DEVELOPMENT OF MODULAR, REDUCED ORDER MODELS FOR PREDICTION OF COMBUSTION INSTABILITIES

AGTSR-SCIES Subcontract

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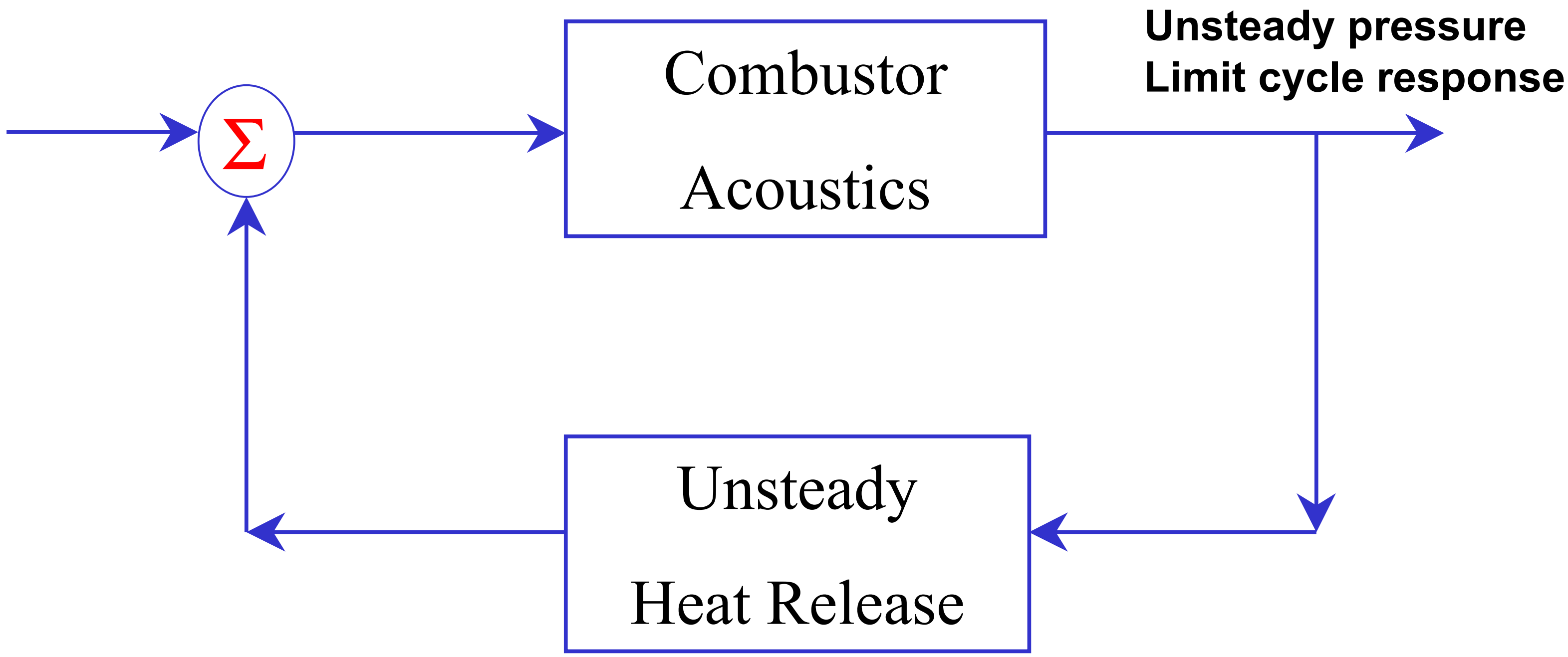
A Physically-Based Model of Thermoacoustics Instability



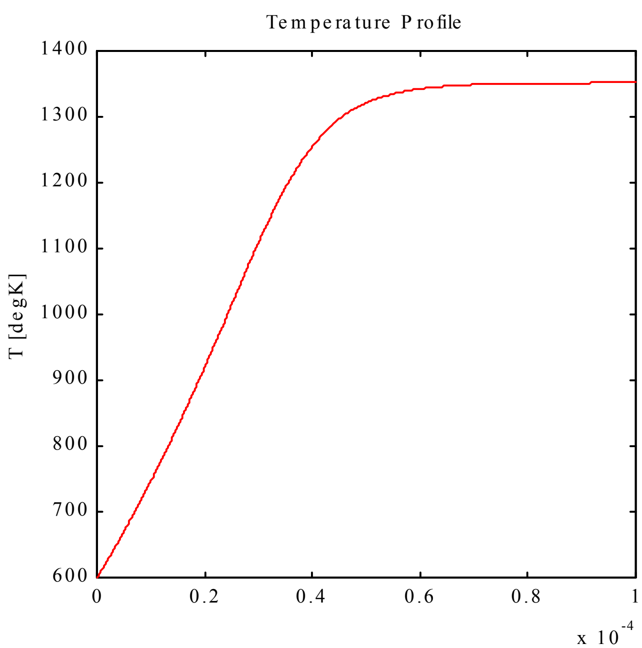
A feedback structure for linear/nonlinear parametric model

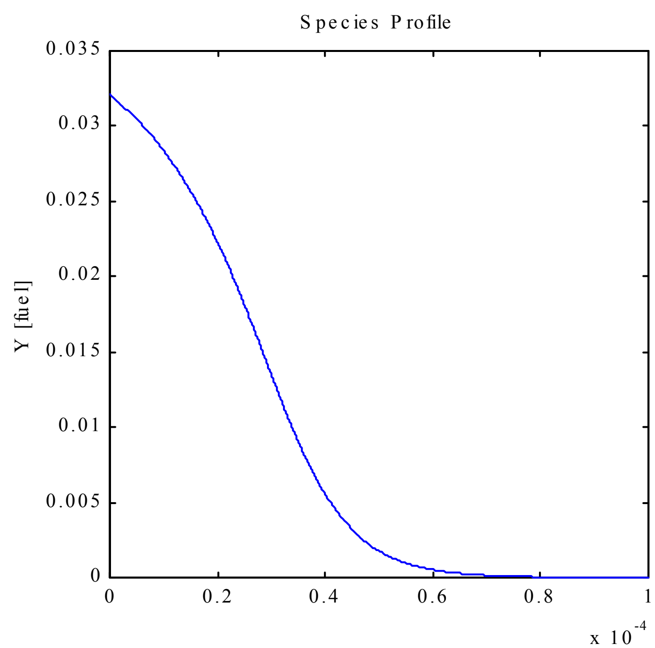
$$\frac{\partial Y}{\partial t} + m_o \frac{\partial Y}{\partial \psi} = \rho^2 D \frac{\partial^2 Y}{\partial \psi^2} - \rho^{-1} RM$$

$$\frac{\partial T}{\partial t} + m_o \frac{\partial T}{\partial \psi} = \frac{\rho \lambda}{c_p} \frac{\partial^2 T}{\partial \psi^2} + \frac{RM}{\rho c_p}(h_r^o - h_p^o)$$

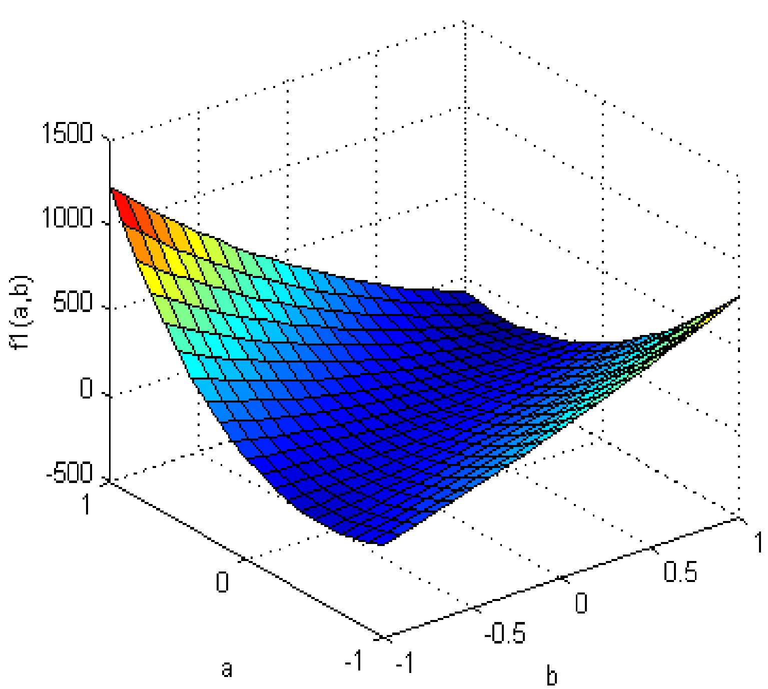
$$R = \upsilon_f k \rho^{\upsilon_f + \upsilon_o} M_o^{-\upsilon_o} M_f^{-\upsilon_f} Y_o^{\upsilon_o} Y_f^{\upsilon_f} e^{-E/RT}$$

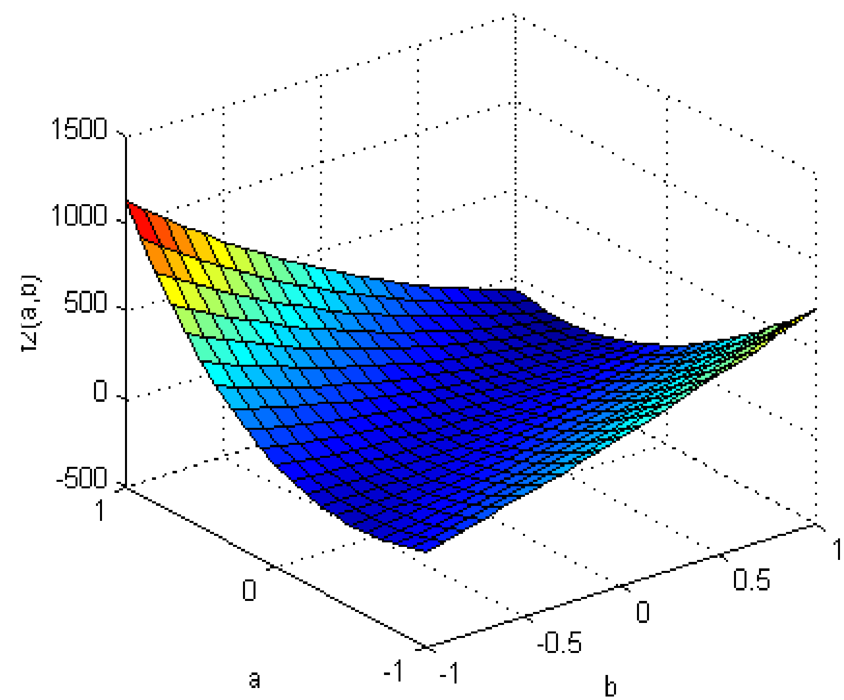
$$\psi(x,t) = \int_0^x \rho(x,t)\,dx$$





Nonlinear flame dynamics





First order expansion

$$T(\psi, t) = T_o(\psi) + a(t) \cdot T_1(\psi)$$

$$Y(\psi, t) = Y_o(\psi) + b(t) \cdot Y_1(\psi)$$

Nonlinear functions

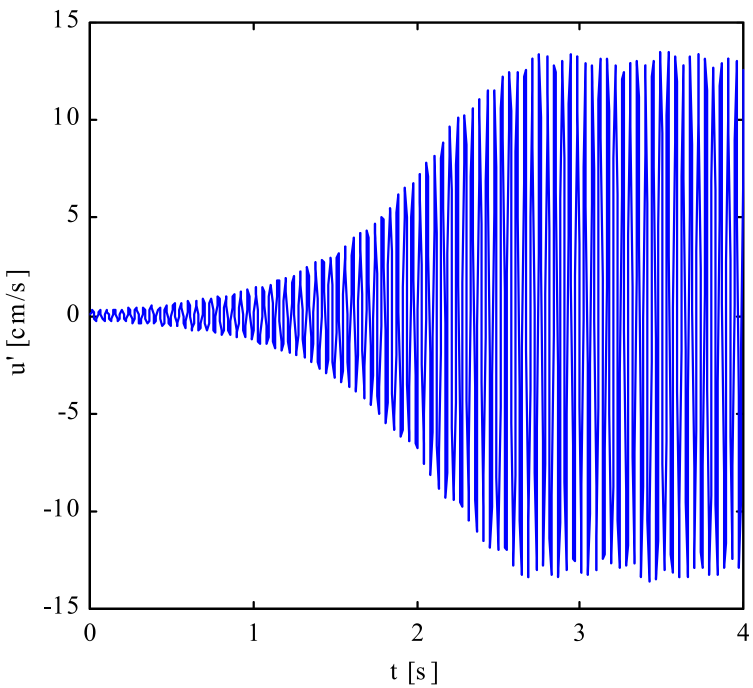
$$f_1(a, b) = \frac{1}{\rho C_p} \sum_{k=1}^{n} R_k (h_r^0 - h_p^0)$$

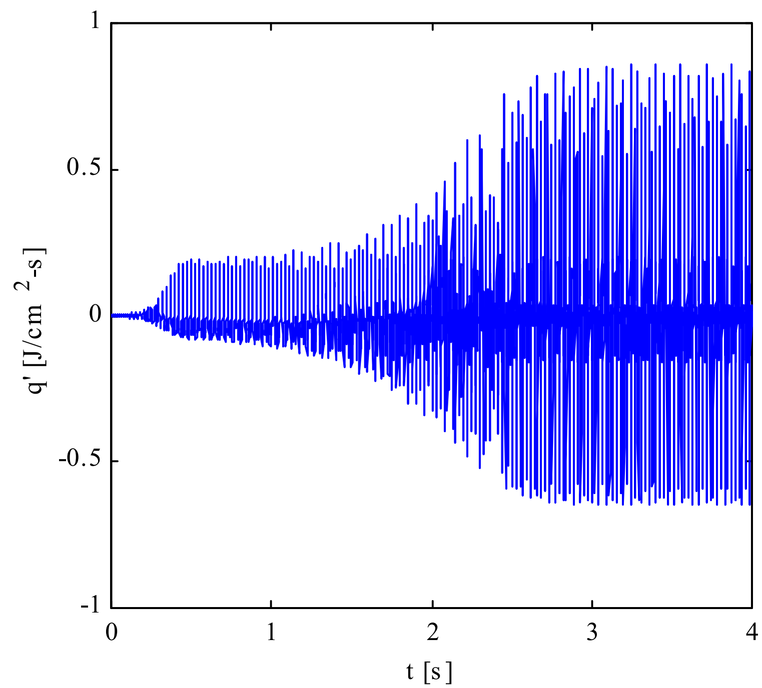
$$f_2(a, b) = \frac{1}{\rho} R_f M_f$$

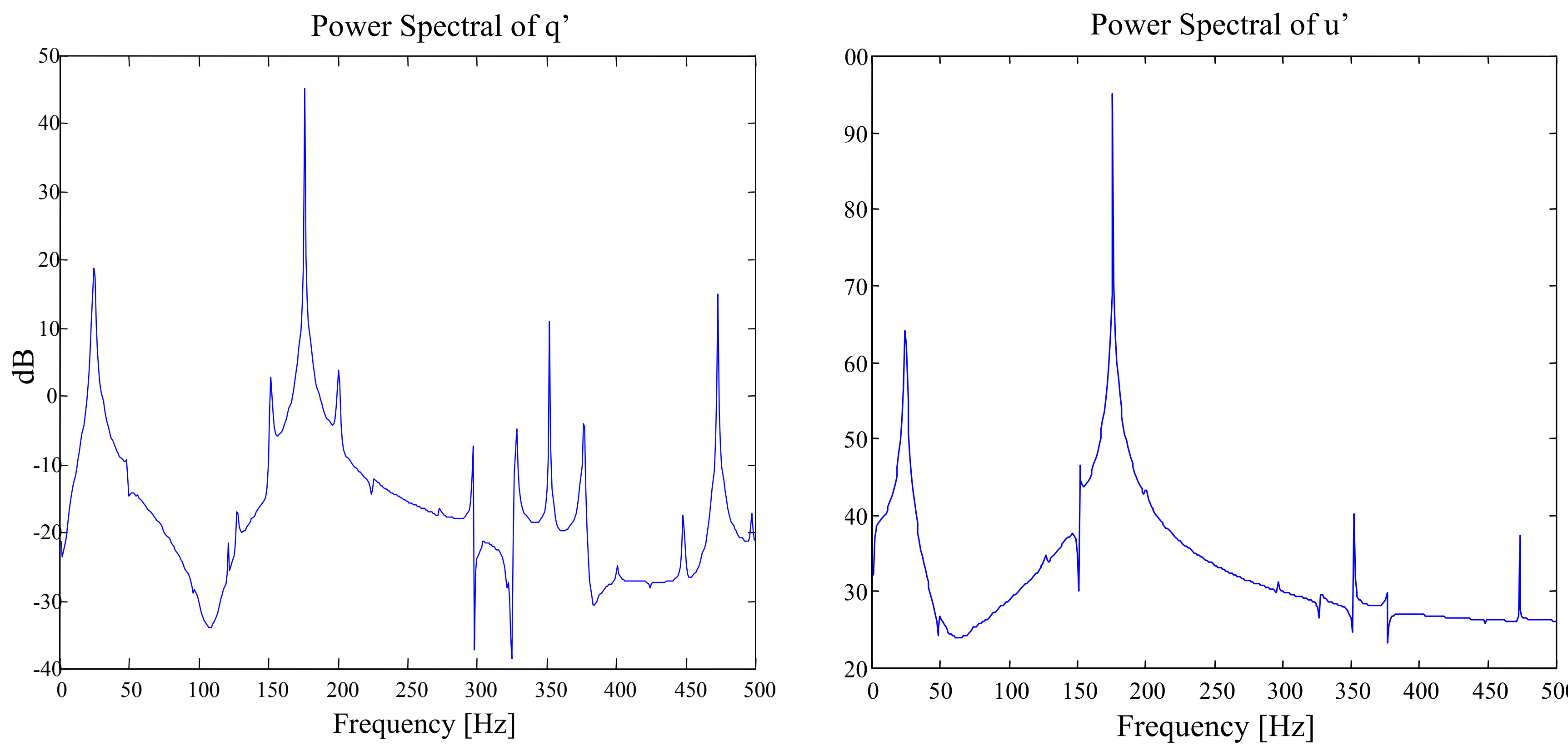
Heat release model

$$Q_{fluid} = \int_0^{\infty} R \Delta H_{reac} \rho d\psi - \rho \lambda \frac{\partial T}{\partial \psi}\bigg|_{\psi = 0}$$

Thermal Acoustic Limit Cycle

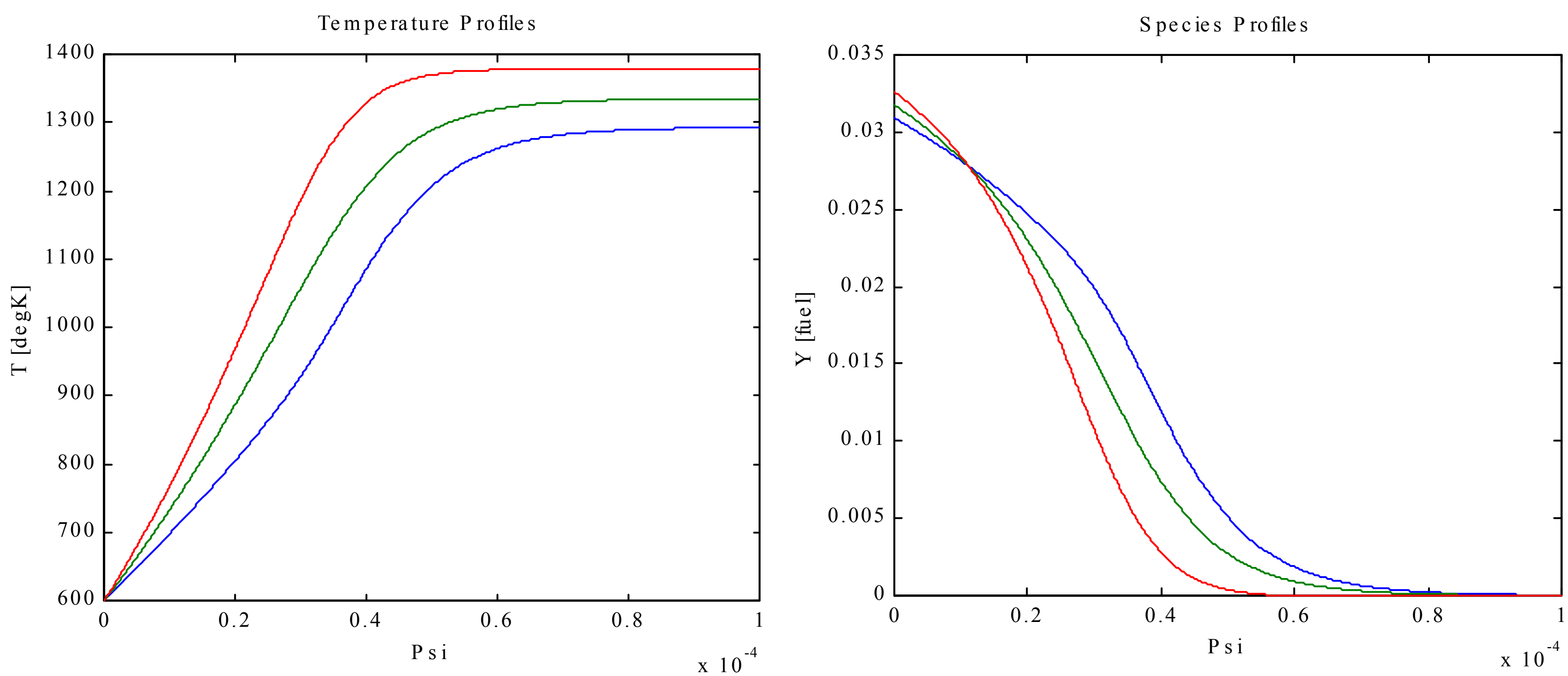






The figures above show the power spectral densities for the unsteady pressure and heat release rate. The pressure spectrum is the result of filtering the heat release rate through the two-mode (60 and 180 Hz) acoustic model.

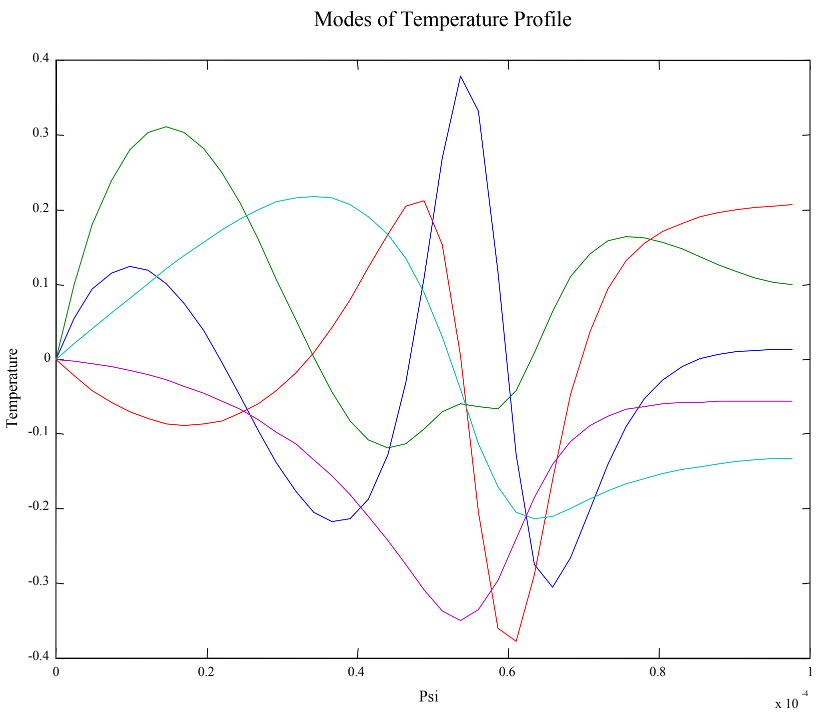
Temperature & species profile oscillation



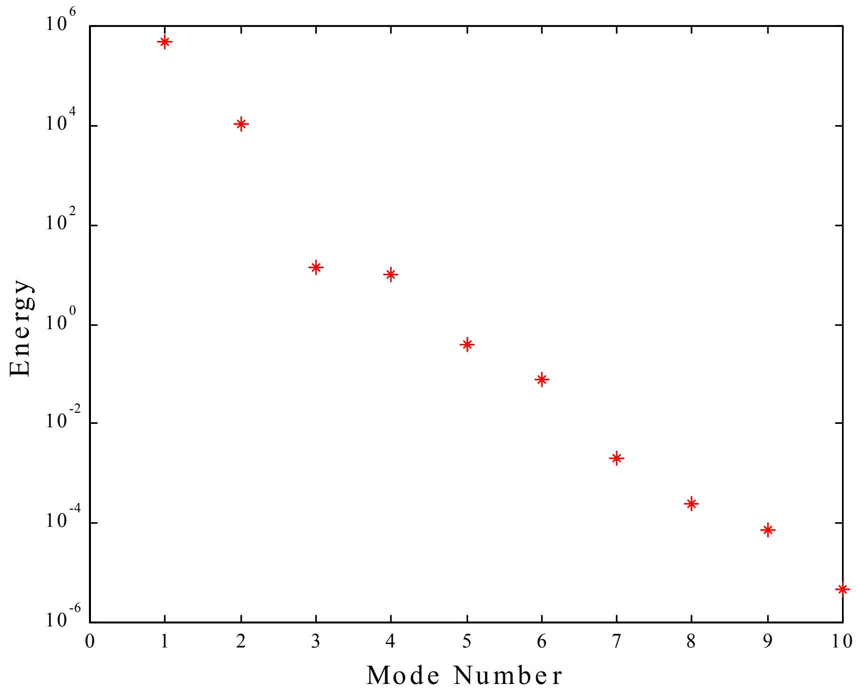
Principal Orthogonal Decomposition

The key problem in deriving a reduced-order model for a system of partial differential equations is choosing a basis, a set of mode shapes. The POD method uses the results of high-order finite-difference or finite-element simulations to choose a basis which minimizes the error in representing the simulation results with the basis.

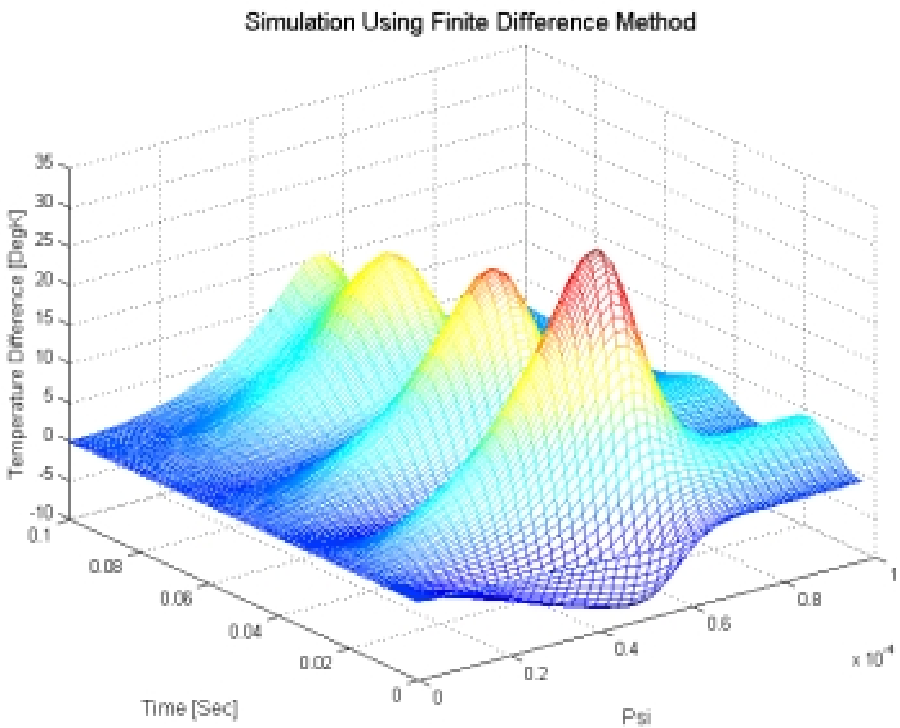
Principle Modes



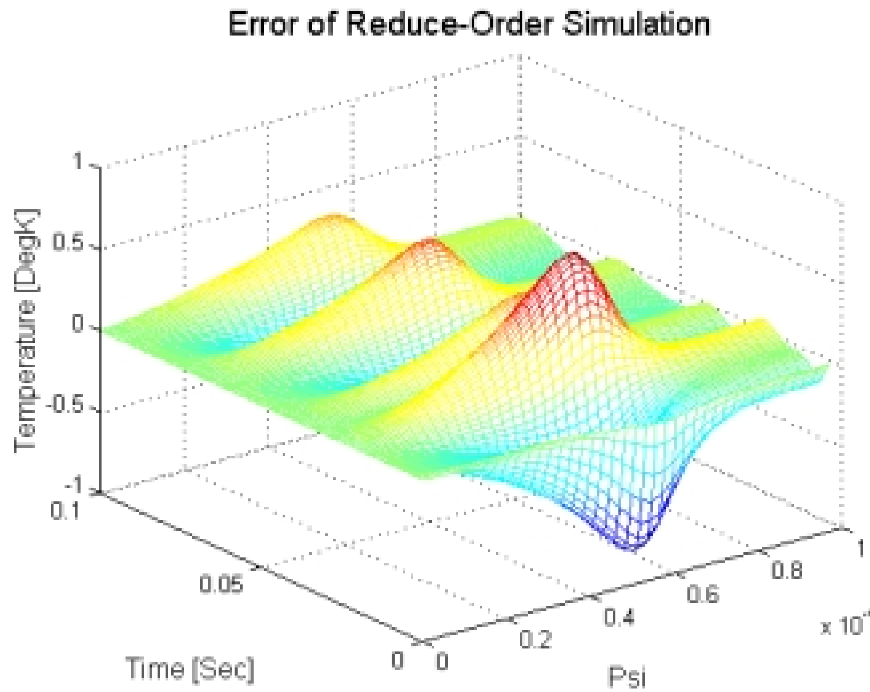
Energy for Each Mode



Finite Difference Simulation



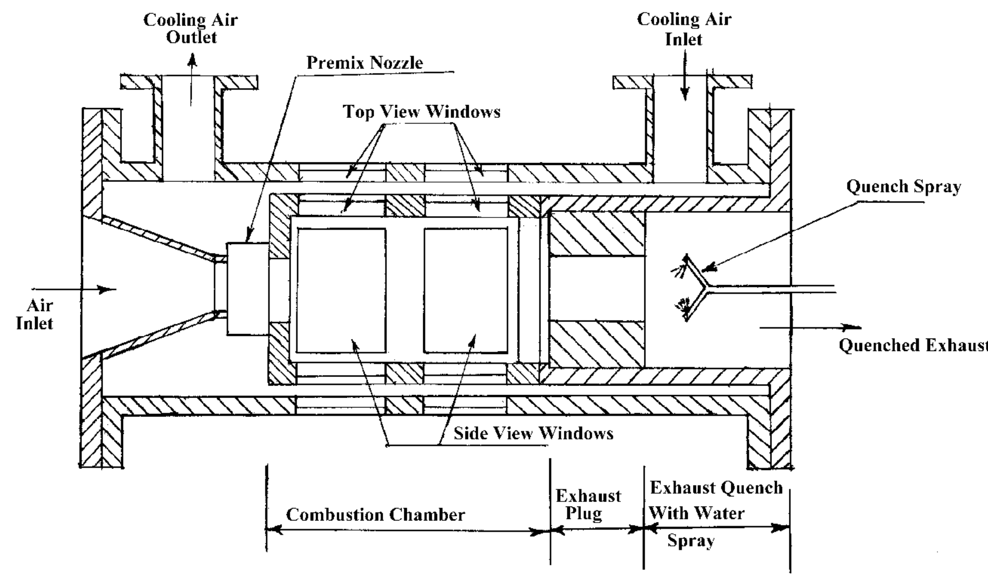
Error of Fifth-Order Model



VACCG Combustors

VACCG Combustors

1-D Tube Combustor



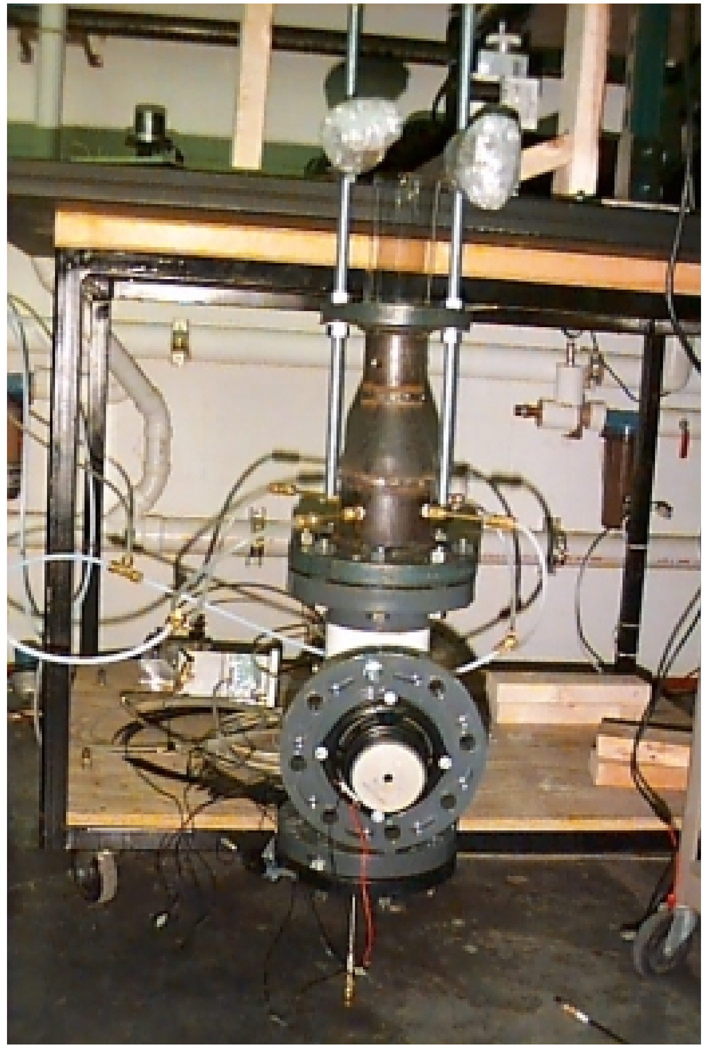
Sudden Expansion Gen-1 Combustor

Laminar Premix Burners

- Chemiluminescence Burner

Flame Dynamics Burner Gen-1

Laminar Premix Burners



Flame Dynamics Burner Gen-2

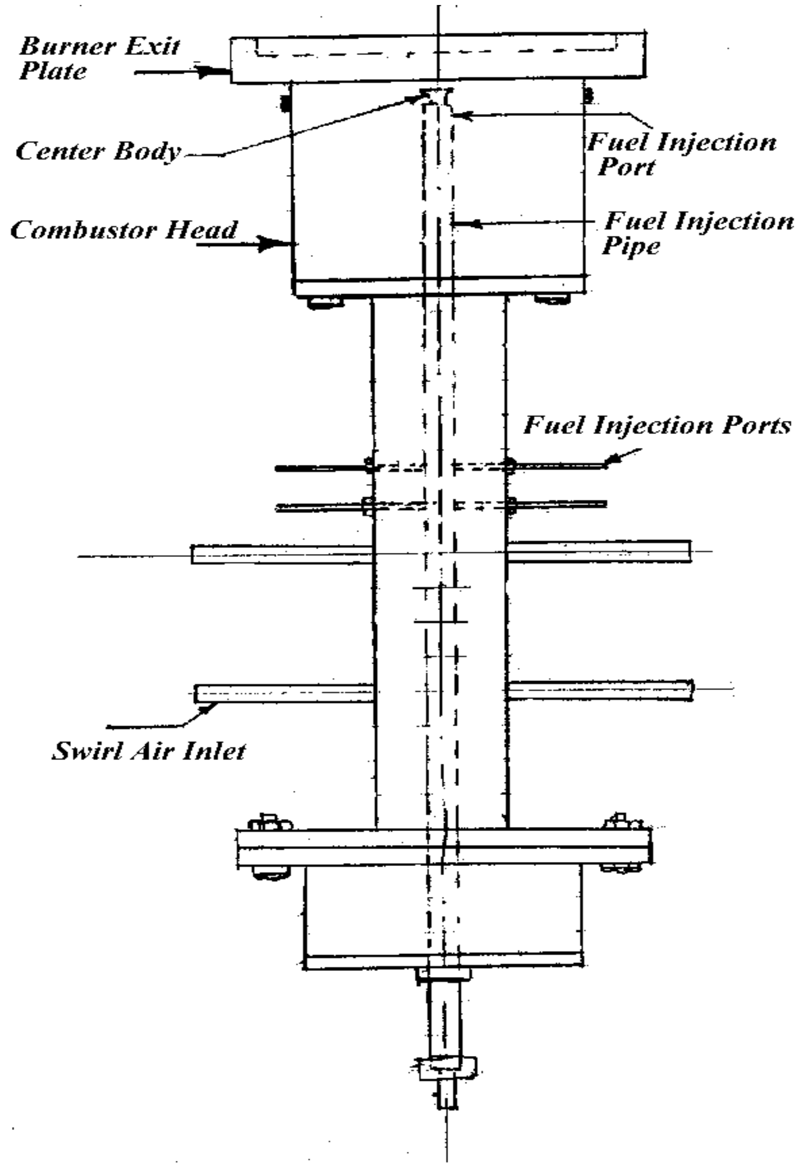
Multi Phase Swirl Combustor

Combustor

Pressure Vessel

VACCG Multi-Phase Combustor

Schematic



Burner Exit Plate
Center Body
Fuel Injection Port
Combustor Head
Fuel Injection Pipe
Fuel Injection Ports
Swirl Air Inlet

Specifications

- Flow rates:
  - Air : 200 scfm max
- Power: **400 kW**
- Reynolds Number: **120,000 max**
- Swirl Number: **0.4 to 1.8**
- Pressures: **Atmospheric to 10 bar**

Studies Proposed

- I. Gaseous Fuels
  - **Ia. Effect of Degree of Premixing on**
    - Stability Range
    - Emissions i.e. CO, NO, NO_x, Hydrocarbons
    - Combustion Efficiency - heat release and flame compactness
    - Thermo-Acoustic Instabilities and their control
      - Acoustic studies cold & hot
      - Flame dynamics studies; free open loop, and closed loop
      - Actuators, multi point injection
      - Optical sensor location
      - controllers

Studies Proposed

- Ib. Variation of Gaseous-Fuel Composition
  - Study the parameters mentioned in Ia for varying composition of fuel
    - Example:
    - a. 90% Methane, 10% ethane
    - b. 80% Methane, 10% ethane, 10% propane
    - c. Methane, Alkanes/Alkenes/Alkynes blends

Studies Proposed

- II. Liquid Fuel Sprays
  - **Degree of Pre-vaporization**
  - **Degree of premix**
    - **Their Effects on**
    - **a.** Stability Range
    - **b.** Emissions i.e. CO, NO, NO_x, Hydrocarbons
    - **c.** Combustion Efficiency - heat release and flame compactness
    - **d.** Thermo-Acoustic Instabilities, free flame, open and closed loop control.

Parameters

- **The following parameters can be varied to conduct the above studies**
  - Reynolds Number
  - Swirl Number
  - Equivalence Ratio
  - Axial distance of the fuel injection plane from the exit of the burner
  - Pulsation of air flow (for induced instabilities)
  - Pulsating main fuel actuation (for control)

Diagnostics

- Chemiluminescence from OH* & CH* relate to heat release. Direct Heat flux measurements using heat flux gages
- PLIF to study the degree of premix both for cold flow and for conditions with the flame.
- PIV to study the degree of swirl and exit stream velocities - both for cold flows and with the flame.
- Exhaust gas stream emissions recorded using gas analyzers

Analysis

- System ID
  - Map the acoustics of the combustor both with and without the flame
  - Correlate measured p' to u'
  - Obtain the transfer function for the flame relating q' to u' both for linear and nonlinear response.

Analysis

- Determine the influence of key processes
    - Droplet Vaporization
    - Mixing
    - Heat transfer
    - Swirl
    - Vortical Flow

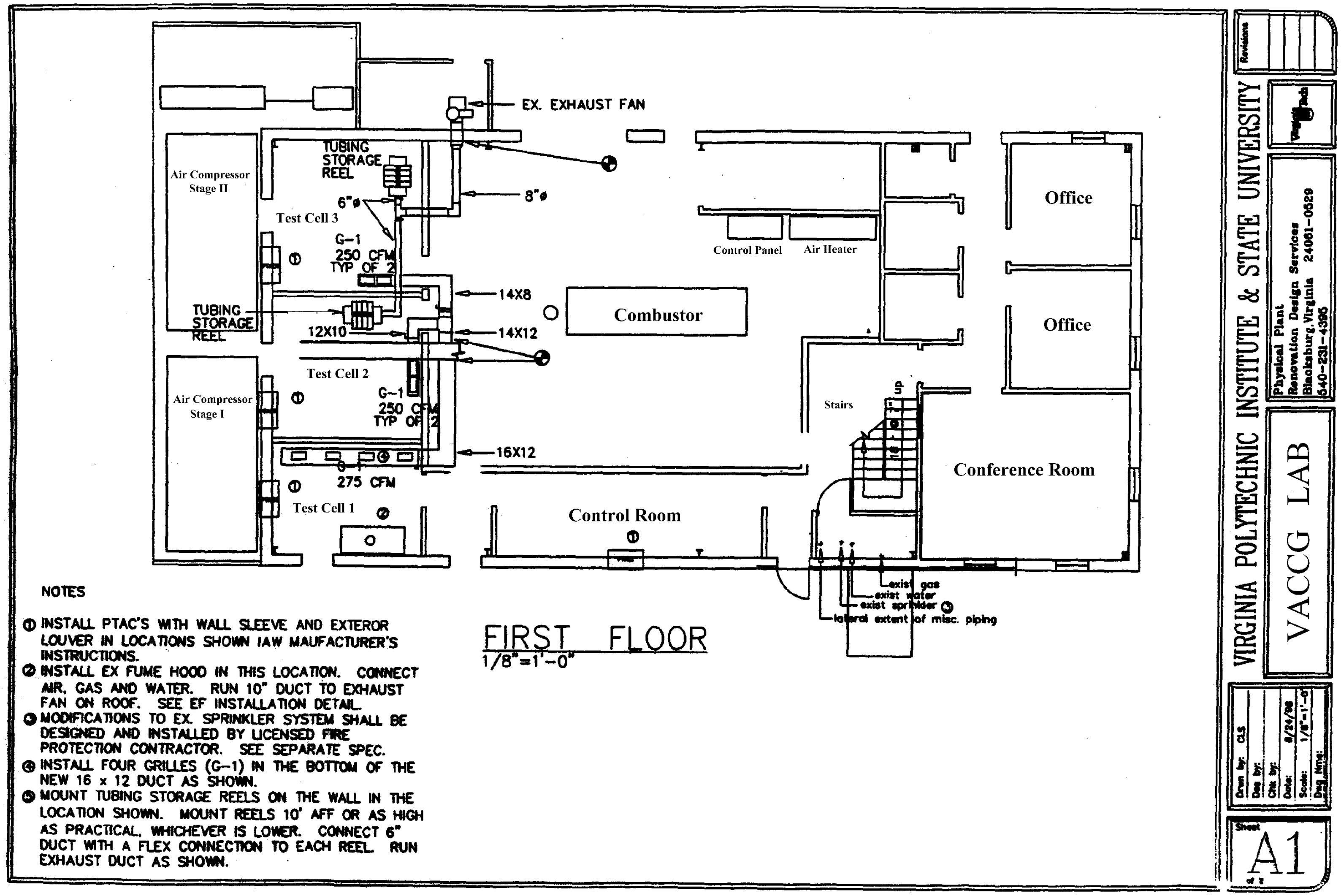
Modeling

- Physics based numerical model of the Combustor shall be developed using existing codes and expertise.

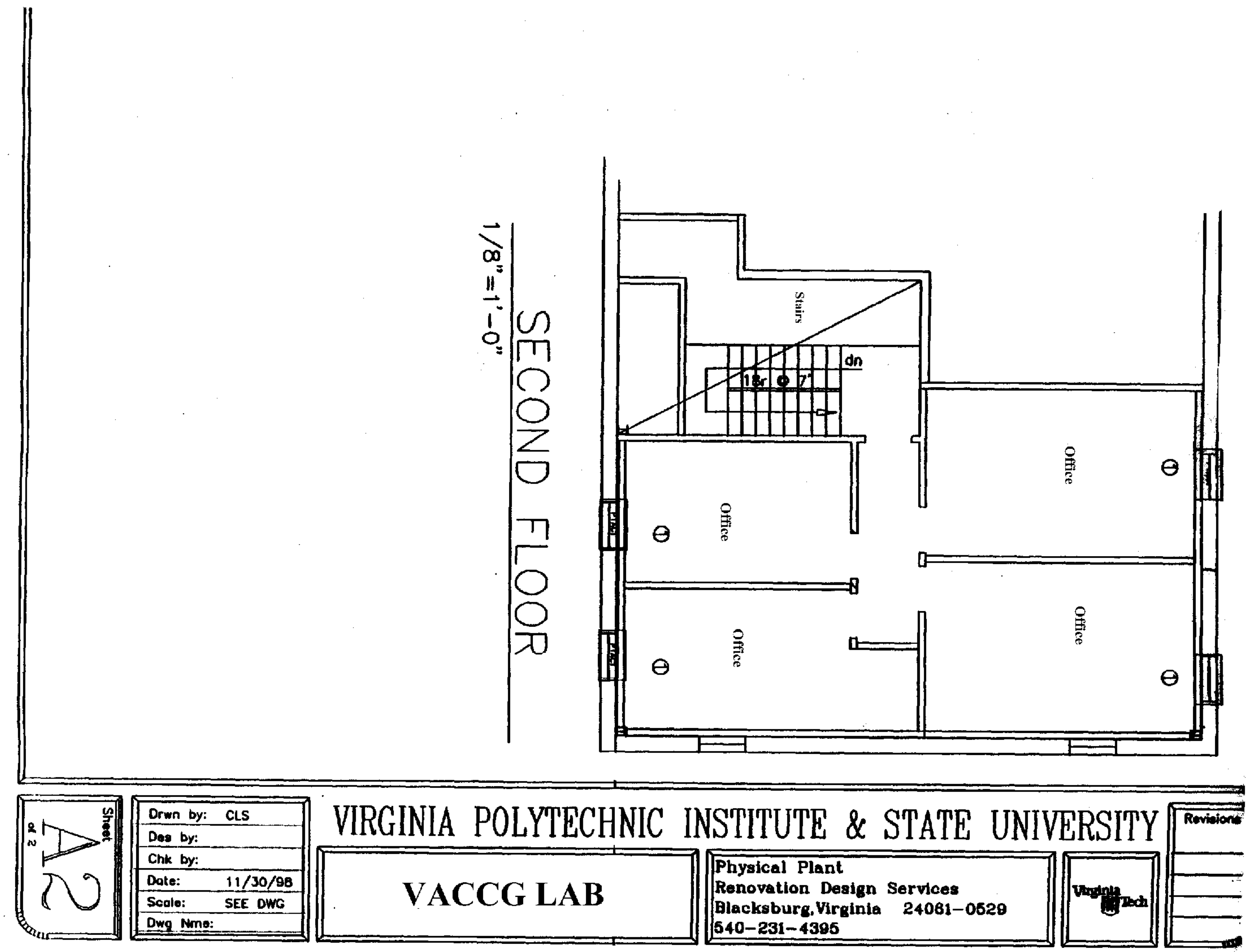
- The model shall be anchored on the experimental data.

VACCG Combustor Facility

New VACCG Lab Layout



New VACCG Lab Layout



Gen-1 Combustor Specifications

- Mass flow rate
    - $_{fuel}$ = 0.09 Kg/min to 1.72 Kg/min
    - $_{air}$ = 0.06 Kg/sec to 0.5 Kg/sec
- Thermal Power: 1.5 Megawatts (max)
- Reynolds Number: 78,000 to 981,000
- Swirl Number: 0.5 to 2
- Inlet mixture temperature (T_3): 500 K to 840 K
- Combustor Pressures:
    - Stage 1: up to 10 bar
    - Stage 2: up to 30 bar

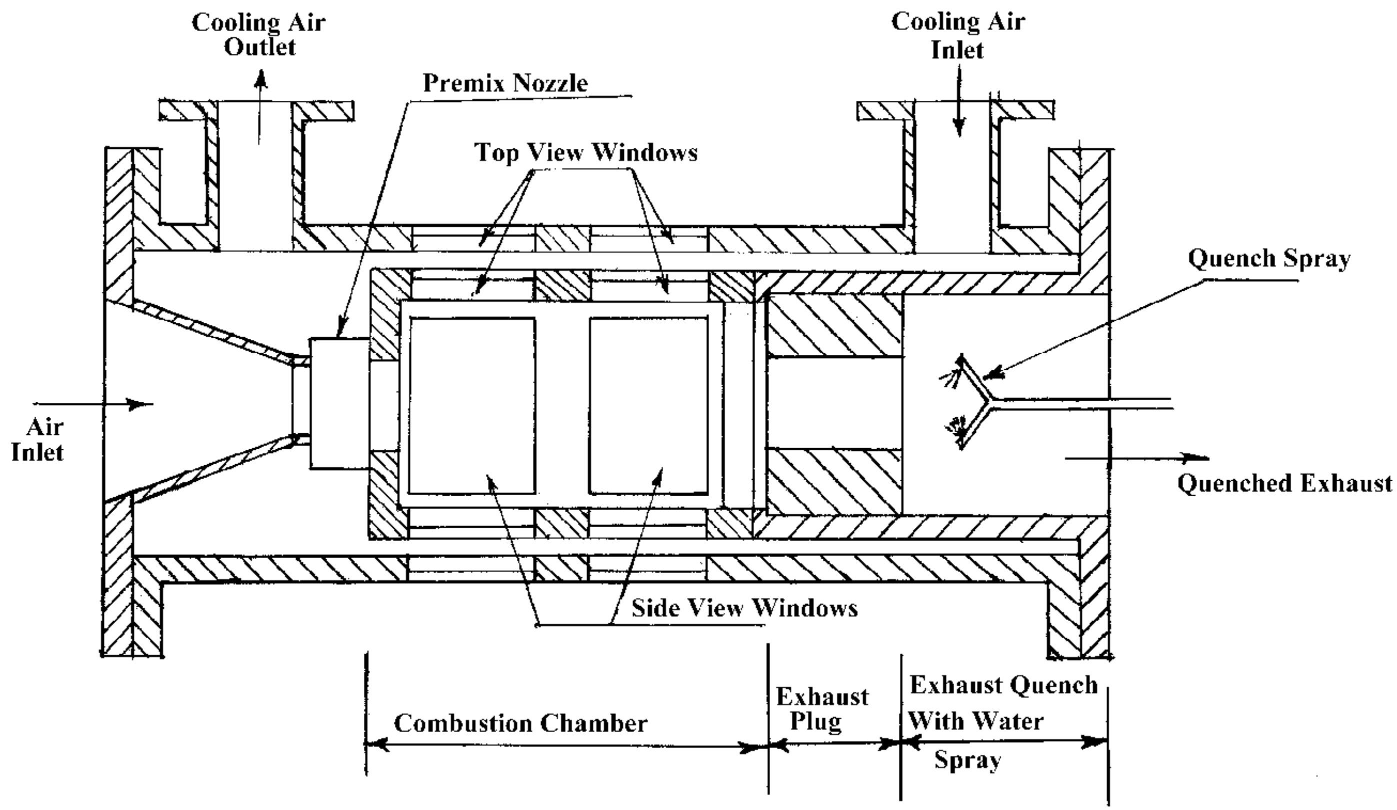
Gen-1 Combustor Design

- Square cross section 0.2 m x 0.2 m (8" x 8").
- The side walls have quartz windows.
- Cooling is by cold pressurized air.
- Designed to sustain a swirl stabilized flame.
- Different exit plugs can be used to excite different acoustic frequencies.

Gen-1 Combustor Design

- The fuel nozzles injecting Natural gas into the swirling air shall be choked.
- The exhaust from the combustor is immediately quenched with water spray to a temperature of about 600 ^{o} K

Gen-1 Combustor Schematic



New VACCG Facility

- Equipment Specifications
  - Air Compressors- Stage I
    - Air Flow rate (maximum): 900 scfm
    - Discharge Pressure: 190 psig
  - Air Compressors- Stage II
    - Air Flow rate (maximum): 900 scfm
    - Discharge Pressure: 508 psig
  - Air Drying System
    - Capacity: 1200 scfm at a dew point of 35 degrees F

New VACCG Facility

- Air Heater
  - Air Flow rate (maximum) 900 scfm
  - Air Flow rate (minimum) 100 scfm
  - Air Outlet Temperature: 1050 ^{o} F
  - Air Pressure (maximum): 508 psig
- Natural Gas Compressor and Storage
  - NG flow rate: 31 scfm
  - Discharge Pressure: 5000 psig
    - Storage: 34 ft^3 vessel that can store 12114 SCF of Natural Gas at 5000 psig
    - The system shall deliver 118 scfm of natural gas at 662 psig for a period of 2 hours. The period of recovery between two usage intervals shall be 10 hours.

Process Flow Diagram

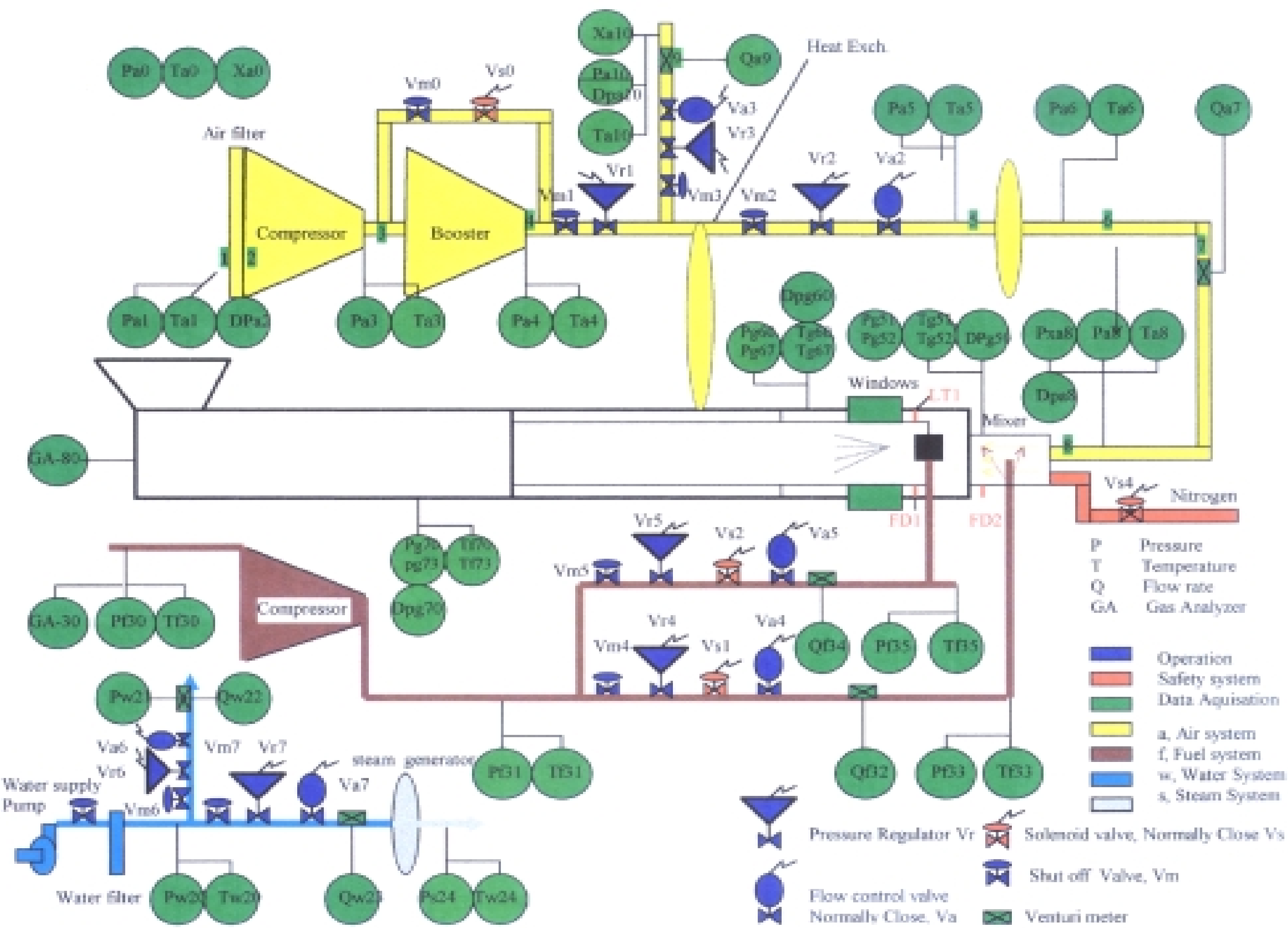


Fig. (1) Flow diagram of Measuring and control parameters

Flow Diagram Nomenclature

- **Parameters for control & measuring system:**
  - a   Air system
  - f   Fuel system
  - P   Pressure
  - s   Steam system
  - T   Temperature
  - Q   Flow rate
  - GA   Gas analyzer
  - Va   Flow control valve normally closed,
  - Vm   Shut off valve,
  - Vr   Pressure Regulation valve,
  - Vs   Solenoid valve, normally closed
  - w   Water system

Nomenclature and Explanations for Flow Diagram

- **Location of measuring points:**
  - 1-10 in air system.
  - 20-29 in water system.
  - 30-39 in fuel system
  - 50-59 in the mixer
  - 60-69 in combustor