Change of evaporation rate of single monocomponent droplet with temperature using time-resolved phase rainbow refractometry

Yingchun Wu¹,²,*, Haipeng Li³, Xuecheng Wu¹, Gérard Gréhan⁴, Lutz Mädler³, Cyril Crua²

¹ State Key Laboratory of Clean Energy Utilization, Zhejiang University, China
² Advanced Engineering Centre, University of Brighton, UK
³ Leibniz Institute for Materials Engineering IWT, University of Bremen, Germany
⁴ CNRS UMR 6614/CORIA, France

* wycgsp@zju.edu.cn
Presenter: Yingchun Wu
1. Introduction
   - Droplet evaporation

2. Experiments
   - Phase rainbow refractometry (PRR)
   - Setup

3. Results and discussions
   - Transient evaporation rate
   - Maxwell and Stefan-Fuchs model comparison
   - Uncertainty analysis

4. Conclusions
1. Droplet evaporation

Evaporation is a key process in spray combustion

Power generation
Internal combustion

Jet engine

Metal drop combustion

Aluminized Propellant
1. Droplet evaporation measurement

- **Evaporation rate**

\[
k_e = \lim_{\Delta t \to 0} \frac{[D_{t+\Delta t}^2 - D_t^2]}{\Delta t} = \lim_{\Delta t \to 0} \frac{[(D + \Delta D)^2 - D^2]}{\Delta t} = \lim_{\Delta t \to 0} \frac{2D\Delta D}{\Delta t} + O\left(\frac{\Delta D^2}{\Delta t}\right) = 2D\Delta D
\]

Phenomenon: tiny droplet size variation
Challenging: multiple scale, multiple processes

D: diameter
T: temperature
C: concentration

D~20-200μm
ΔD~10 nm-1μm

Diameter and temperature vs time

1. Droplet evaporation measurement

- Evaporation rate measurement techniques
  - Liquid phase
    - Lagrangian strategy: monitor size via direct or holographic imaging
      Low accuracy, long time observation (hanging)
    - Morphology Dependent Resonance (MDR) [1]: Spherical droplet
    - Phase Rainbow Refractometry (PRR) [2]
    - PHase Interferometric Particle Imaging (PHIPI) [3]
  - Gaseous phase
    - Interferometric imaging [4]: measure vapor gradient
    - Spectroscopic imaging: LIF
  - Objective: measure droplet transient evaporation rate of a single isolated droplet at different droplet temperatures under a transient heat using PRR

2. Rainbow refractometry

Light Scattering by droplet

- Rainbow Formation
  - Refraction: Airy rainbow
  - Reflection+ Refraction: Ripple structure
- Rainbow refractometry measures the refractive index, droplet size by analyzing light around rainbow angle
  - Rainbow angle: refractive index $n$
  - Refractive index depends on temperature
  - Intensity profile: size $D$
2. Phase rainbow refractometry

**Principle:** variation $\rightarrow$ optical path $\rightarrow$ phase change

$$(\Delta n, \Delta T, \Delta D)$$

**Direct measure**

$\Delta D = \Delta \varphi \frac{\lambda}{2\pi} \left( \frac{3n^2}{8 + 10n^2} \sqrt{\frac{3}{n^2 - 1}} \right)$

**Optical paths length**

**Refraction:** $L_{p2} = L_{AB} + nL_{BC} + nL_{CK} + L_{KM}$

**Reflection:** $L_{p0} = L_{FH} + L_{HI}$

**Phenomenon:** Phase shift leads to tilted ripples

**Measurement:** Phase shift determines size change
2. Phase rainbow refractometry

Flow chart of data processing

### PRR accuracy validation

**Table 1:** List of simulation parameters for the 9 different test cases.

<table>
<thead>
<tr>
<th>case</th>
<th>liquid</th>
<th>$n$</th>
<th>$D_{\text{min}}$ (μm)</th>
<th>$D_{\text{max}}$ (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>water</td>
<td>1.333</td>
<td>50</td>
<td>50.6</td>
</tr>
<tr>
<td>2</td>
<td>water</td>
<td>1.333</td>
<td>100</td>
<td>100.6</td>
</tr>
<tr>
<td>3</td>
<td>water</td>
<td>1.333</td>
<td>150</td>
<td>150.6</td>
</tr>
<tr>
<td>4</td>
<td>ethanol</td>
<td>1.360</td>
<td>50</td>
<td>50.6</td>
</tr>
<tr>
<td>5</td>
<td>ethanol</td>
<td>1.360</td>
<td>100</td>
<td>100.6</td>
</tr>
<tr>
<td>6</td>
<td>ethanol</td>
<td>1.360</td>
<td>150</td>
<td>150.6</td>
</tr>
<tr>
<td>7</td>
<td>octane</td>
<td>1.400</td>
<td>50</td>
<td>50.6</td>
</tr>
<tr>
<td>8</td>
<td>octane</td>
<td>1.400</td>
<td>100</td>
<td>100.6</td>
</tr>
<tr>
<td>9</td>
<td>octane</td>
<td>1.400</td>
<td>150</td>
<td>150.6</td>
</tr>
</tbody>
</table>

2. Phase rainbow refractometry

Processing of rainbow signals in phase rainbow refractometry

(a) A comparison of a reference and a target rainbow signals. (b) Optimal fitting of the reference rainbow signal in (a). (c) A comparison of a pair of ripple structures obtained from (a). (d) The amplitude (lower part) and phase (upper part) spectra of CPSD of the ripple pair in (c). (e) The wrapped and unwrapped phase shift angles. (f) The size changes measurements

Size change measurement:
PRR resolution : <1nm
PRR accuracy : <0.6%
2. Experimental setup

- **N-heptane droplet**
  - PZT droplet generator
  - Frequency: 4 Hz
  - Size: 81-82.5 μm
  - Relative velocity: 0.5-2 m/s

- **Laser**
  - Continuous laser, 532 nm

- **Camera**
  - Linear camera: 1024 pixels
  - Fourier imaging system
  - 67 kHz sampling

- **Heating**
  - Spark heating

Devices are synchronized
3. Time-resolved PRR image

A PRR image of n-heptane droplets with a spark heating

- Natural evaporation
- Spark
- Oscillating
- Heated evaporation

Droplet is deformed

droplet restores spherical shape

Evaporation
3. Results and Discussions

- Evolutions of temperature and evaporation rate
- About 10 ms duration is analyzed
- Sixty droplets are investigated

- Droplet temperatures
  - Before spark: 293.2±0.8K
  - Lower than the ambient temperature (295.9K)
  - After spark: 294 K to 315 K

- Evaporation rate
  - Before spark: \(-1.28±0.04\times10^{-8}\) m\(^2\)/s,
  - After spark: \([-1.5, 8]\) \times10^{-8}\ m\(^2\)/s
3. Results and Discussions

- Evaporation model comparison
  - Maxwell and Stefan-Fuchs model

$$k_t = 4D_v \frac{\rho_g}{\rho_l} \text{Sh} \ln (1 + B_M)$$

<table>
<thead>
<tr>
<th>Evaporation rate /m²/s</th>
<th>Theory</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before spark</td>
<td>$-1.36 \times 10^{-8}$</td>
<td>$-1.28 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

After spark: consistent with each other

Local relative velocity varying

$D_v$: diffusion coefficient of the vapor
Sh: Sherwood number
$B_M$: Spalding mass transfer number
$\rho_g$ and $\rho_l$: densities of the gas surrounding the droplet, and of the droplet's liquid phase, respectively.

Comparison of sixty n-heptane droplets
3. Uncertainty analysis

- **Sources**
  - **Systematic uncertainty:** 1.4° C
    Scattering angle calibration, 0.6° C
    Inversion algorithm: 0.8° C
  - **Droplets inhomogeneity**
    Light is curved inside droplet
    Problem: Optical path unknown
    Inhomogeneity: change or unchange
  - **Evaporation rate uncertainty up to 8-15%**
4. Conclusions

- **Tool development**: A time resolved one-dimensional phase rainbow refractometry has been applied to measure droplet refractive index/temperature, size and size changes/droplet evaporation characterization.

- **Applications**: The evolutions of temperature and evaporation rate of single isolated droplet after a transient spark heating are investigated, and results are well consistent with predictions by evaporation model.

- **Future work**:
  - Tools: to measure evaporation rate of gradient droplet
  - Cases: Droplet evaporation rate of different liquids, different T&P
  - Evaporation rate of nonshperical droplet
  - Metal drop evaporation measurement
Thank you