Planar laser-induced fluorescence imaging of fuel droplets exposed to asymmetric radiant heating

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research background

**Fuel droplet vaporization**
- Experimental/analytical work
- Radiative/convective heat transfer
- Mechanical design and solid modeling
- Laser based diagnostics
- Two-phase flow (liquid-gas)

**Particle de-agglomeration (EPRI)**
- Mercury emission reduction from coal power plants
- Experimental work
- Ultrasonic de-agglomeration
- Fluid shear nozzles
- Two-phase flow (solid-gas)

**Summer Institute on Sustainability and Energy (UIC)**
- Electrical smart grid
- Implementation of renewable energy
- Identification of social/economic barriers
Importance of droplet vaporization studies:

- critical parameter in designing combustion devices
- dictates residence time in combustion chamber
- determines when combustion takes place

where is asymmetric radiant heating common?

- Conventional spray flames
- Counter-flow diffusion flames
- Spray periphery of conventional combustors
- Potential asymmetric heating from gases and soot in combustion chamber
- LIQUID-FUELED MICROCOMBUSTORS
microcombustors

- Uprising field in power generation
- Micro-electro mechanical systems (Power MEMS)
- Prototypes only tested with gaseous fuel

MIT 4mm diameter gas turbine (1997)
UC Berkeley mini rotary engine (1998)
Ritsumeikan University MEMS ICE (2008)

High power density dependent on high mass flow rate of fuel: achievable with liquid fuels
microcombustors

- Uprising field in power generation
- Micro-electro mechanical systems (Power MEMS)
- Prototypes only tested with gaseous fuel

<table>
<thead>
<tr>
<th>Device</th>
<th>Power Density (MW/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro Lithium Batteries</td>
<td>0.4</td>
</tr>
<tr>
<td>Micro Solar Cells</td>
<td>1</td>
</tr>
<tr>
<td>Micro Electric Motor</td>
<td>1.7</td>
</tr>
<tr>
<td>Micro Reactors (Si)</td>
<td>20</td>
</tr>
<tr>
<td>Large Scale Combustor</td>
<td>40</td>
</tr>
<tr>
<td>Micro Channel Reactors</td>
<td>150</td>
</tr>
<tr>
<td>Micro Magnetic Motors</td>
<td>200</td>
</tr>
<tr>
<td><strong>Si Microcombustors</strong></td>
<td><strong>2000</strong></td>
</tr>
</tbody>
</table>

High power density dependent on high mass flow rate of fuel: achievable with liquid fuels
Advantages of liquid fuel

- Higher power densities
- Smaller storage volumes (liquid-to-vapor density ratios of 500-700)
- Longer refueling intervals

Development challenges

- Liquid fuel delivery
- Need for rapid fuel vaporization and mixing
- Increased property gradients
  1. Strong velocity gradient
  2. Asymmetric heat fluxes
  3. Asymmetric thermal radiant heating
thermal radiation consideration

- Microcombustor fabrication: silicon and silicon compounds
  - High emissivity: silicon compounds (0.84-0.87) conventional iron alloy combustors (0.14-0.30)

- High surface area-to-volume ratio
  - High heat loss rates

- Insulation required for microcombustor walls
  - Increase in wall temperature

High emissivity + High wall temperatures = Asymmetric radiant heating

2 orders of magnitude larger than conventional combustors (Spadaccini, 2007)
objectives of study

• Experimental investigation
  • PLIF imaging of monodisperse stream of droplets irradiated by infrared panel

• Thermal radiation absorption model
  • Geometrical optics model with complex refractive index spectra of liquid components
experimental method

Planar Laser-Induced Fluorescence

- Laser beam converted into a sheet and illuminates flow of interest
- Tracer species excited by laser
- Resulting fluorescence signals captured on camera
tracer: acetone

- Absorption spectrum: 225 nm to 320 nm
- Fluorescence emission: 350 nm to 550 nm
- Fluorescence lifetime: 4 ns
- Chemically stable up to 1000 K
- High vapor pressure at room temperature (easy seeding)
- High fluorescence signals

PLIF diagnostic components

- Laser system: Nd:YAG at 266 nm
- EMCCD camera (Electron Multiplying Charged Couple Device)
- UV camera lens and filters (for $350 < \lambda < 550$ nm transmission)
- UV grade optical lenses
  - Plano-concave ($f = -19$ mm)
  - Symmetric convex lens ($f = 120$ mm)
acetone PLIF calibration

\[ S_f \propto \frac{X_{acetone} P \lambda}{T} \]

- \( S_f \)  Fluorescence signal
- \( \lambda \)  Excitation wavelength
- \( X_{acetone} \)  Acetone mole fraction
- \( P \)  Pressure
- \( T \)  Temperature

Fluorescence signal \( S_f \):

1. proportional to acetone mole fraction (\( P \), \( T \) and \( \lambda \) constant)
2. inversely proportional to temperature (\( P \), \( \lambda \) and \( X_{acetone} \))
3. proportional to pressure (\( T \), \( \lambda \) and \( X_{acetone} \))
acetone PLIF calibration

\[ S_f \propto \frac{\chi_{acetone} P \lambda}{T} \]

Temperature dependence data (Thurber, 1999)

| \( \lambda = 266 \text{ nm} \) |
|---------------------|----------------|
| T(K)    | \( S^*_f \) |
| 296     | 1.000        |
| 329     | 0.880        |
| 374     | 0.770        |
| 424     | 0.660        |
| 483     | 0.552        |

\( S^*_f \), Measured relative fluorescence per unit acetone mole fraction

Fluorescence calibration data at \( T = 296 \text{ K}, P = 1 \text{ atm} \)

(Ammigan, 2007)
asymmetric radiant heating set-up

EMCCD camera with lens and filters

Nd-YAG pulsed laser at 266nm

Lens and laser sheet

Non reflecting sheath

Radiant panel heater

Droplet generator head (VOAG)

Contour plot of acetone mole fraction around a droplet

Raw fluorescence image of droplet stream at 296 K
experimental conditions

- Pure and bi-component (1:1 volume ratio) droplets
  - Alkanes: octane and hexane
  - Alcohols: ethanol and 2-propanol

<table>
<thead>
<tr>
<th>Properties</th>
<th>Acetone</th>
<th>Hexane</th>
<th>Octane</th>
<th>Ethanol</th>
<th>2-propanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling point (K)</td>
<td>330</td>
<td>342</td>
<td>399</td>
<td>351</td>
<td>355</td>
</tr>
<tr>
<td>Latent heat (kJ/mol)</td>
<td>30.1</td>
<td>30.7</td>
<td>34.6</td>
<td>38.97</td>
<td>43.9</td>
</tr>
<tr>
<td>Specific heat (kJ/kg.K)</td>
<td>2.15</td>
<td>2.26</td>
<td>2.15</td>
<td>2.46</td>
<td>2.56</td>
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<tr>
<td>Density (kg/m³)</td>
<td>790</td>
<td>655</td>
<td>703</td>
<td>789</td>
<td>785</td>
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<tr>
<td>Molecular weight (kg/kmol)</td>
<td>58.08</td>
<td>84.16</td>
<td>114.23</td>
<td>46.07</td>
<td>60.1</td>
</tr>
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</table>
**Experimental conditions**

- Pure and bi-component (1:1 volume ratio) droplets
  - Alkanes: **octane** and **hexane**
  - Alcohols: **ethanol** and **2-propanol**

- Exposure length of 5.5 cm

- Panel heater surface temperatures: 455 K (2400 W/m$^2$) and 475 K (2900 W/m$^2$)

- Droplet diameters: 145, 158, 193, 235 µm

- Ambient pressure: 1 atm

- Droplet stream axis temperatures: 322 K and 333 K
experimental results

**contour plots**

*Acetone/Hexane bi-component droplets, $D = 145 \mu m$*

- No radiant heating
- 455 K
- 475 K

- Laser sheet propagating from left to right
- Right side of droplet irradiated by IR panel heater
- Colorbar represents acetone mole fraction, $X$
- Pixel values on x and y axes (1 pixel = 17.5 µm)
- Highly localized surface vaporization induces asymmetric **Stefan flow**
radial vapor distribution

Acetone/Alkanes bi-component droplets, \( D = 193 \, \mu m \)

- Acetone mole fraction (\( X \)) against normalized radial distance (\( x/D \))
- Each graph is an average of 10 droplets
- Error bars: \( \pm 1 \) standard deviation
data interpretation

droplet convective model

• Droplets are exposed to both convective and radiant heating

• Convective effects analyzed using a droplet vaporization model
  (Miller, 1998; Varanasi, 2004)
  • Simulates droplets in an isothermal air flow (axisymmetric)
  • Droplet stream axis temperature of 322 K and 333 K

• Input data into model:
  • Droplet composition and volume fraction
  • Droplet initial temperature (296 K)
  • Ambient air temperature (droplet stream axis temperature)
  • Droplet diameter
  • Reynolds number (based on exit velocity from VOAG)
Pure and bi-component 193 µm droplets at droplet stream axis temperature of 333 K

Average droplet temperature

Acetone mole fraction in bulk liquid droplet

Acetone vapor mole fraction at droplet surface
**dروplet radiation absorptivity – geometrical optics model**

- **Absorptivity**: fraction of incident thermal radiation absorbed by droplets

![Diagram](image)

- Transmission and reflection at gas-liquid interface
- Internal reflections within droplet
- Input data: complex refractive index spectrum of each component

\[ \tilde{n}_\lambda = n_\lambda + ik_\lambda \]

- Wavelength range: \(2.5 \, \mu m < \lambda < 15 \, \mu m\)
- Spectrum obtained from Dr. Keefe (Cape Breton University) and Dr. Bertie (University of Alberta)
complex refractive index spectra

Bertie (2009), Keefe (2005, 2009)
Total spectral absorptivity
\[ \alpha_\lambda = \int_0^{\pi/2} \frac{[1 - \rho_\perp(\theta)][1 - \exp(-4\pi k_\lambda \cos \phi)]}{1 - \rho_\perp(\theta)\exp(-4\pi k_\lambda \cos \phi)} \sin \theta \cos \theta d\theta 
+ \frac{[1 - \rho_\parallel(\theta)][1 - \exp(-4\pi k_\lambda \cos \phi)]}{1 - \rho_\parallel(\theta)\exp(-4\pi k_\lambda \cos \phi)} \sin \theta \cos \theta d\theta \]

Spectral blackbody emissive power of radiant panel heater
\[ E_{\lambda,b}(\lambda, T) = \frac{C_1}{\lambda^5[\exp(C_2/\lambda T) - 1]} \]

Total absorptivity
\[ \alpha = \int_{\lambda_1}^{\lambda^2} \frac{\alpha_\lambda(\lambda) \cdot E_{\lambda,b}(\lambda, T) \cdot d\lambda}{\int_{\lambda_1}^{\lambda^2} E_{\lambda,b}(\lambda, T) \cdot d\lambda} \]

Total absorptivity dependent on: panel temperature, droplet diameter and liquid composition
## Absorptivity Values

<table>
<thead>
<tr>
<th>T (K)</th>
<th>Acetone</th>
<th>Hexane</th>
<th>Octane</th>
<th>2-propanol</th>
<th>Ethanol</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>455</td>
<td>475</td>
<td>455</td>
<td>475</td>
<td>455</td>
</tr>
</tbody>
</table>

**D (µm):**

| 145   | 0.578   | 0.573  | 0.294  | 0.291      | 0.323   | 0.321   | 0.750   | 0.741   | 0.766   | 0.757   |
| 158   | 0.596   | 0.591  | *      | *          | *       | *       | 0.764   | 0.755   | 0.782   | 0.773   |
| 193   | 0.637   | 0.631  | 0.348  | 0.344      | 0.383   | 0.380   | 0.792   | 0.785   | 0.804   | 0.796   |
| 235   | 0.676   | 0.669  | 0.387  | 0.383      | 0.426   | 0.423   | 0.820   | 0.814   | 0.826   | 0.819   |

- Absorptivity of bi-component mixtures varies non-linearly with composition (Chapados and Max, 2007)

**Droplet diameter increases → α increases**

**Radiant panel temperature increases → α decreases**
peak acetone mole fraction and integrated area

- Average integrated areas under the peak
- Average values of the peak acetone mole fraction
- Measured bi-component areas and peak mole fraction scaled by initial mass of acetone evaporated
193 µm and 235 µm droplets irradiated at 475 K

Absorptivity

<table>
<thead>
<tr>
<th>Component</th>
<th>Absorptivity</th>
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<th>Component</th>
<th>Absorptivity</th>
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<tr>
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<td>Ace/2-prop</td>
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<td>Ace/Eth</td>
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<td>Ace/2-prop</td>
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<td>Ace</td>
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<td>Ace/Eth</td>
<td>0.4</td>
<td>Ace/2-prop</td>
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<td>Ace/Oct</td>
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<td>Ace/Eth</td>
<td>0.2</td>
<td>Ace/2-prop</td>
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<td>Ace/Hex</td>
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<td>Ace/Eth</td>
<td>0.0</td>
<td>Ace/2-prop</td>
<td>0.0</td>
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</table>

Latent heat (kJ/mol)

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<th></th>
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</tr>
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<tbody>
<tr>
<td>Ace/Eth</td>
<td>40</td>
<td>Ace/2-prop</td>
<td>30</td>
<td>Ace/Eth</td>
<td>40</td>
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<td>Ace/2-prop</td>
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<td>10</td>
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<tr>
<td>Ace/Hex</td>
<td>0</td>
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<td>20</td>
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<tr>
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<td>Ace/Eth</td>
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</tbody>
</table>

Droplet temperature (K)

<table>
<thead>
<tr>
<th>Component</th>
<th>Temperature</th>
<th>Component</th>
<th>Temperature</th>
<th>Component</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ace/Eth</td>
<td>286</td>
<td>Ace/2-prop</td>
<td>284</td>
<td>Ace/Eth</td>
<td>284</td>
</tr>
<tr>
<td>Ace/2-prop</td>
<td>282</td>
<td>Ace/Eth</td>
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<tr>
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<td>Ace/Eth</td>
<td>284</td>
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<td>278</td>
</tr>
</tbody>
</table>
effects of D & T on total absorptivity

- Geometrical optics model
Typical operating conditions of combustion devices

<table>
<thead>
<tr>
<th>Device</th>
<th>Diameter range (µm)</th>
<th>Wall temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas turbine</td>
<td>10 – 400</td>
<td>500 – 1000</td>
</tr>
<tr>
<td>Typical ICE</td>
<td>20 – 200</td>
<td>450 – 500</td>
</tr>
<tr>
<td>Micro gas turbine</td>
<td>20 - 100</td>
<td>600 – 750</td>
</tr>
<tr>
<td>Microcombustor</td>
<td>1 - 100</td>
<td>600 - 750</td>
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</table>

- Diameter range of 1 – 400 µm
  - 800 % increase in alcohol absorptivity
  - 600 % increase in acetone absorptivity
  - 500 % increase in alkane absorptivity

- Temperature change of 500 K
  - Less than 10 % change in absorptivity

- Absorptivity highly sensitive to diameter change
internal distribution of radiation absorption

Spectral radiation absorption (W/µm)

\[ Q(y) = 4\pi^2 R^2 I_s \int_0^{\theta_{\text{end}}} \left\{ \exp[-2xk_\lambda(\cos \phi - \sqrt{y^2 - \sin^2 \phi})] 
- \exp[-2xk_\lambda(\cos \phi + \sqrt{y^2 - \sin^2 \phi})] \right\} \cdot \sin \theta \cos \theta 
\times \left\{ \frac{[1 - \rho_{\perp}(\theta)]}{[1 - \rho_{\perp}(\theta)\exp(-4xk_\lambda \cos \phi)]} + \frac{[1 - \rho_{\parallel}(\theta)]}{[1 - \rho_{\parallel}(\theta)\exp(-4xk_\lambda \cos \phi)]} \right\} \, d\theta \]

Local volumetric spectral radiation absorption

\[ q_V(y) = \frac{dQ(y)}{4\pi r^2 dr} \]

Total local volumetric radiation absorption

\[ q_V^T(y) = \int_{\lambda_1}^{\lambda^2} q_V(y) \, d\lambda \]

Average volumetric spectral radiation absorption

\[ q_{V\text{av}} = \frac{4\pi^2 R^2 I_s \alpha_\lambda}{4/3\pi R^3} \]

Total average volumetric radiation absorption

\[ q_{V\text{av,T}} = \int_{\lambda_1}^{\lambda^2} q_{V\text{av}} \, d\lambda \]

Local dimensionless volumetric spectral radiation absorption

\[ \beta(y) = \frac{q_V(y)}{q_{V\text{av}}} \]

Total local dimensionless volumetric radiation absorption

\[ \beta^T(y) = \frac{q_{V\text{av,T}}(y)}{q_V} \]
effects of D & T on $\beta^T(y)$

$\beta^T(y)$ – Total local dimensionless volumetric radiation absorption

acetone
effects of D & T on $\beta^T(y)$

$\beta^T(y)$ – Total local dimensionless volumetric radiation absorption

octane
effects of D & T on $\beta^T(y)$

$\beta^T(y)$ – Total local dimensionless volumetric radiation absorption

hexane
effects of D & T on $\beta^T(y)$

$\beta^T(y)$ – Total local dimensionless volumetric radiation absorption

ethanol
effects of D & T on $\beta^T(y)$

$\beta^T(y)$ – Total local dimensionless volumetric radiation absorption

2-propanol
Temperature change from 500 K to 1000 K significantly affect radiation absorption in hydrocarbons

- T decreases from 1000 K to 500 K – Peak absorption shifts toward droplet core

Diameter < 100 µm (all components)
- Peak absorption shifts toward droplet core

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<td>Microcombustor</td>
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</tr>
</tbody>
</table>
conclusions

Experimental work:

• PLIF successfully implemented to image vapor distribution around droplets

• Highly asymmetric vapor distribution observed for asymmetric radiant heating (asymmetric Stefan flow)
  • not previously reported in the literature

Analytical work:

• Radiation absorption distribution high dependent on $n$-$k$ spectrum, diameter and irradiation temperature

• Peak absorption shifts toward droplet interior: $D < 100 \, \mu m$

• Hydrocarbon radiation absorption highly sensitive to temperature ($500 – 1000 \, K$)
implications

• Highly localized vaporization will affect overall vaporization rate
  • Affects eventual combustion of fuel/air mixture

• Fuel rich and fuel lean regions in combustor
  • Longer mixing time with air

• Increased pollutant formation
  • Nitrogen monoxide (lean)
  • Carbon monoxide, hydrocarbons (rich)

• Analytical results used to improve existing combustion models
future work

• ATESR Lab
  
  • Droplet vaporization under velocity/temperature gradients
  • Collaboration with Dr. Miller (Clemson University) for numerical simulation of current work

Circular Couette Flow Reactor (CCFR)
publications

Peer-reviewed publications:


acknowledgements

• National Science Foundation (Grant No. CTS-0346297)

• Advanced Thermal and Environmental Systems Research Laboratory
  
  Adviser: Dr. H.L. Clack
  Current and past members: Eric Lee, Peter Bittner, Yasmine Khakpour, Nekheel Gajjar, Vinit Prabhu, Pierre Coutris, Violaine Todoroff

• Dr. Miller (Clemson University)

• Dr. Keefe (Cape Breton University) and Dr. Bertie (University of Alberta)
Questions ?

Kavin Ammigan – Fermilab Technical Seminar – 19th April 2012