Ablation of Liquids for Laser Propulsion with TEA CO₂ Laser (Briefing Charts, PREPRINT)

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Time-resolved force sensing and intensified charge-coupled device (ICCD) imaging techniques were applied to the study of the force generation mechanism for laser ablation of liquids. A Transversely Excited at Atmospheric pressure (TEA) CO₂ laser operated at 10.6 μm, 300 ns pulse width, and 9 J pulse energy was used to ablate liquids contained in various aluminum and glass vessels. Net imparted impulse and coupling coefficient were derived from the force sensor data and relevant results will be presented for various container designs and liquids used. ICCD imaging was used in conjunction with the dynamic force techniques to examine dependencies on absorption depth, irradiance, surface curvature, and container geometry. ICCD imaging was also used to determine whether surface or volume absorption should be preferable for laser propulsion using liquid propellants. Finally, ballistic experiments were conducted in order to verify the dynamic force data and lend additional evidence as to the predominant methods of force generation.

Unclassified
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Gene Nelson
UAH Glassblower

Scott Anderson
Audio Arrangement
Outline

1. Introduction
2. Force
3. ICCD Ballistics
4. ICCD Imaging
5. Results and Discussion
6. Conclusions
Laser Ablation

- **Laser Ablation**: removal of material by any physical process under laser irradiation

- **Laser Ablation of Liquids**
  - \( C_m \) up to 350 dyne/W
  - Irradiance: \( 10^7-10^8 \) W/cm\(^2\)
  - \( I_{sp} \) up to 50 s
Motivation

(1) What is the physical mechanism generating thrust during the laser ablation of a liquid?
   - Plasma formation
   - Vaporization
   - Explosive boiling / Phase explosion
   - Cavity collapse / splashing

(2) How do the ablation mechanisms for surface and volume-absorbing liquids differ?

(3) How does $C_m$ depend on:
   - Container geometry
   - Liquid surface curvature
   - Absorption depth
Force Experiments
Experimental Setup
(Force Sensors)
# Piezoelectric Force Sensors

**Small Force Sensor**
- **Maximum Force:** 9.786 N
- **Linearity:** < 1%
- **Sensitivity:** 526.6 mV/N
- **Discharge time constant:** > 1.0 s
- **Rise Time:** 5 μs
- **Resolution:** $10^{-4}$ N

![Small Force Sensor Image](PCB-209C01)

**Large Force Sensor**
- **Maximum Force:** 444.8 N
- **Linearity:** < 0.4%
- **Sensitivity:** 11.96 mV/N
- **Discharge time constant:** > 500 s
- **Rise Time:** 8 μs
- **Resolution:** $10^{-3}$ N

![Large Force Sensor Image](PCB-200B02)
Force-Time Curve

- Measurements are as follows:
  - Single laser shot
  - Force vs. time
  - Large force peak observed (10-90 μs, centered 40-50 μs)

- Integrate to find I, then derive $C_m$
## Coupling Coefficients and Peak Force

### Peak Force (N)

<table>
<thead>
<tr>
<th></th>
<th>Hexane</th>
<th>Ethanol</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cylinder</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flat</td>
<td>3.4 ± 0.4</td>
<td>5.2 ± 0.6</td>
<td>4.1 ± 0.4</td>
</tr>
<tr>
<td>Concave</td>
<td>3.1 ± 0.2</td>
<td>6.0 ± 0.1</td>
<td>5.7 ± 0.5</td>
</tr>
<tr>
<td><strong>Cone</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flat</td>
<td>3.6 ± 0.3</td>
<td>5 ± 1</td>
<td>4.1 ± 0.4</td>
</tr>
<tr>
<td>Concave</td>
<td>3.7 ± 0.3</td>
<td>5.8 ± 0.4</td>
<td>5.3 ± 0.4</td>
</tr>
</tbody>
</table>

### $C_m$ (dyne/W)

<table>
<thead>
<tr>
<th></th>
<th>Hexane</th>
<th>Ethanol</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cylinder</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flat</td>
<td>22 ± 3</td>
<td>50 ± 3</td>
<td>43 ± 4</td>
</tr>
<tr>
<td>Concave</td>
<td>22 ± 3</td>
<td>56 ± 4</td>
<td>60 ± 6</td>
</tr>
<tr>
<td><strong>Cone</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flat</td>
<td>23 ± 1</td>
<td>49 ± 6</td>
<td>47 ± 5</td>
</tr>
<tr>
<td>Concave</td>
<td>24 ± 3</td>
<td>56 ± 3</td>
<td>56 ± 6</td>
</tr>
</tbody>
</table>

(1.6 x $10^7$ W/cm², 0.4 J, Force Sensor)
Surface Curvature

- Radius of Curvature $R$

- Curvature $\kappa$ (cm$^{-1}$)

\[ \kappa \equiv \frac{1}{R} \]

- $C_m$ directly dependent on $\kappa$

Water, flat, cylinder, 0.4 J, $2 \times 10^7$ W/cm$^2$
Imaging Experiments
ICCD Imaging

Information on:
Initial plume velocities
Cavity growth rates
Characteristic physical processes
Timeline of processes
ICCD Ballistics Setup

- Gated CCD technique
- Single laser shot per image
- Highly repeatable
- Composite sequences

- 382 x 574 pixel images
- >5 ns gate width (exposure)
- 5 ns - 83 ms delay
Coupling Coefficients, dyne/W

(Water, 3 mm² spot size)

<table>
<thead>
<tr>
<th>Energy (J)</th>
<th>Irradiance (W/cm²)</th>
<th>Small Force Sensor</th>
<th>Large Force Sensor</th>
<th>Ballistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>4 x 10⁷</td>
<td>110 ± 14</td>
<td>-</td>
<td>98 ± 9</td>
</tr>
<tr>
<td>1.2</td>
<td>1 x 10⁸</td>
<td>44 ± 24</td>
<td>53 ± 21</td>
<td>37 ± 5</td>
</tr>
<tr>
<td>3.6</td>
<td>5 x 10⁸</td>
<td>-</td>
<td>14 ± 3</td>
<td>14 ± 2</td>
</tr>
</tbody>
</table>

\[
C_m = \frac{I}{E_{\text{pulse}}} = \frac{m}{E_{\text{pulse}}} \sqrt{2 \, g \, h_{\text{max}}}
\]
Imaging Setup

- TEA CO$_2$ laser
- Mirror 1
- Mirror 2
- Attenuators
- 12" ZnSe lens
- ICCD camera
- HV pulser
- Controller
- PC
- Chiller
- Target
- Light Source

This presentation is Distribution A: Approved for public release, distribution unlimited
ICCD Images

Volume-absorbing
(hexane)
- No observed plume
- No cavity formation
- Boiling

Surface-absorbing
(ethanol, isopropanol, water)
- Vapor plume
- Cavity formation
Surface Absorption

Ethanol, 0.4 J, $4 \times 10^7$ W/cm$^2$
Volume Absorption (Hexane)

- 0.4 J
- $4 \times 10^7$ W/cm²
- No plasma
- No cavity
- No plume
- Boiling

- 1.1 J
- $1 \times 10^8$ W/cm²
- Plasma
- Surface cavity
- Vapor plume
Containers: Cylinder vs. Cone

- Water, 10-100 μs
- Virtually no difference observed
Surfaces: Flat vs. Concave

- Ethanol, 5-50 μs:

<table>
<thead>
<tr>
<th></th>
<th>5μs</th>
<th>50μs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat</td>
<td><img src="image1" alt="Flat 5μs" /></td>
<td><img src="image2" alt="Flat 50μs" /></td>
</tr>
<tr>
<td>Concave</td>
<td><img src="image3" alt="Concave 5μs" /></td>
<td><img src="image4" alt="Concave 50μs" /></td>
</tr>
</tbody>
</table>

Effect of Initial Curvature (100 μs)

Flat: ![Flat 100μs](image5)

Concave: ![Concave 100μs](image6)
Analysis of Mass Loss and Cavity Growth

Model as oblate spheroid

\[
V = \frac{2}{3} \pi a b^2
\]

Correction for distortion

Subtraction of rim volume

Cavity measurement
Liquid Mass Loss

- All data using cylinder, flat surface, 0.4 J, $7 \times 10^7$ W/cm$^2$

- Increased cavity growth during initial $100 \ \mu s$

- **ICCD imaging:** Mass (mg) removed during initial $100 \ \mu s$

- **Scientific Balance:** Total mass (mg) removed in entire process

### Mass Loss (mg)

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Hexane</th>
<th>Ethanol</th>
<th>Isopropanol</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-100 μs</td>
<td>0</td>
<td>2 ± 1</td>
<td>1 ± 1</td>
<td>1 ± 1</td>
</tr>
<tr>
<td>Total Process</td>
<td>4 ± 1</td>
<td>51 ± 6</td>
<td>51 ± 2</td>
<td>51 ± 5</td>
</tr>
<tr>
<td>Ratio</td>
<td>0 %</td>
<td>4 %</td>
<td>2 %</td>
<td>2 %</td>
</tr>
</tbody>
</table>
Analysis of Initial Velocities

Center plume front height $h$

$\Delta h$ paired with known $\Delta t$

$$\lim_{t \to 0} \frac{\Delta h}{\Delta t} = v_0$$

Surface absorbing liquids

transonic – supersonic

initial velocities observed

Volume absorbing liquids:

subsonic to transonic

velocities observed
### Specific Impulse and Internal Efficiency

\[ I_{sp} \equiv \frac{I}{w} \approx \frac{u_e}{g} \]

(1.6 x 10^7 W/cm², 0.4 J)

<table>
<thead>
<tr>
<th>Specific Impulse (s)</th>
<th>Hexane</th>
<th>Ethanol</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>from ( v_0/g )</td>
<td>-</td>
<td>42 ± 1</td>
<td>84 ± 3</td>
</tr>
<tr>
<td>1st 100 μs</td>
<td>-</td>
<td>10 ± 5</td>
<td>20 ± 10</td>
</tr>
<tr>
<td>Total process</td>
<td>2.3 ± 0.6</td>
<td>0.40 ± 0.05</td>
<td>0.34 ± 0.05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Internal Efficiency (%)</th>
<th>Hexane</th>
<th>Ethanol</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>from ( v_0/g )</td>
<td>-</td>
<td>10.3 ± 0.7</td>
<td>18 ± 2</td>
</tr>
<tr>
<td>1st 100 μs</td>
<td>-</td>
<td>3 ± 1</td>
<td>4 ± 2</td>
</tr>
<tr>
<td>Total process</td>
<td>0.24 ± 0.08</td>
<td>0.10 ± 0.01</td>
<td>0.07 ± 0.01</td>
</tr>
</tbody>
</table>
Force Data with ICCD Imaging

(Water, cylinder, concave, 0.4 J, 4 x 10^7 W/cm²)
Conclusions
Conclusions

1) A series of experiments with time-resolved force sensors and ICCD imaging were conducted on liquids.
2) 2 major physical ablation processes are observed: vaporization and splashing. In some cases plasma formation was also achieved.
3) The major source of thrust generation in the laser ablation of liquids is vaporization.
4) ICCD imaging shows vaporization occurs from 0 to 100 $\mu$s after the laser pulse. Splashing is initiated after about 100 $\mu$s.
5) Force generation occurs during the vaporization regime.
6) The peak force was observed $\sim$40-50 $\mu$s after the laser pulse.
7) Ballistics experiments corroborate the impulse measurements with force sensors.
8) Surface absorbing liquids show higher $C_m$ ($\sim$50-150 dyne/W) than volume absorbing liquids ($\sim$10-50 dyne/W).
Conclusions (continued)

9) $C_m$ is dependent on surface geometry for surface absorbing liquids.
   Changing geometry does not affect $C_m$ for volume absorbing liquids.

10) $C_m$ is dependent on container geometry for volume absorbing liquids.
    Changing container geometry does not affect $C_m$ for surface absorbing liquids.

11) The majority of mass loss occurs due to splashing (>95%) rather than vaporization (<5%).

12) Momentum coupling was observed to be about 3 times more sensitive to changes in the surface curvature for surface absorbing liquids than to changes in the container geometry for volume absorbing liquids. This is additional evidence in favor of a dominant vaporization mechanism.
THANK YOU
Cavity Growth

- 2 Regimes:
  - Approximately linear growth
  - Vaporization – fast growth
  - Splashing – slow growth
Challenges of Using Piezoelectric Force Sensors

• Measurements in an accelerating frame
  – Distortion
  – Solution: Sensor at rest
• Rise time limits detection speed
  – Plasma processes ~ 1 μs
  – Liquid vaporization ~ 100 μs
  – Cavity Collapse ~ 1 ms
  – Liquid splashing ~ 10 ms
  (Force sensors: 5 μs rise time)
• Natural frequencies
  – Solution: Fourier analysis
Drag vs. Velocity

Coefficient of Parasite Drag Vs. Velocity

Subsonic  Transonic  Supersonic  Hypersonic

$C_{dp}$

$V_s$  $M_{cr}$  $M_{DR}$  $M_1$  $M_{AT}$

Velocity
Force Sensor Distortion

- Spring mounted vs. Hard mounted sensor
Laser Properties

- Graphs showing voltage (volts) over time (microseconds)
- Signal [V] and time [µs] axes
## Liquids

<table>
<thead>
<tr>
<th></th>
<th>Hexane</th>
<th>Ethanol</th>
<th>Isopropanol</th>
<th>Acetone</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chemical Formula</strong></td>
<td>C₆H₁₄</td>
<td>C₂H₅OH</td>
<td>C₃H₇OH</td>
<td>C₃H₆O</td>
<td>H₂O</td>
</tr>
<tr>
<td><strong>Absorption Coefficient (cm⁻¹)</strong></td>
<td>~0</td>
<td>17</td>
<td>67</td>
<td>~100</td>
<td>~3300</td>
</tr>
<tr>
<td><strong>Absorption Depth (μm)</strong></td>
<td>large</td>
<td>574</td>
<td>149</td>
<td>78</td>
<td>3</td>
</tr>
<tr>
<td><strong>Density (g/ml)</strong></td>
<td>0.66</td>
<td>0.79</td>
<td>0.785</td>
<td>0.790</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Molecular Weight (g/mol)</strong></td>
<td>86.18</td>
<td>46.07</td>
<td>60.10</td>
<td>58.08</td>
<td>18.02</td>
</tr>
<tr>
<td><strong>Enthalpy of Vaporization (kJ/mol)</strong></td>
<td>28.85</td>
<td>38.6</td>
<td>39.85</td>
<td>29.1</td>
<td>43.99</td>
</tr>
<tr>
<td><strong>Surface Tension (dyne/cm)</strong></td>
<td>18</td>
<td>22.3</td>
<td>21.7</td>
<td>23.7</td>
<td>73.05</td>
</tr>
<tr>
<td><strong>Viscosity (mPa-s)</strong></td>
<td>0.3</td>
<td>1.07</td>
<td>2</td>
<td>0.306</td>
<td>1.002</td>
</tr>
</tbody>
</table>
Quartz Target Containers

Cone

- 10.1 mm
- 5.2 mm
- 6.3 mm
- 10.2 mm
- 1.672 g
- 67.5 μl

Cylinder

- 10.0 mm
- 5.9 mm
- 5.5 mm
- 11.1 mm
- 1.601 g
- 146.9 μl
Surface Distortion