Effect of Structural Heat Conduction on the Propagation of Flames in Microchannels

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Motivation

- Propulsion systems for Nano and Pico-satellites
  - 0.1 to 10 kg
  - High energy density of chemical propellants is attractive
  - Combustion well established means for energy release
- Behavior of deflagration wave may be different when stabilized in small passages
  - Increased exchange with structure
    - *Quenching*
    - *Increased burning rate*
    - *Enhanced flame stability*
  - Potentially important effects on performance of micro-rocket motors

Previous Work: Fundamental

U N I V E R S I T Y O F M A R Y L A N D

- Quenching in small passages
  - Zeldovich (1941)
  - Lewis and Von Elbe (1961)
- Effect of heat loss on RR and flammability limits
  - Spalding (1954)
    - *Heat loss decreases burning rate and broadens flammability limits*
- Effect of heat recirculation (excess enthalpy burners)
  - Weinberg (1970)
  - Weinberg and Hardesty (1974)
  - Takeno(1979,81)
    - *Constant T walls, single-step reaction*
  - General observations:
    - *Super-adiabatic flame temperatures*
    - *Elevated burning rates*

Previous Work: Micro-Channels

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- Burning rate and flammability measurements in conductive tubes
  - Zamaschikov (1997)
    - *Combustion below 'quenching limit' possible*
- Model of flame propagation in a narrow, conductive, channel
  - Zamaschikov and Minaev (2001)
    - Fast chemistry
    - Conduction broadens flammability limits
    - Hysteresis possible
- Minimum 'practical' volume for an HCCI combustor
  - Aichlmayr (2002)
    - *Thermal coupling between gas and structure*
    - *Full chemistry*
    - *No conduction within structure*
- Effect of velocity, heat loss, and passage width on burning rate in microchannel
  - Matalon and Daou (2002)
    - *Constant T walls, single-step overall reaction*
    - *Heat loss to environment decreases burning rate*
- Effect of axial conduction in heat recirculating burner
  - Ronney (2003)
    - *PSR with full chemistry*
- Effect of axial conduction in silicon micro-combustor
  - Current work: Effect of heat transfer within structure (conduction)

Objective

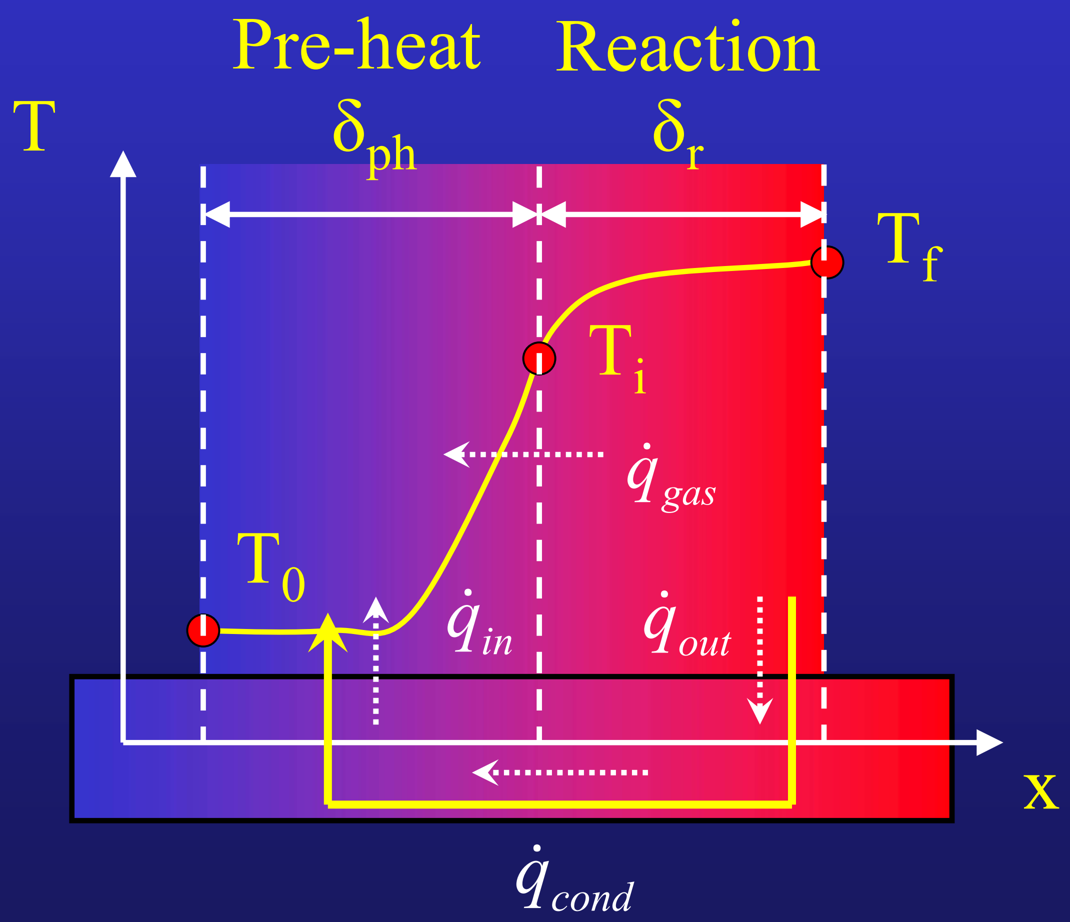
- Investigate physics of fluid structure coupling that occurs in chemically reacting systems operating at micro-scales.
  - Enable development of small, efficient combustors for micro rocket motors
  - How small can *practical* micro-rockets be built?
    - *Efficient and stable combustion*
  - What level of performance is available?
    - *Thrust/weight (power density)*
    - *Specific impulse (efficiency)*

Approach

- Modeling and Simulation
  - Simple model for effect of thermal coupling on δ_r
    - *Modification of Mallard-Le Chatelier approach*
  - Numerical simulation
    - *1-D geometry, Full chemistry, Conjugate heat transfer, Heat conduction in structure*
- Experiments
  - Develop novel non-intrusive diagnostic technique
  - Investigate behavior in parallel plate flow reactor with conductive, temperature-controlled walls

Analytical model

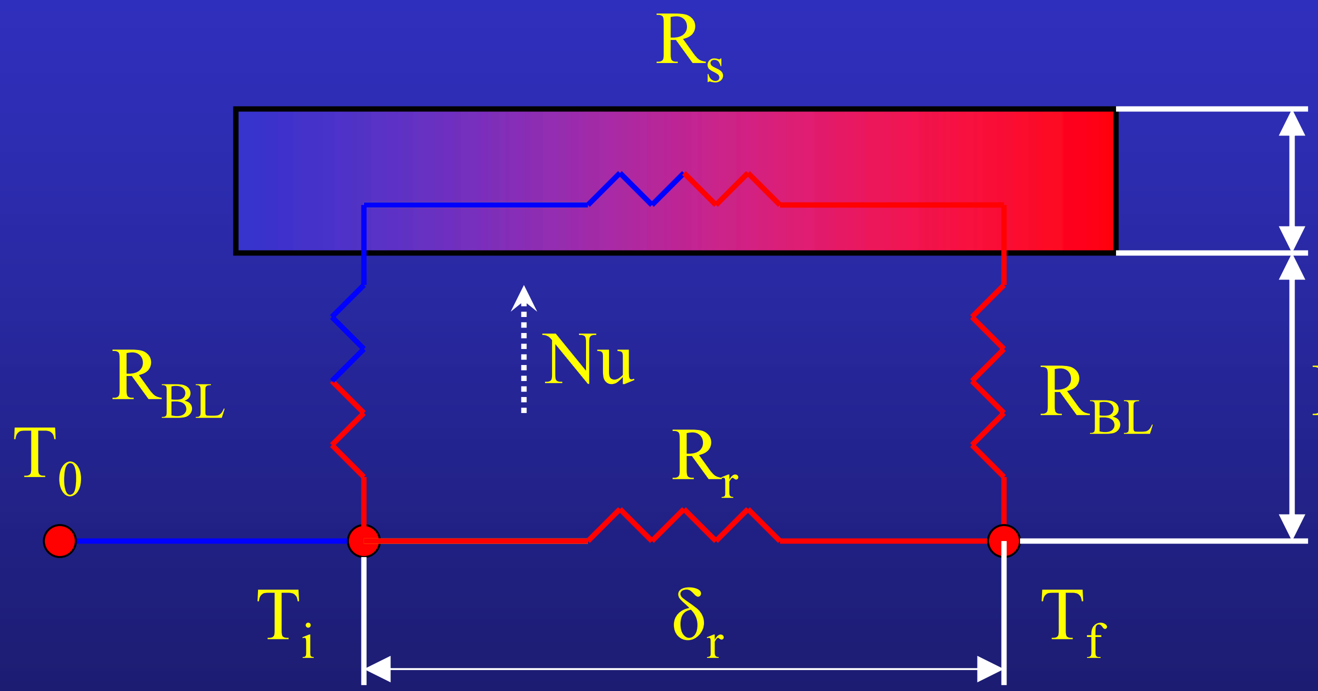
- Include thermal coupling with structure:



Structure provides another path for heat transfer

Analytical model

- Thermo-electrical analogy:



Conduction area ratio:

$$\zeta \equiv \frac{A_s}{A_r} = \frac{2t}{H}$$

(Parallel plate)

$$R_r = \frac{\delta_r}{k_r A_r} \qquad R_s = \frac{\delta_r}{k_s A_s} \qquad R_{BL} = \frac{1}{h_T A_{CONV}}$$

Analytical model

- Flame thickness:

$$\delta_r = \sqrt{\beta}\underbrace{\sqrt{\frac{k_r}{\rho C_p}\frac{T_f - T_i}{T_i - T_0}\frac{1}{RR}}}_{\delta_{r,fr}} \quad \text{with} \quad \beta = \frac{1+\zeta\frac{k_s}{k_r}\left(1+\frac{4H}{\delta_r}\frac{1}{Nu}\right)}{1+4\zeta\frac{k_s}{k_r}\frac{H}{\delta_r}\frac{1}{Nu}}$$

- Asymptotic behavior:
  - $Nu \rightarrow 0$ or $H \rightarrow \infty$: No thermal coupling

$$\delta_r \rightarrow \delta_{r,fr}$$

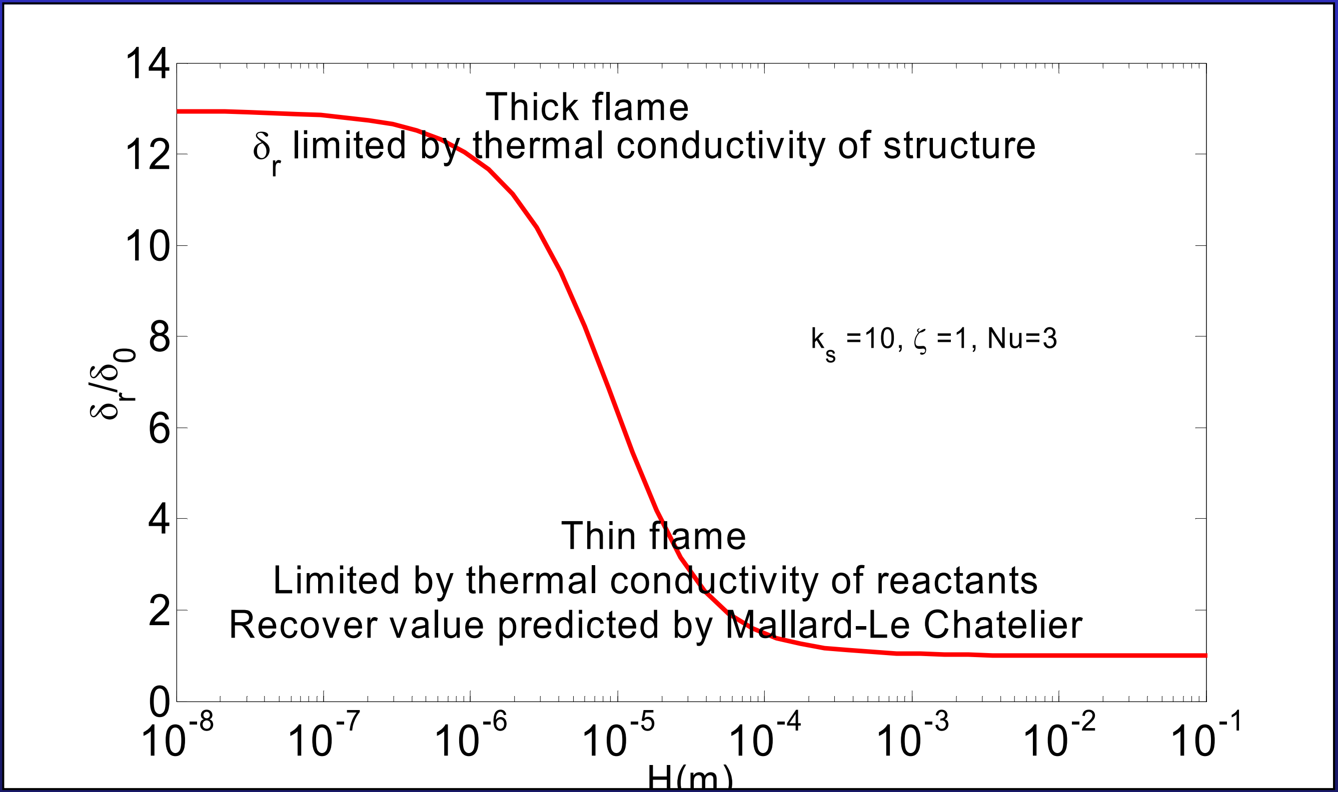
  - $Nu \rightarrow \infty$ or $H \rightarrow 0$: Perfect thermal coupling

$$\frac{\delta_r}{\delta_{r,fr}} \rightarrow \sqrt{1+\frac{k_s}{k_r}\zeta} > 1$$

Limit-cycle behavior of δ_r in H
Large H: limited by k_r
(thin flame)
Small H: limited by k_s
(thick flame)

Analytical model

- Solving for δ_r ⇔ third order polynomial

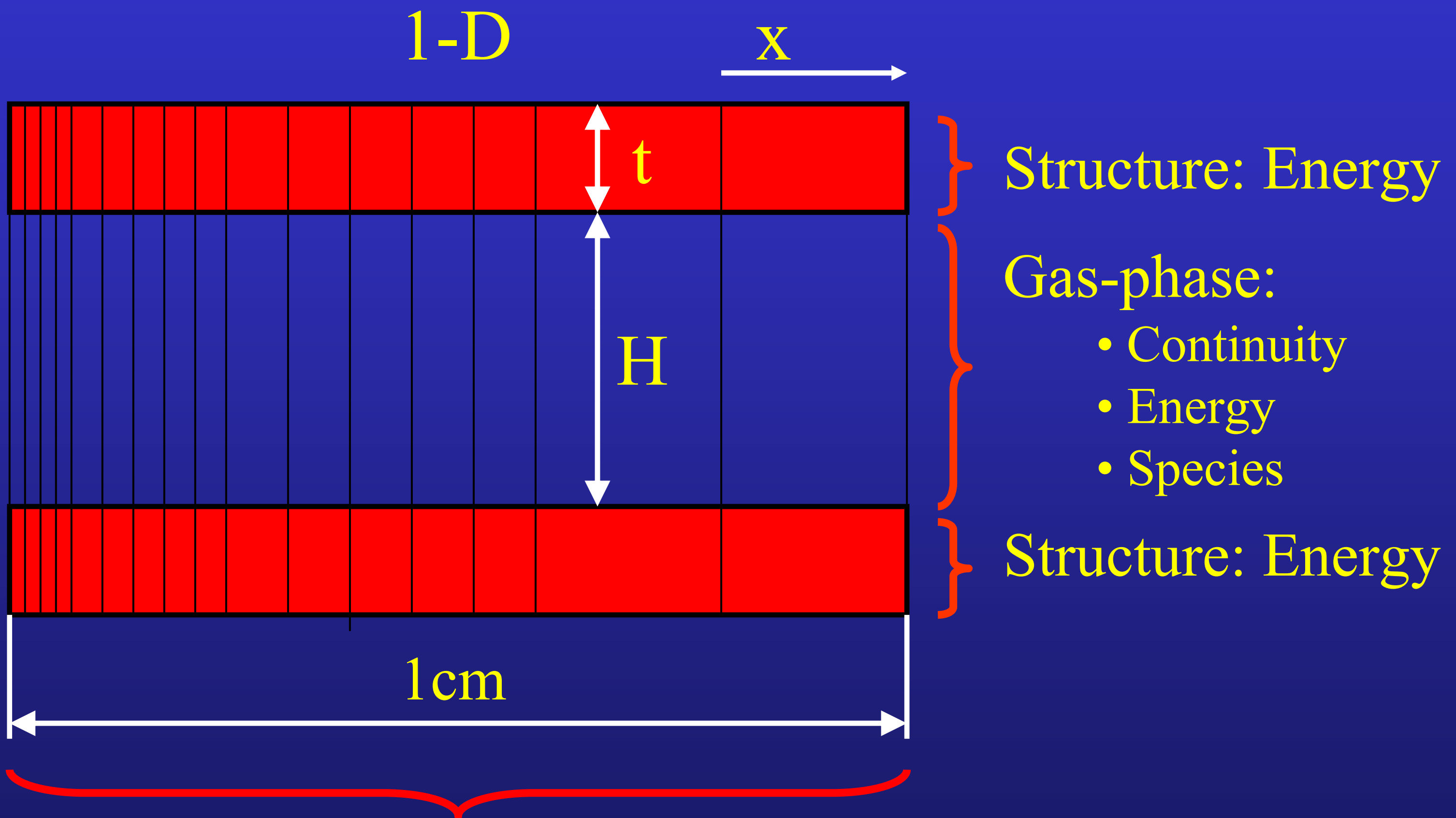


Questions:

- Influence of Nu?
- Influence of k_s?

Numerical Simulation

T_0=300K
P=1atm
H_2-air
Φ=0.5



201 grid points
Unevenly spaced mesh

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Numerical Simulation

- Differences wrt. analytical model:
  - Chemistry (9 species and 19 reactions)
  - Include species diffusion
  - Transient capability, but consider steady-state solution
- Assumptions:
  - 1-D
  - P=const
  - Laminar, incompressible, inviscid
  - Nu=const
  - No thermal diffusion
  - Fourier conduction and Fickian diffusion
  - $\zeta \equiv A_s/A_r = 1$
  - Adiabatic and non-adiabatic operation

Numerical Simulation

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State

$$\rho = \frac{PW_m}{RT}$$

Mass

$$\frac{d(\rho u)}{dx} = \rho \sum_k \left(\frac{W_m}{W_k} \frac{dY_k}{dt} \right) + \frac{\rho}{T} \frac{dT}{dt}$$

Energy (gas)

$$\rho C_P \frac{dT}{dt} = -\rho u \frac{d\left(\sum_k (h_k Y_k) \right)}{dx} + \frac{d}{dx}\left(k_r \left(\frac{dT}{dx} \right) \right) - a_{ch} h_T (T - T_s) - \sum_k (W_k h_k \dot{\omega}_k)$$

Species (gas)

$$\rho \frac{dY_k}{dt} = \frac{d}{dx}\left(\rho D_k \frac{dY_k}{dx} \right) - \rho u \frac{dY_k}{dx} + W_k \dot{\omega}_k$$

Energy (structure)

$$\rho_s C_{P,s} \frac{dT_s}{dt} = \frac{d}{dx}\left(k_s \left(\frac{dT_s}{dx} \right) \right) + a_s h_T (T - T_s) - a_s h_{T,e} (T_s - T_e)$$

Flame Thickness

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- Estimate based on temperature change through the flame*

$$\delta_r = \frac{T_f - T_0}{\left(\frac{dT}{dx}\right)_{\max}}$$

* Law, C.K. and Sung, C.J., 'Structure, Aerodynamics, and Geometry of Premixed Flamelets', Progress in Energy and Combustion Science 26 (2000) 459-505

Effect of Nusselt Number

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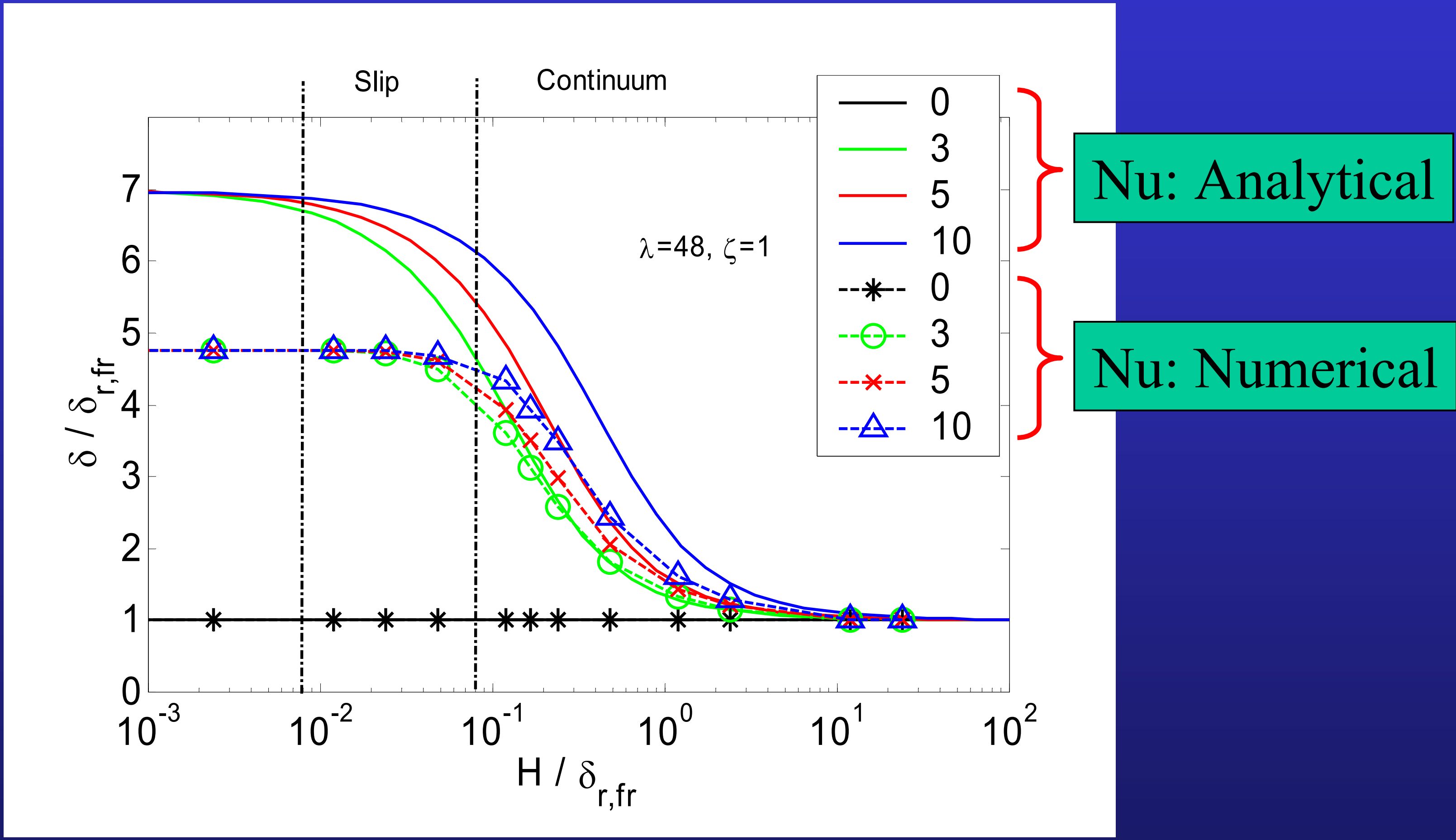
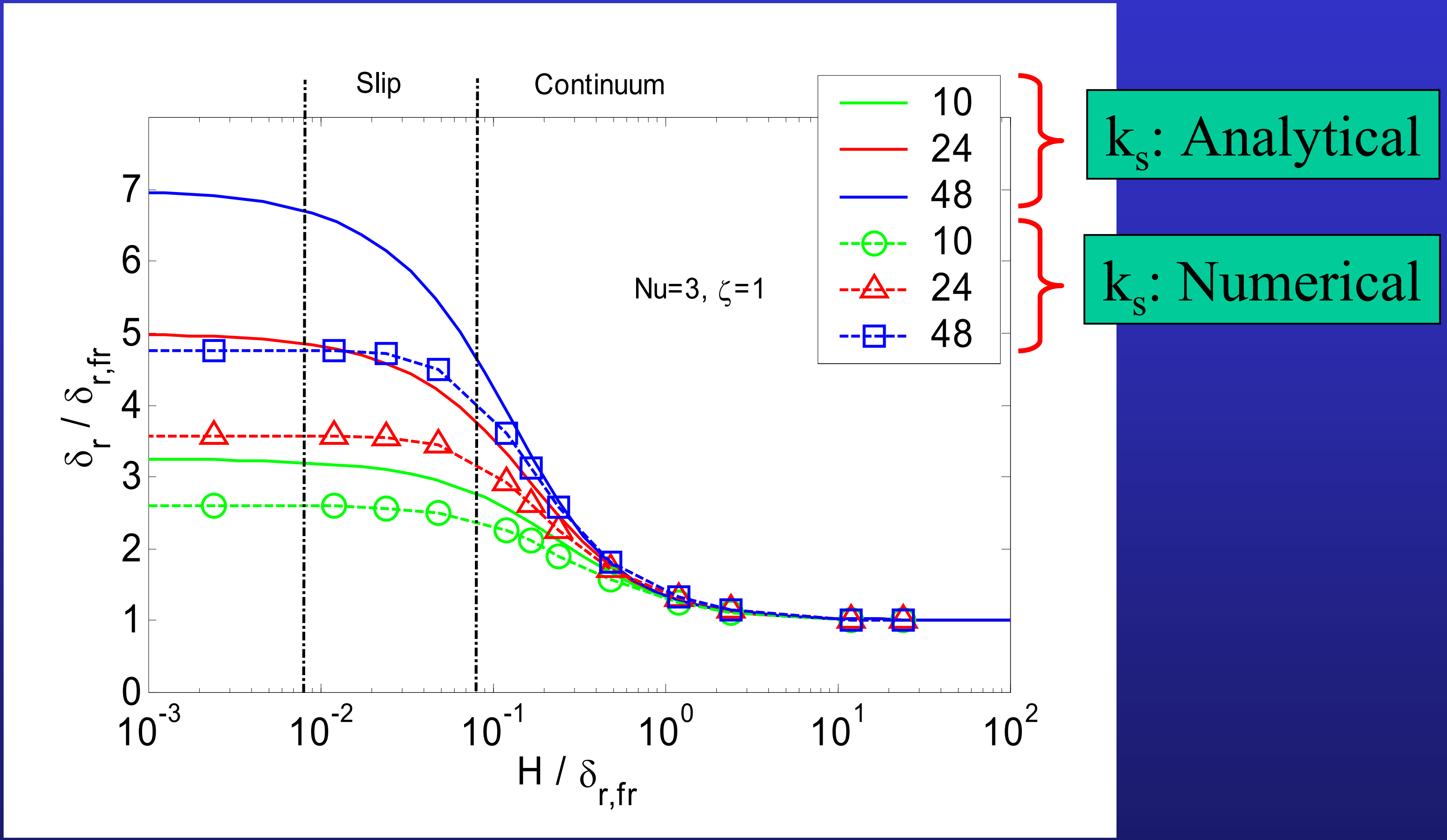


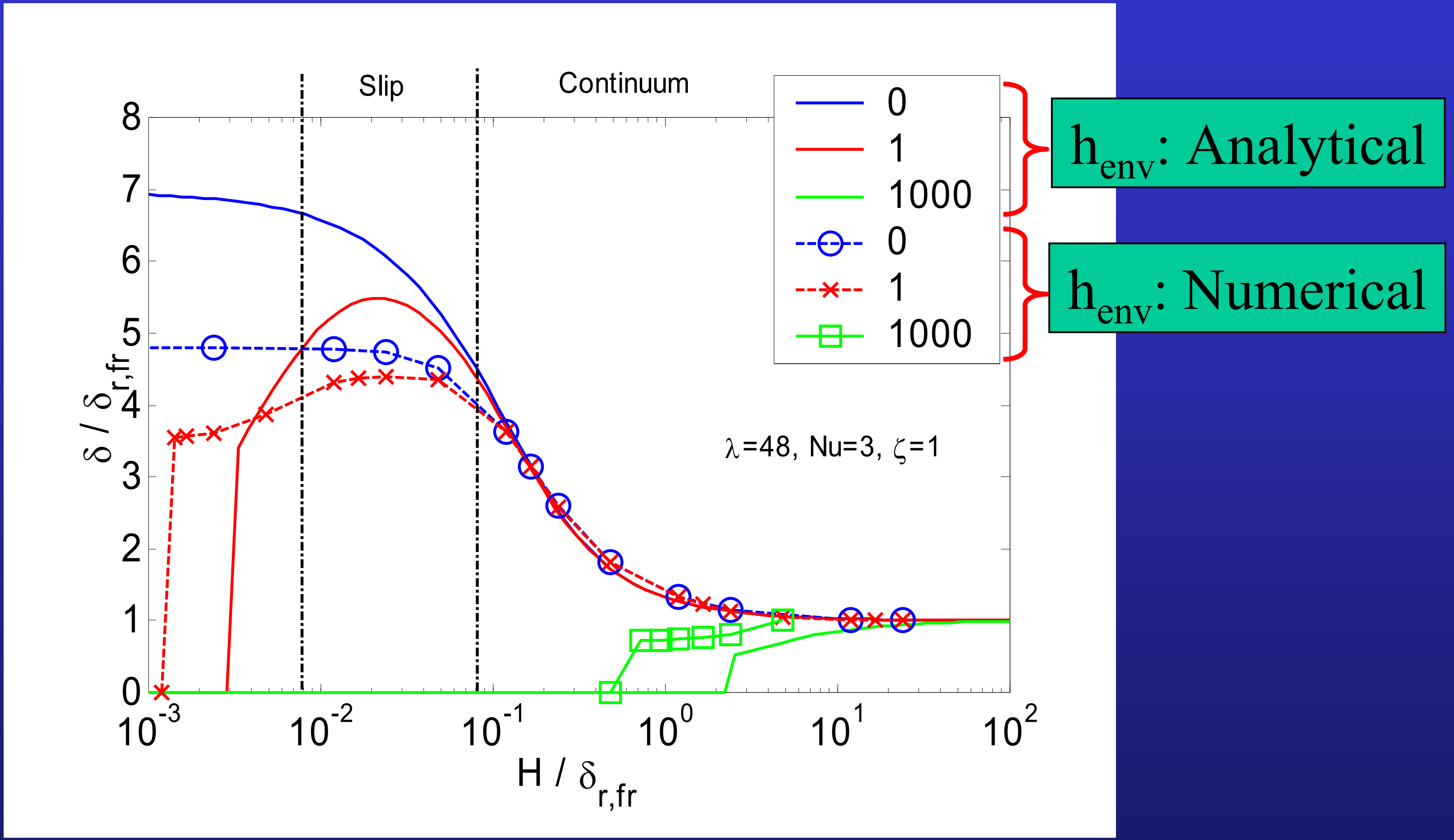
- *Increasing Nu causes broadening to occur at larger H*
- *Consistent with model predictions*

Effect of Thermal Conductivity



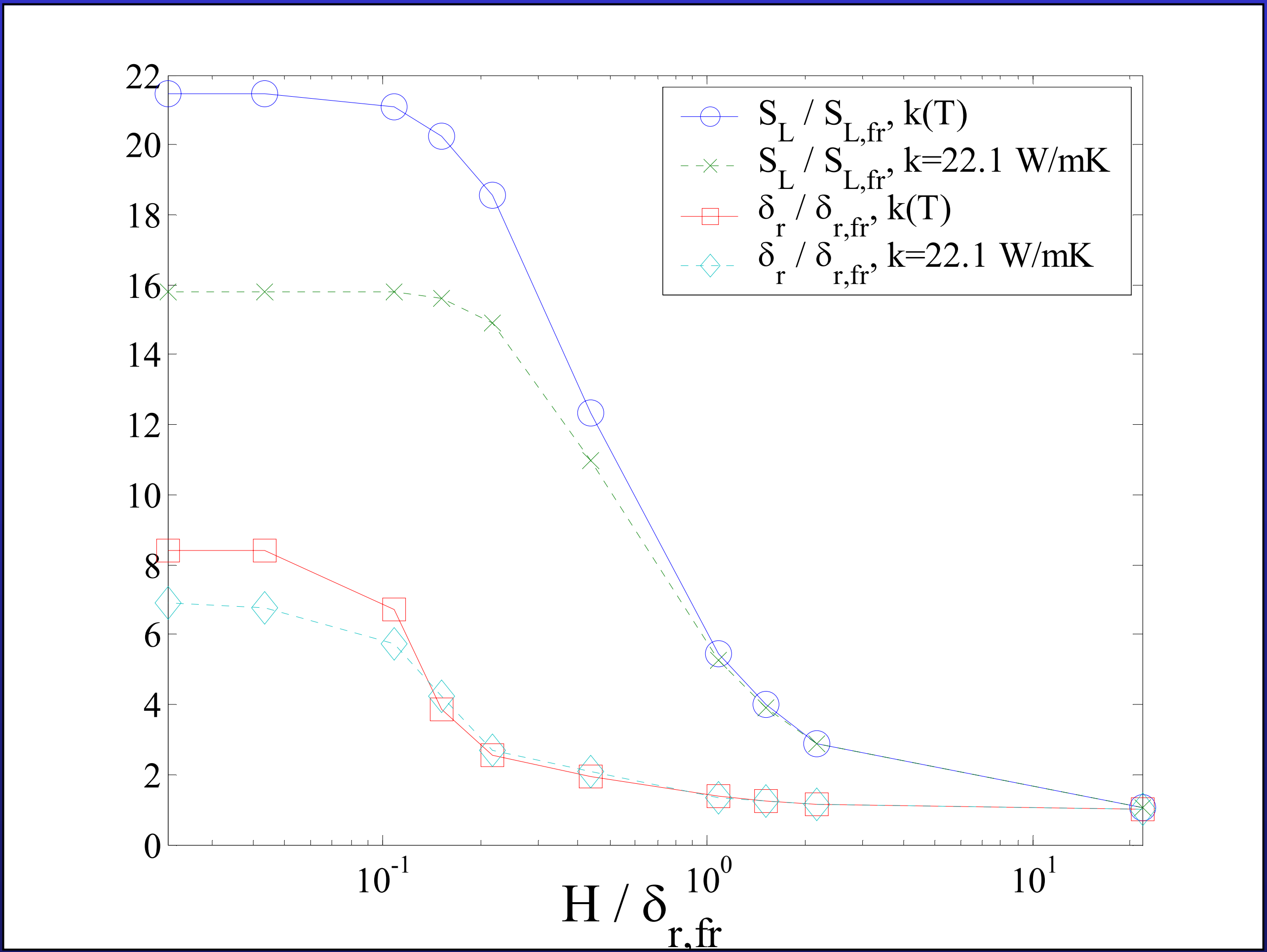
- *Increasing k_s increases broadening effect*
- *Consistent with model predictions*

Effect of Heat Loss



- *Heat loss reduces broadening and leads to quenching*
- *Consistent with model predictions*

Silicon Micro-Combustor



- *Conduction also increases burning rate.*
- *Including $k_{si}(T)$ is important*

Silicon Micro-Combustor

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Definition of Power Density

$$\dot{w}_D = \frac{\rho S_L \int_{T_o}^{T_f} C_p(T)\,dT}{L}$$

Note: In following plots, power density is non-dimensionalized by a 'reference' value corresponding to combustion at the laminar flame speed S_L in a volume of 1 cm^3.

Silicon Micro-Combustor

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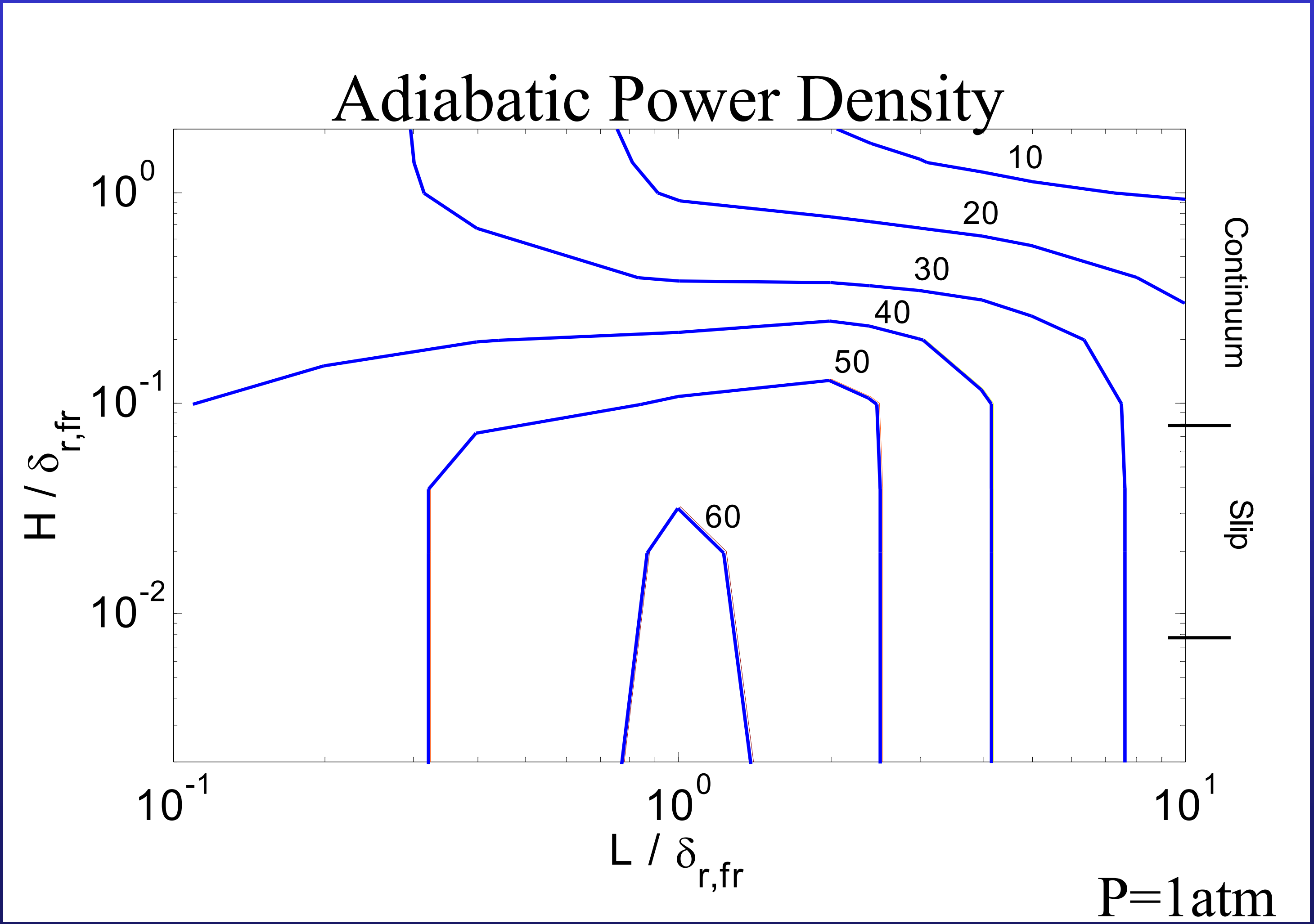

Power density increases as reduce H; optimum L

Silicon Micro-Combustor

Definition of Efficiency

$$\eta = \frac{\dot{m}_{f+a} C_P \left(T_{out} - T_{in}\right)}{\dot{m}_f Q_R}$$

Silicon Micro-Combustor

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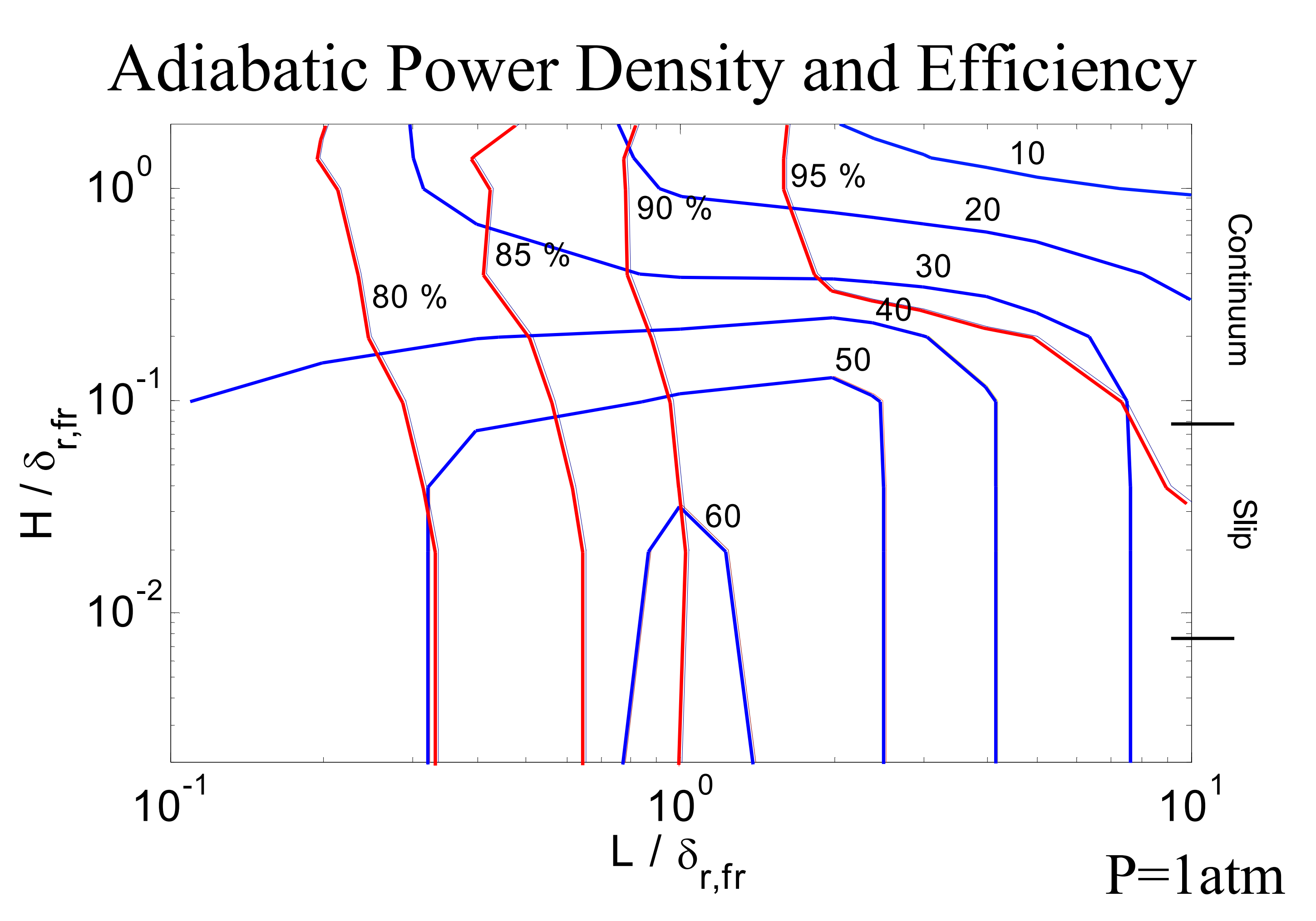

Config. That maximizes power density does **not** *maximize efficiency.*

Silicon Micro-Combustor

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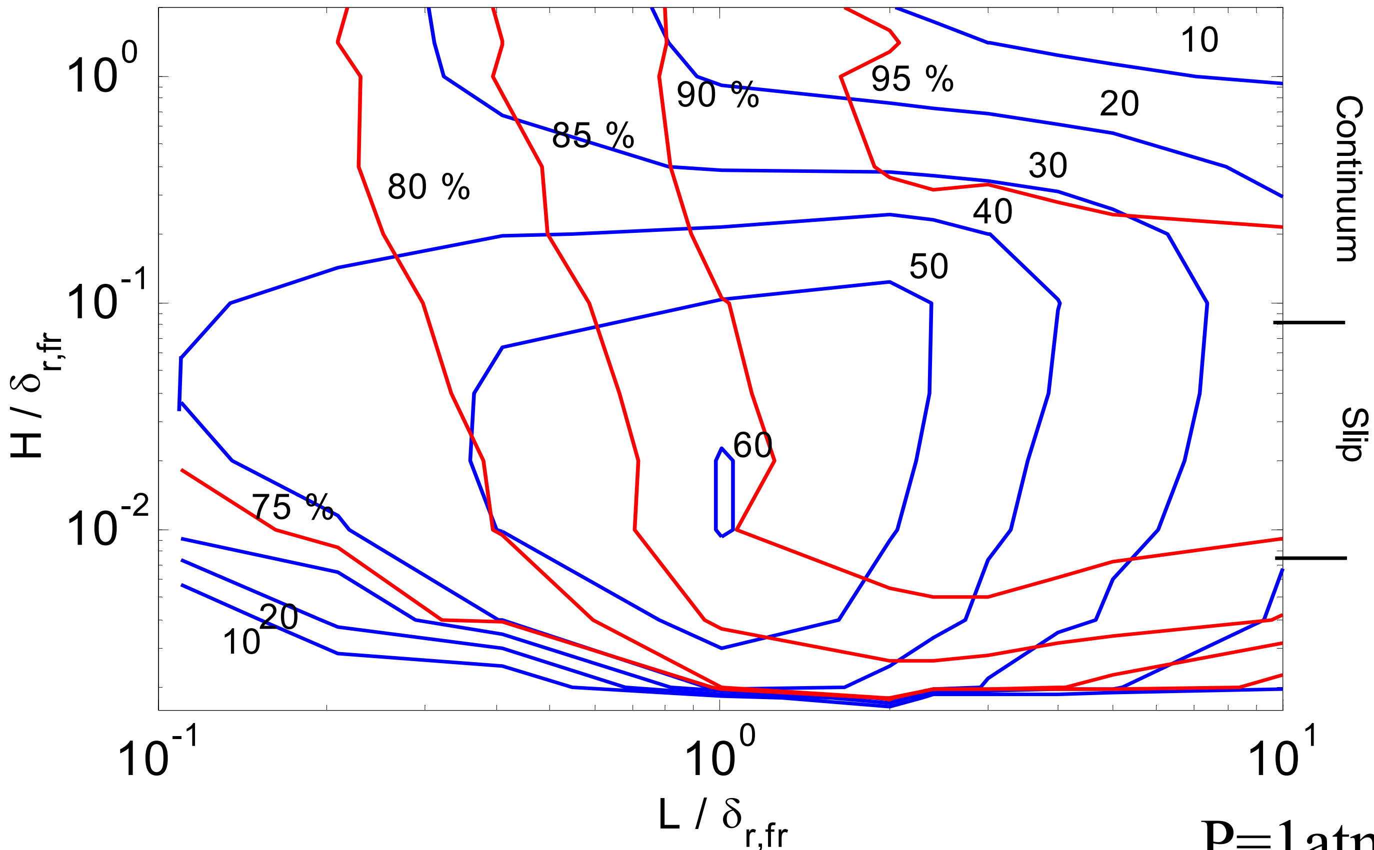
Non-adiabatic Power Density and Efficiency



P=1atm

Including heat losses leads to optimum H and L

Silicon Micro-Combustor

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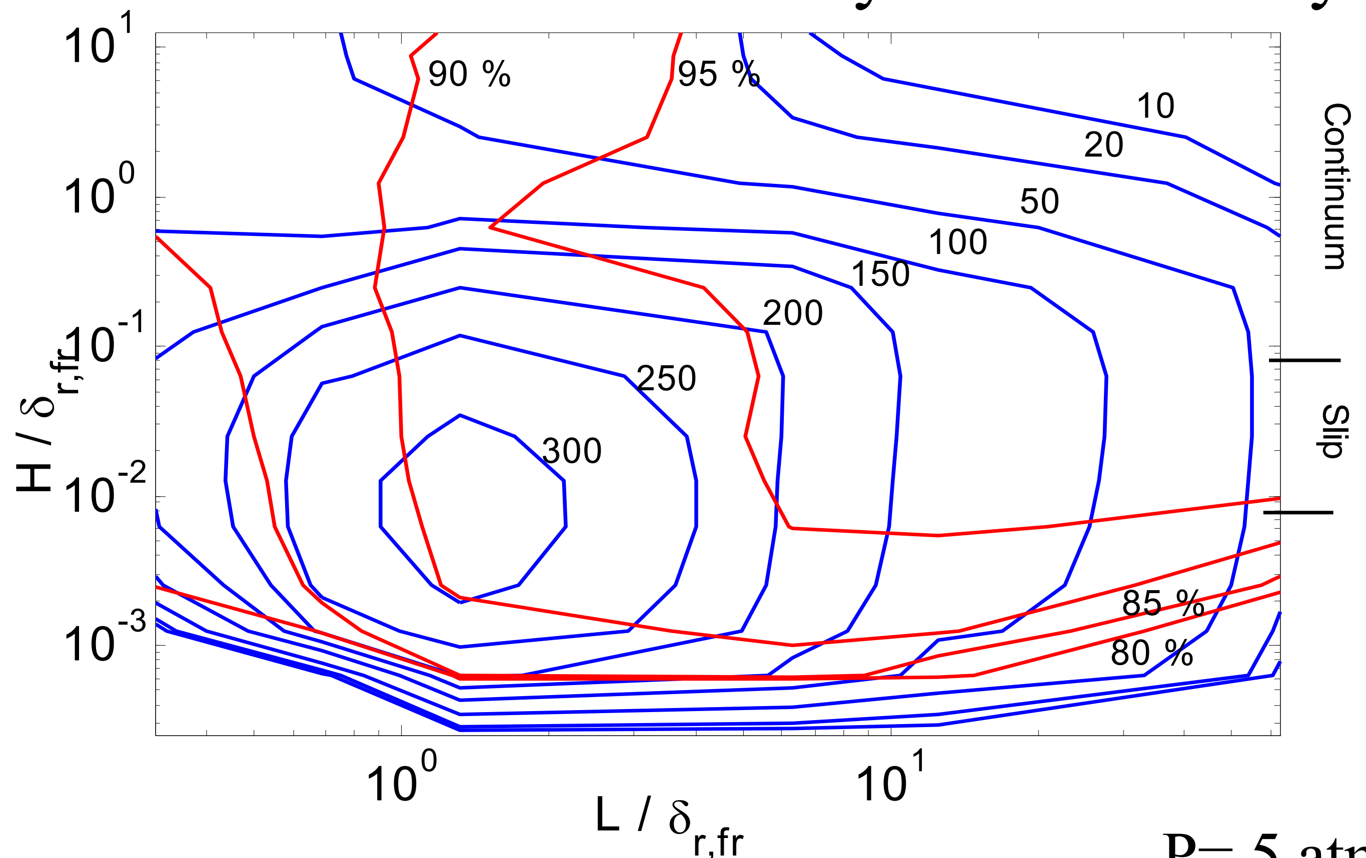
Non-adiabatic Power Density and Efficiency



P= 5 atm

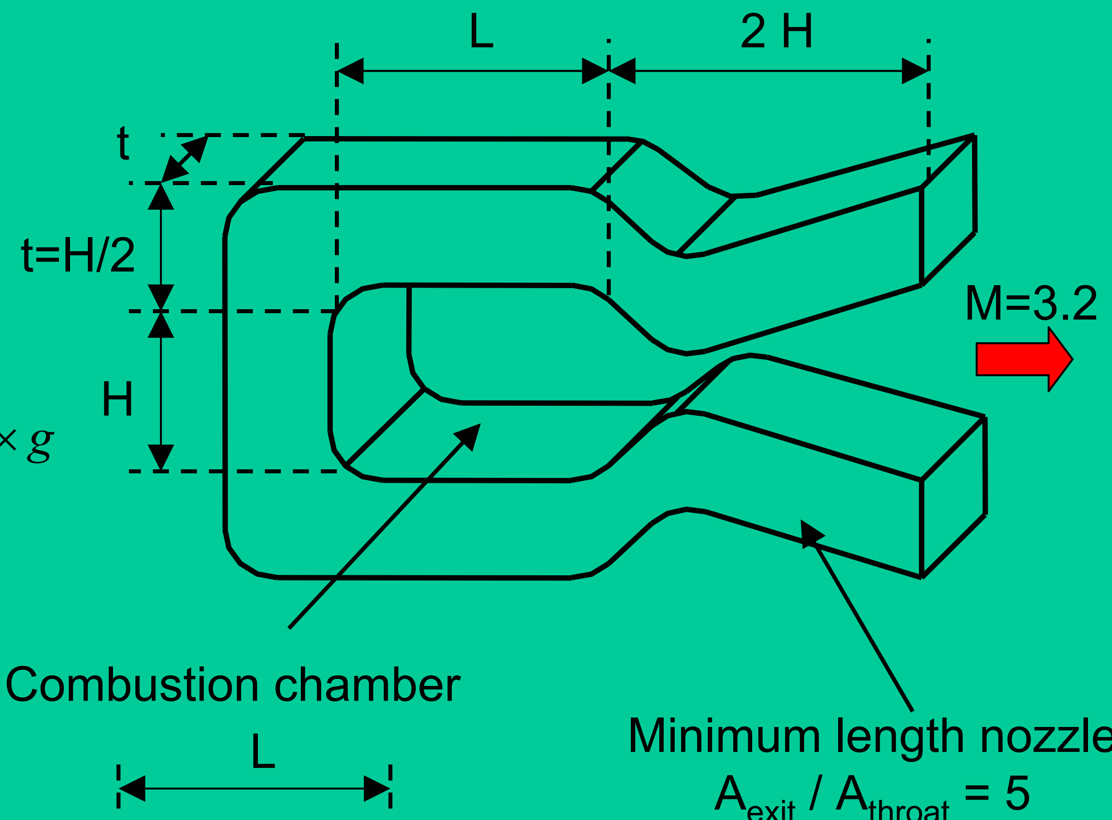
Increasing pressure increases power density

Silicon Micro-Rocket

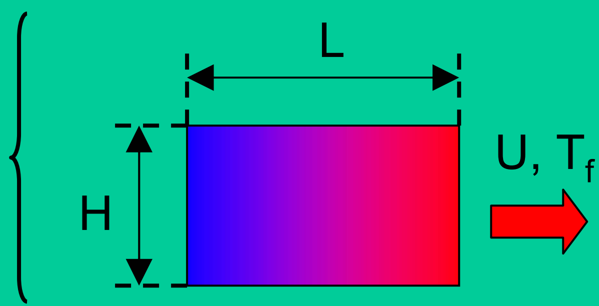
$$T = \dot{m}\left(U_e - U_i\right)$$

$$I_{sp} = U_e / g$$

$$Weight = Volume \times \rho_{Si} \times g$$



From numerical computations



Silicon Micro-Rocket I_{sp}

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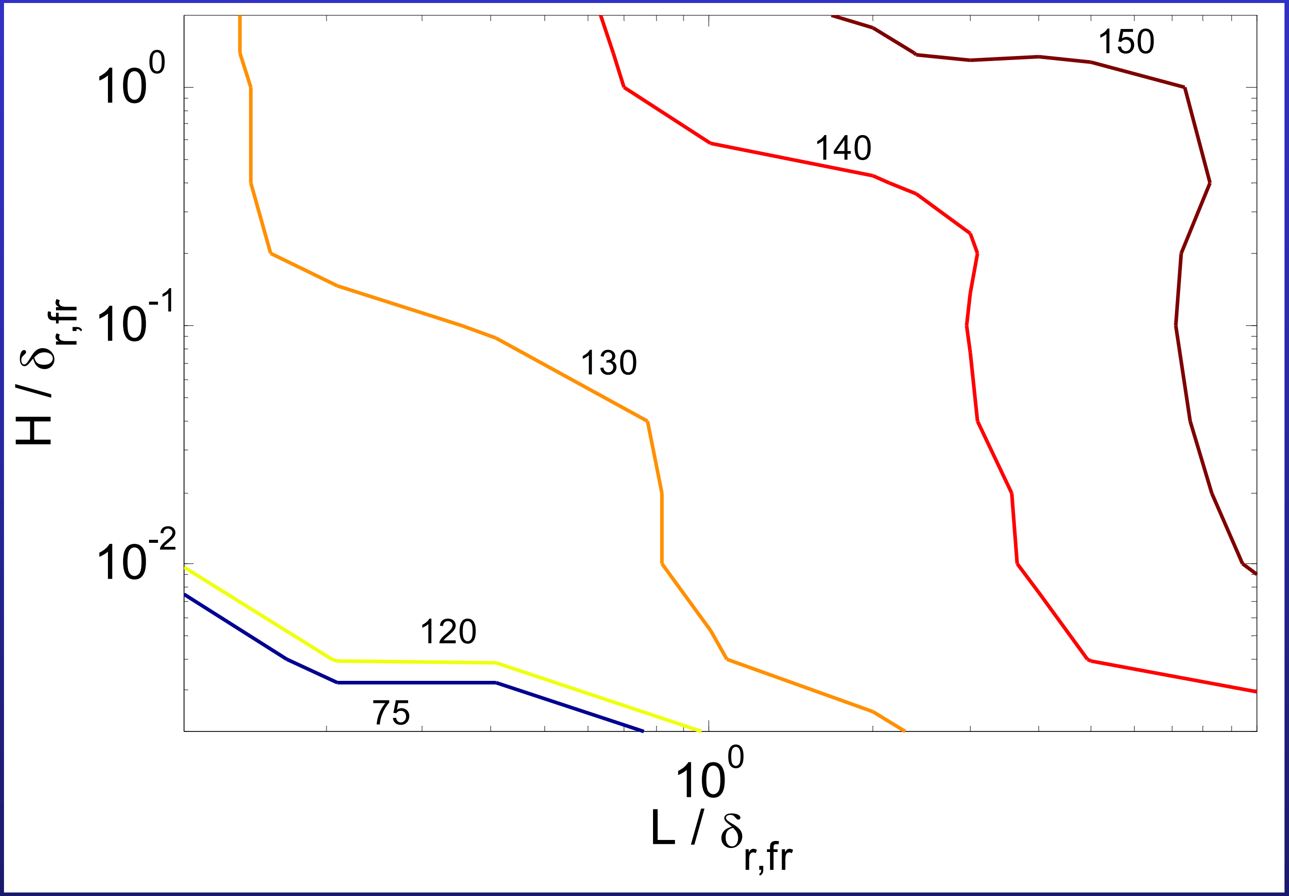
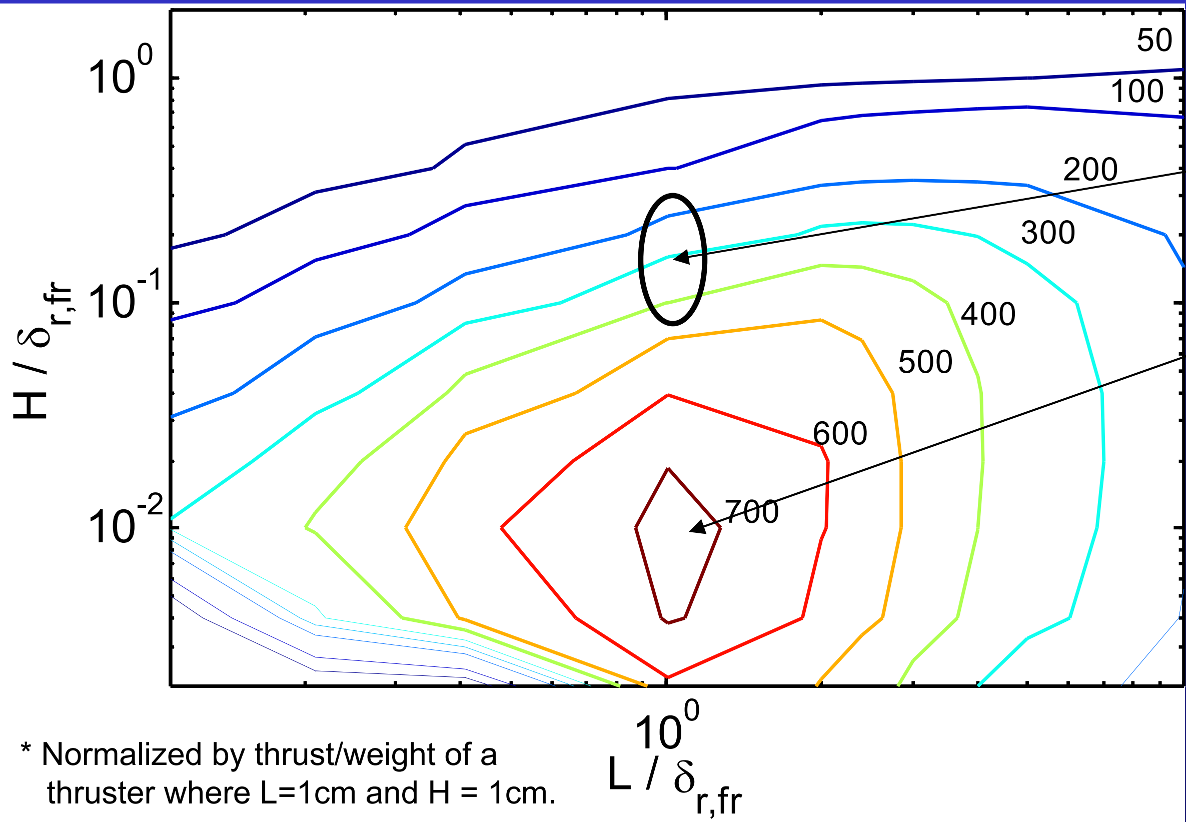


Maximum I_{sp} at large H and large L

– Reflects trend in combustor efficiency

Silicon Micro-Rocket Thrust/Weight



* Normalized by thrust/weight of a thruster where L=1cm and H = 1cm.

Practical Design Region?

Optimum Configuration (Neglecting Pressure Loss)

- L=0.5 mm
- H = 5 μm
- $T=72 \times 10^{-9}$ N
- T/W = 943

- *Maximum T/W corresponds to maximum power density*
- *Very high T/W may be possible*

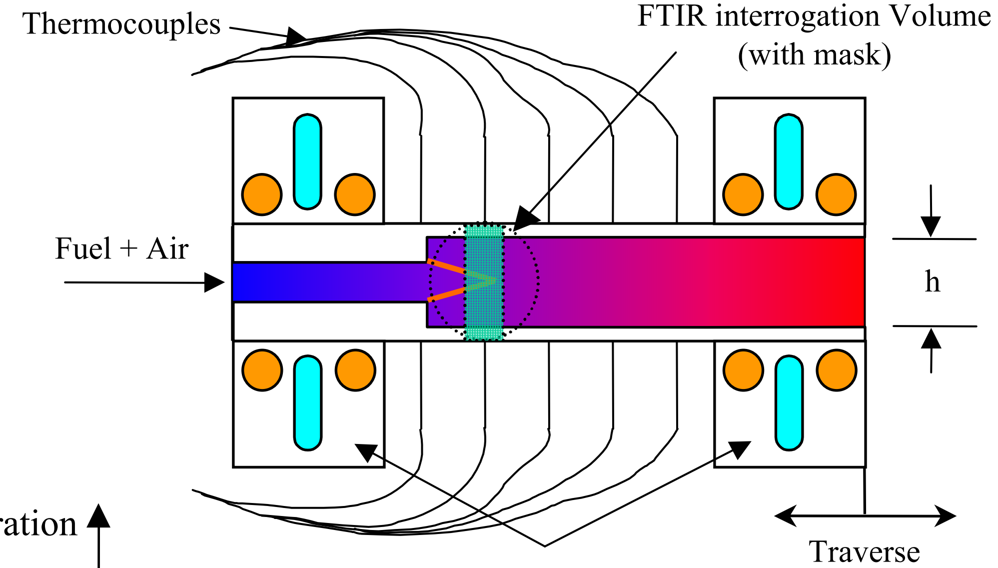
Experiments

- Provide data to validate model and simulations
  - Effect of T_{wall}, $k_{structure}$ on
    - *Burning rate*
    - *Reaction zone thickness*
- Approach
  - Construct parallel plate reactor
    - *Conductive, temperature-controlled walls*
    - *Re-configurable (0.5 mm < H < 10 mm)*
    - *Build using conventional mfg. processes (avoid MEMS)*
  - Develop appropriate diagnostic techniques
    - *Measure temperature and species concentration*
    - *Sub-millimeter spatial resolution*
    - *Non-intrusive*

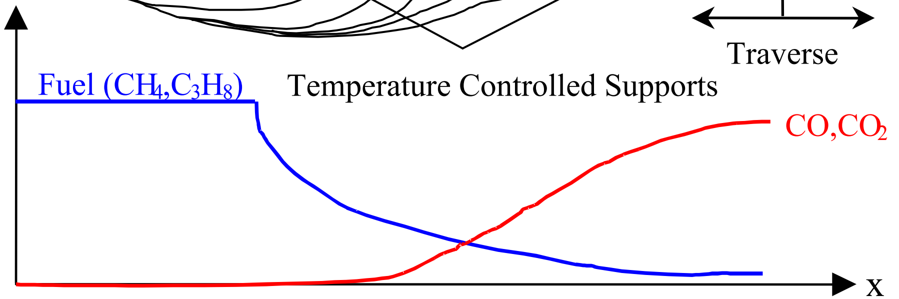
Parallel Plate Reactor

Features:

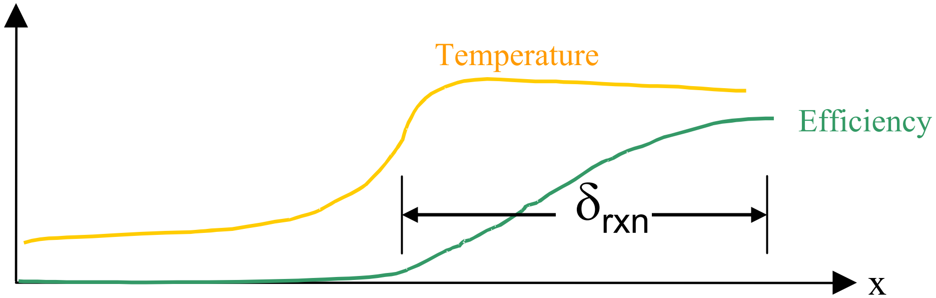
- *Controllable BC's*
- *Detailed Measurements*
  - *Temperature*
  - *Heat Flux*
  - *Species conc.*



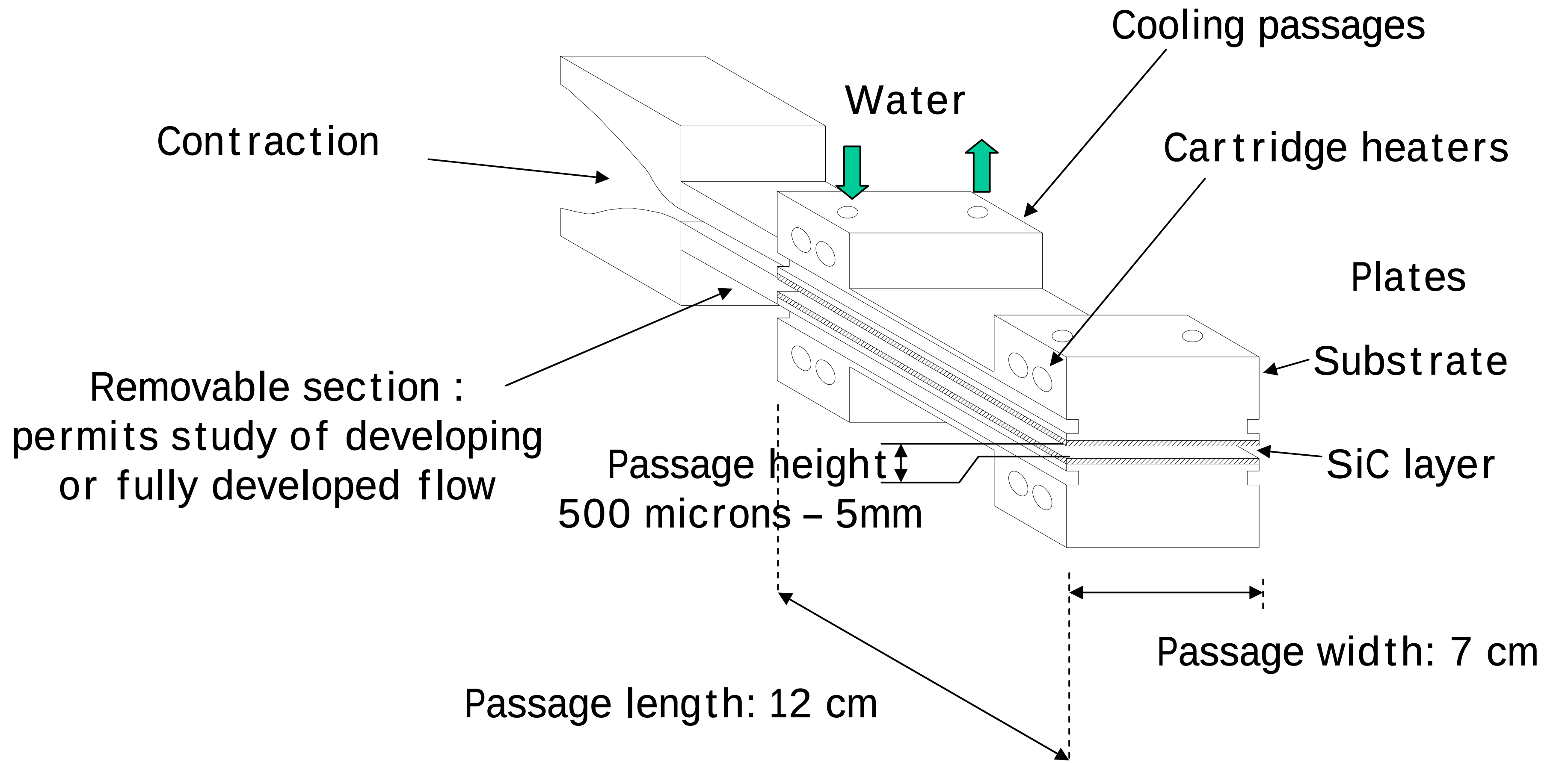
Measure



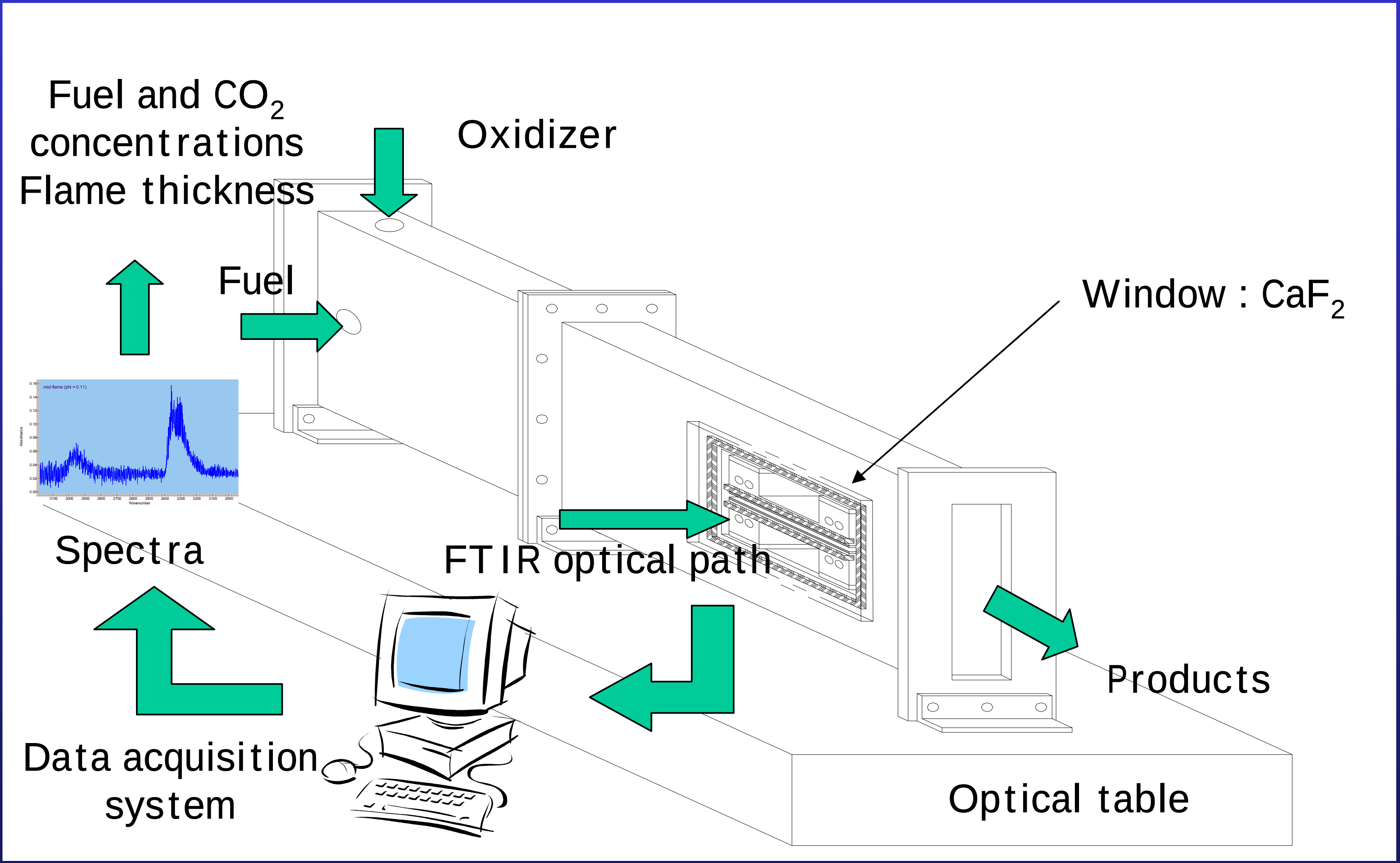
Compute



Parallel Plate Reactor



Parallel Plate Reactor



FTIR Proof of Concept

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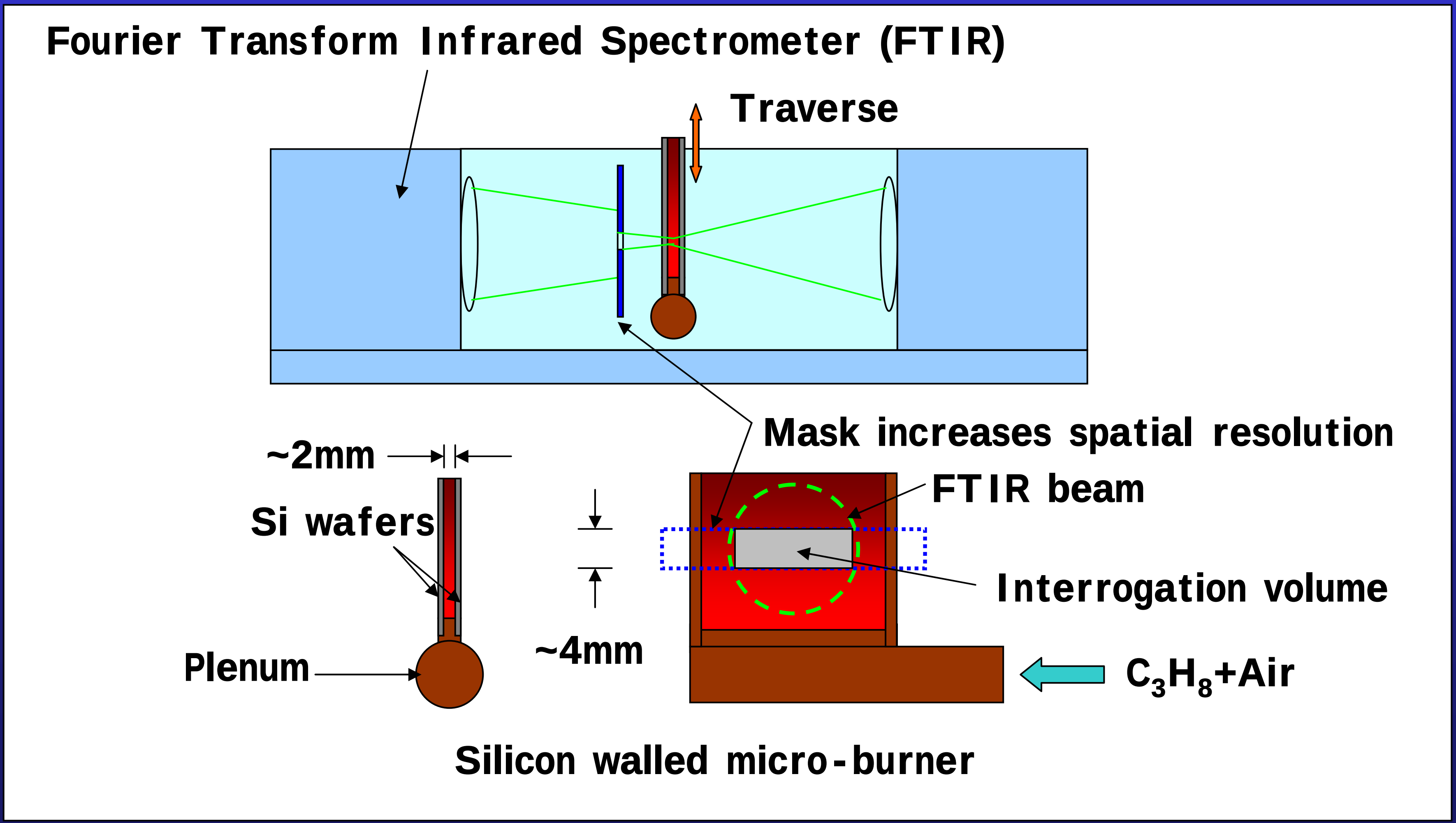
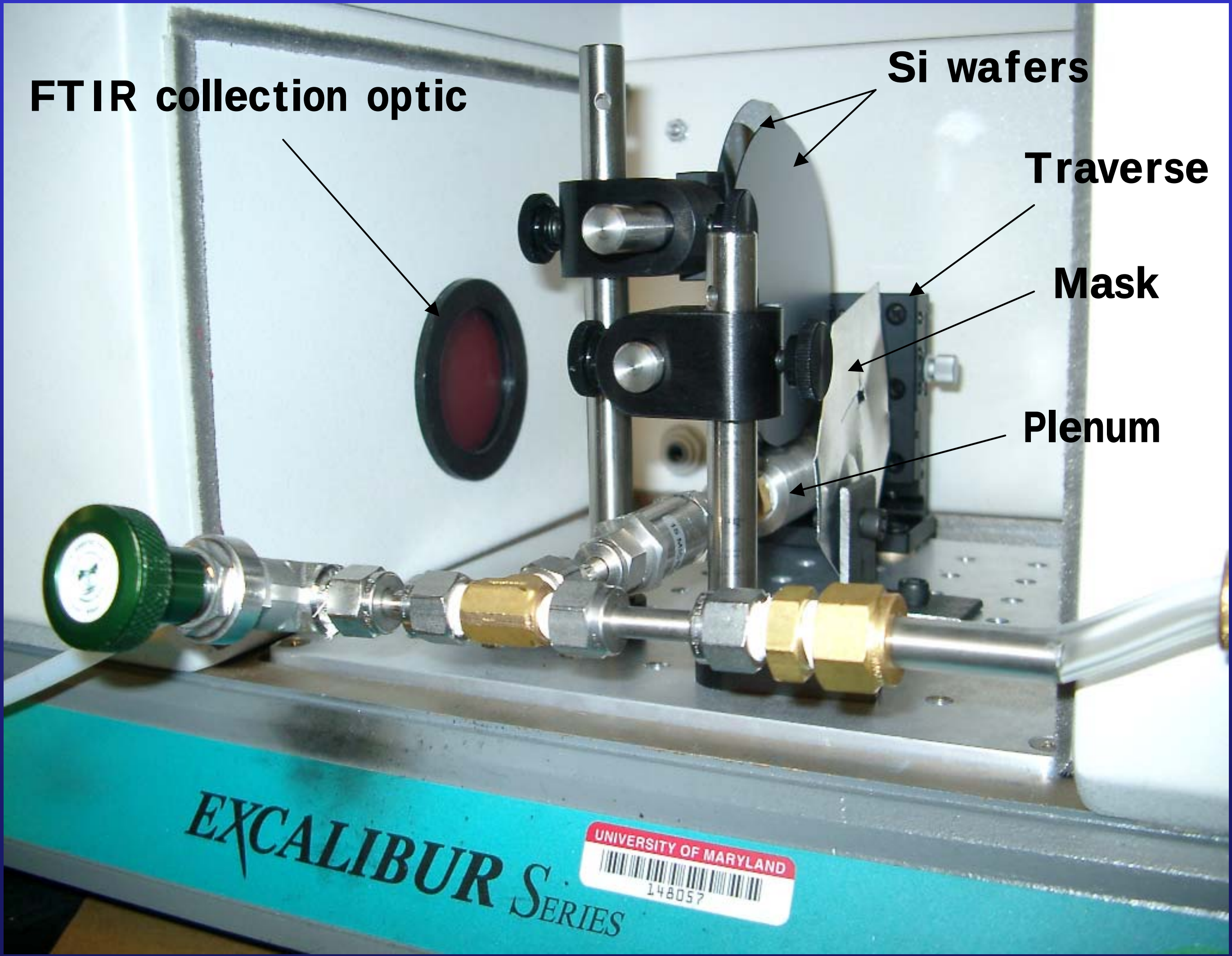
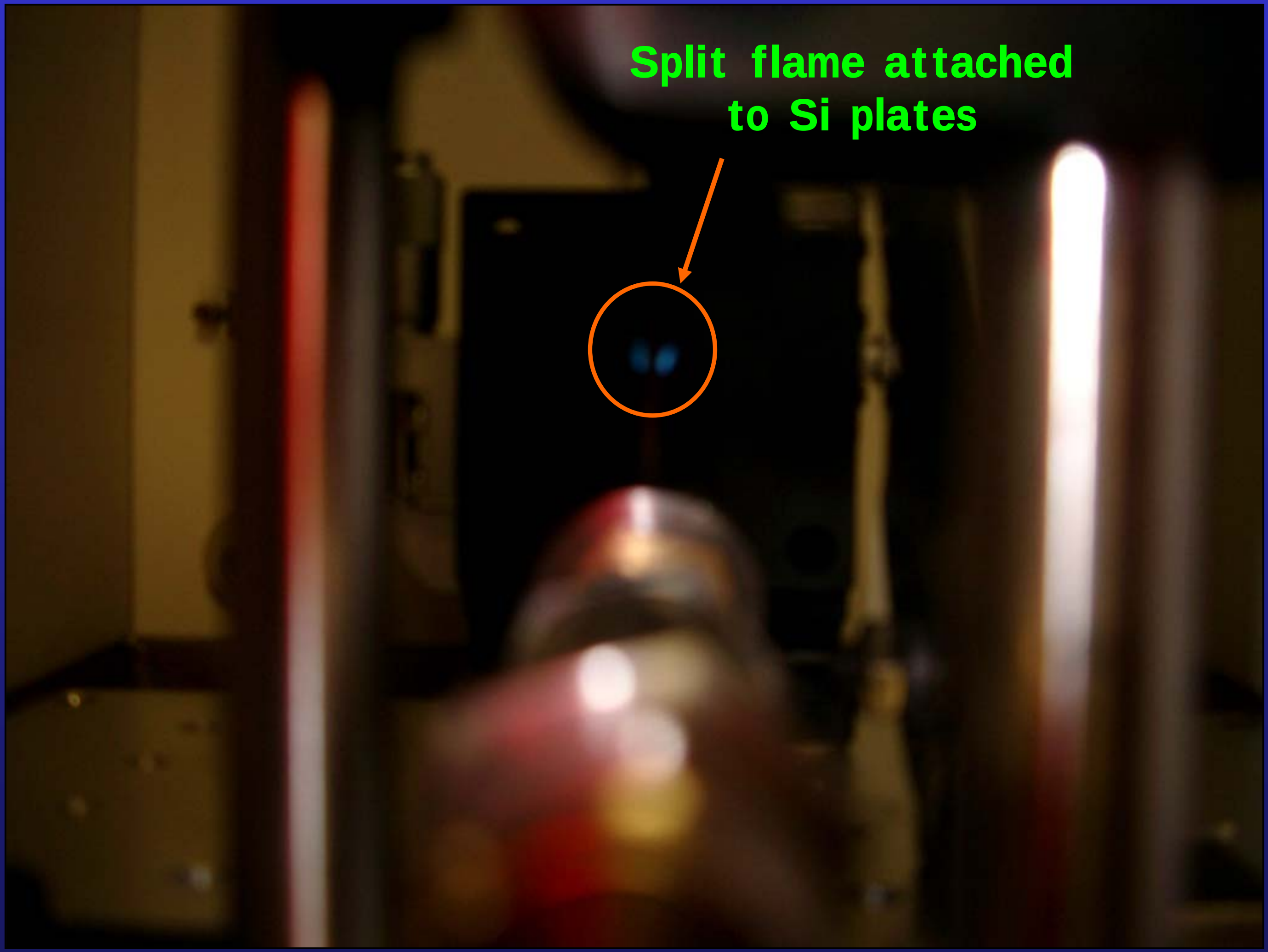


FTIR Proof-of-Concept

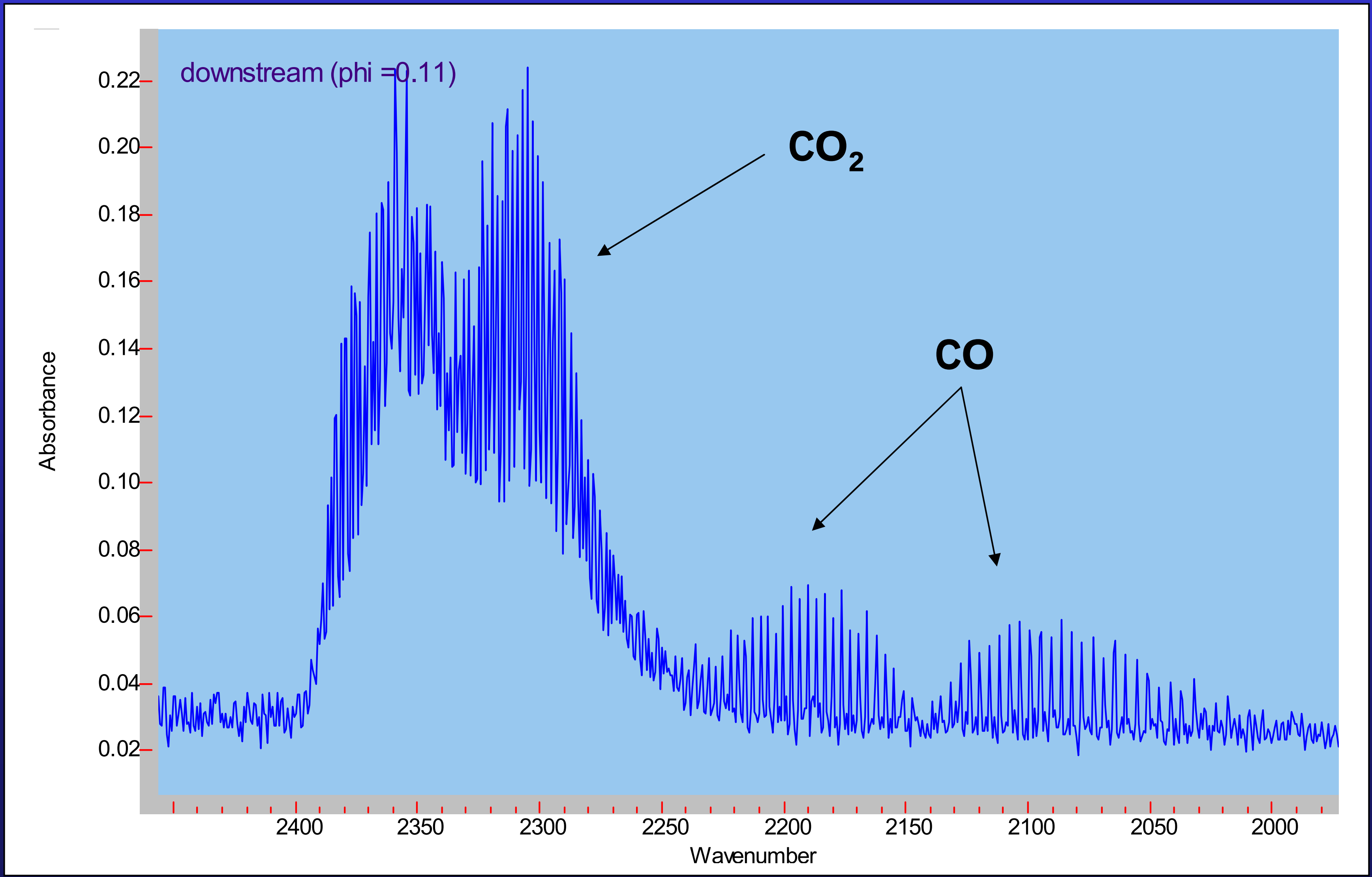


Silicon Micro-burner Operation

U N I V E R S I T Y O F M A R Y L A N D



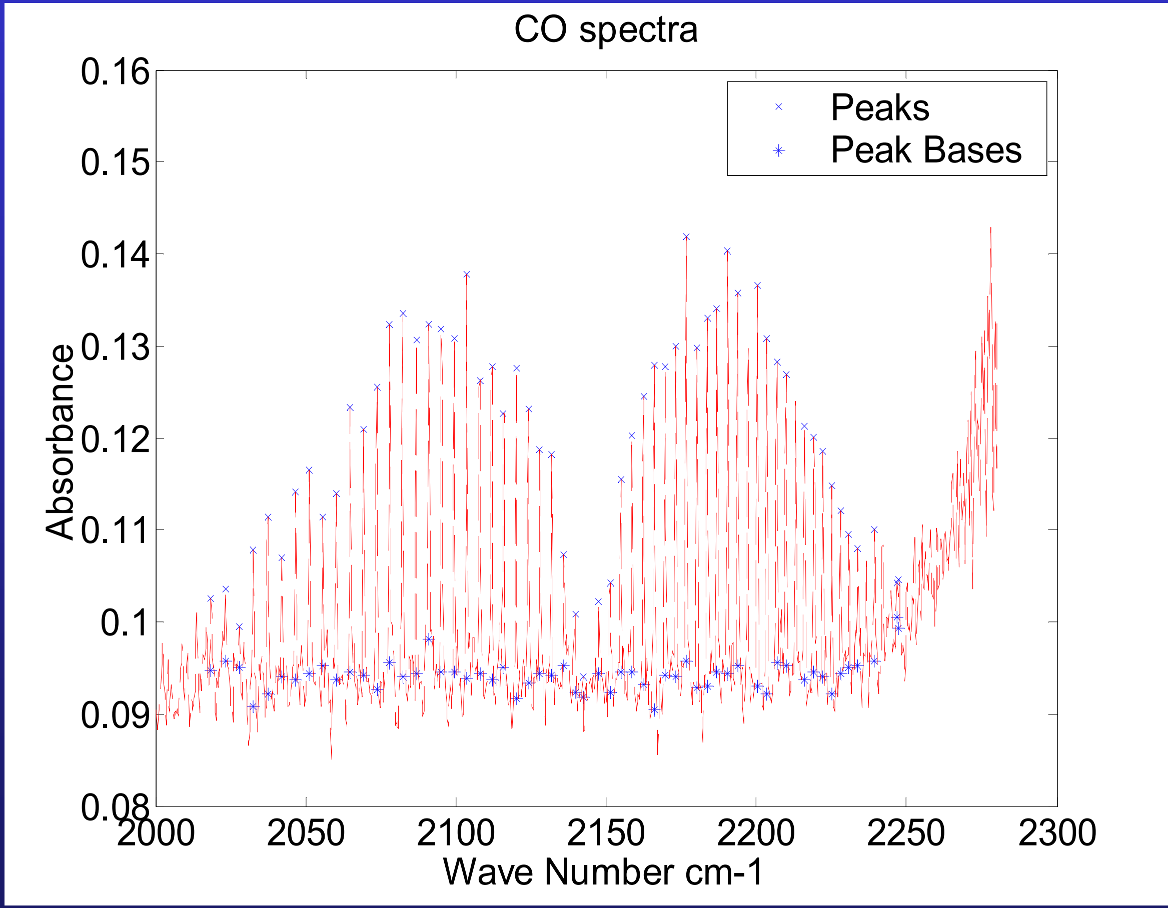
Sample Spectra



Temperature Calculation from CO

U N I V E R S I T Y O F M A R Y L A N D

1. Identify peaks



Temperature Calculation from CO

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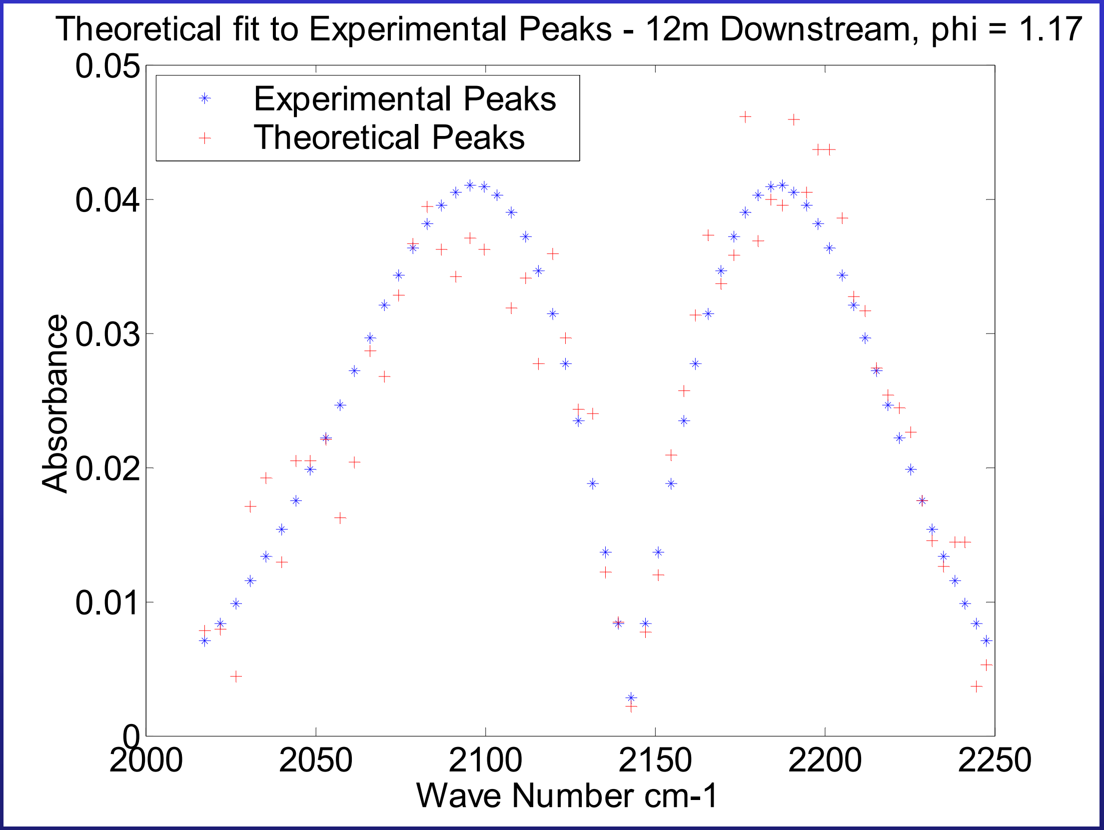
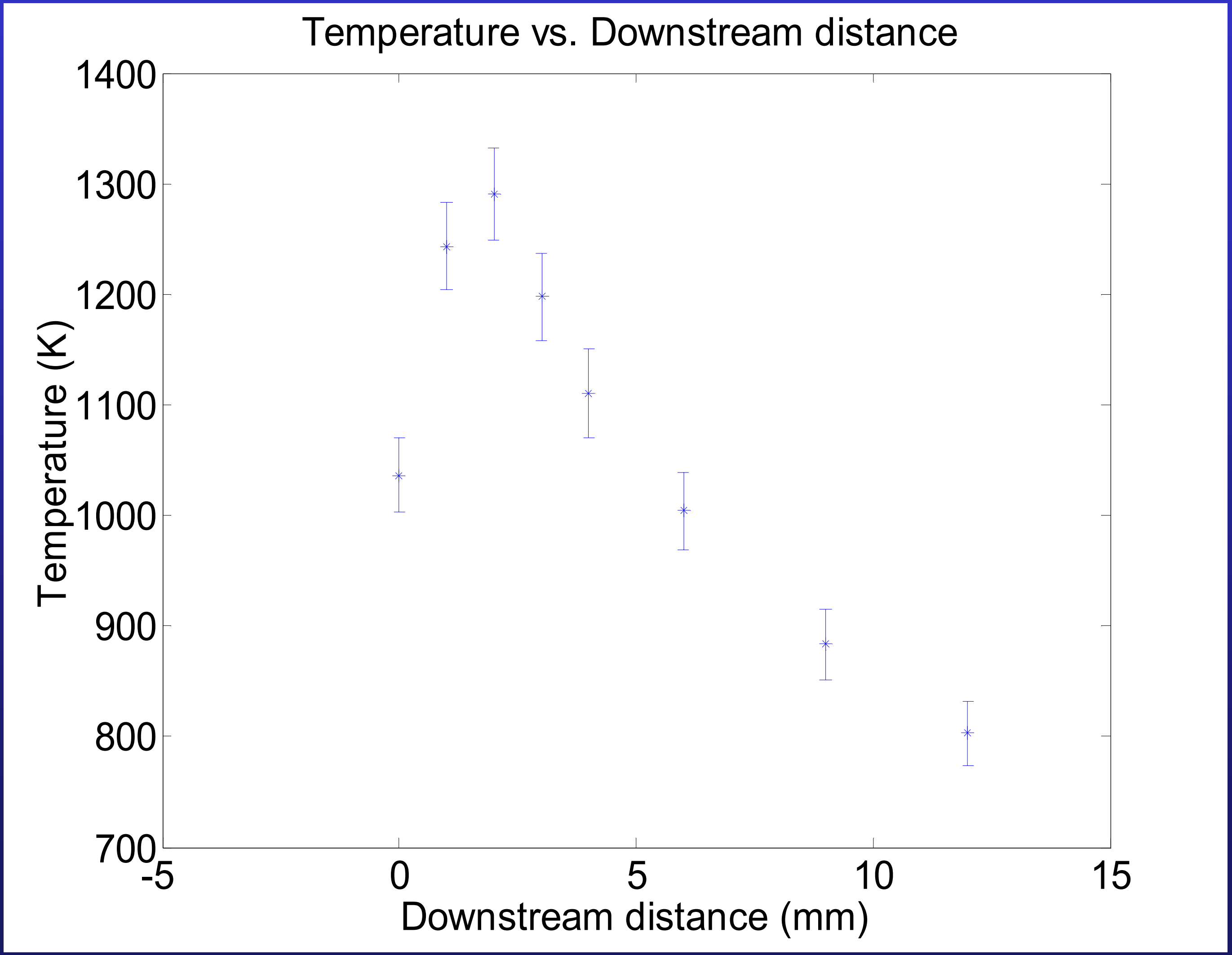
2. Fit peaks



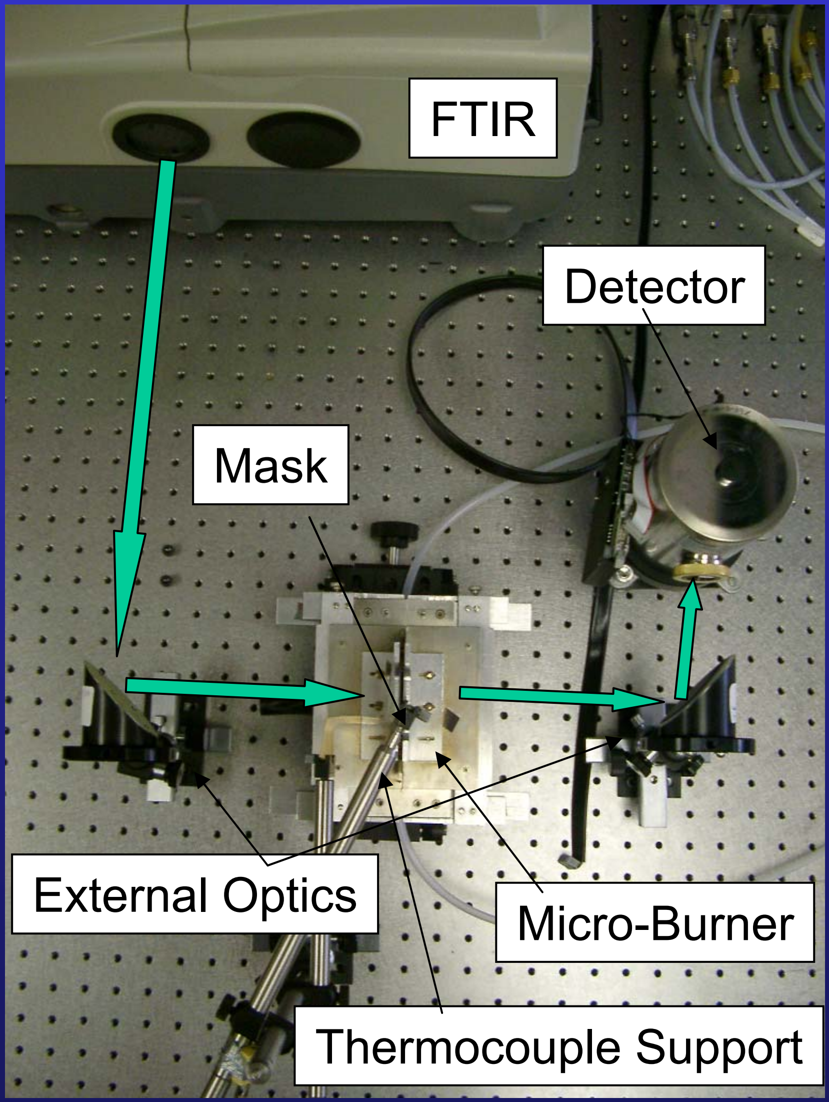
$$N_r = (2j+1)\frac{e^{-\frac{E_r(v,j)}{kT}}}{\sum_{j=0}^{\infty}(2j+1)e^{-\frac{E_r(v,j)}{kT}}}$$

$$E_r(v,j) = hc\left[B_v j(j+1) - D_v j^2 (j+1)^2\right]$$

Axial Temperature Distribution

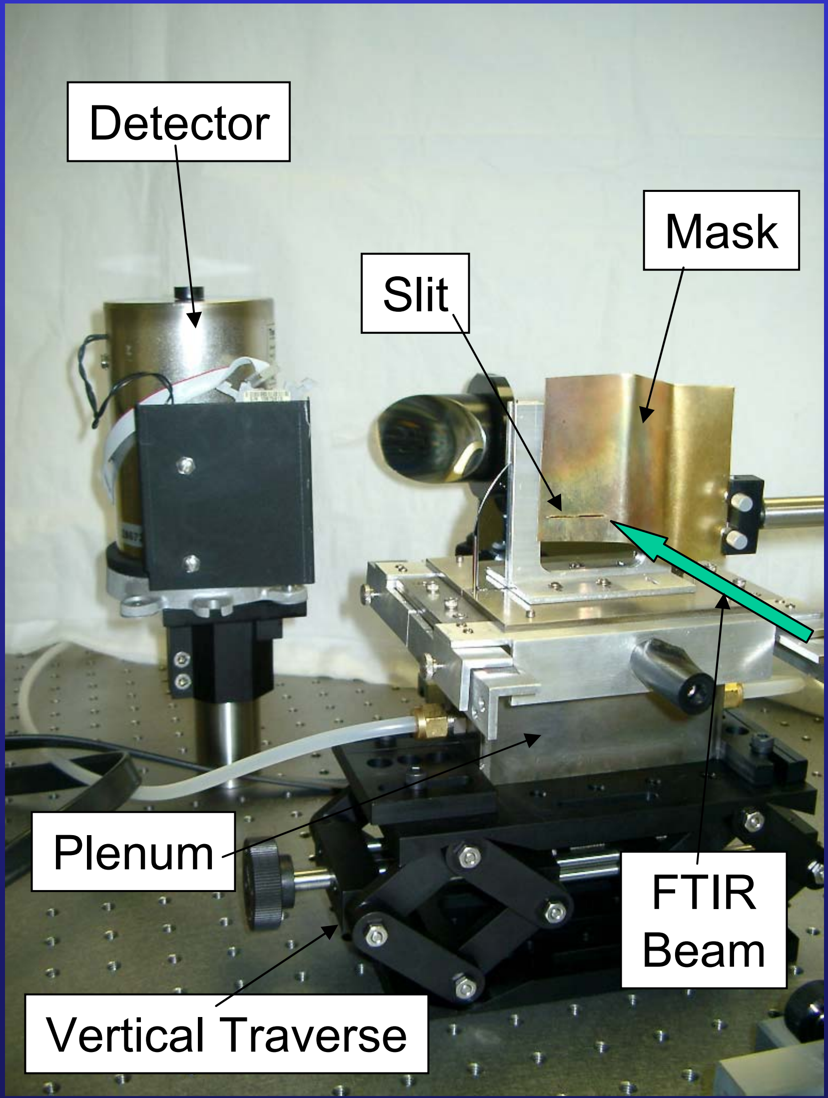


Present Work



- Improved Optics
  - Better FTIR
  - Higher throughput external beam path
- IR Camera for Plate T
- Improved spectral interpretation

Present Work



- Improved burner
  - Adjustable H
  - Improved traverse
  - Improved flow control

Conclusions

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- Structural heat conduction has important effects on performance of micro-combustors
  - Increases reaction zone thickness
  - Increases burning rate
  - Leads to optimum power density configurations
    - *Rocket motors with T/W > 400 appear possible*
- Chemical quenching still important
- Viability of micro-rockets hinges on tradeoff between T/W and I_{sp}.
- Experimental verification ongoing

U N I V E R S I T Y O F M A R Y L A N D

Future Work

- Simulation
  - Incorporate radiation boundary condition
  - Incorporate surface chemistry
  - Investigate different fuels
- Experiments
  - Measure $\delta_r(H)$ in micro-burner
  - Construct parallel plate flow reactor
  - Replace external optics with optical fiber system

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