stabilized combustor; Natural Gas LP
  - High temperature/pressure cross-flow liquid fuels combustors
  - Custom sector combustors

CSDL Capabilities: Air Supply

<u>Mass Flow</u>
- 1200 scfm
- 0.68 kg/s
- 1.5 lbm/s

<u>Dew Point</u>
- 35 °F
- 1.7 °C

<u>Pressure</u>
- 190 psi
- 1.31 MPa
- 13.1 bar
- 12.9 atm

<u>Maximum Preheated Temperature</u>
- 1050 °F
- 566 °C

Fuel Supplies

Natural Gas	Liquid Fuel (Kerosene or Jet-A)	Hydrogen
Mass Flow	**Mass Flow**	**Mass Flow**
•118 scfm	•30 gal/hr	•25 scfm
•0.036 kg/s	•1.54 kg/s	•1.0 kg/s
•0.08 lbm/s	•3.4 lbm/s	•2.2 lbm/s
Pressure	**Pressure**	**Pressure**
•650 psi	•435 psi	•225 psi
•4.5 MPa	•3 MPa	•1.6 MPa
•45 bar	•30 bar	•15.5 bar
•44.4 atm	•29.6 atm	•15.3 atm