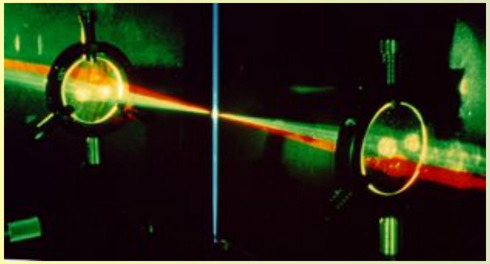


Burning Old Fuels in New Ways

Recent Projects in Combustion Research

Derek Dunn-Rankin
Mechanical and Aerospace Engineering
University of California, Irvine

China Lake Naval Air Warfare Center – August 10, 2011

Combustion Research at UCI

Computational/ Theoretical

W.A. Sirignano
Multiphase flows, droplets and droplet groups, pool fires

R.H. Rangel
Droplet streams, multiphase flows, fluid instability

S.E. Elghobashi
DNS

F. Liu
CFD, turbomachinery

Experimental

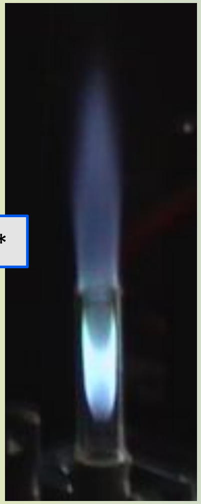
D. Dunn-Rankin
Droplet stream flames, laser diangostics, coal combustion, miniature power

J.C. LaRue
Turbulence

G.S. Samuelsen
Spray combustion, practical systems, environmental impact

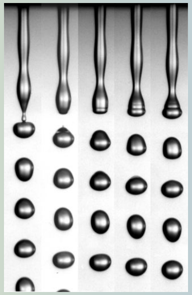
4-stroke reciprocating

Film combustor*



Miniature Engines

emissions, luminosity, CARS

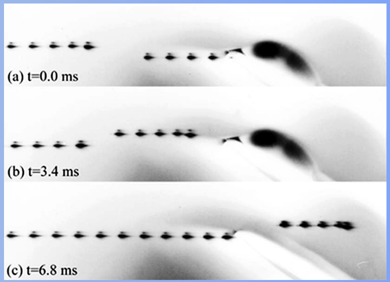


fringe analysis, rainbow

photography, light scattering, LDV

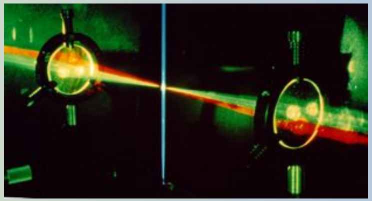
Droplet Streams & Flames

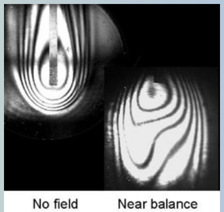
LIF, CARS, PLIF, RHIS

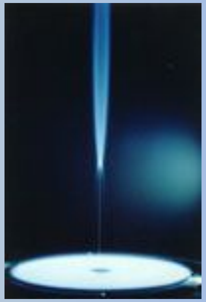


laser induced breakdown

spatial averaging







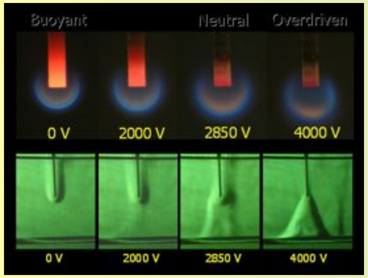
Coal and Biomass

PCSV, Sampling, QCL, Pyrometry, LOI

oscillating combustion

Combustion Control*

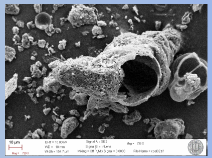
luminosity, chemiluminescence, RHI

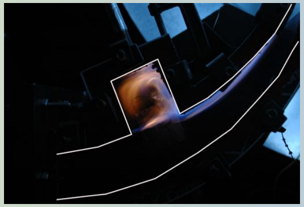


electric field control

Advanced Turbine Burner*

PIV, schlieren, PCSV, CARS

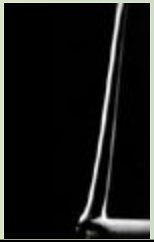




Laminar Flames

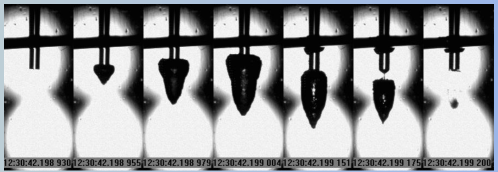
LDA, schlieren

axially symmetric flames



Dental Laser Drill

shadowgraphy, laser deflection



Cigarette Smoke

light scattering, PCSV, TTV

Lasers, Flames, and Aerosols RESEARCH

*collaborative

Burning Old Fuels in New Ways

- Coal combustion
  - control of carbon-in-ash from pulverized coal and coal/biomass combustion
  - QCL absorption measurements for zonal control of combustion
  - control of mercury emissions
- Combustion in chambers
  - Improved miniature liquid fueled combustion systems
  - flame holding in a model turbine burner channel
- Electrical properties of flames
  - small diffusion flames
  - partially premixed flames
- Alternative fuels
  - biofuel combustion
  - methane and propane hydrate combustion

Fluid/Thermal Sciences

- Fuel preparation and sprays
  - controlled breakup of droplet streams
  - fuel injection for small-scale homogeneous charge compression ignition (HCCI) engine
- Multiphase flow and particle interaction
  - particle interaction in viscoelastic fluid
  - turbulence effects on droplet vaporization
- Biomedical applications
  - Dental laser drilling, sterilization, and therapy

Lasers Flames and Aerosols - website

Lasers, Flames & Aerosols Research Group

UNIVERSITY of CALIFORNIA · IRVINE

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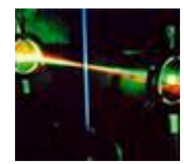
Simplified Systems

Sprays: droplet stream combustion, supercritical behavior, emulsion flows; Gas burners: flat flames, slot burners, electric flames; Coal combustion: entrained flow reactor, ammonia bisulfate condensation, mercury formation and capture; Aerosols: Ion driven flows, indoor air modeling.

Goals

Simplified systems that mimic a specific behavior of interest of a more complex systems, such as spray combustion, utility coal plants, and IC engines, are studied to obtain fundamental information. In many cases, numerical simulations are developed in conjunction with the experiments to provide insight into influencing factors. Although our motivation remains in better understanding of a practical systems, diagnostic tools utilized to meet these goals are concurrently being evaluated in to prove flexibility and accuracy in non-ideal settings.

Diagnostics in use



LDV, PIV, PCSV, PLIF, CARS, schlerien, high speed videography, shadowgraphy, the deconvolution of mie scattered fringes, polarization sizing technique, and fluorescence techniques.

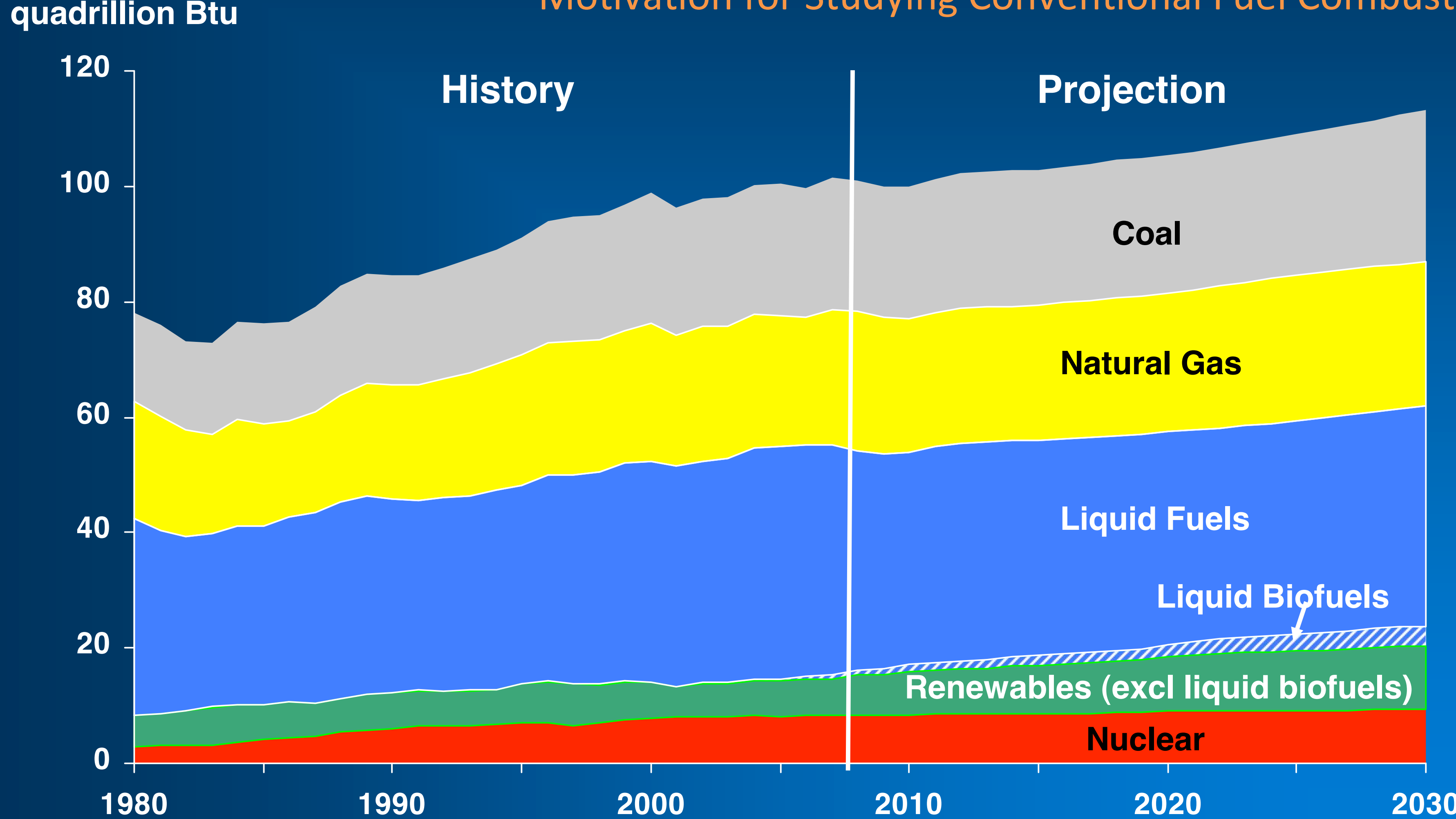
ıneral Electric and Industry-University Cooperative Research Program has begun testing in the newly built 2 meter entrained flow reactor. Thi

The Henry Samueli School of Engineering | UC Irvine | MAE Faculty Profile | ANTLink | FACNET

- lfa.eng.uci.edu

Non-fossil energy use grows rapidly, but fossil fuels still provide 79 percent of total energy use in 2030

Motivation for Studying Conventional Fuel Combustion

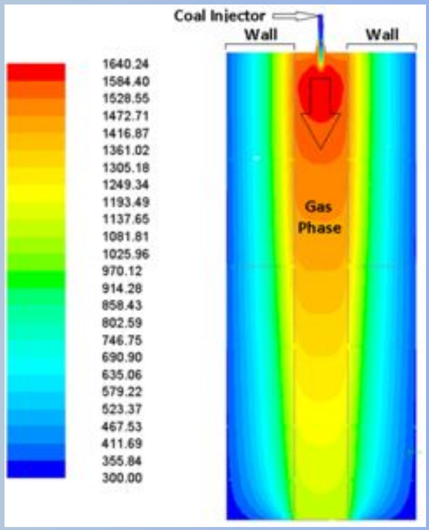


Char Burnout Kinetics

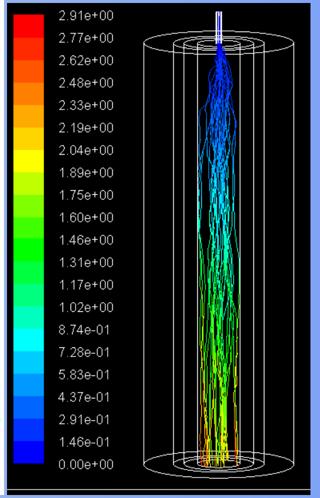
- **Background**
  - A major waste product after the combustion of coal and biomass is ash.
  - High carbon content (> 5%) prevents the sale of the fly ash to cement industries.
- **Objectives**
  - Predict relationships between boiler operating conditions and residual carbon in ash.
  - Predict latter stages of carbon burnout.
- **Entrained Flow Reactor**
  - 6 ft. length and 8 in. dia. combustion zone.
  - Coal feed rate is 6.3 g/min.
  - Residence time is 2 secs at 1 m/s flow rate.
- **Numerical Modeling**
  - A numerical model of coal burning in EFR to evaluate common char burnout kinetic models, including CBK.
  - The CFD simulation includes heat transfer, fluid dynamics, as well as coal/ash particle tracking and combustion chemistry.

Current Image of EFR

Solid Model of UCI EFR



Temperature Contour (K)



Particle traces colored by residence time (second)

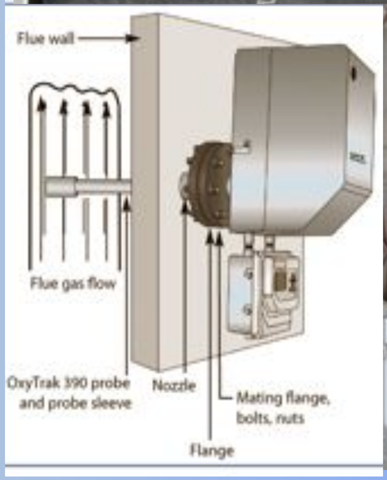
Char Burnout Kinetics

- **Diagnostic Instruments**
  - **Loss On Ignition Measurements**
    - The percentage of carbon in ash can be found.

$$LOI = \frac{Carbon\_in\_dry\_ash}{Carbon + Ash\_residue}$$

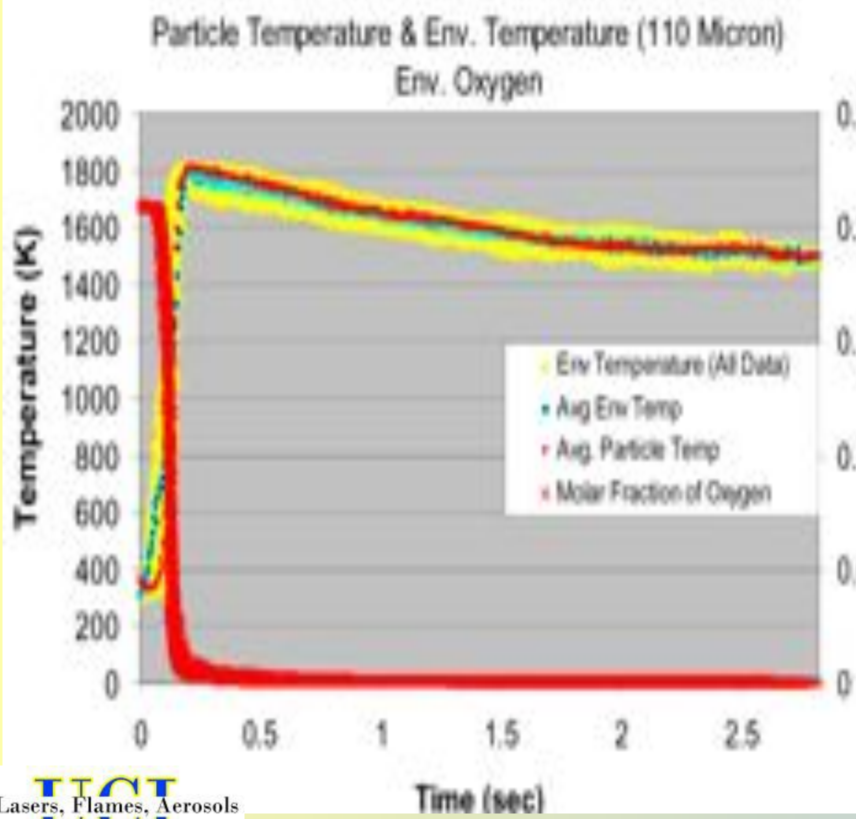
  - **Sample Extraction Probe**
    - Inserted through ports on side for extraction at nearly any residence time.
    - Water cooled probe with Nitrogen gas quench freezes sample at extraction.
  - **TESTO Gas Analyzer**
    - Oxygen profile (radial, axial)
  - **GE Oxytrak 390 Flue Gas Analyzer**
    - Continuous measurement of Oxygen and Combustibles concentration at the exit.
  - **Scanning Electron Microscope**
    - Coal morphology analysis and individual particle size measurement.

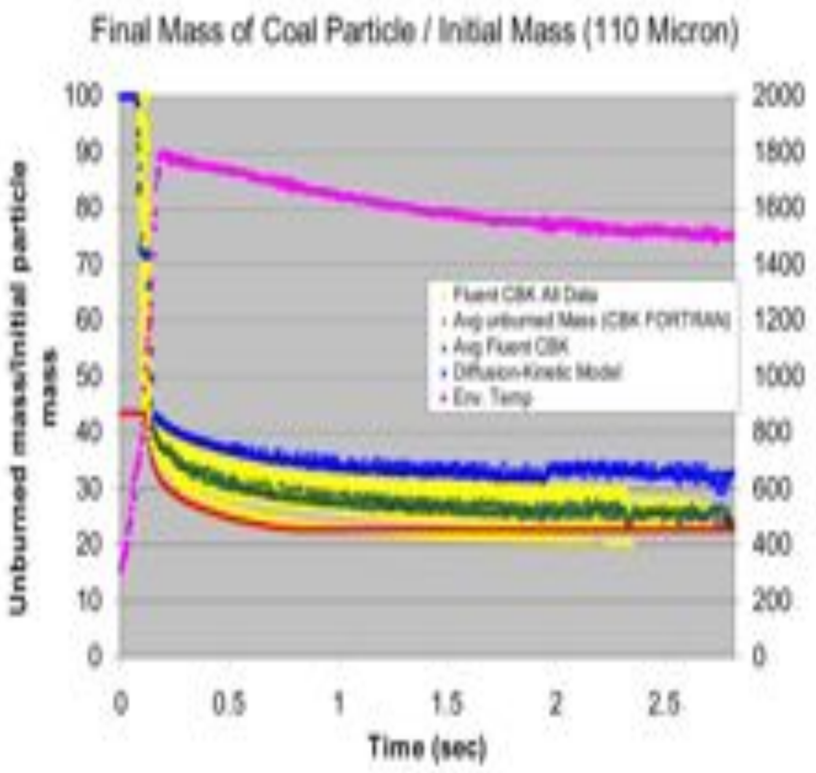


Comparison of Char Burnout Models

- The coal particle life histories were studied by applying 3 char burnout models (Fluent CBK, External CBK and Kinetic-Diffusion Limited Model) and time-temperature, stoichiometric history of particles were compared with one another.
- Although CBK is the most rigorous model it has not been validated.
- We have all different tools and numerical models to predict char burnout, but experimental results will give us some idea how accurate these tools are.



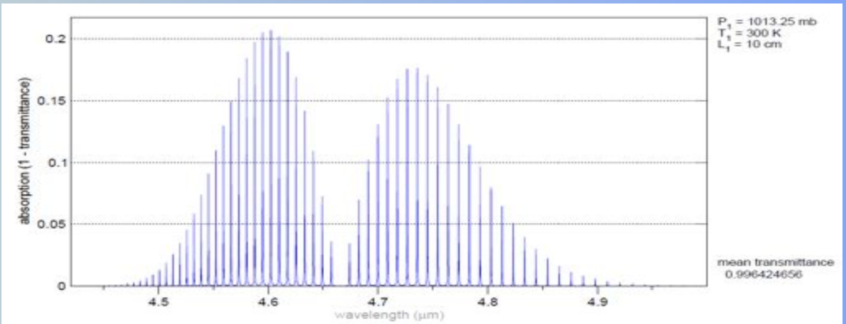


Tomographic analysis of quantum cascade laser absorption by carbon monoxide

- Spectral absorption- environmental monitoring, industrial process monitoring, medical diagnostics, defense and security

Laser

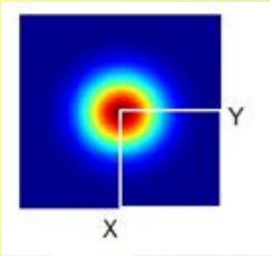
Gas species

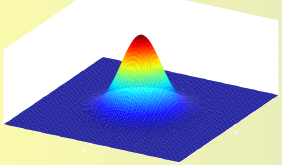


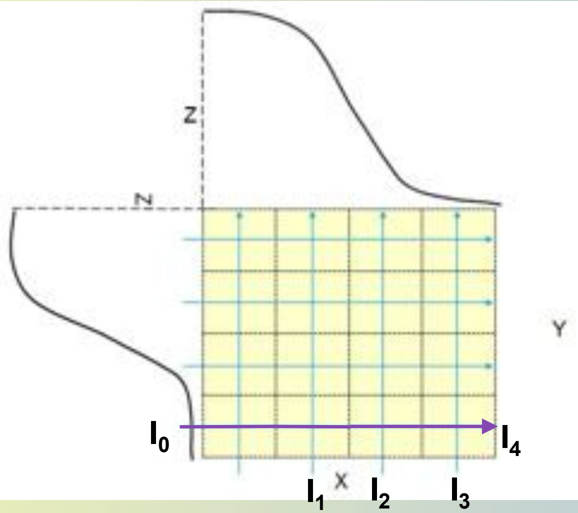
Absorption Spectrum (predicted from HitranPC)

- Comparing numerical prediction of CO concentration in a coarse of line-of-sight values by Beer-Lambert Law.

$$A = \ln\left[\frac{I_o}{I}\right] = -\ln\left[\frac{I}{I_o}\right] = \varepsilon c l = \alpha l$$







A – absorbance
I – transmitted light
Io – incident light
ε – molar absorptivity
L – path length
α – absorption coefficient

Tomographic analysis of quantum cascade laser absorption by carbon monoxide

Predicting intensity ratio I_0/I_{sig} in different ways

Average:100 points/grid
Actual value:1000 points/grid along the center line

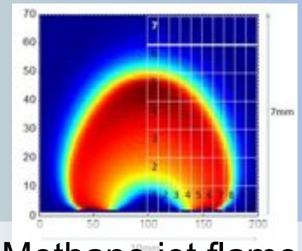
Grid row	Mid point	Average	Actual value
P1	3.208 (R^2=5.86E-3)	3.146 (R^2=2.19E-4)	3.132
P2	1.943 (R^2=3.72E-5)	1.949 (R^2=3.6E-7)	1.949
P3	1.241 (R^2=2.34E-4)	1.253 (R^2=7.29E-6)	1.256
P4	1.041 (R^2=1.54E-3)	1.045 (R^2=5.69E-5)	1.046

Grid columns: P1 P2 P3 P4

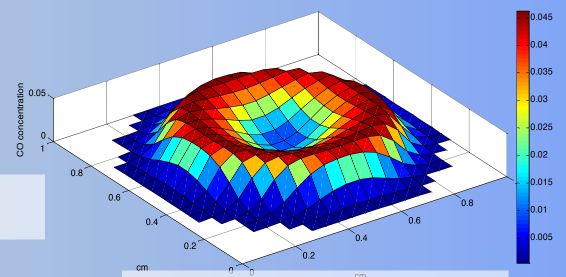
The average of:
Midpoint error = 1.5 E-3
Average error = 5.69 E-5

In comparison of I_0/I_{sig}, mid point and average are close to each other. Both still differ from the actual value.

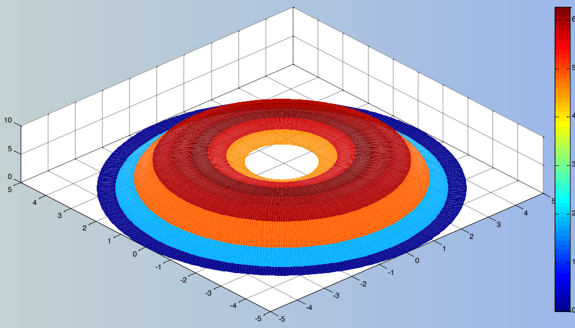
Numerical prediction of CO concentration of a methane jet flame



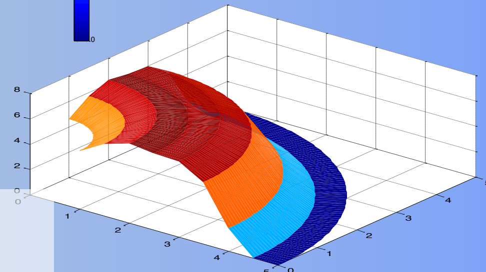
Methane jet flame



CO concentration



Bottom 1 mm slab



Predicted CO concentration by Abel inversion

Mercury Emission Control

- Motivation
  - Anthropogenic mercury emission from power plants -- approx. 48 tons per year
  - USGS survey found mercury in every fish tested from 291 streams; fish at more than 25% of sites had mercury above EPA safe level
  - A typical 250 MW coal-fired power requires more than $1 million in commercial sorbent annually
  - Effective & inexpensive technology for mercury capture is needed
- Goals
  - Simultaneous CO2 sequestration and mercury capture

Mercury Removal from Flue Gas by Aqueous Precipitation

Background

- Natural occurrence of mercury

  Hg^0, as vapor in atmosphere

  Hg_2^{2+}, Hg^{2+}, as part of inorganic and organic compounds in water, soil, plants and animals
- average Hg content in coal in US is 0.06 ppm
- Recent estimation of mercury emission from power plants in US, 40-52 tons/yr
- United Nations' estimation of mercury speciation from coal combustion plant in 1995

  Hg^0 50% insoluble

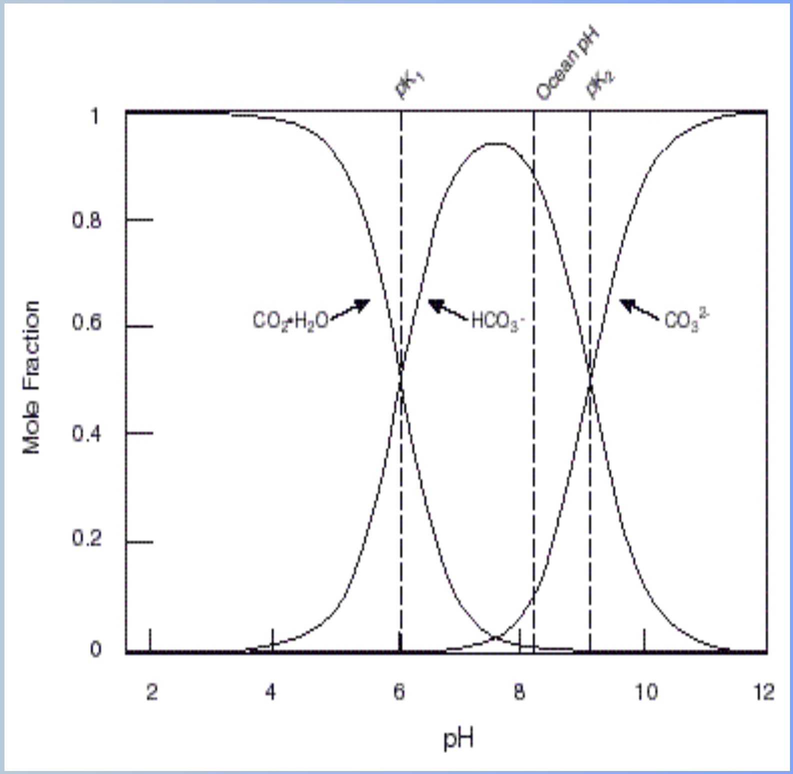
  Hg^{2+} 40% soluble

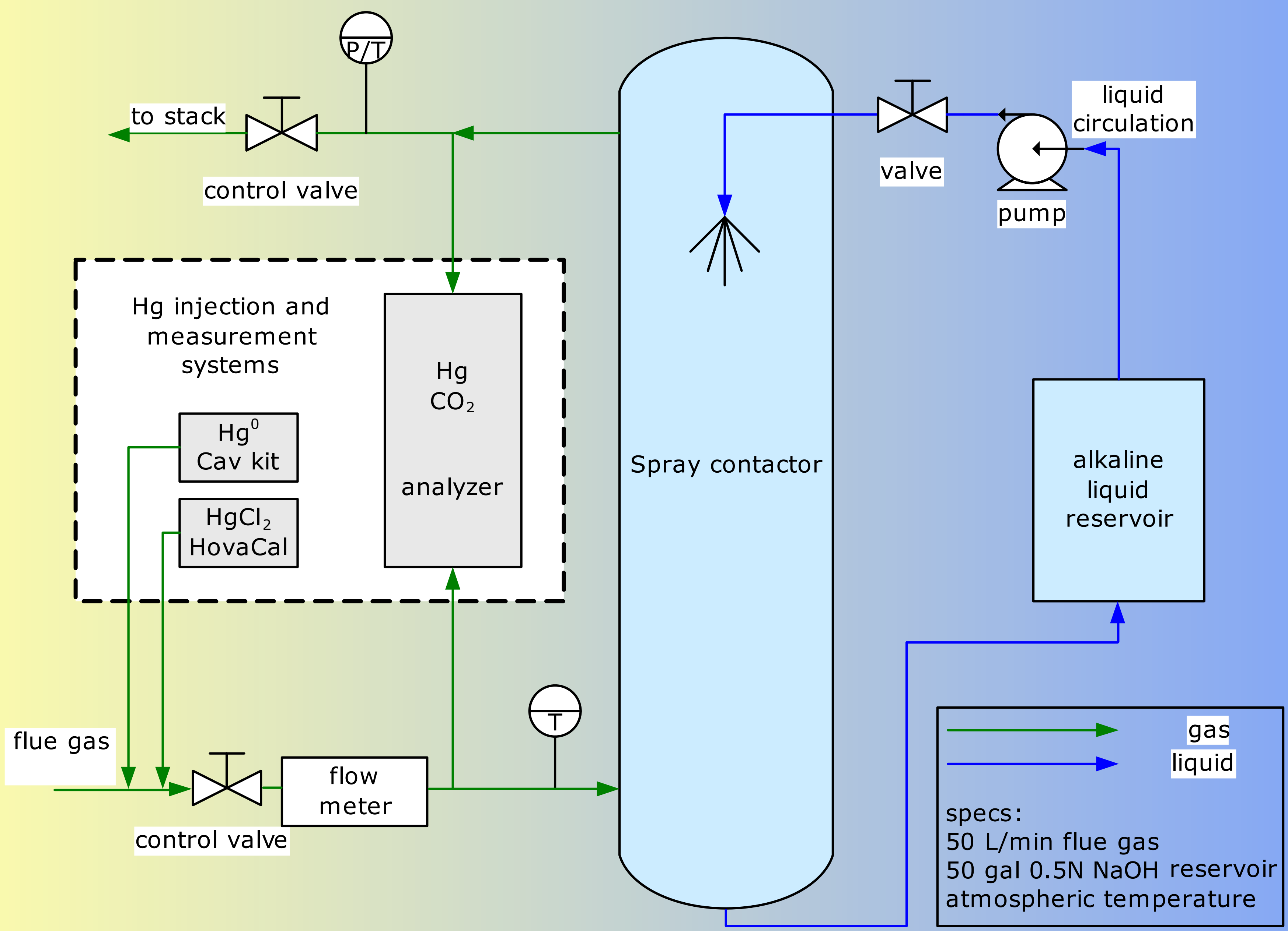
  Hg_p 10%
- Carbonate Mineralization by Aqueous Precipitation (CMAP)
  - CO_2 sequestration (Calera corp.)
  - Seawater contains the following pertinent chemical species:

  Ca^{2+}, Mg^{2+}, CO_3^{2-}, HCO_3^-, $(CO_2)_{aq}$, H_2CO_3, H^+ and OH^-

  Precipitation occurs when $[M^{2+}][CO_3^{2-}] > Ksp$

System is running under strong alkaline conditions to ensure the equilibrium favors the formation of $[CO_3^{2-}]$





P/T
to stack
control valve
Hg injection and measurement systems
Hg^0 Cav kit
$HgCl_2$ HovaCal
Hg
CO_2
analyzer
Spray contactor
valve
liquid circulation
pump
alkaline liquid reservoir
flue gas
control valve
flow meter
T
gas
liquid
specs:
50 L/min flue gas
50 gal 0.5N NaOH reservoir
atmospheric temperature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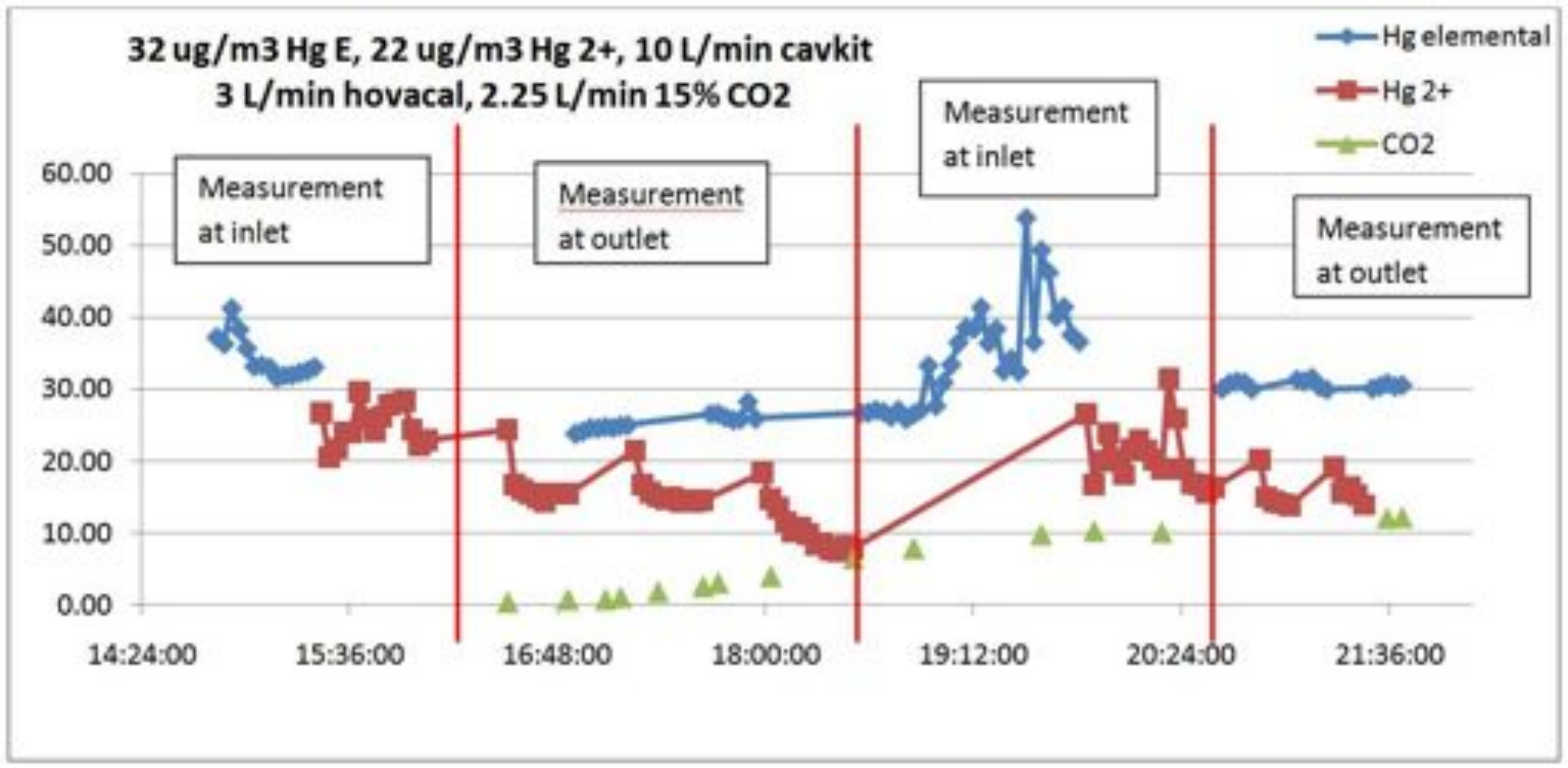
Example Test Run – Mercury Capture



15% of elemental mercury was removed with very stable result.

30% of oxidized mercury seemed to have been removed, however, the reading at outlet dropped continuously. This might be a contamination issue, since mercury sticks to metal and even teflon tubing. After prolonged operation, oxidized mercury at outlet lowered to a background level at around 6ug/m3. It suggests that this process actually has the ability to remove a high ratio of Hg2+.

The CMAP process is comparable with other wet scrubbing processes, i.e. FGD, with respect to mercury removal.

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  - control of carbon-in-ash from pulverized coal and coal/biomass combustion
  - QCL absorption measurements for zonal control of combustion
  - control of mercury emissions
- Combustion in chambers
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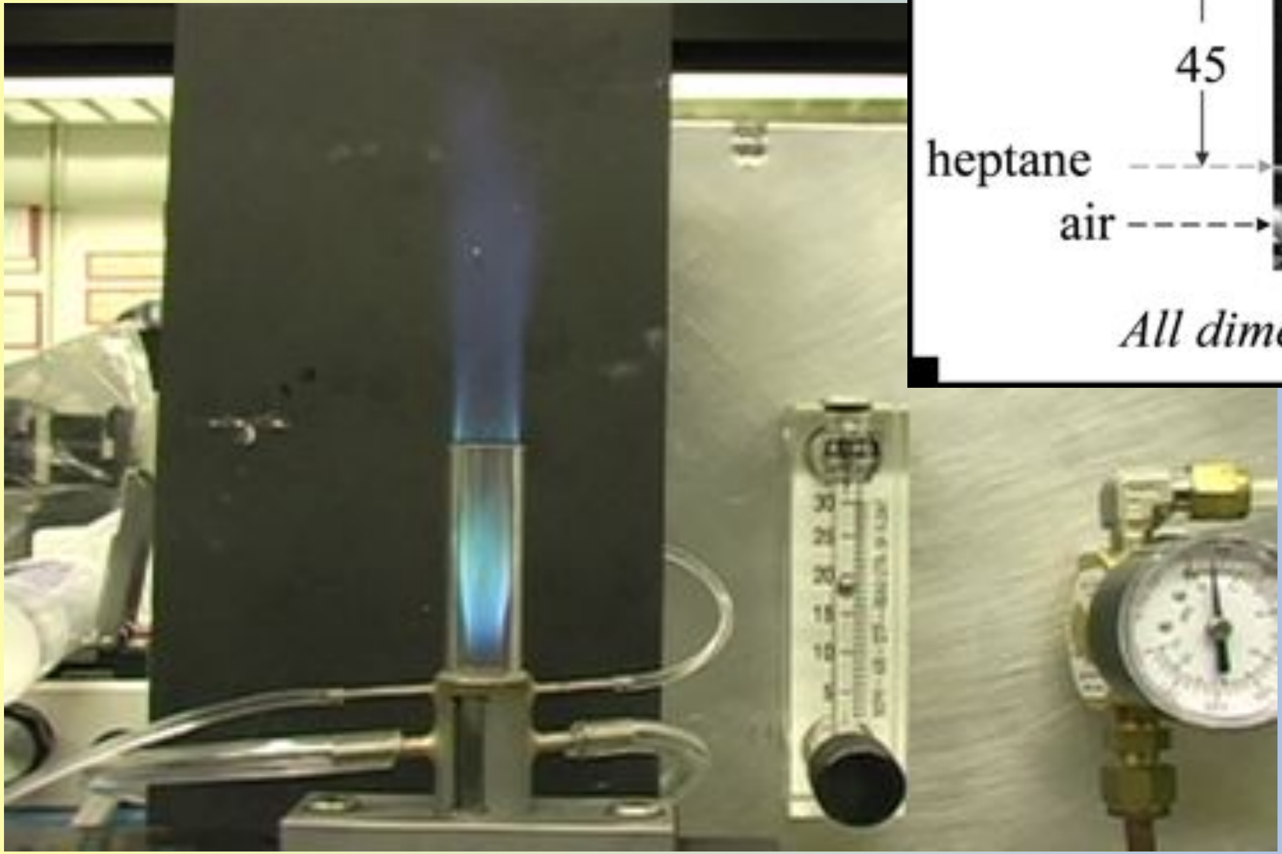
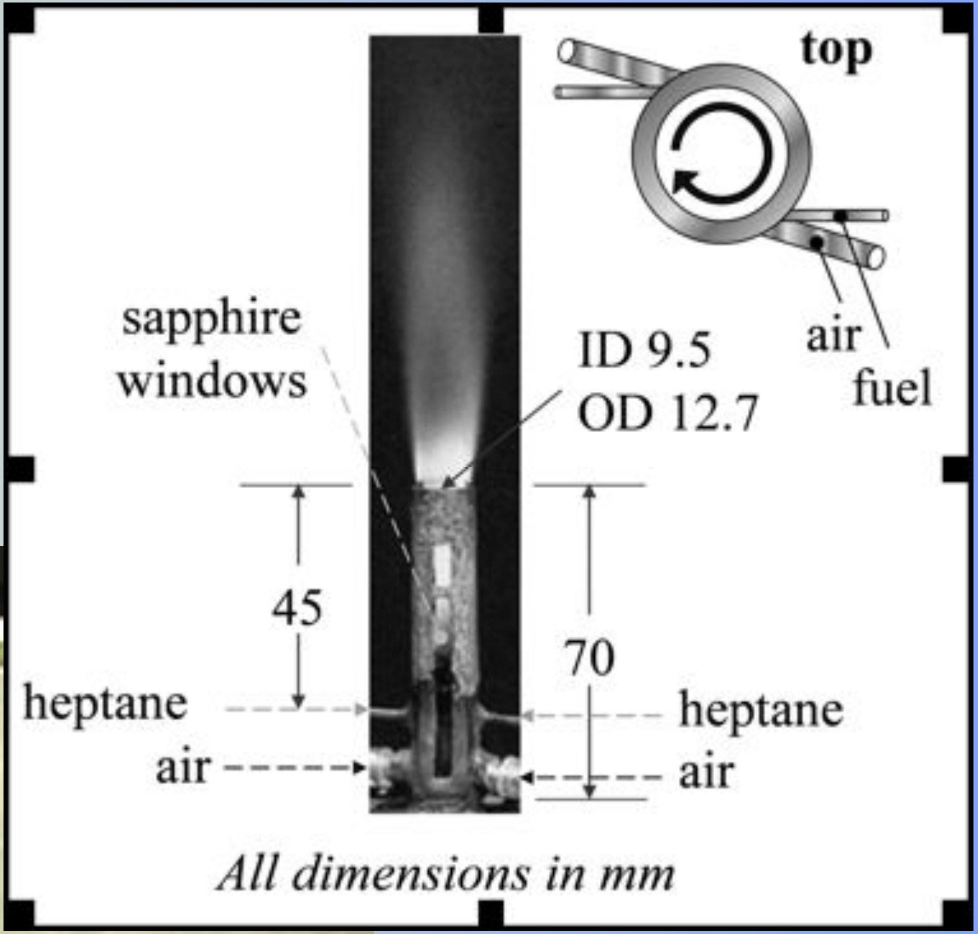
  - biofuel combustion
  - methane and propane hydrate combustion

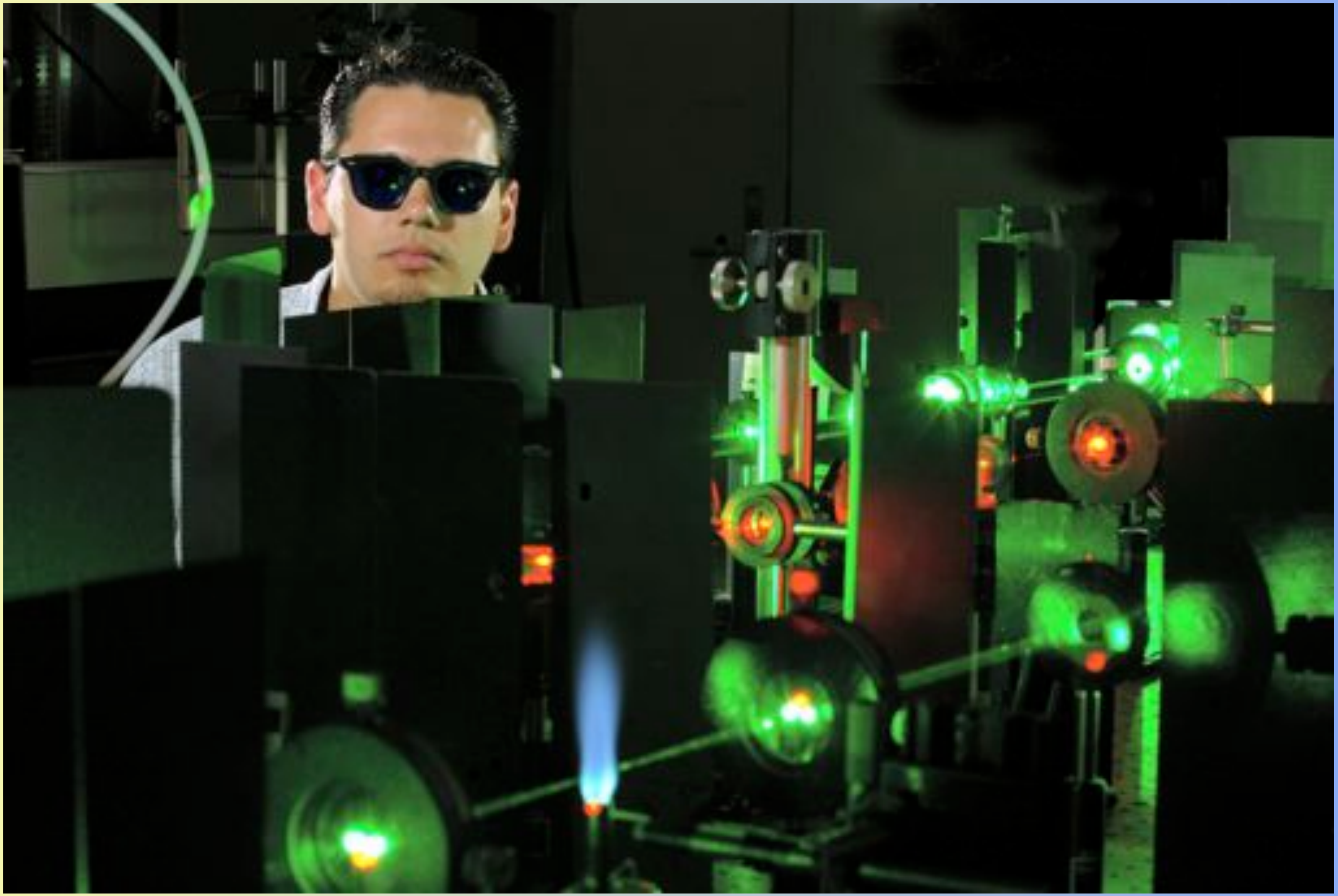
Miniature Liquid Fuel Film Combustor with Air injection



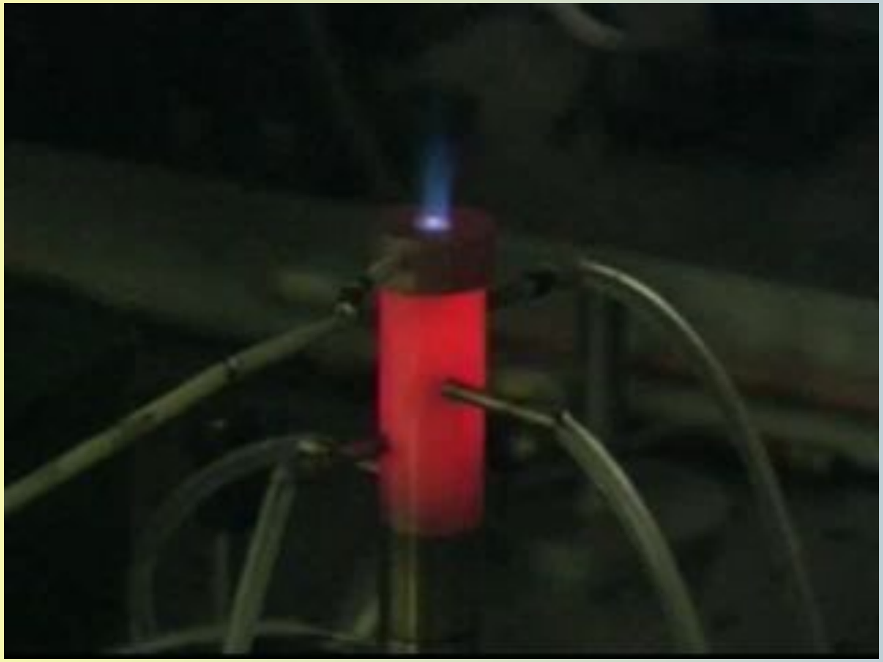


Collaboration with Professor Sirignano

CARS Temperature Measurements above a Miniature Liquid Film Combustor

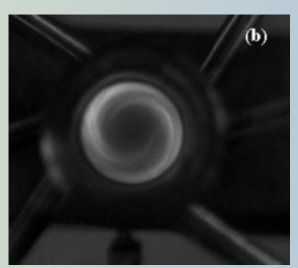


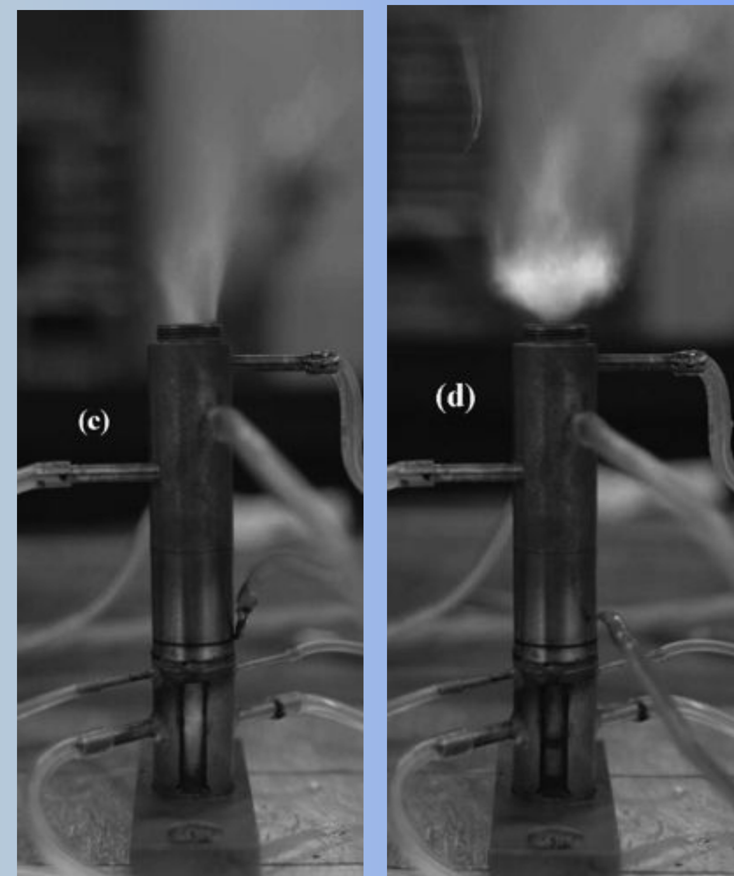
Liquid Film Combustor – with air injection



Horizontal orientation has no effect

Typical swirl flow of a tubular flame



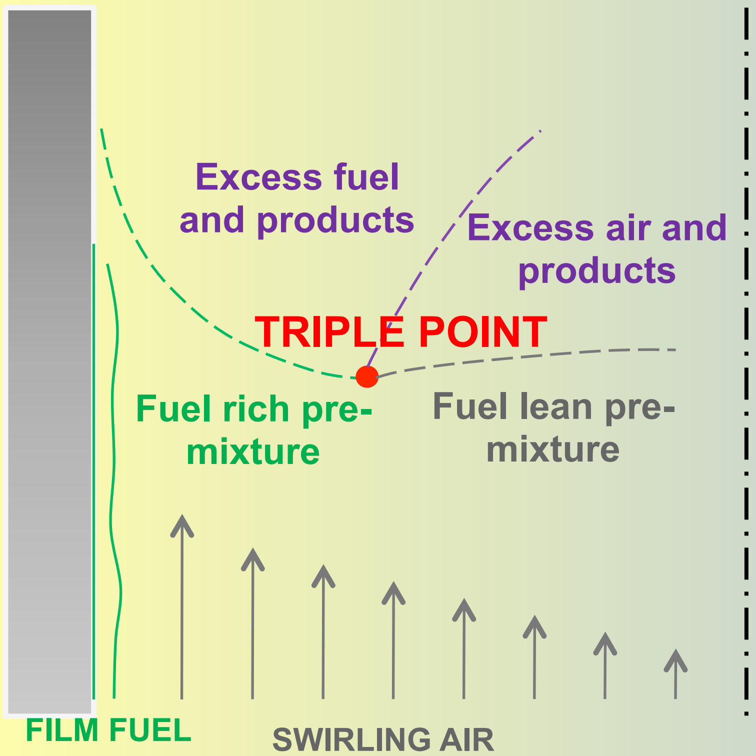


When fuel pool is present, flame condition oscillates between internal and external burning

Swirl Vane Design For Miniature Fuel Film Combustor

Motivation:

- High specific power and energy density
- Portable power system applications with power range of 10 to 1000 W



Concept:

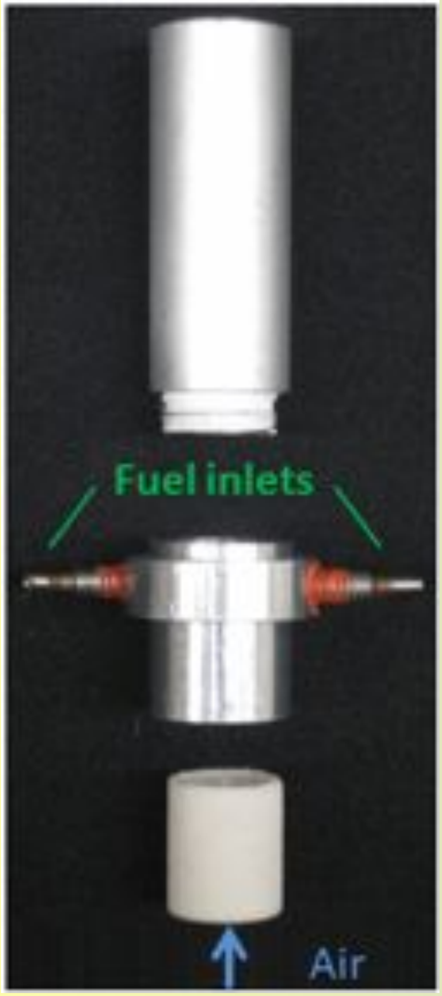
A fuel film along the chamber with swirling air to enhance mixing and recirculation. The model of combustion is based on triple flame theory and the tubular flame.

Objective:

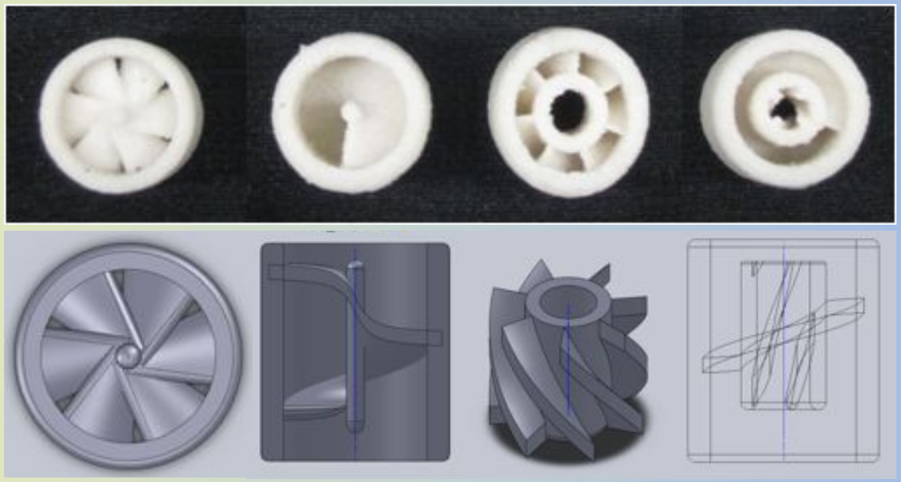
- Design swirl vane by rapid prototyping
- Confine the flame inside the chamber
- Improve miniaturization

Claudio Giani

Results:



Burner components



Swirl vanes designed

Tubular flame top view

Stable flame

Claudio Giani

Turbine Burner Combustion

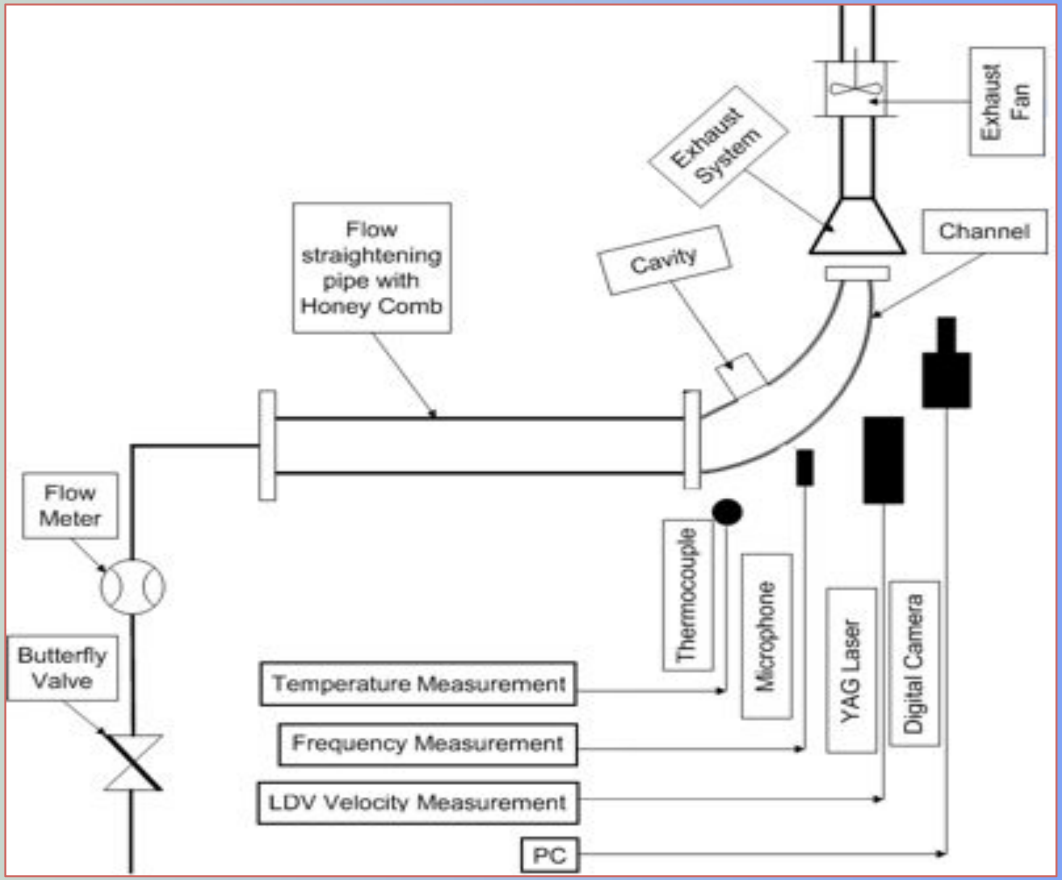
- Improve gas turbine engine performances (specific thrust, thrust/ power to volume ratios, SCF, etc...) by adding energy in the turbine stages.

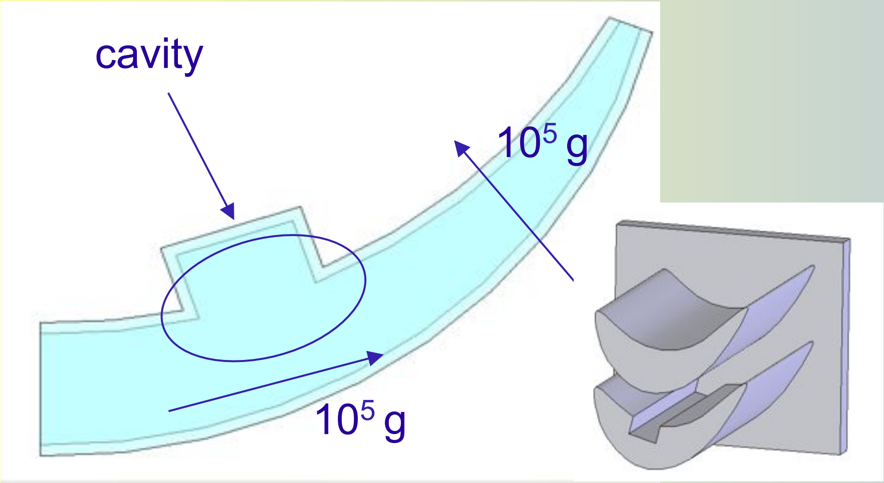
↓

- Combustion in a turbine stage means high speed and accelerating flow.

↓

- A cavity is used to create a low speed zone for mixing and flame holding.





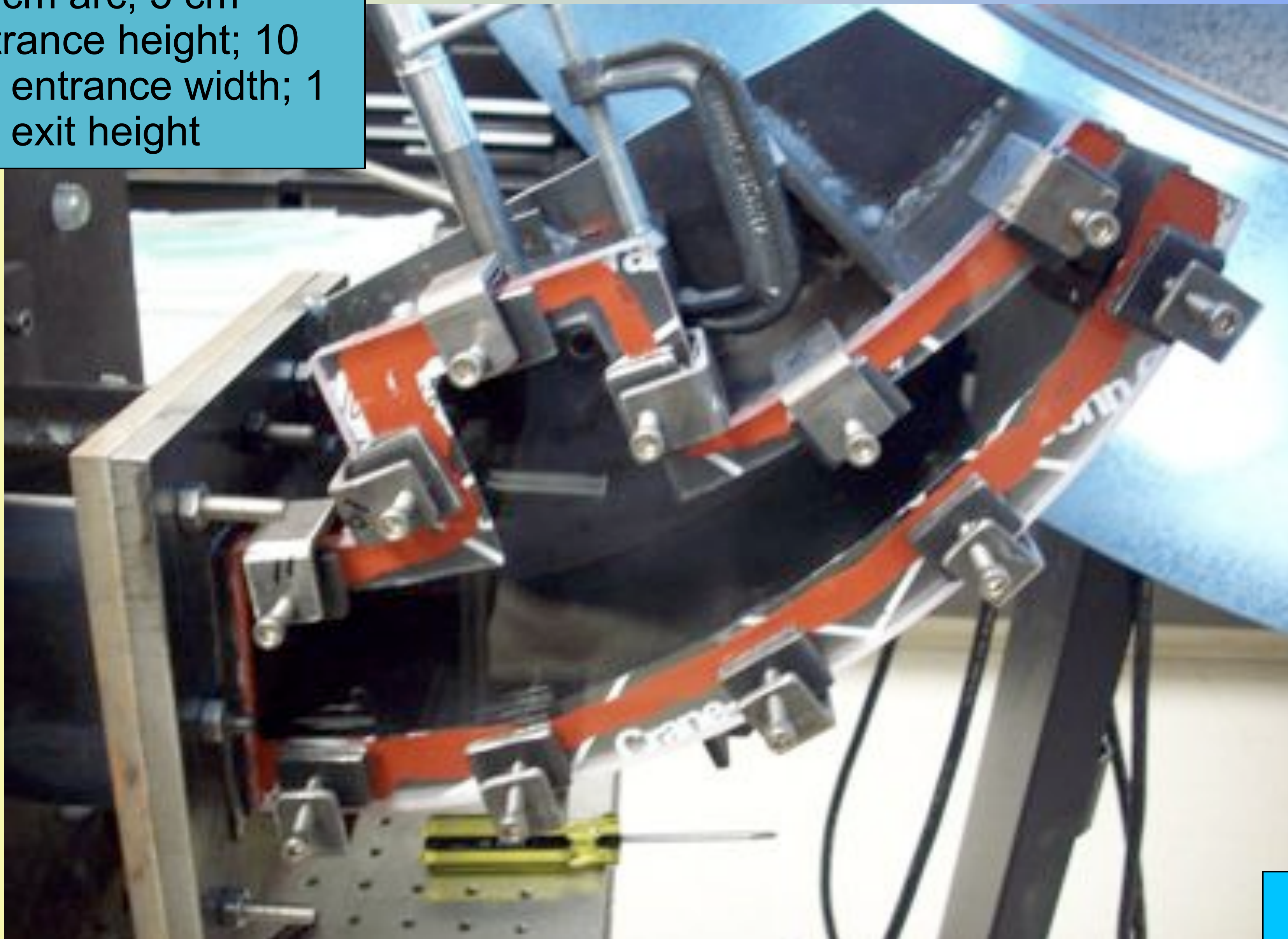
Challenges:

- Ignition and flame-holding of spray flame in high-speed, high-acceleration flow;
- Mass/thermal transport between channel flow and cavity flow.

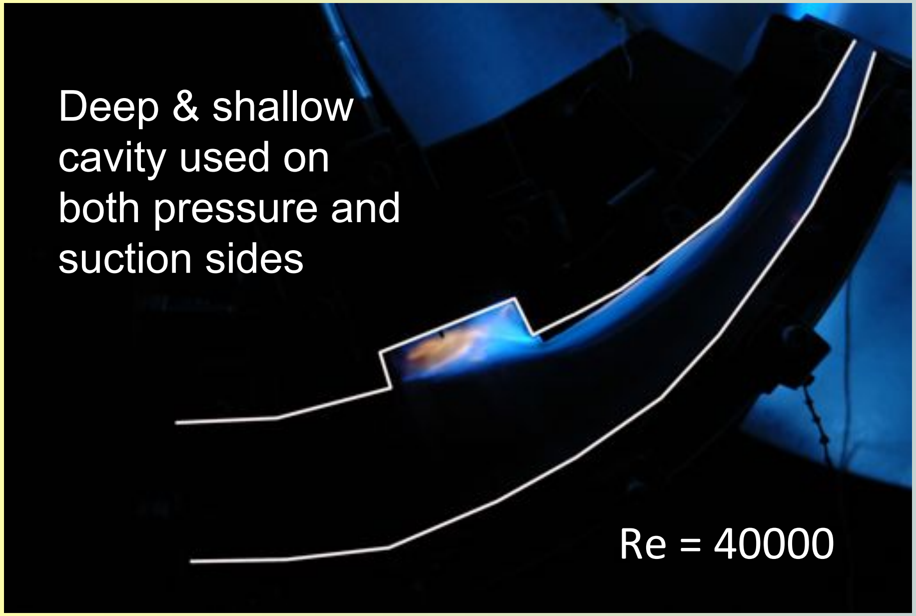
Collaboration with Professors Sirignano and Liu

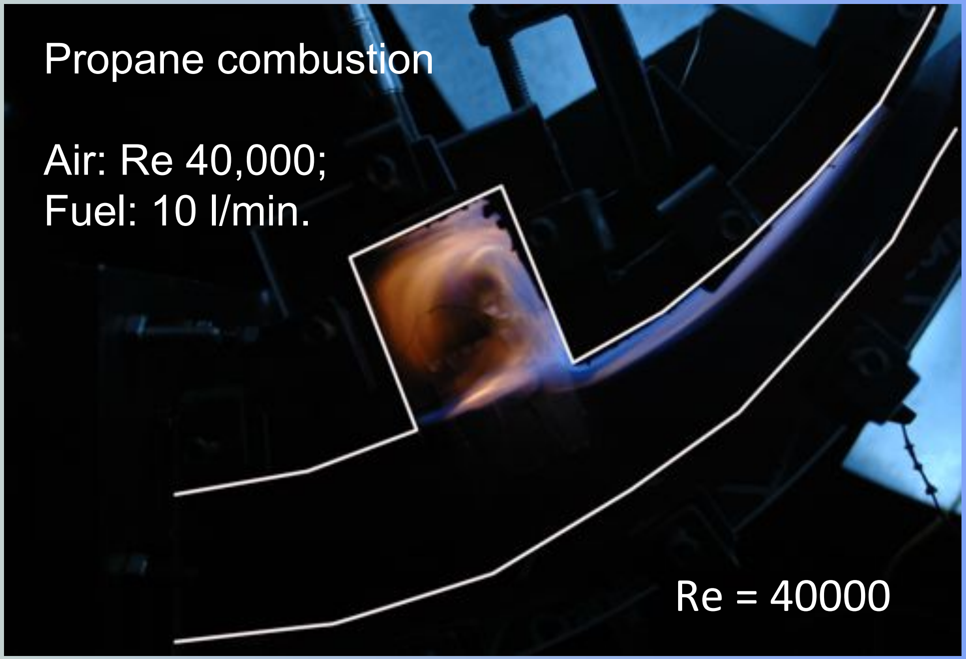
Test Section

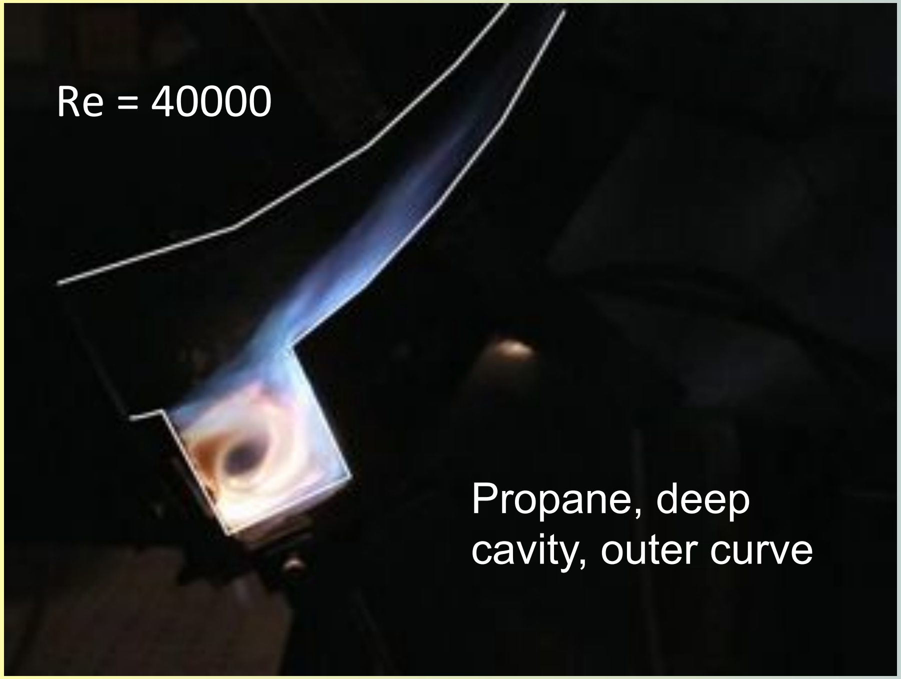
30 cm arc; 5 cm entrance height; 10 cm entrance width; 1 cm exit height

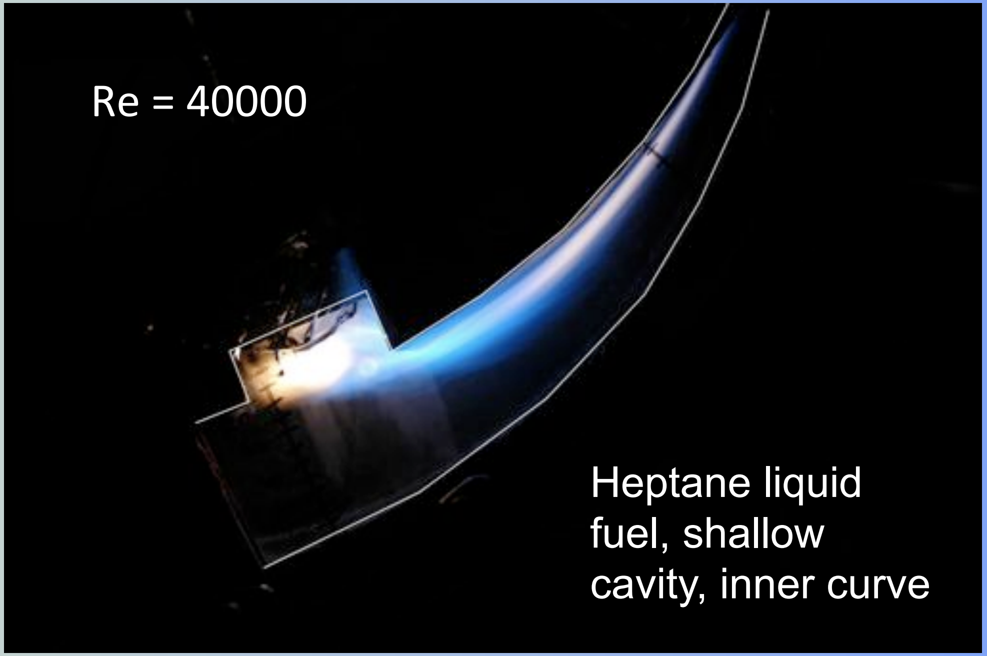


Flame Images









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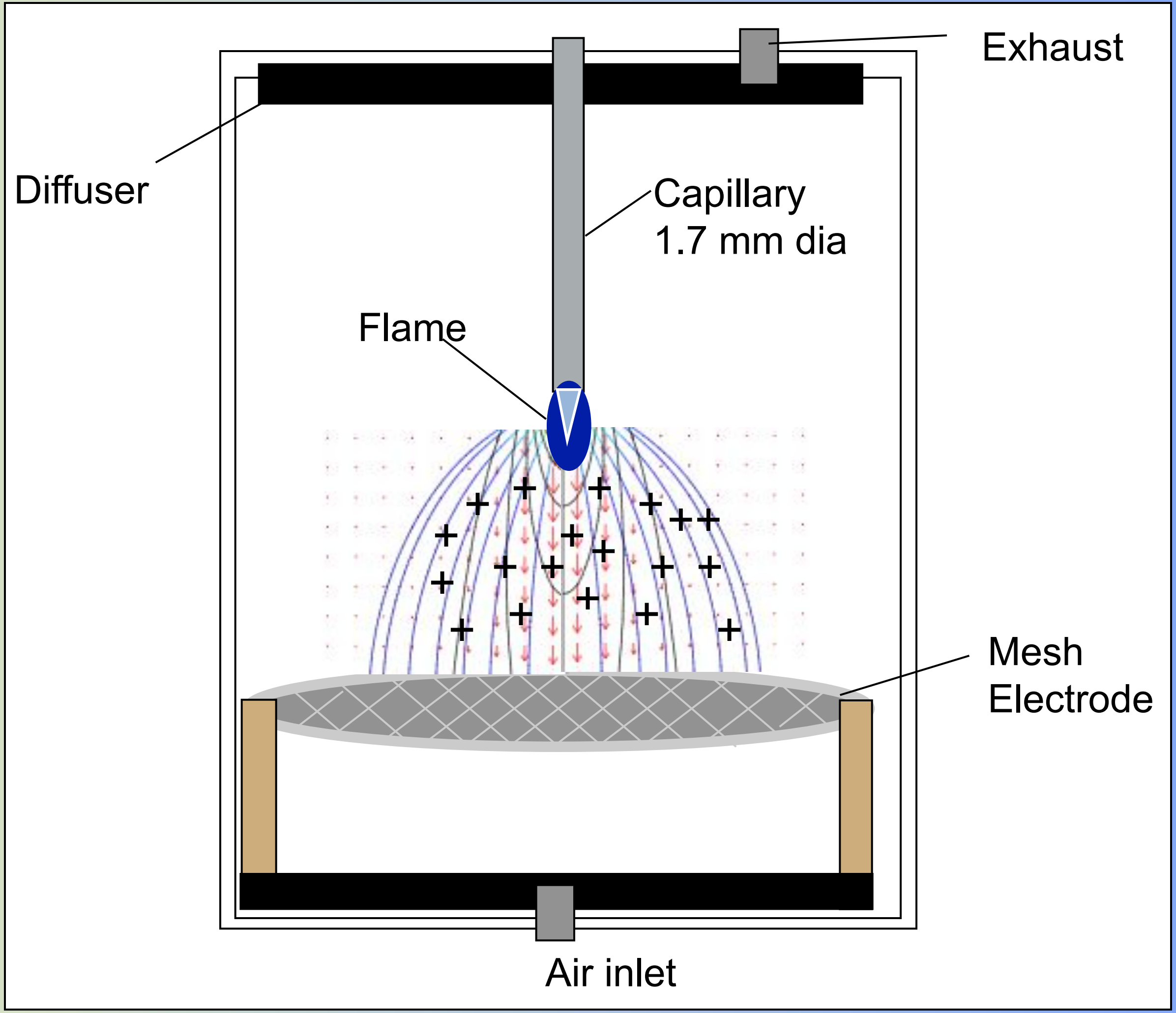
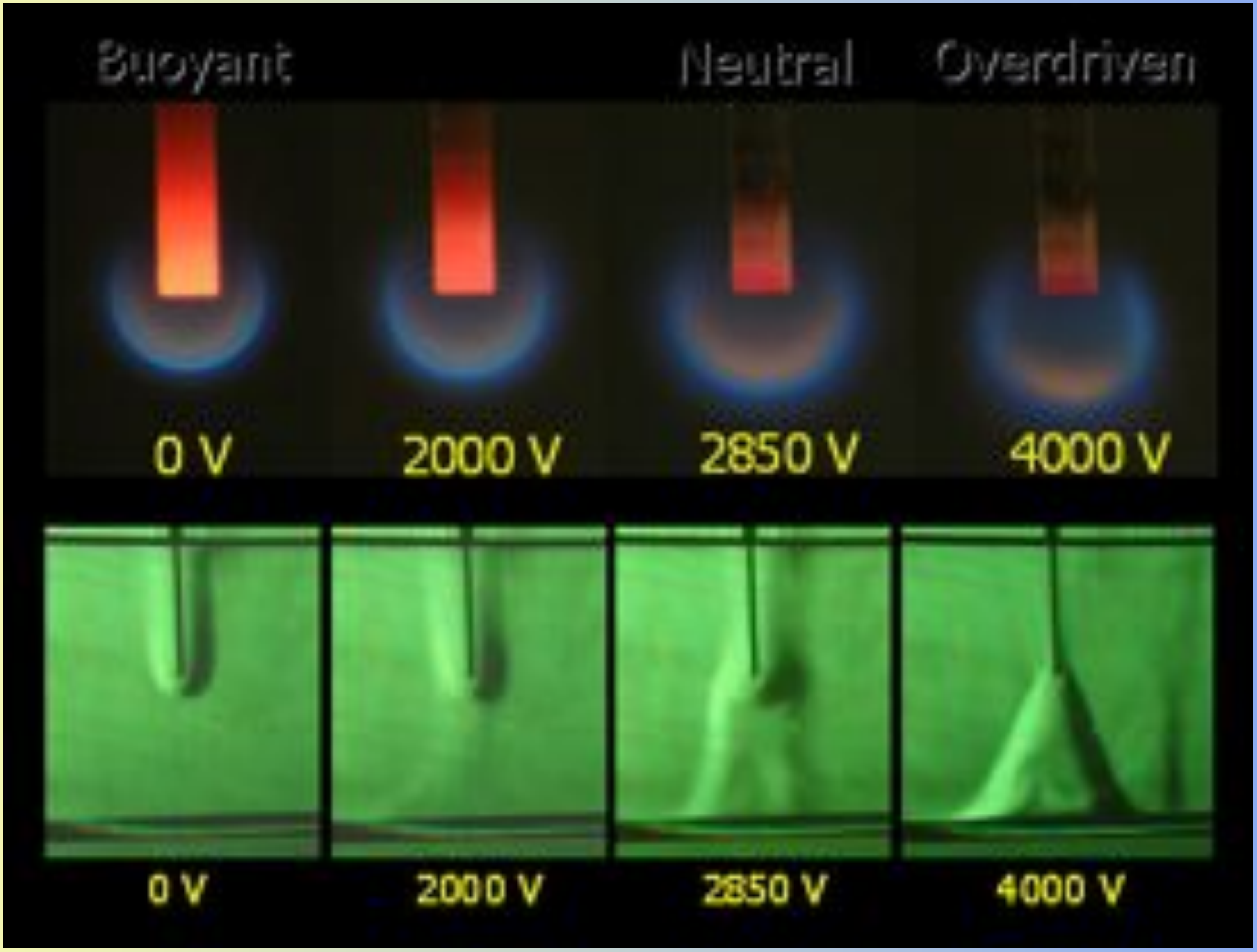
- Combustion in chambers
  - Improved miniature liquid fueled combustion systems
  - flame holding in a model turbine burner channel
- Electrical properties of flames
  - small diffusion flames
  - partially premixed flames
- Alternative fuels
  - biofuel combustion
  - methane and propane hydrate combustion

Electrical Properties of a Jet Diffusion Flame

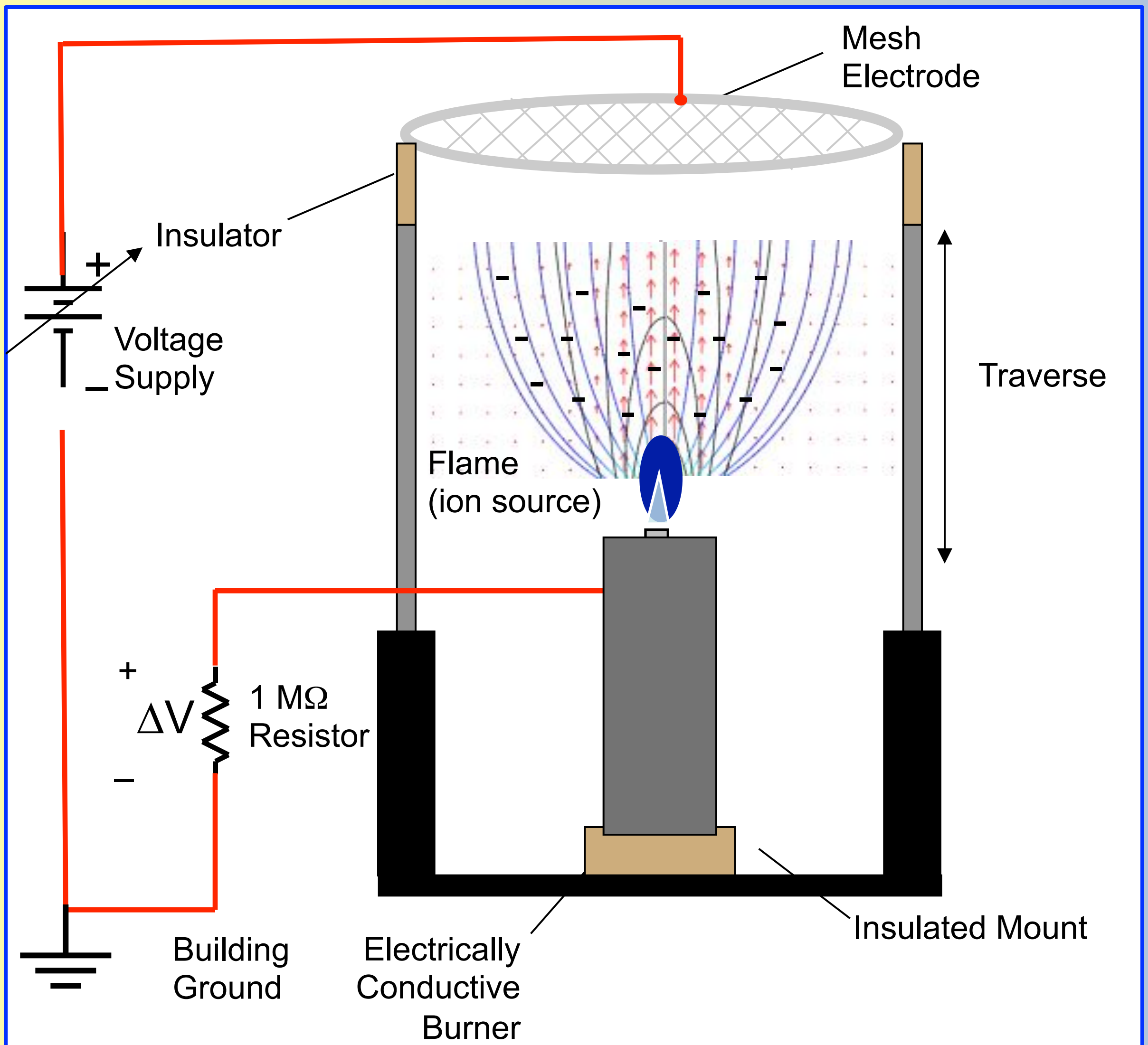
- Point-to-Plane configuration
- H_3O^+ is the dominant ion
- Ion-driven wind created by ions drifting through neutral gas after charge separation



Chemiluminescence & Schlieren

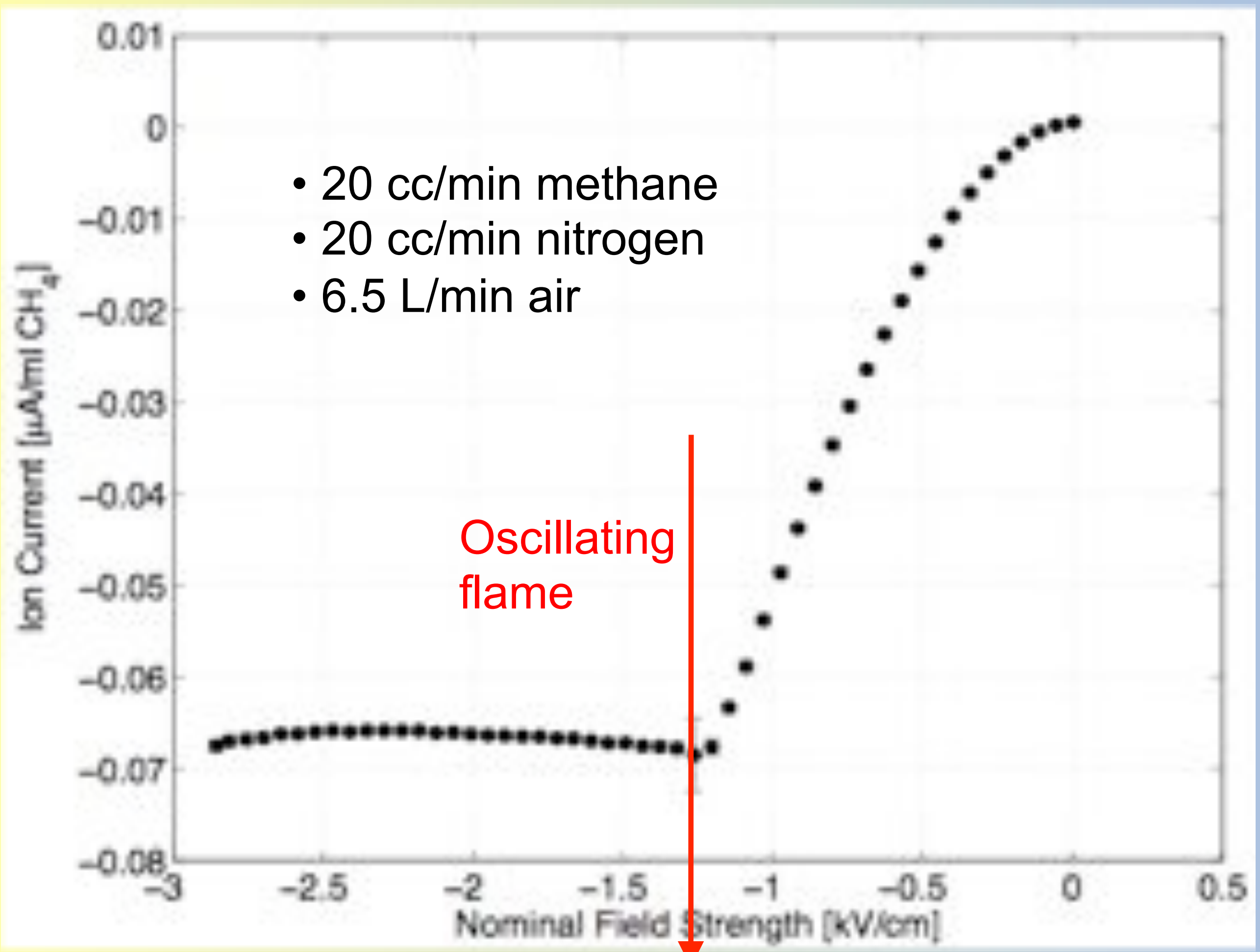


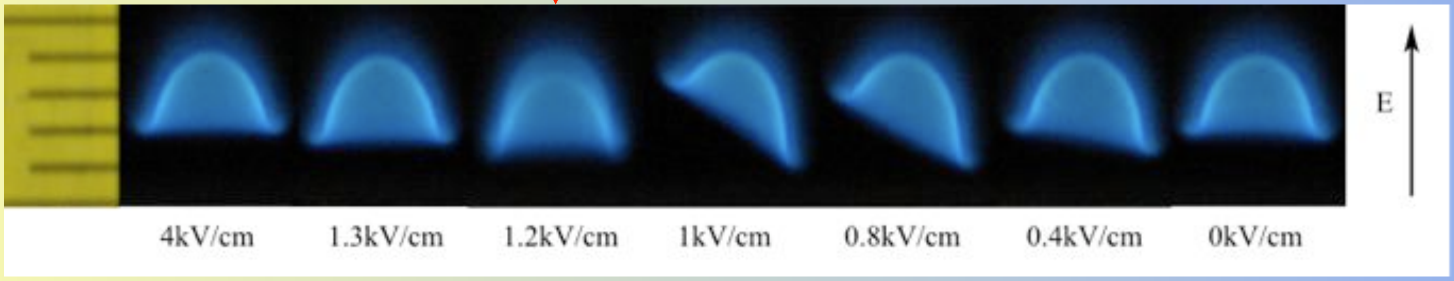
Electrical Effects: Co-Flow Diffusion Flame



- Nascent ions in flames have ~100ppb number density.
- Role of chemi-ions in combustion not fully understood.
- Many of the observed effects have been attributed to an ion-driven wind.
- As an actuator, an electric field acting on a flame through an ion/neutral gas coupling can enhance stability and flammability limits.
- As a sensor, ion detection can indicate the presence of a flame or incipient quenching.

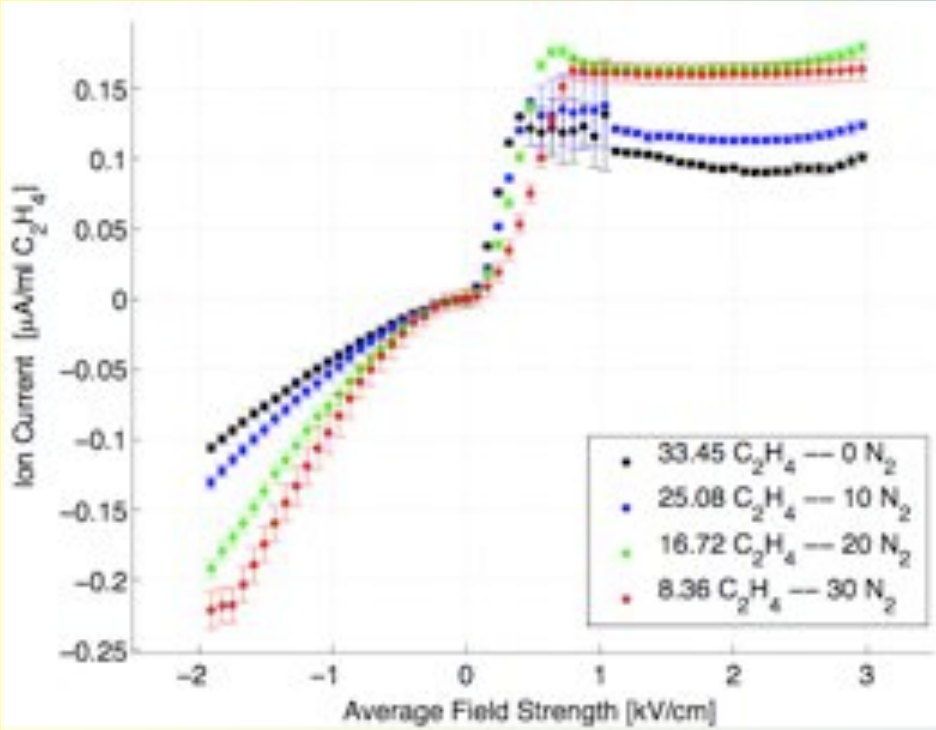
Methane/Nitrogen Coflow Flame – Negative Mesh

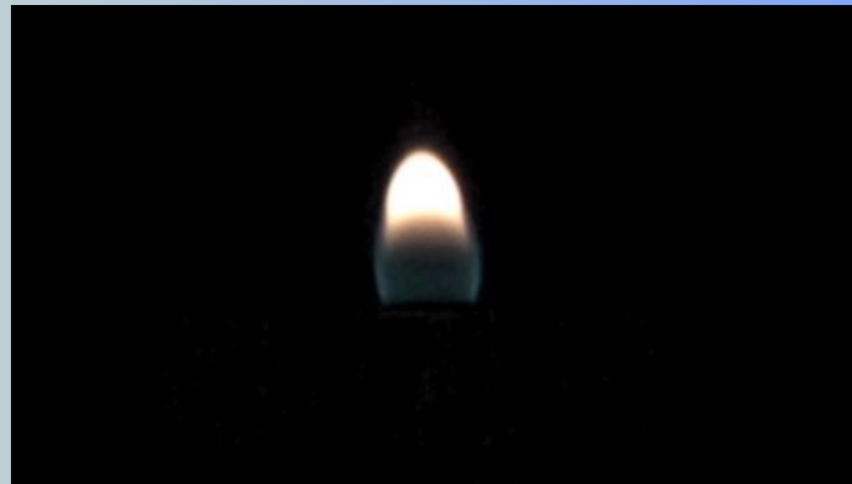


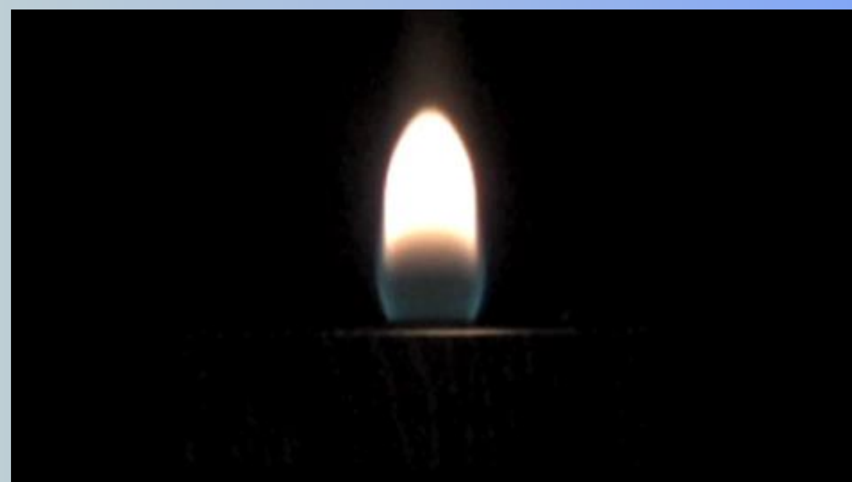


- Ion drift upward initially destabilizes the flame.
- Flame oscillations begin near current saturation.

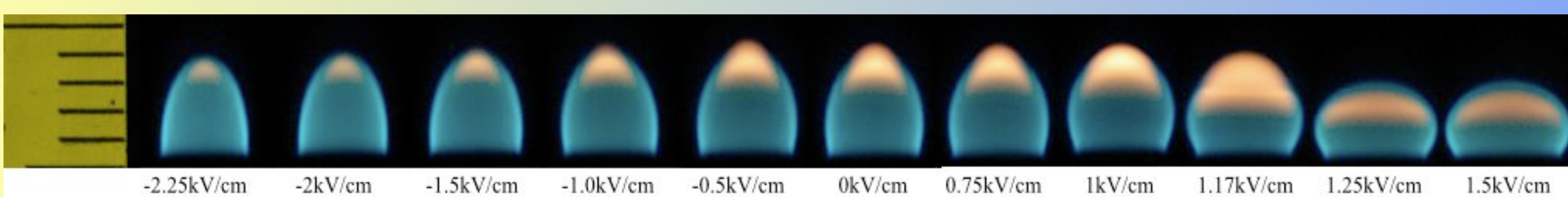
Ethylene Coflow Flame







- Higher flow rates produce a lower ion current when scaled to flow rate.
- Oscillations occur with a downward directed field.
- Soot complicates the phenomenon



Electrical Properties of Flames

-4kV field in microgravity

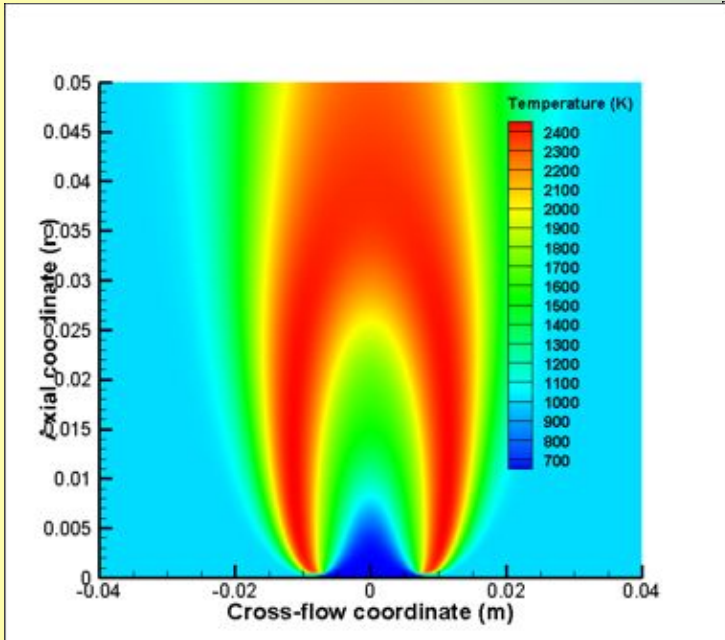
No field in 1g

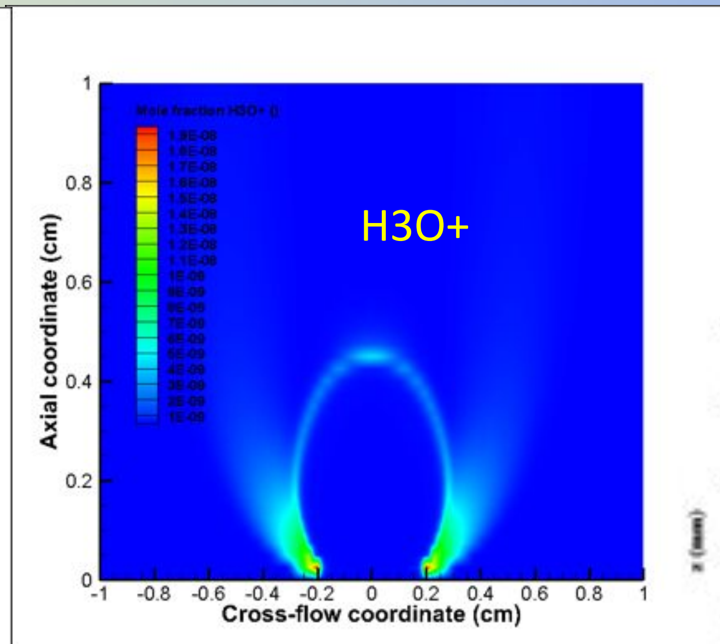
Schlieren in 1g and microgravity with a field shows common features between buoyant forcing and electrical forcing.

Simulations – E-Field Flames

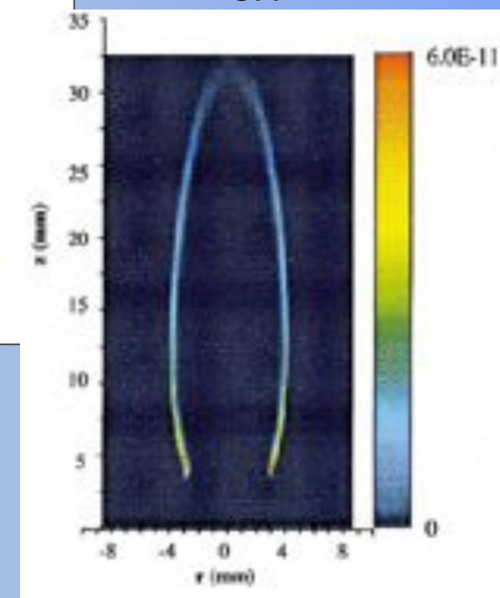
- Goals
  - Better knowledge of the chemical structure of the flame
  - Simulate concentrations of species profiles from CH_4/air laminar diffusion flame
  - Relate chemiluminescence to ion production
- Approach
  - 491 reactions steps mechanism assembled which includes: radicals, ions and chemiluminescence species (64)
  - CHEMKIN PRO package software - 2D simulation of a cylindrical shear flow

Computational study of ions and excited state species in a methane/air co-flow diffusion flame

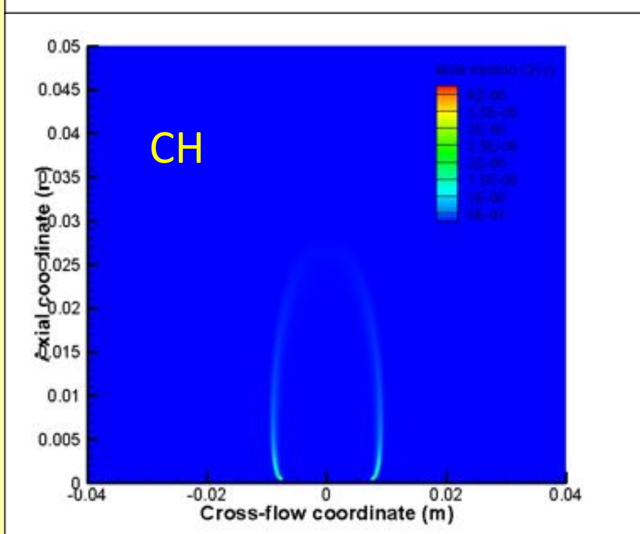


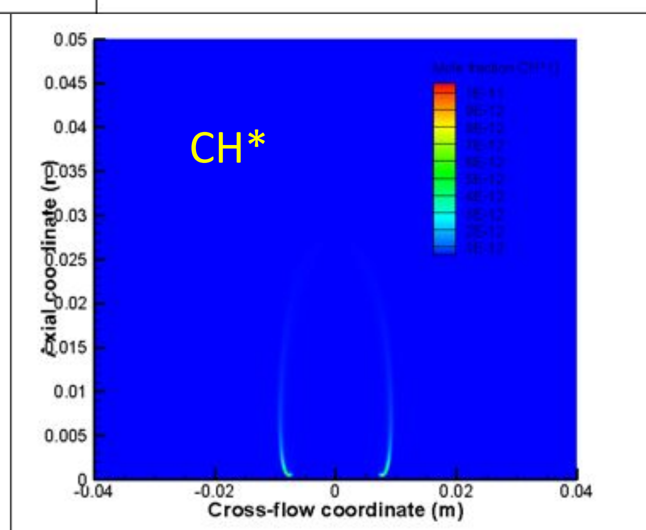


CH*



Walsh, et al.

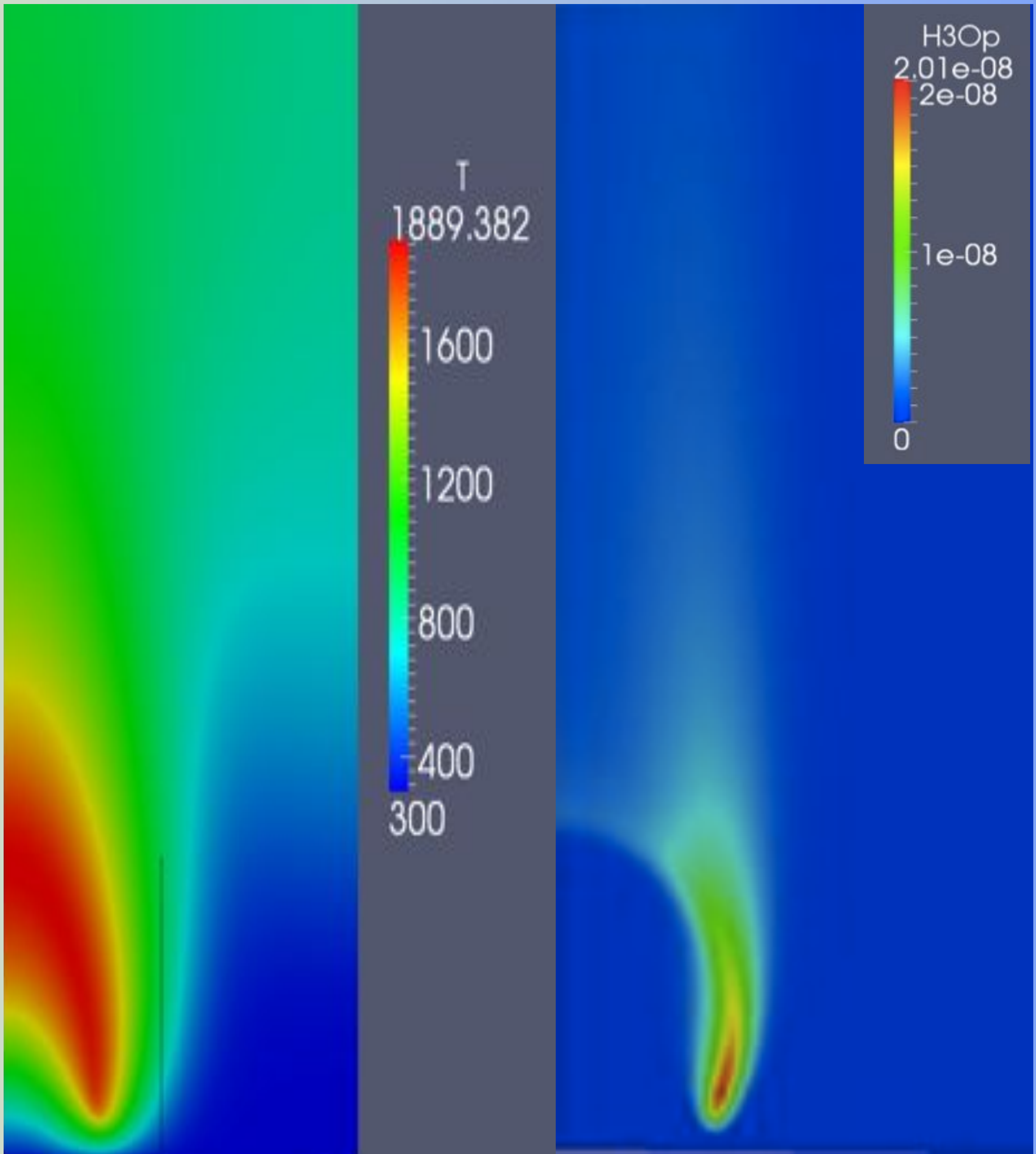




Julien Glorian

Simulations: E-field Flames

- OpenFOAM simulations using GRI Mech 3.0 with a chemi-ion mechanism
- Coflowing, axisymmetric geometry
- Solving for chemistry, N-S with electrostatic coupling, and Poisson's equation



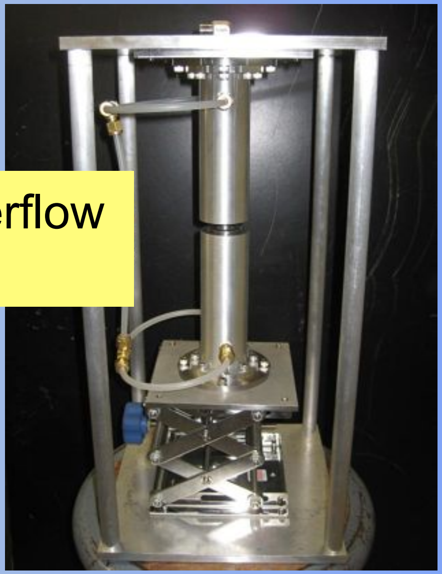
Burning Old Fuels in New Ways

- Coal combustion
  - control of carbon-in-ash from pulverized coal and coal/ biomass combustion
  - QCL absorption measurements for zonal control of combustion
  - control of mercury emissions
- Combustion in chambers
  - Improved miniature liquid fueled combustion systems
  - flame holding in a model turbine burner channel
- Electrical properties of flames
  - small diffusion flames
  - partially premixed flames
- Alternative fuels
  - biofuel combustion
  - methane and propane hydrate combustion

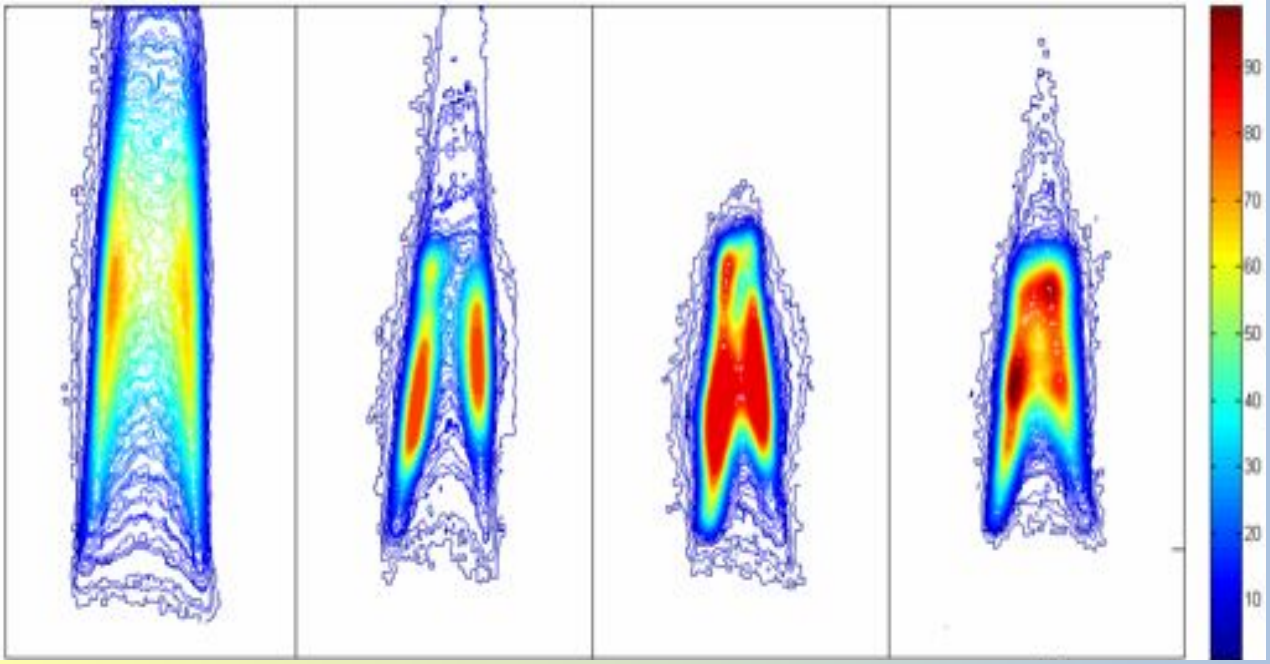
Sooting Behavior of Biofuels

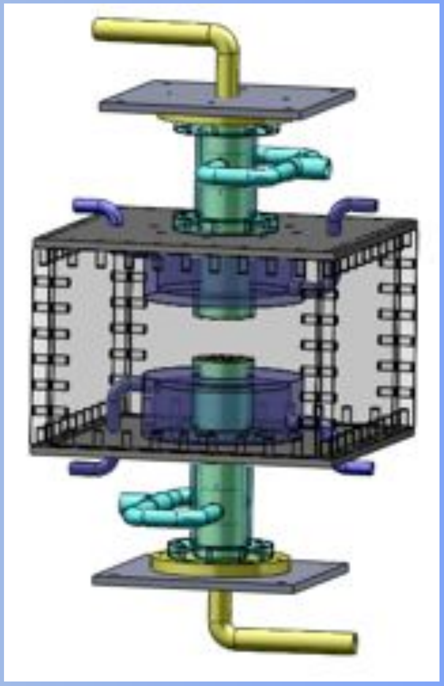
with Prof. Pham, CSULA

Laser Induced Incandescence LII in a smoke lamp



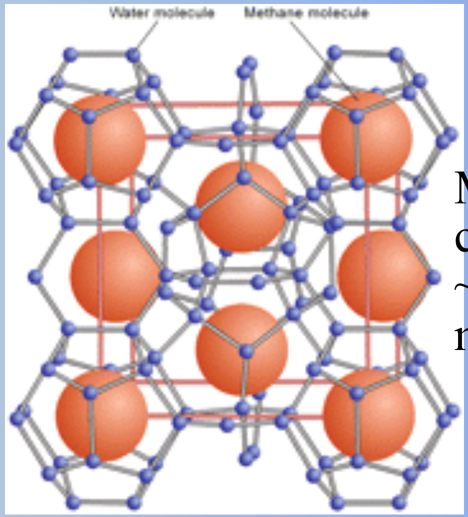
Counterflow burner





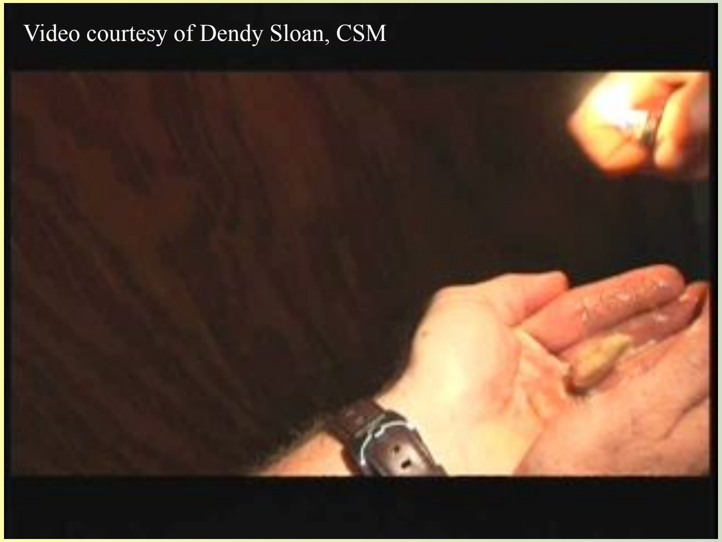
Significance of Fuel Hydrates

- Enormous stored deposits of natural gas
  - Permafrost
  - Deep oceans
    - Potentially dangerous resource
    - CO_2 sequestration opportunity
- Applications
  - Pipelines
  - Gas storage

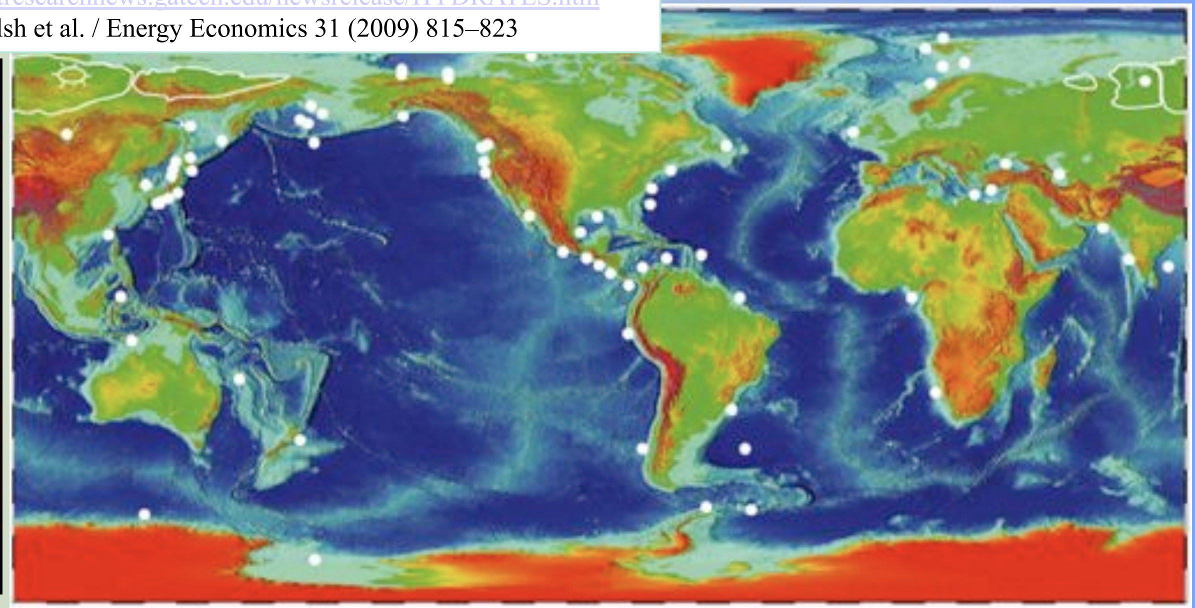


Methane clathrate ~5.75:1 mole ratio

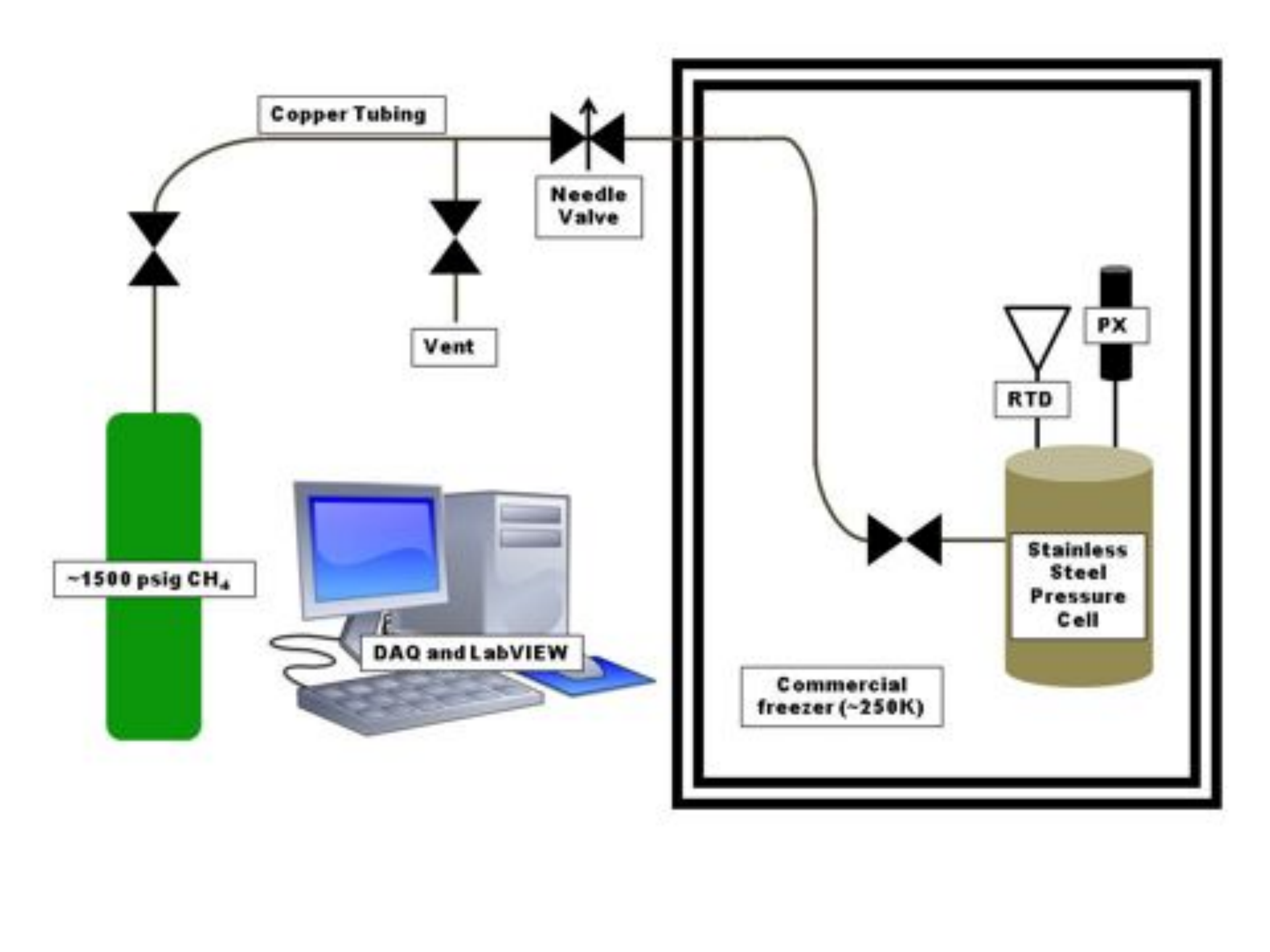
from http://gtresearchnews.gatech.edu/newsrelease/HYDRATES.htm
via M.R. Walsh et al. / Energy Economics 31 (2009) 815–823



Hydrate Deposits



Experimental Apparatus



Methane Hydrate Burning

Powder Hydrate

Experimental Results

Mass of Original Sample	Hydrate Fraction	Water mass in original sample	methane mass in original sample	Ice remaining	water remaining	water evaporated	water vapor/methane molar ratio
35.2	0.87	31	4.2	5.2	10.5	5.3	3.3
57.9	0.86	51.2	6.7	5.9	36.4	8.9	1.2
37.6	0.87	33.2	4.4	5	9.6	18.6	3.7

Experimental Study of Water-Laden Fuel Mixtures Burning in a Non-Premixed Counterflow Configuration

Objective: Characterize non-premixed water/methane/air flames in a counterflow burner; distinguish thermal from chemical effects, e.g., when water vapor is injected into a methane stream.

Applications: Methane hydrate combustion, emulsified water/fuel combustion, and LNG pool fires on bodies of water.

1. Experimental Apparatus

Components: (1) co-flow in both upper and lower ducts (2) electronic flow meters, (3) vaporizer, (4) cooling coil, honeycombs, and (4) heating and temperature control system.

2. Opposed-Jet Burner Conditions:

Non-Premixed Fuel/Oxidizer:

Upper Duct: Air oxidizer; Lower Duct: Fuel stream and water vapor.

Burner:

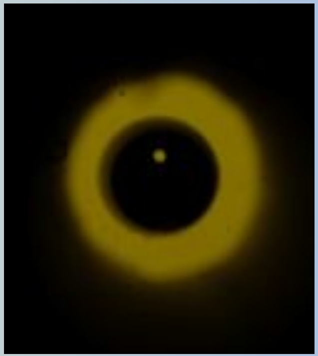
Separation Distance between nozzles ~ 1-2 cm

Flow Rates: Methane 4.4 l/min, Oxidixer 4.7 l/min

3. Flame Temperature Measurements

Thermocouple: Type –S [Pt-Pt 10% Ph], 0.20 mm bead size, fixed on a xyz stage.

Thin Filament Pyrometry (TFP)

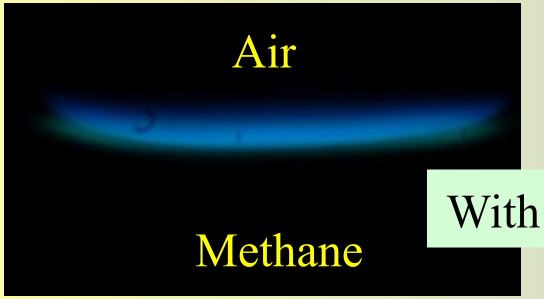


Calibration of Pyrometry

Medium: Emission of light from K-type thermocouple inside furnace of known temperature.

Sensor: Nikon D70 CCD. Red-Green blocking filter reduces RG intensities to below saturation.

Results

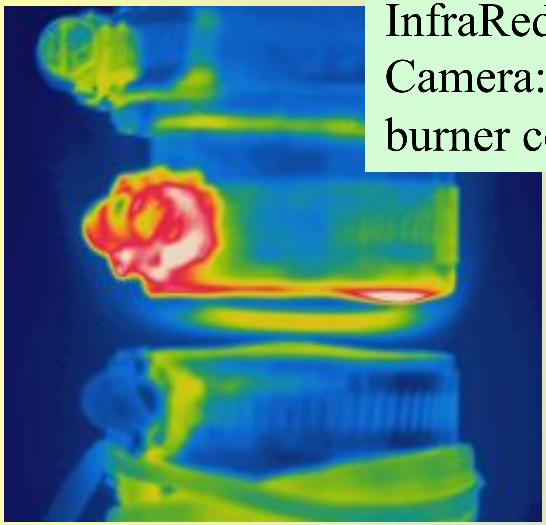


With filter

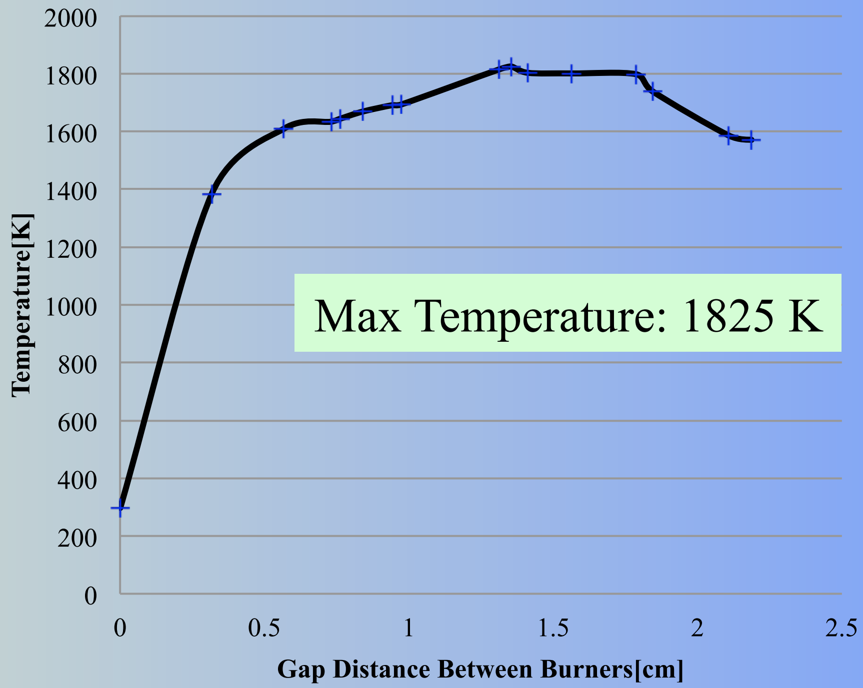
No filter

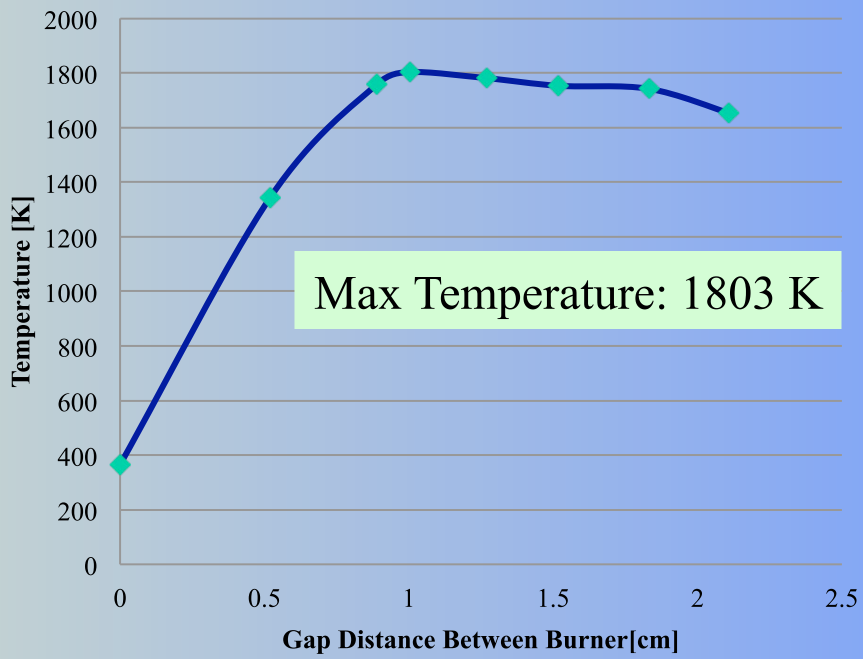
Gap 1.27 cm

Reducing RG Luminosity with Filter



InfraRed FLIR SC 620 Camera: Evaluates burner conditions



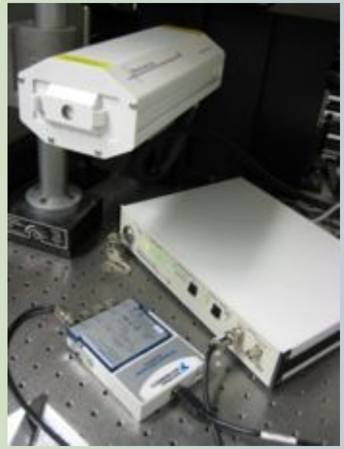


Fluid/Thermal Sciences

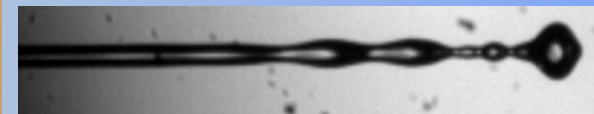
- Fuel preparation and sprays
  - controlled breakup of droplet streams
  - fuel injection for small-scale homogeneous charge compression ignition (HCCI) engine
- Multiphase flow and particle interaction
  - particle interaction in viscoelastic fluid
  - turbulence effects on droplet vaporization
- Biomedical applications
  - Dental laser drilling, sterilization, and therapy

Controlling Liquid Jet Breakup

A piezoelectric applies disturbance in the form of surface waves to the liquid jet by vibrating.

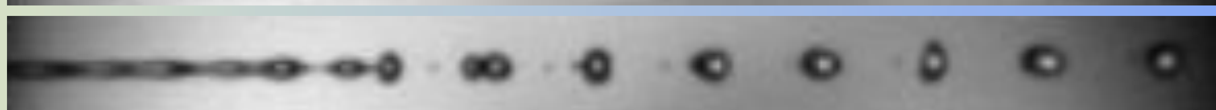


Vibrating axially



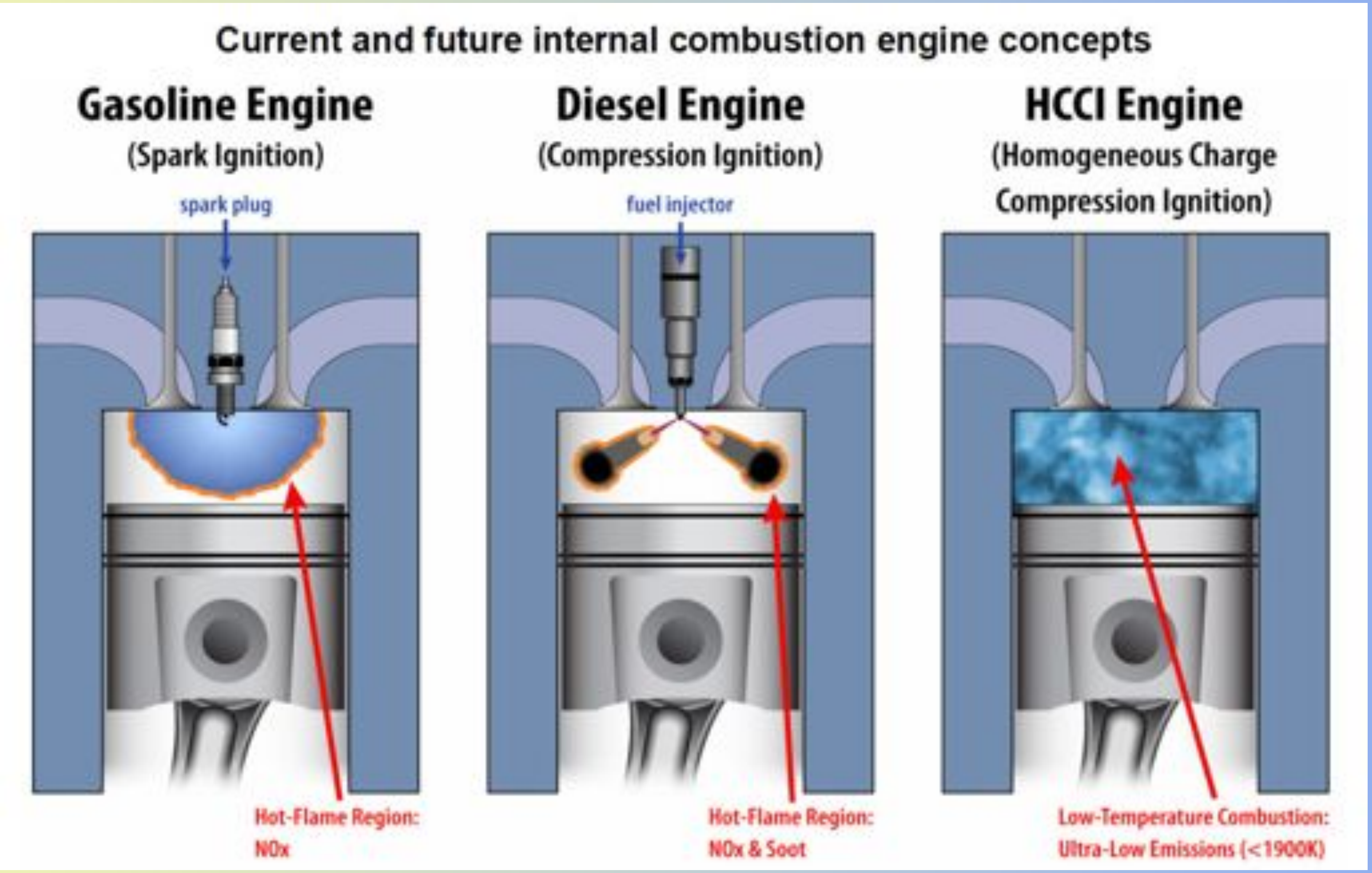
Different vibrations create different droplets patterns.

Controlling piezo's vibration, the breakup is controlled.



with Prof. Jabbari

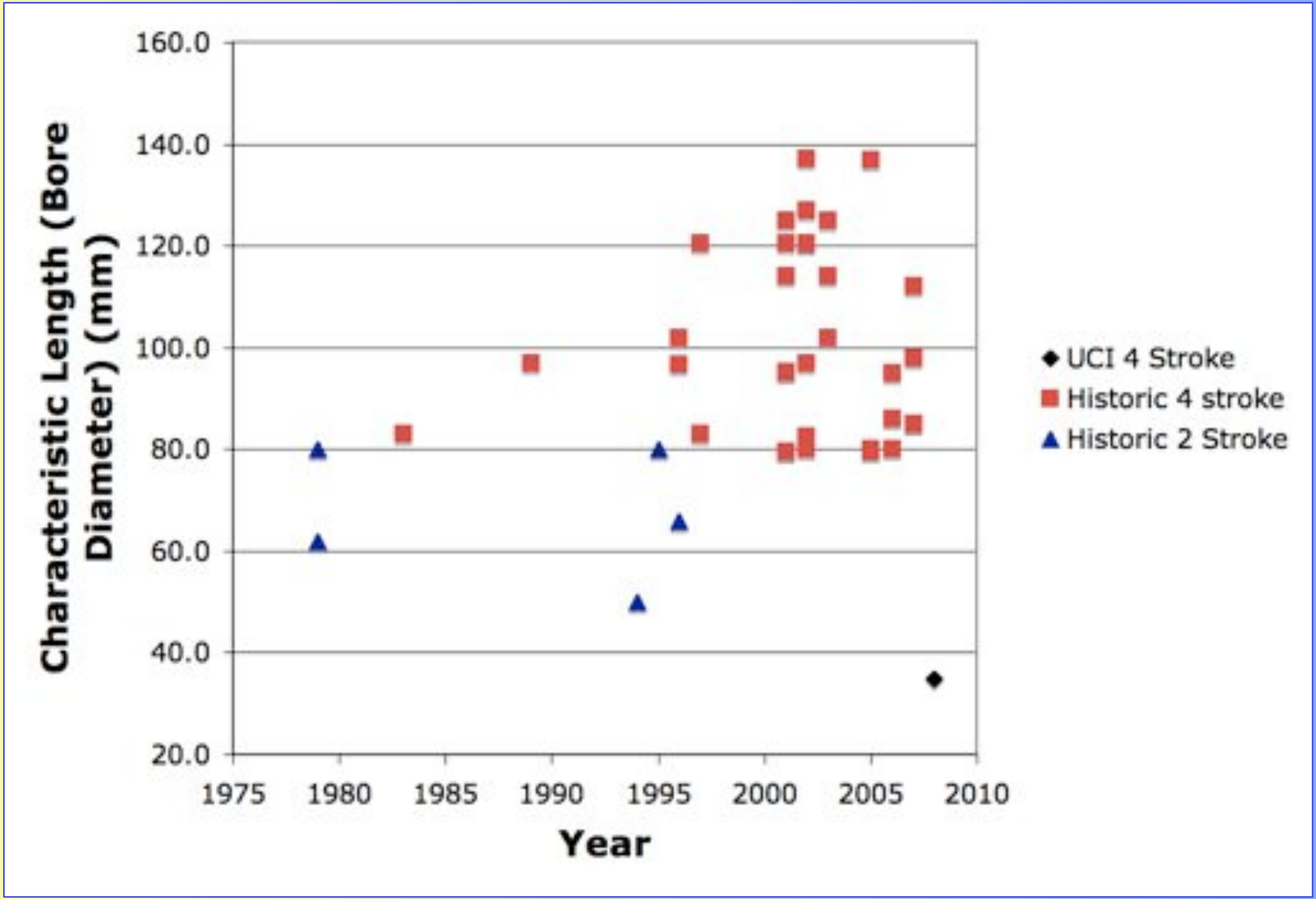
Internal Combustion Engine Concepts

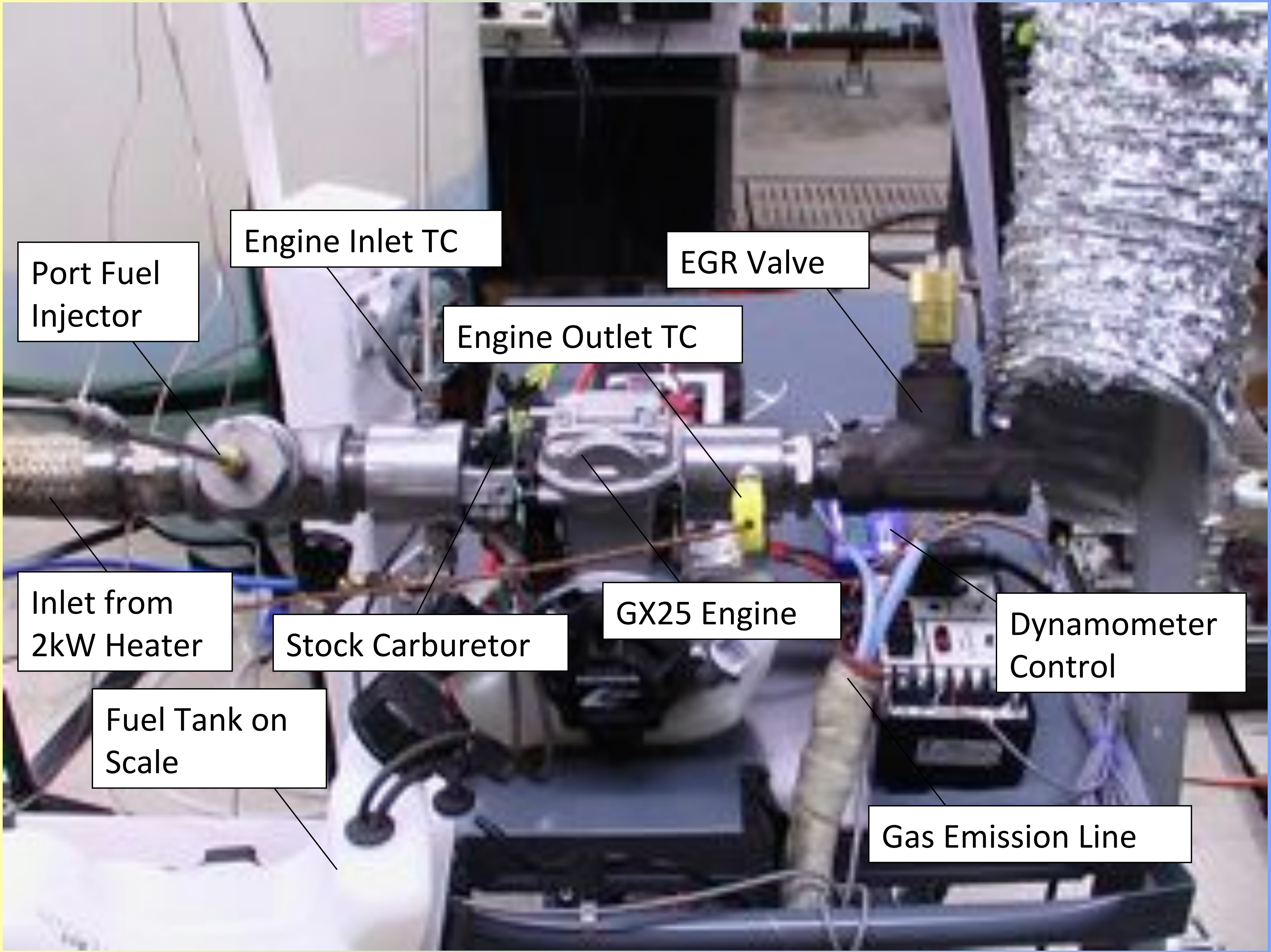


Advantages of HCCI: Low NOx & soot emission (satisfying 2010 emission standard without aftertreatment); 15-20% improvement in fuel economy

Disadvantages of HCCI: High HC and CO emissions under misfire; narrow operating regime; difficulty in ignition timing control

HCCI Test Engines, Single Cylinder Displacements




Port Fuel Injector
Engine Inlet TC
EGR Valve
Engine Outlet TC
Inlet from 2kW Heater
Stock Carburetor
GX25 Engine
Dynamometer Control
Fuel Tank on Scale
Gas Emission Line

Next Step -- Spark Assisted Compression Ignition (SACI) Engine

Previously…

- 25cc, 4-stroke, air-cooled, single cylinder engine.
- Large S/V ratio – rapid heat loss.
- Difficulty in ignition timing control.

Now…

- 49cc, 4-stroke, liquid-cooled, single cylinder engine.
- 49cc: Smaller S/V ratio, thus less heat through the surface.
- Liquid-cooled: Better engine wall temperature control.
- From HCCI to SACI: Better control on the ignition timing.

Goals:

- Finding the operation regime of small-scale SACI: intake temperature, engine wall temperature, equivalence ratio
- Simple model to estimate temperature of the gas in the engine.
- Determine physical processes controlling SACI operation

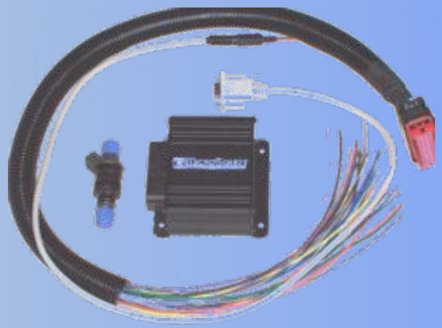
Spray Characterization for Small-Scale Engine EFI System

- Background
  - Spray is widely used in many areas including agriculture, fire suppression, and combustion.
  - Fuel injected IC engine performance depends on the spray. Typically, electronic Fuel Injection (EFI) systems provide higher thermal efficiency and power output, better transient response and also more precise Air/Fuel Ratio (AFR) control compared with traditional carburetor fuel feeding system.
  - Small-scale engines are rarely fuel-injected; this study examines the fundamentals of small scale fuel injection systems.

Typical structure of fuel injector

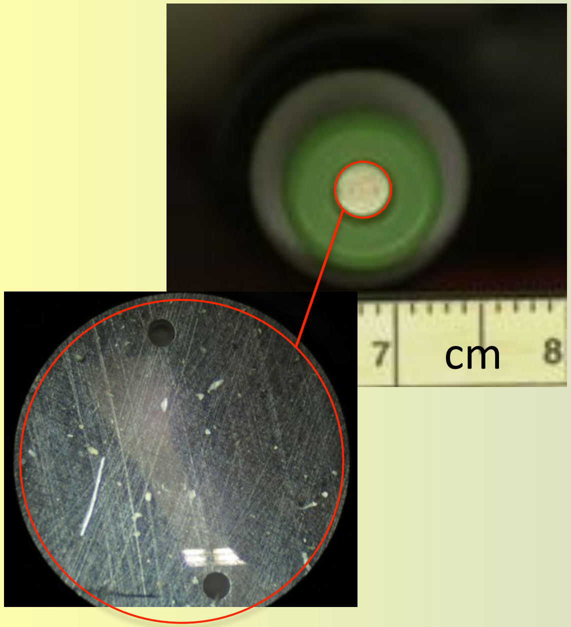
Calibration fluid used as fuel simulent

injector



MicroSquirt EFI system

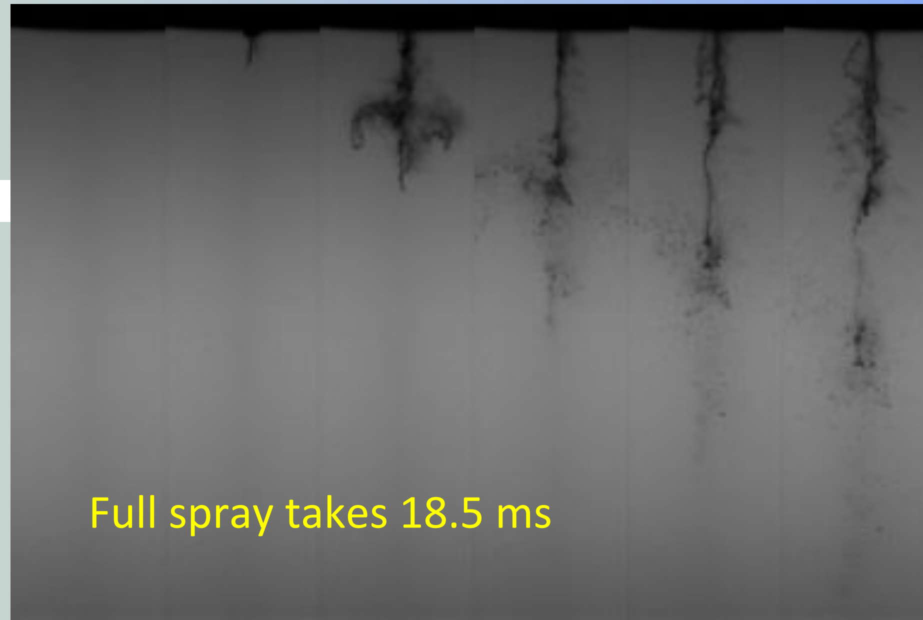
High-Speed Movie of the Starting Stage of Spray



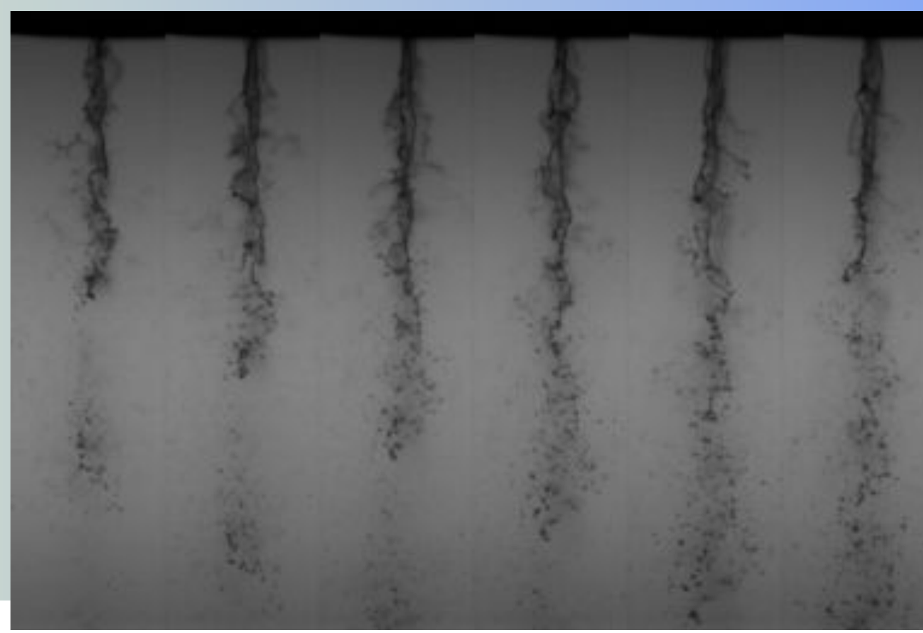
Injector: compatible with Honda NPS50 scooter engine

Spray & Image parameters:

- Camera: Phantom V4.3
- Fuel pressure: 45psi
- Exposure time: 2μs
- Frame rate (fps): 8510
- Resolution: 128*512



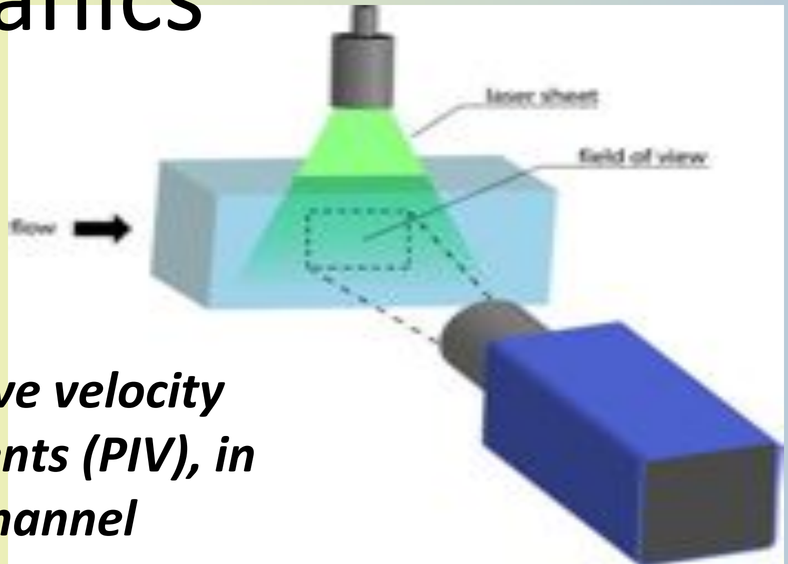
0 0.118 0.235 0.353 0.470 0.588 (msec)



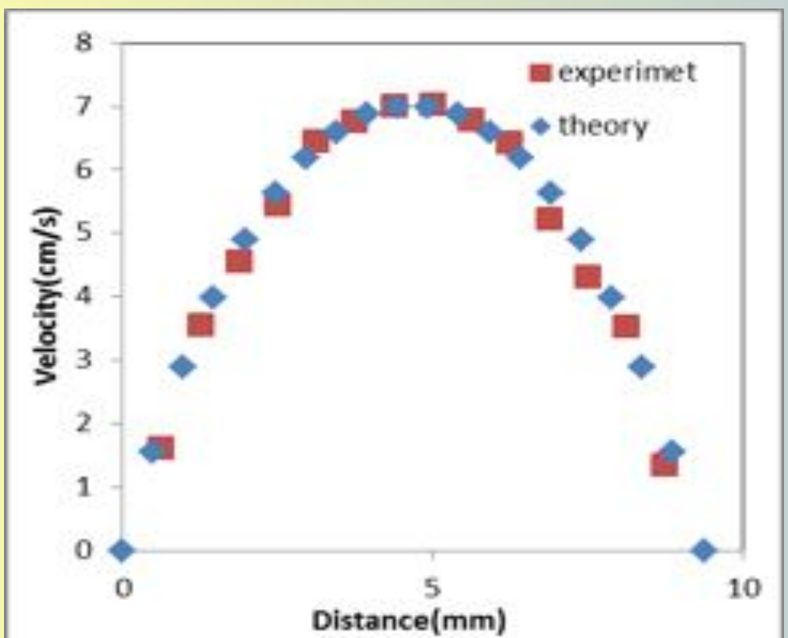
0.705 0.823 0.940 1.058 1.175 1.293 (msec)

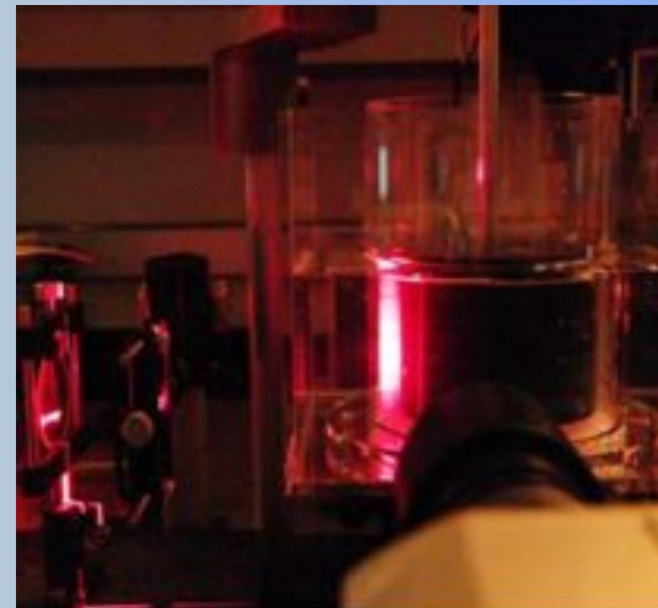
Viscoelastic Fluid Mechanics

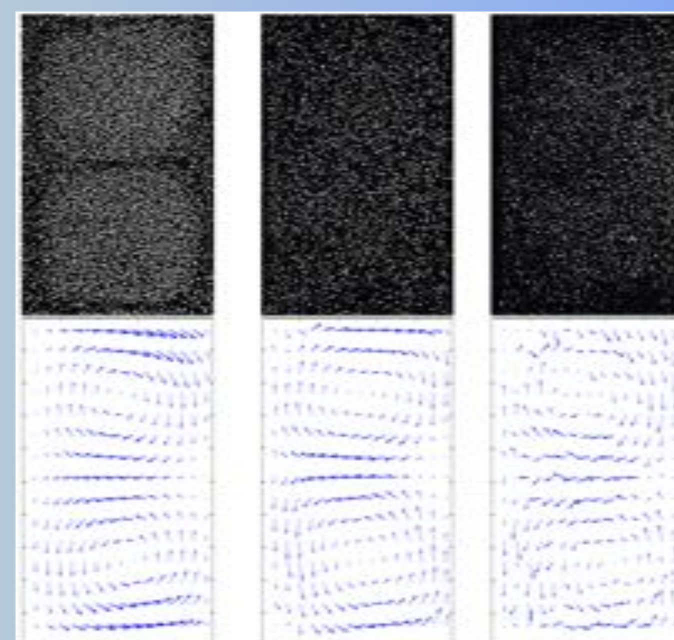
PIV measurements for quantifying Taylor instabilities



Non-intrusive velocity measurements (PIV), in rectangle channel

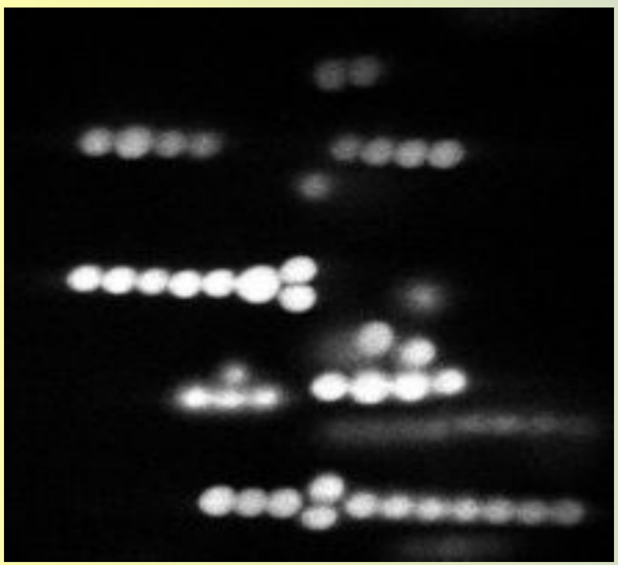




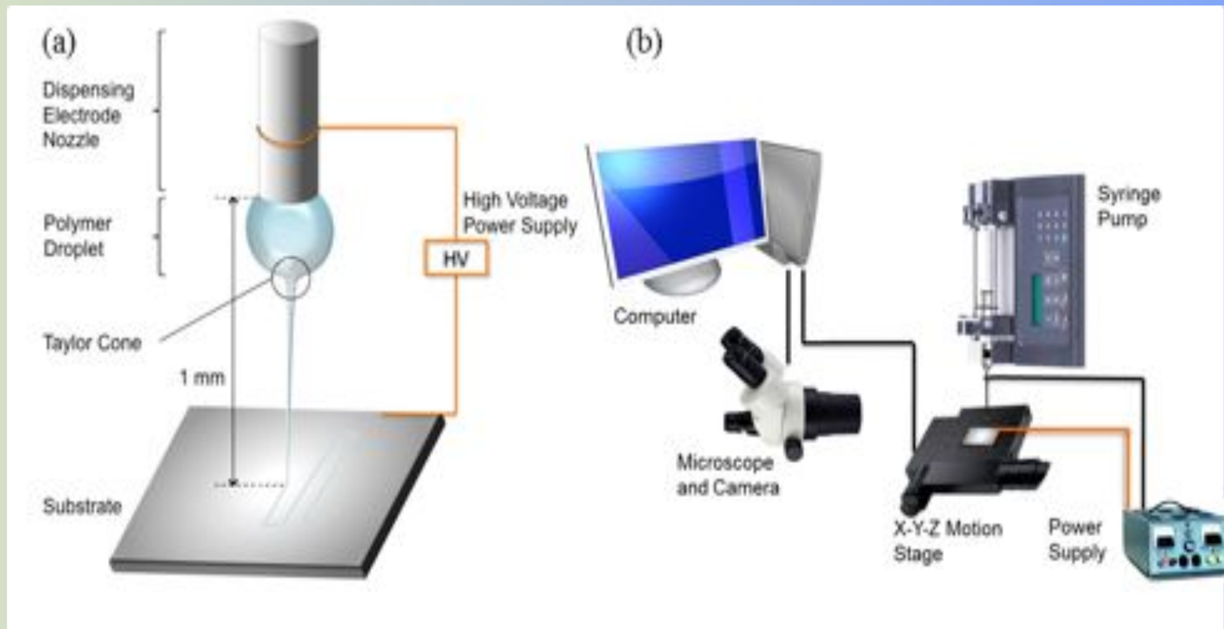


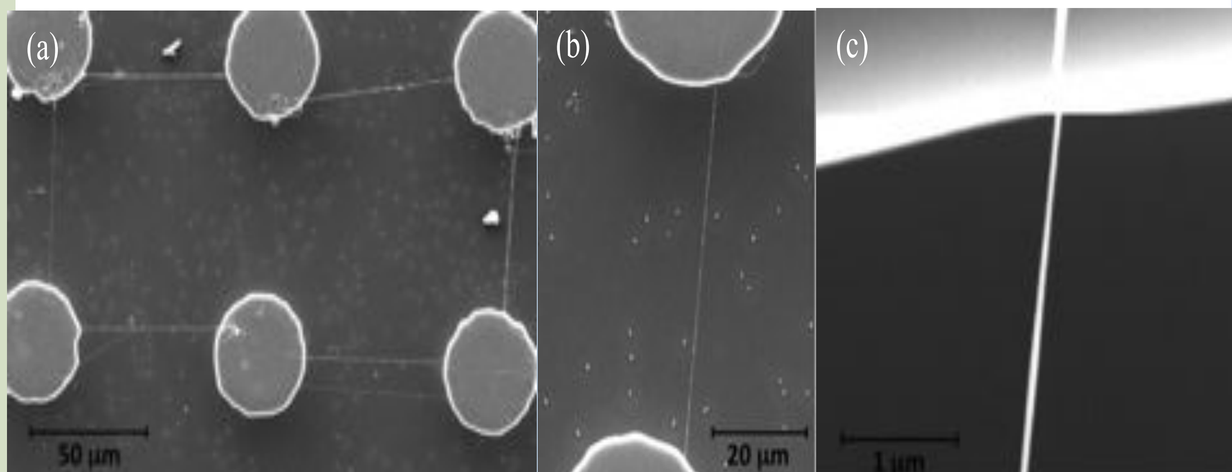
Confocal microscopy

Near-field electrospinning



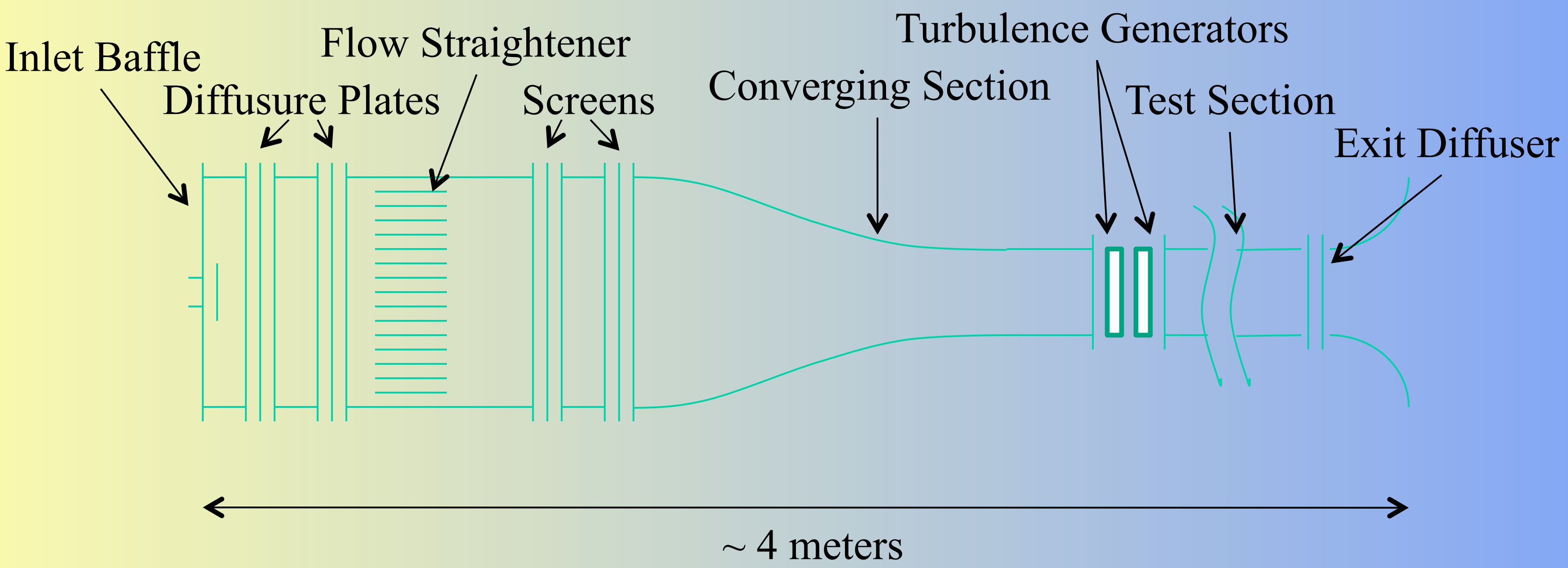
Chaining of 5μm fluorescent particle in viscoelastic fluids





Patterning with nanometer resolution with the help of viscoelastic ink

Droplet Vaporization in Isotropic Turbulence



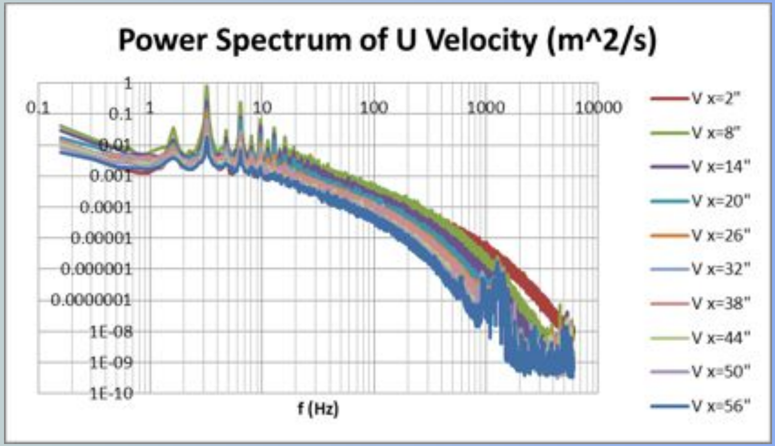
Vertical Wind Tunnel Schematic

OBJECTIVE: Comparison of Measured and DNS Calculated Vaporization Rates of Droplets in Isotropic Turbulence

Droplet Vaporization in Isotropic Turbulence

Hot Wire Anemometry Measurements

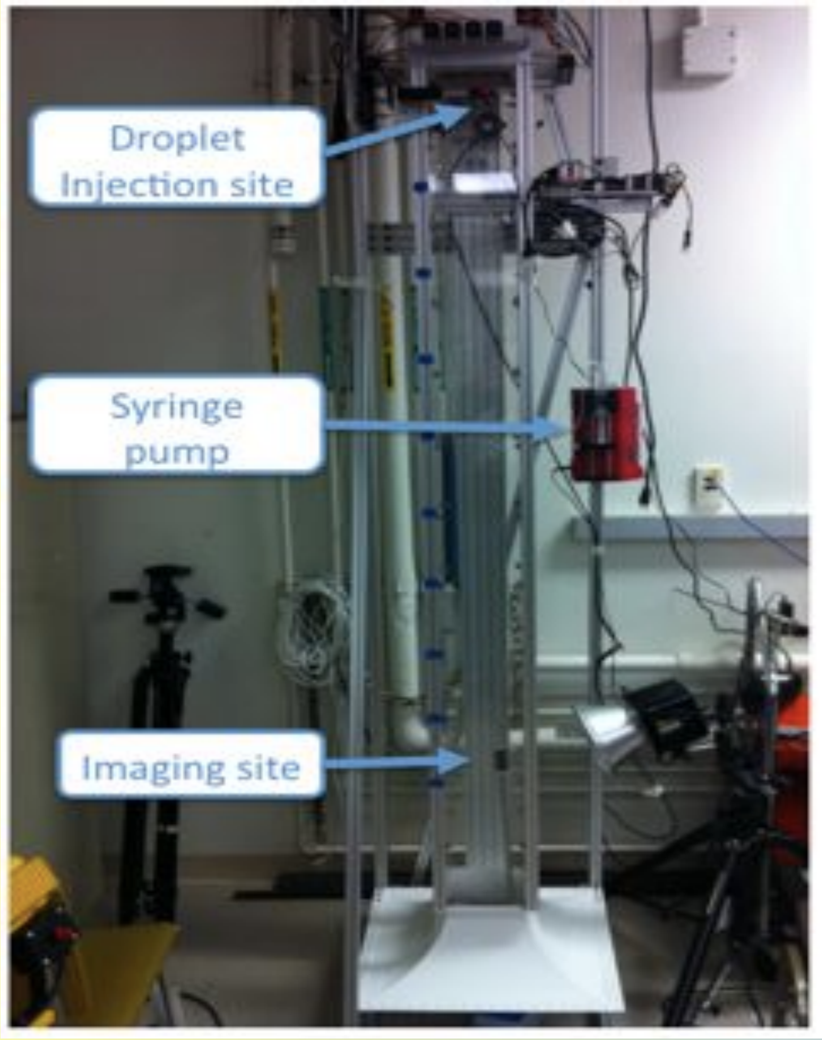
Turbulence Generator

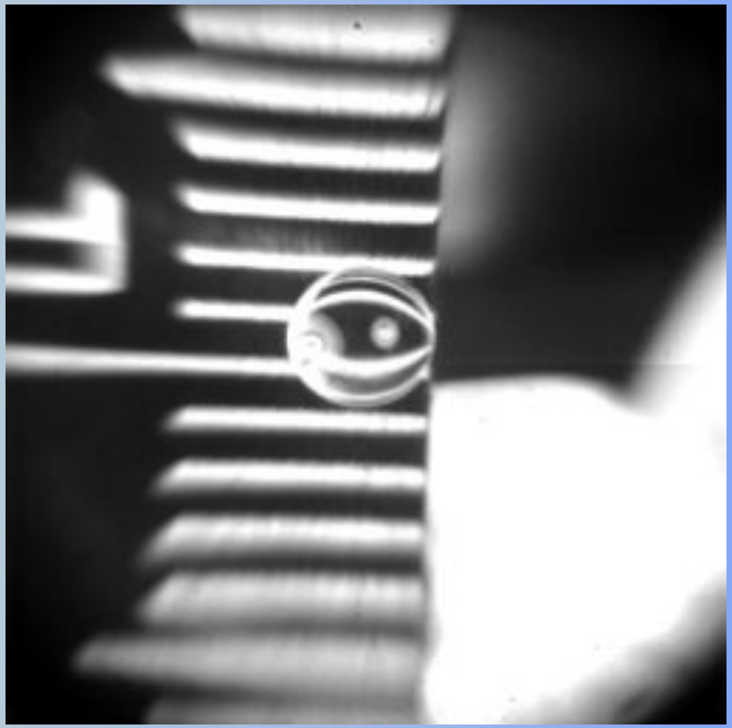


Power spectral density of U velocity at different downstream stations

Droplet Vaporization in Isotropic Turbulence

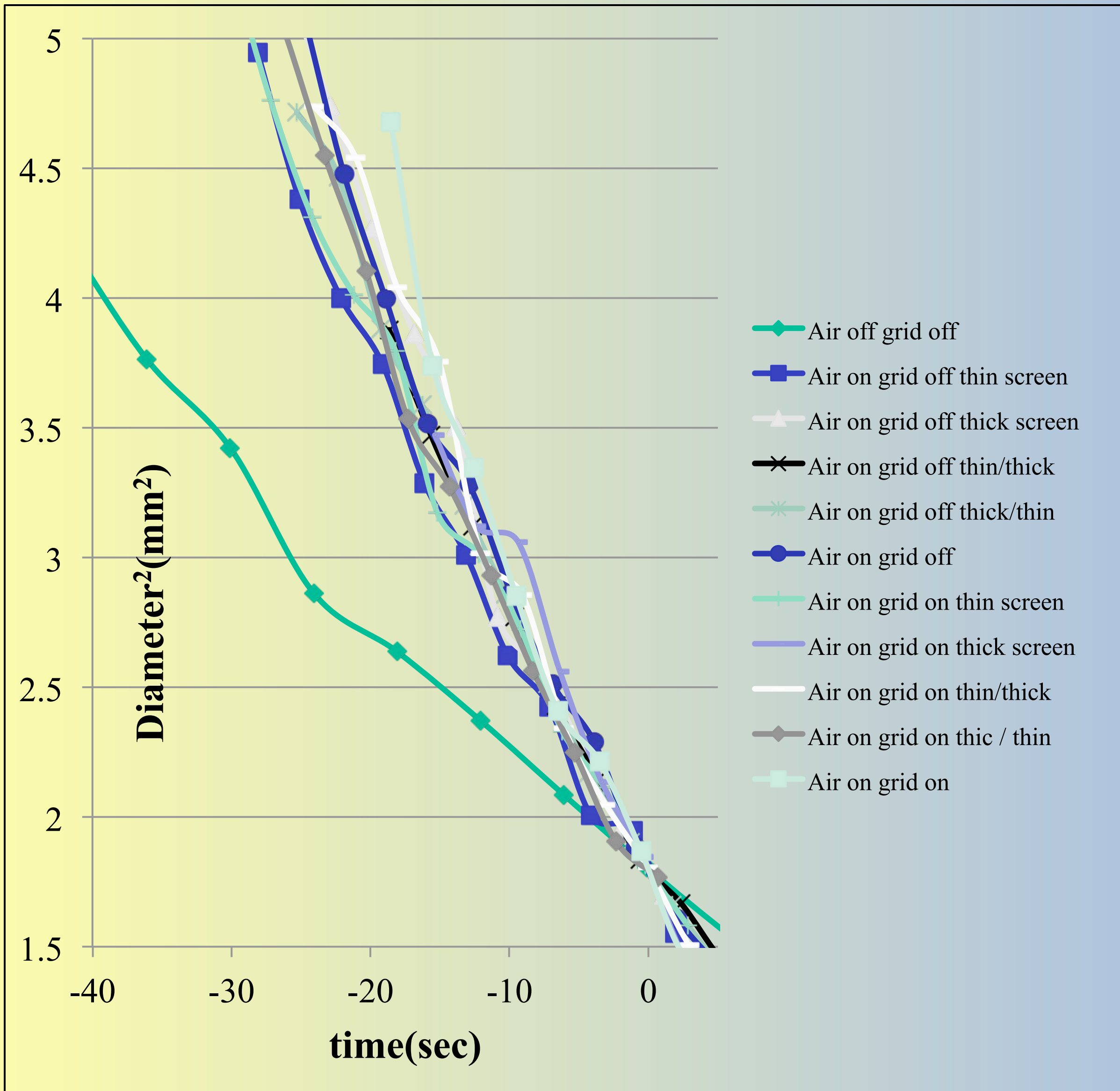
- Heptane droplets are introduced via calibrated syringe pump and initial size based on time between droplet release
- Droplets diameters measured using a DSLR camera near the test section exit



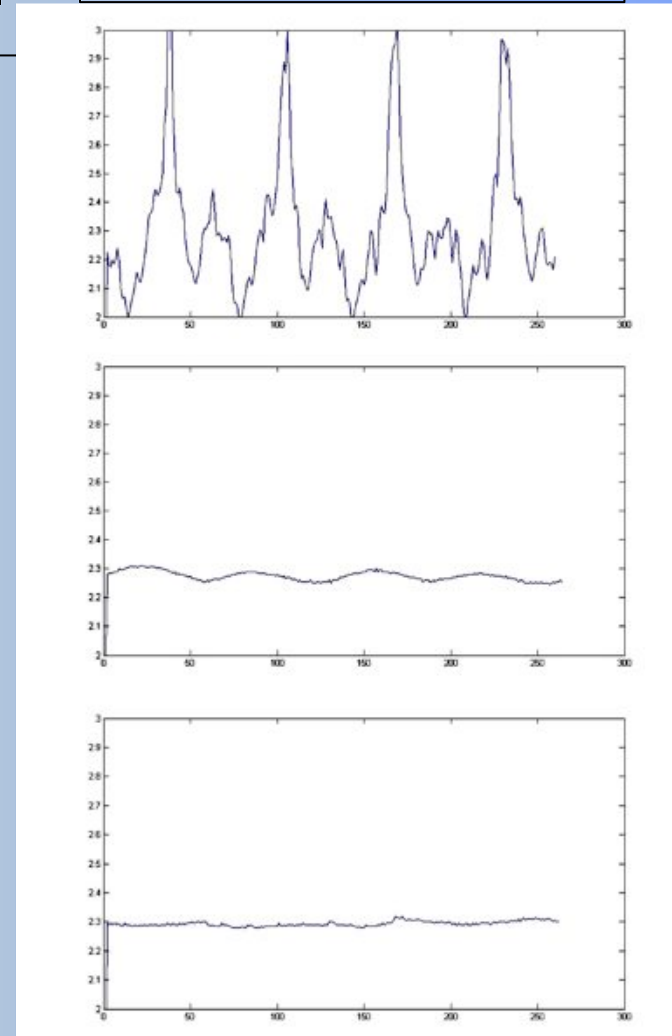


Droplet as imaged near bottom of test section

Suspended Heptane droplet evaporation

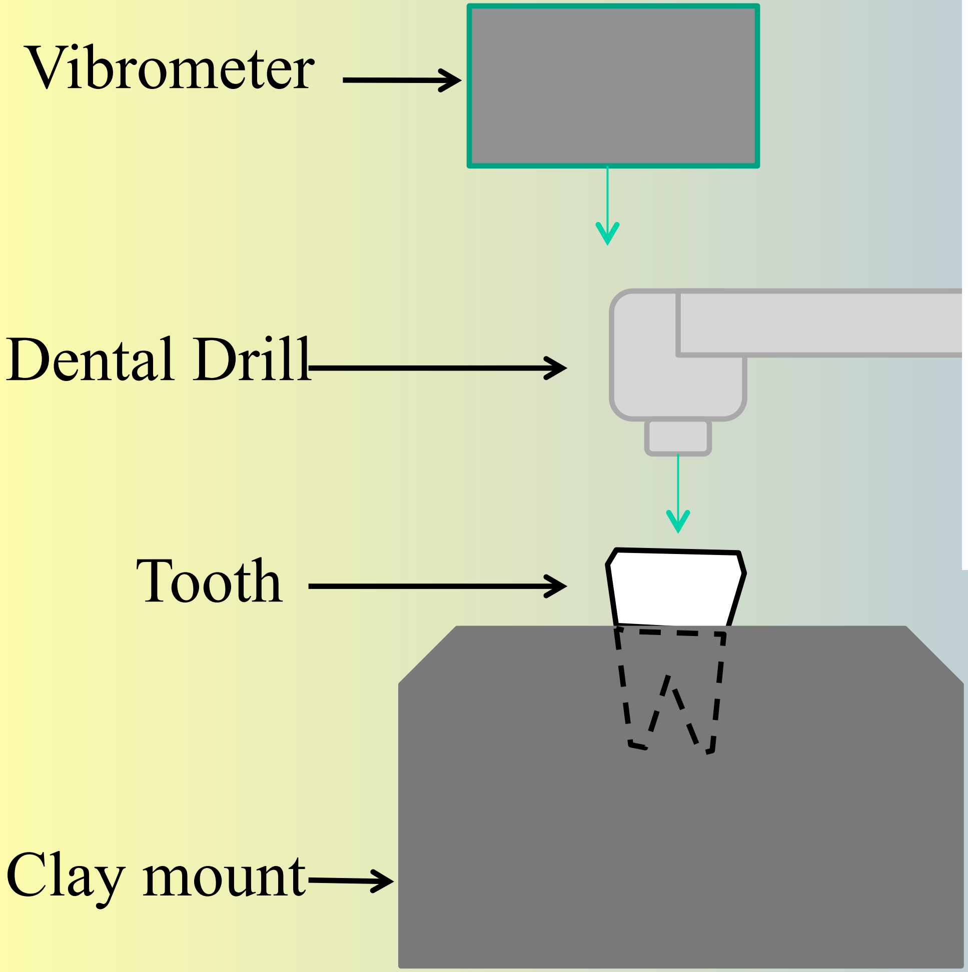


Time between drops



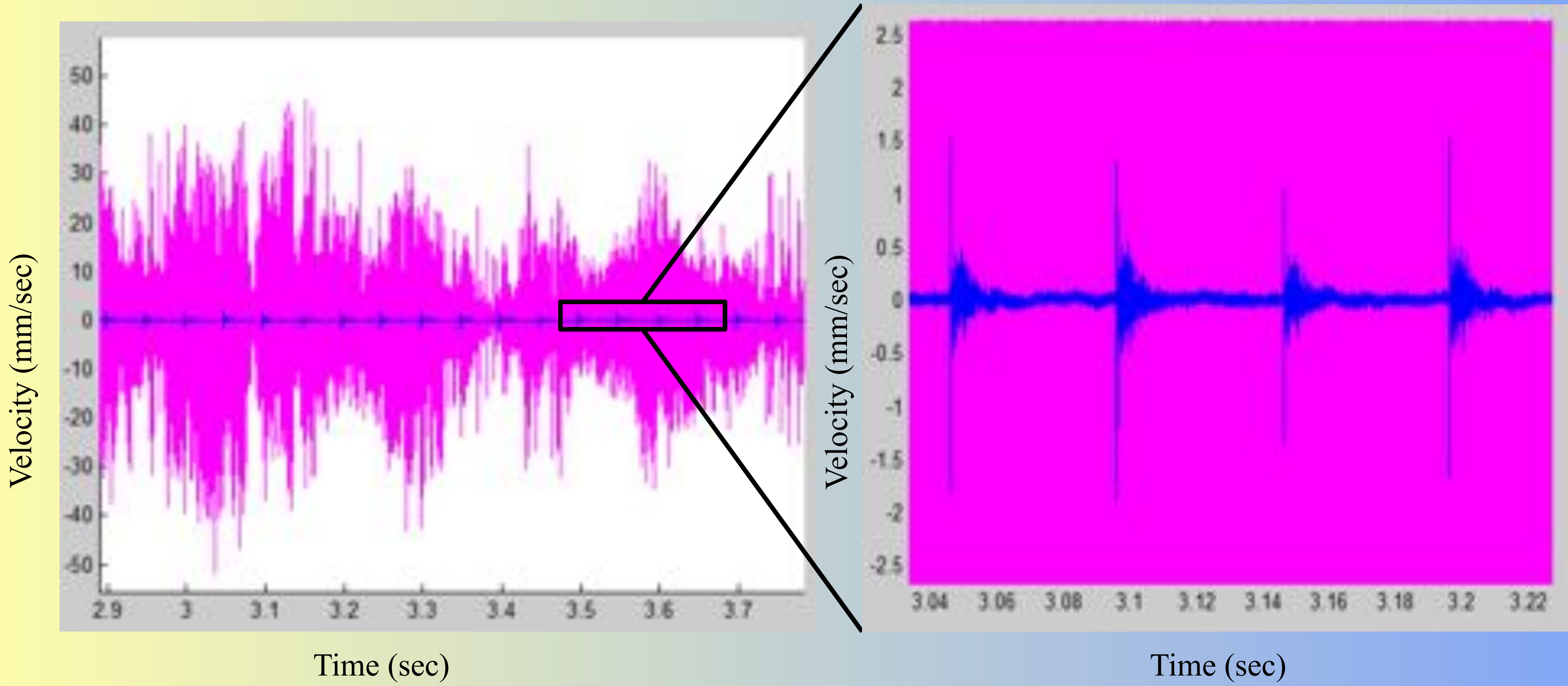
Variation caused by syringe pump removed with damping reservoir

Dynamic Response of Teeth to a Dental Laser



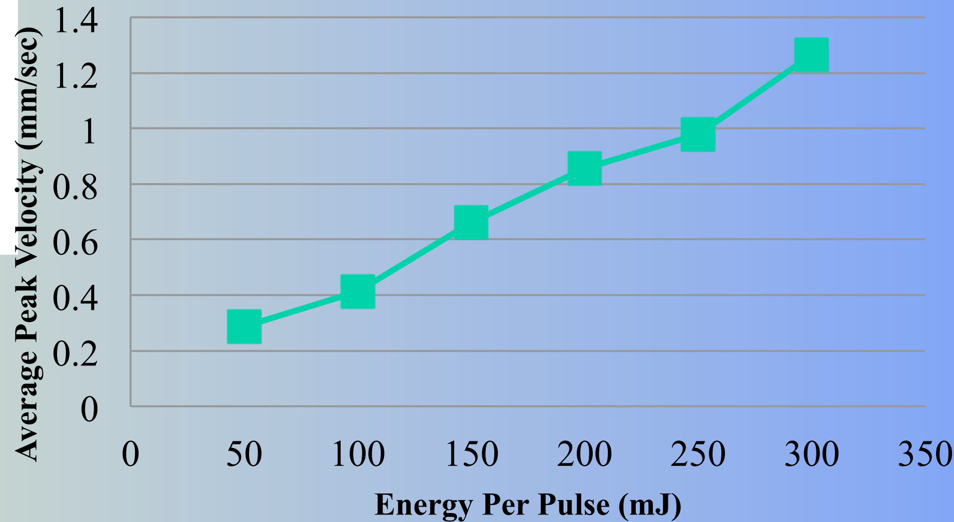
Modern high speed drills have been produced since the mid 20th century. They can run at over 400,000 rpm, but cause much vibration. Starting in the late part of the 20th century, lasers were developed to be used in dentistry. The scope of this study is to find if lasers cause less vibration than traditional high speed drills.

The vibrometer and drill are facing the same direction, down towards the crown of the tooth. As the tooth vibrates from the drilling, the vibrometer measures the vertical motion of the tooth.



- Pink - velocity of the tooth caused by a high speed drill.
- Blue = velocity caused by an Er,Cr:YSGG Laser at 300 mJ per pulse.

High-speed drill causes the tooth to move at 20 times the speed of a tooth ablated by a 300 mJ pulse of laser.



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