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

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Presenter: Yingchun Wu

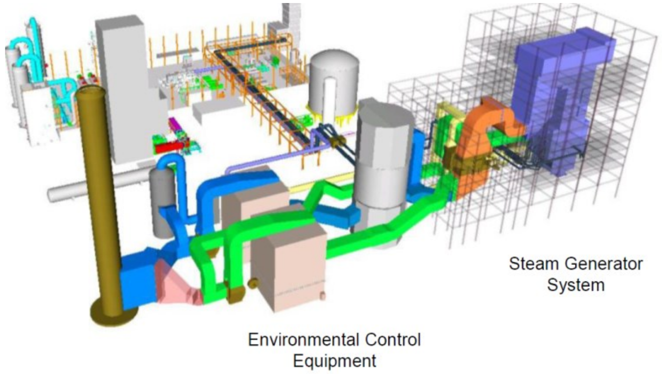
Outline

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

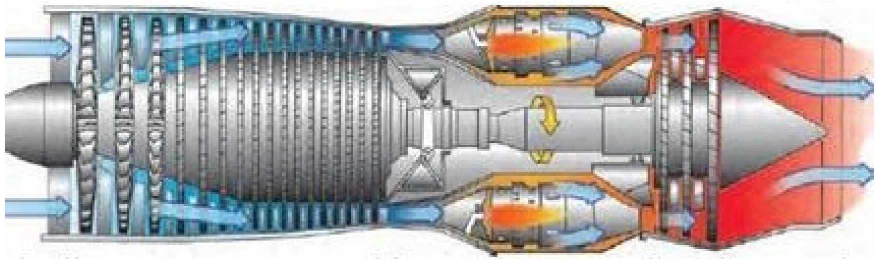
1. Droplet evaporation

☐ Evaporation is a key process in spray combustion

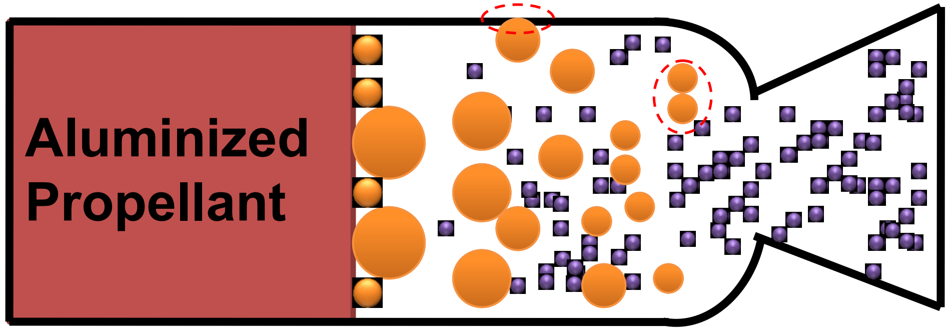
Power generation
Internal combustion



Jet engine



Metal drop combustion

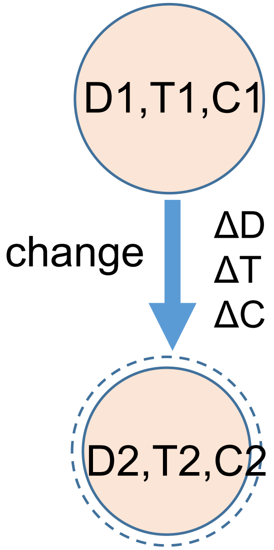


1. Droplet evaporation measurement

☐ Evaporation rate

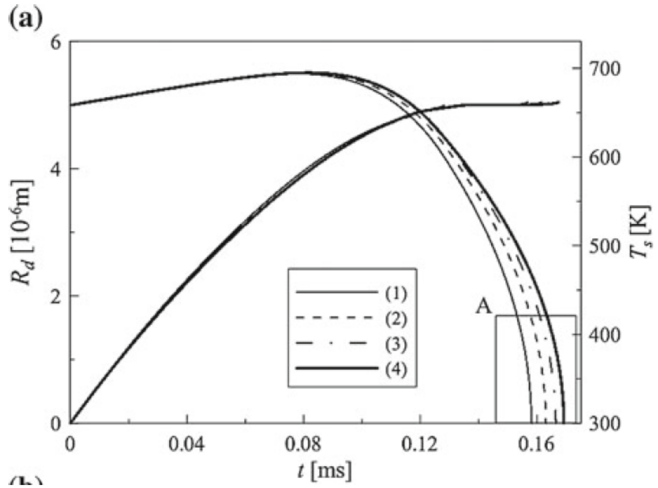
$$k_e = \lim_{\Delta t \to 0} \frac{[D_{t+\Delta t}^2 - D_t^2]}{\Delta t} = \lim_{\Delta t \to 0} \frac{[(D+\Delta D)^2 - D^2]}{\Delta t} = \lim_{\Delta t \to 0} \frac{2D\Delta D}{\Delta t} + \mathrm{O}\left(\frac{\Delta D^2}{\Delta t}\right) = 2D\Delta\dot{D}$$

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

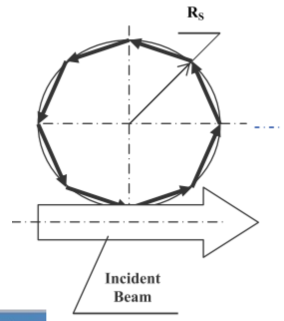
S. Sazhin, *Droplets and sprays* (Springer, 2014).

1. Droplet evaporation measurement

◻ Evaporation rate measurement techniques

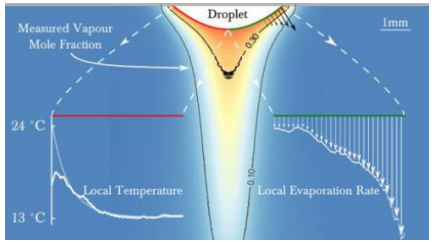
◻ Liquid phase

- 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



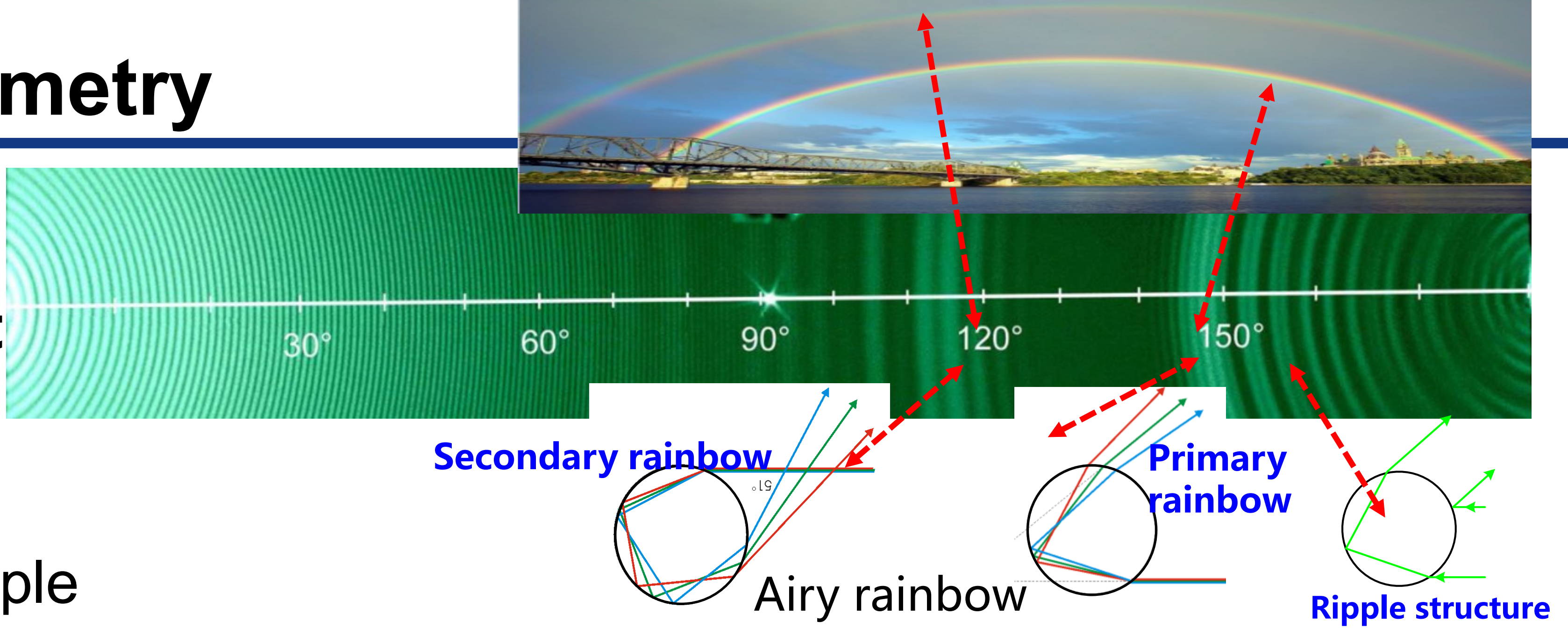
- Interferometric imaging [4]: measure vapor gradient
- Spectroscopic imaging: LIF

◻ **Objective**: measure droplet transient evaporation rate of a single isolated droplet at different droplet temperatures under a transient heat using PRR

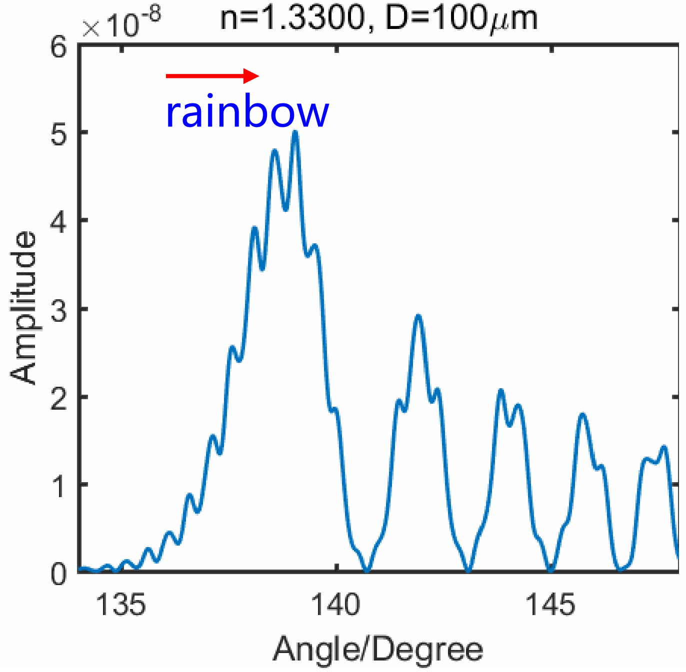
[1] G. Chen, et al, Progress in Energy and Combustion Science 22, 163-188 (1996). [2] Y. Wu, et al, Optics Letters 41, 4672-4675 (2016).
[3] Y. Wu et al, Applied Physics Letters 111, 041905 (2017). [4] S. Dehaeck, et al, Langmuir **30**, 2002-2008 (2014).

2. Rainbow refractometry

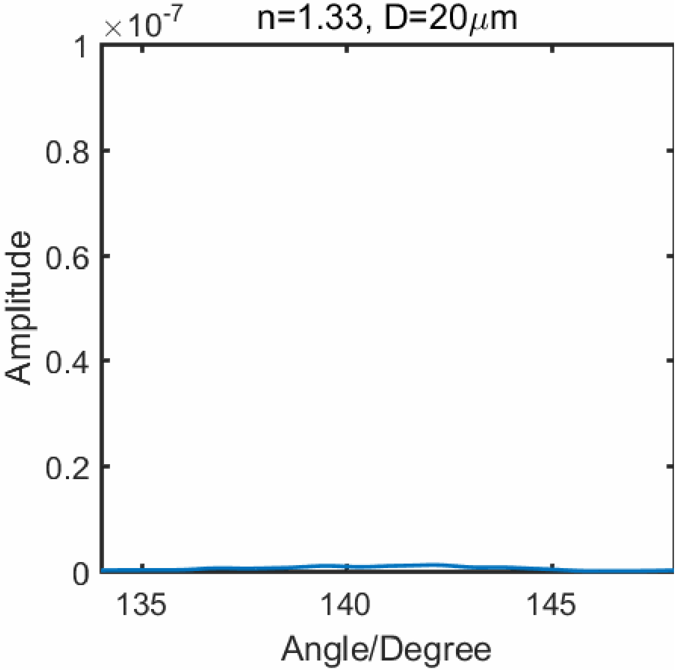
Light Scattering by droplet



- ☐ **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



n---rainbow position

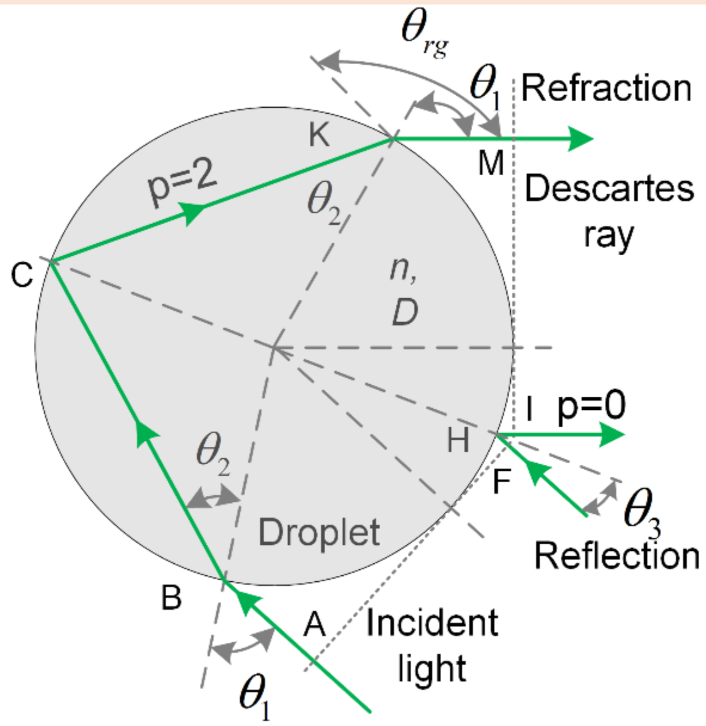


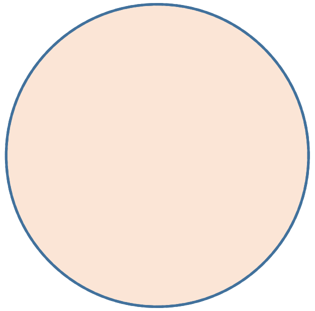
D---rainbow shape

2. Phase rainbow refractometry

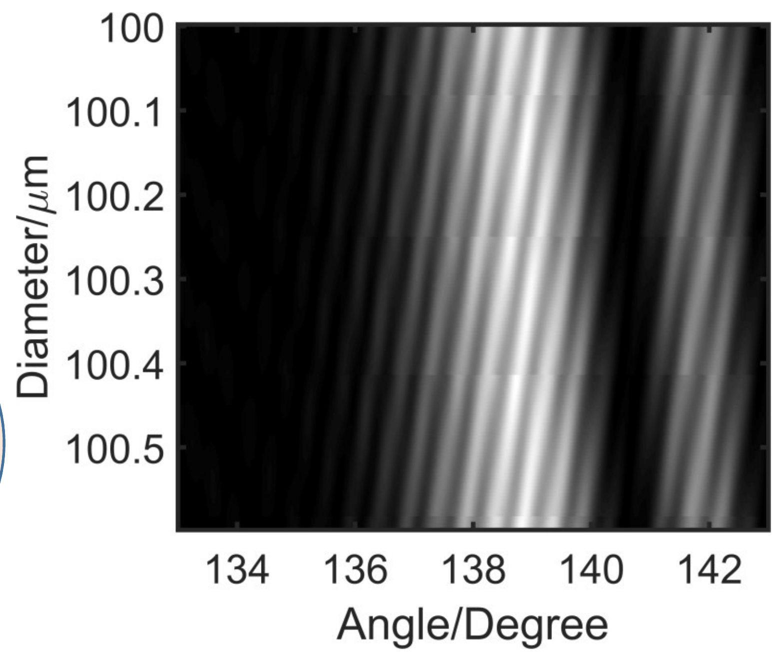
Principle: variation → optical path → phase change
(Δn, ΔT, ΔD) ← Direct measure — — — — Phase shift ←

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

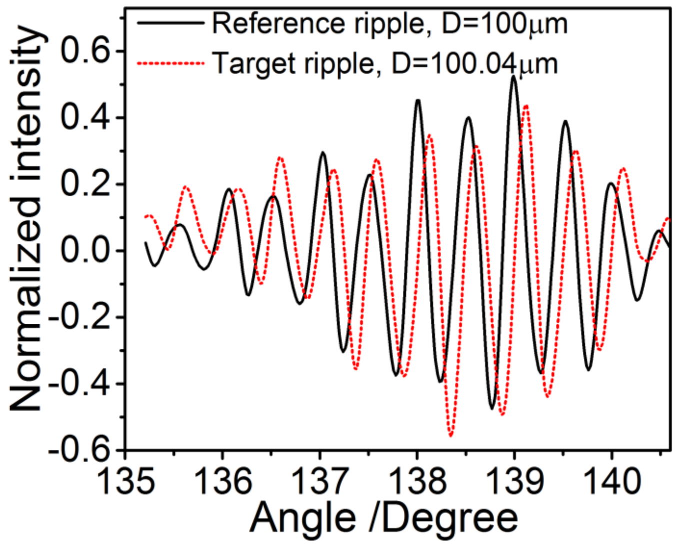




Evaporation



PRR signal



Phase shift of ripples

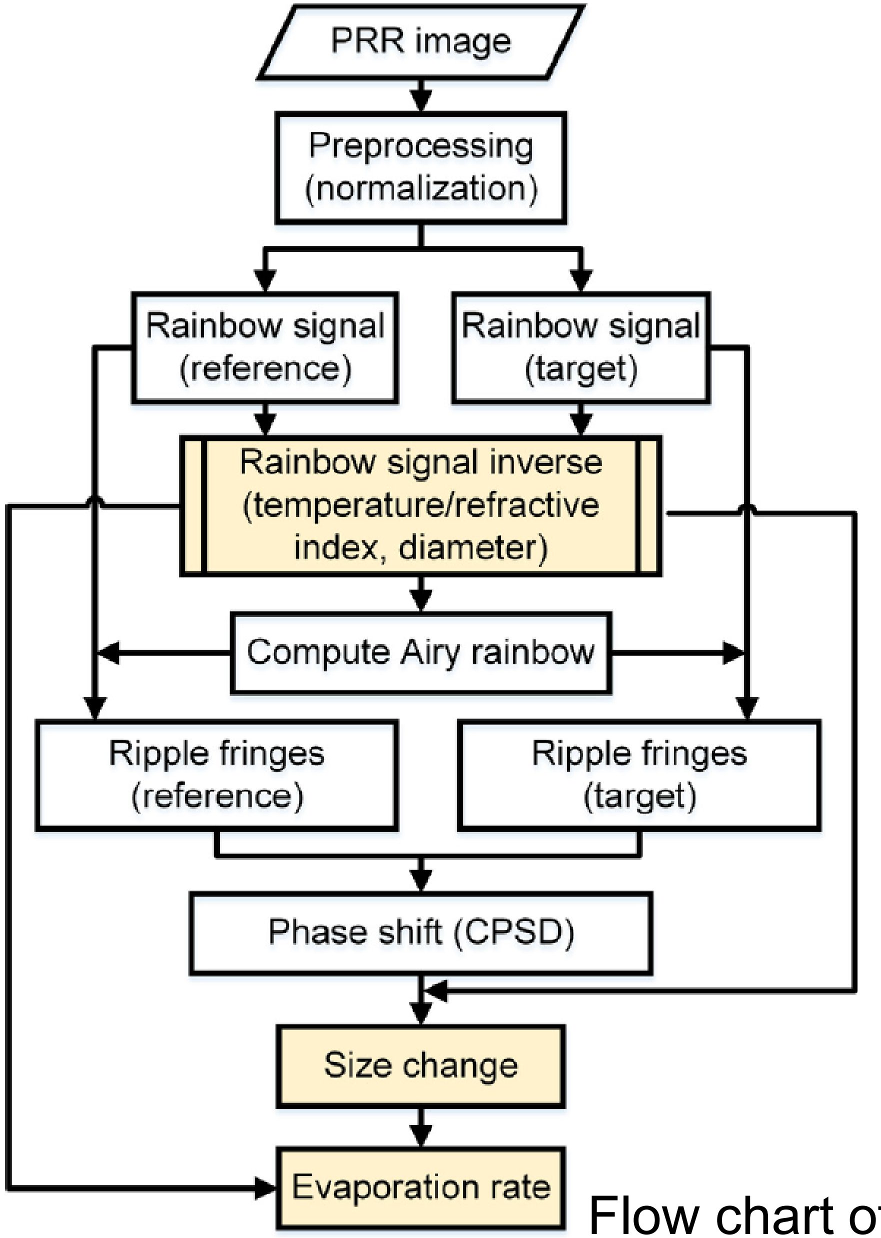
Optical paths length

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

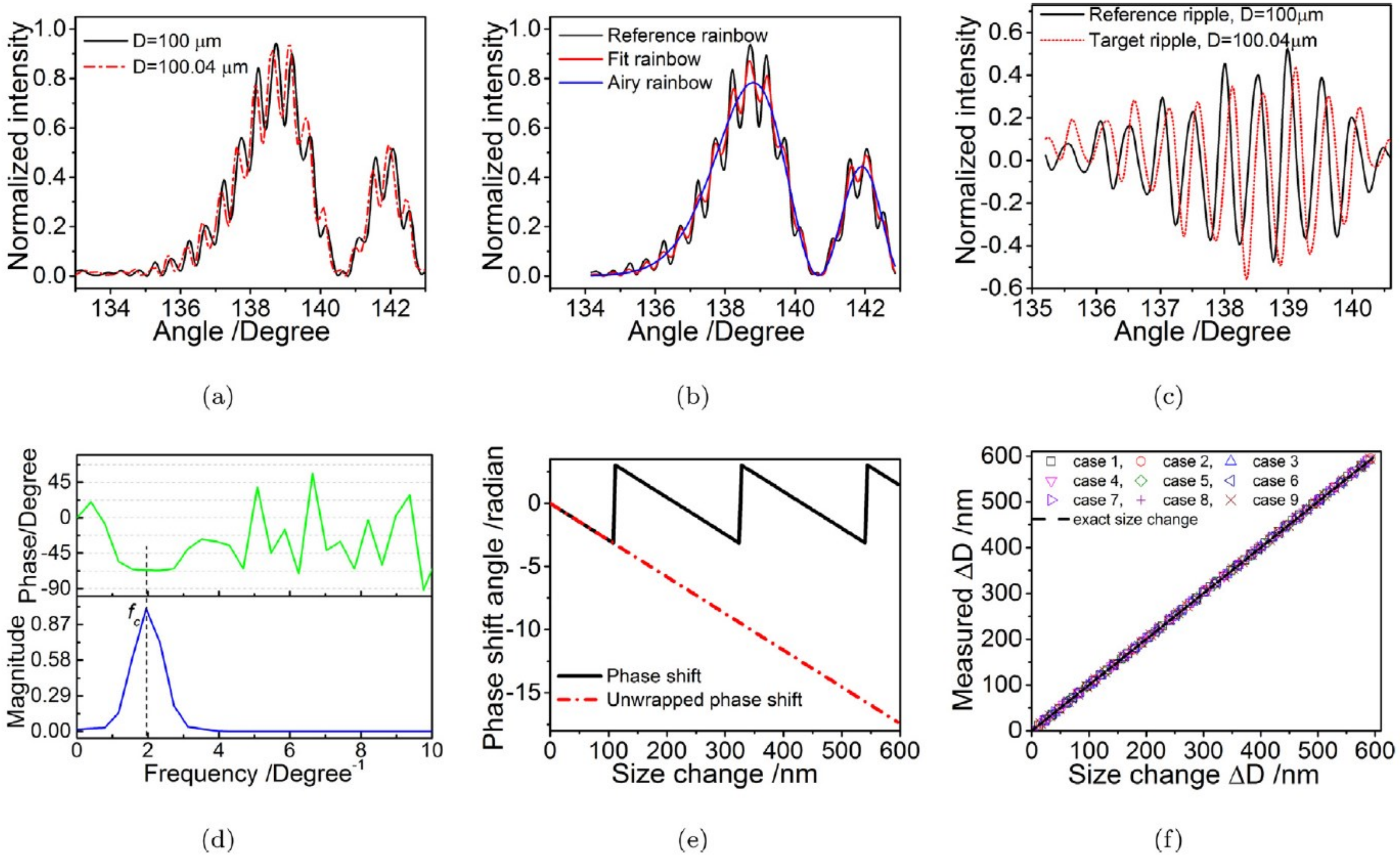
Nine cases

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

case	liquid	n	$D_{\rm min}$ (μm)	$D_{\rm max}$ (μm)
1	water	1.333	50	50.6
2	water	1.333	100	100.6
3	water	1.333	150	150.6
4	ethanol	1.360	50	50.6
5	ethanol	1.360	100	100.6
6	ethanol	1.360	150	150.6
7	octane	1.400	50	50.6
8	octane	1.400	100	100.6
9	octane	1.400	150	150.6

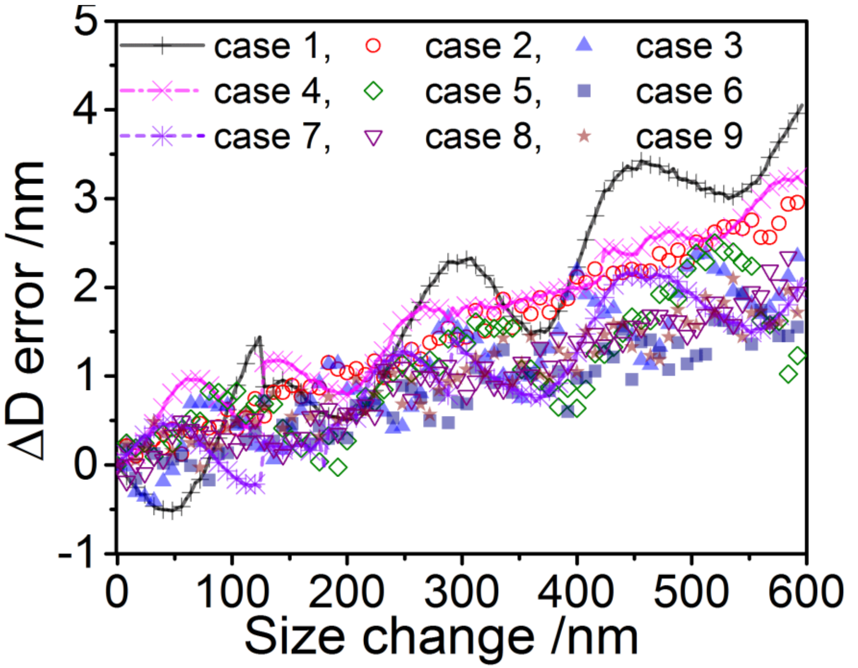
Y. Wu, et al. Journal of Quantitative Spectroscopy and Radiative Transfer 214, 146-157 (2018).

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: 81-82.5μm
- ➢ Relative velocity: 0.5-2 m/s

☐ Laser

- ➢ Continuous laser, 532 nm

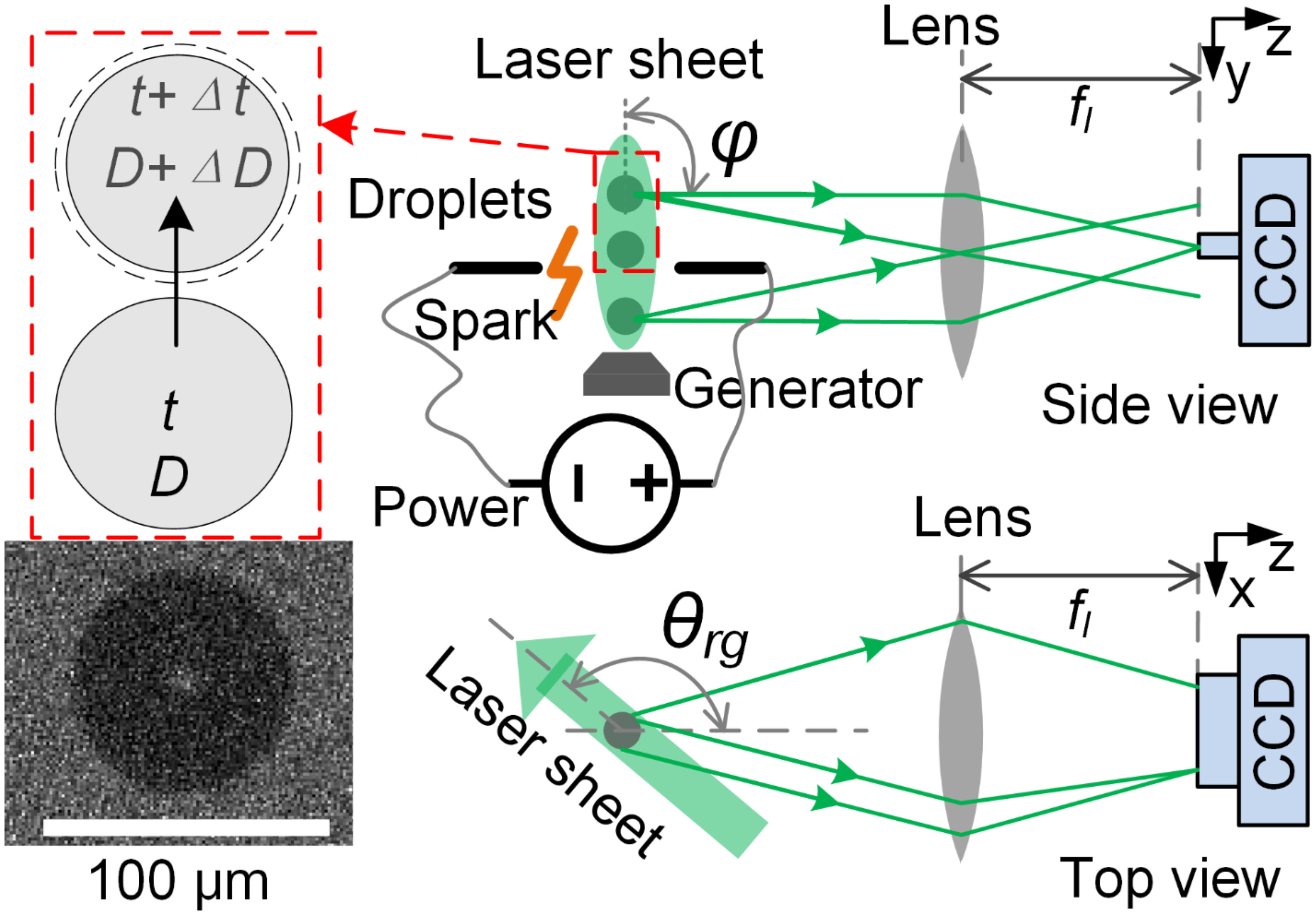
☐ Camera

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

☐ Heating

- ➢ Spark heating

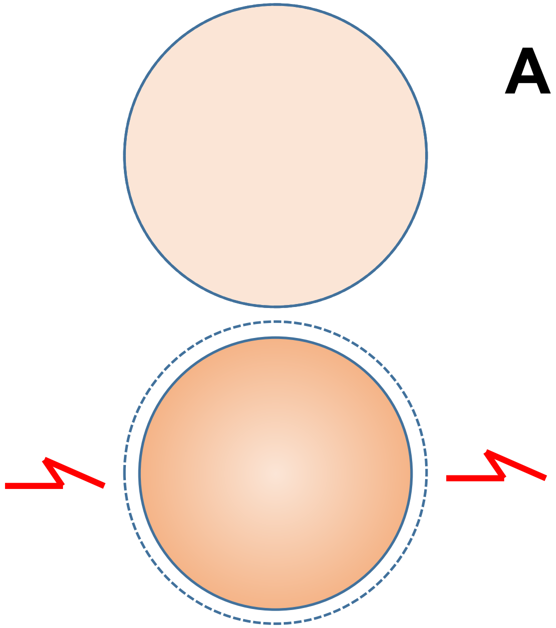
Devices are synchronized



One-dimensional time-resolved PRR

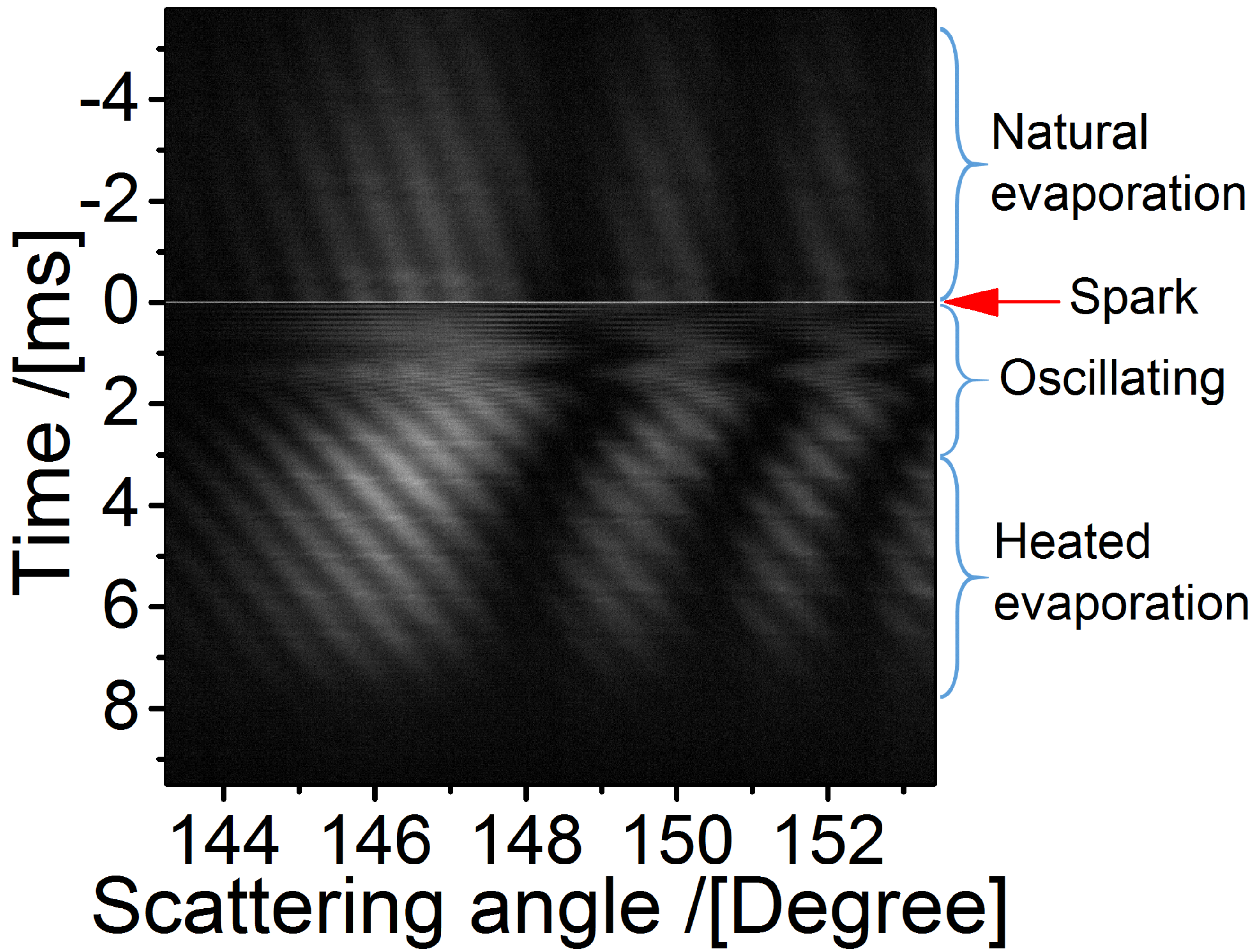
Experimental setup

3. Time-resolved PRR image



Evaporation

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



Droplet is deformed

droplet restores spherical shape

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

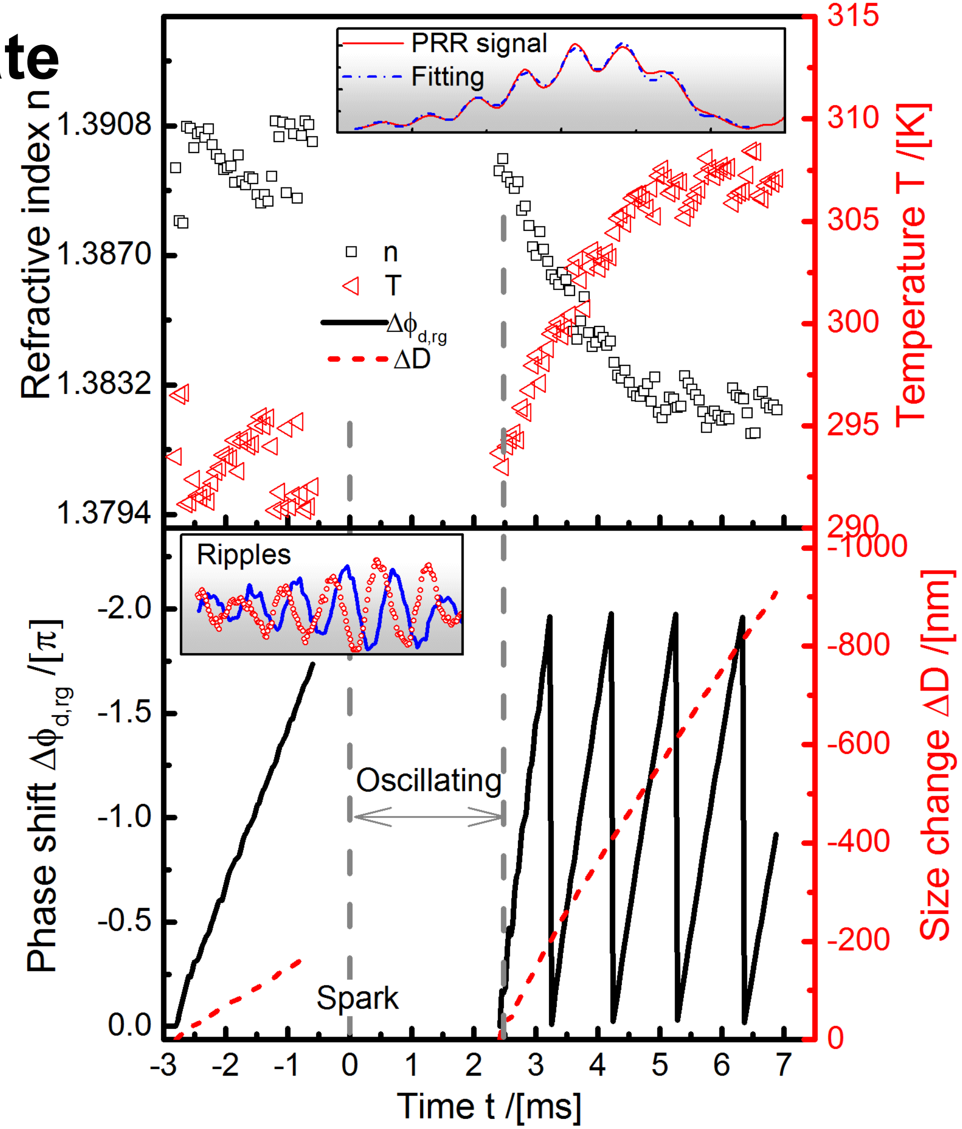
Lower than the ambient temperature (295.9K)

➢ After spark: 294 K to 315 K

☐ Evaporation rate

➢ Before spark : $-1.28 \pm 0.04 \times 10^{-8}$ m^2/s,

➢ After spark: $-[1.5, 8] \times 10^{-8}$ m^2/s



Upper:refractive index and temperature evolution of droplet

Lower: the phase shift angle and the size change

3. Results and Discussions

☐ Evaporation model comparison

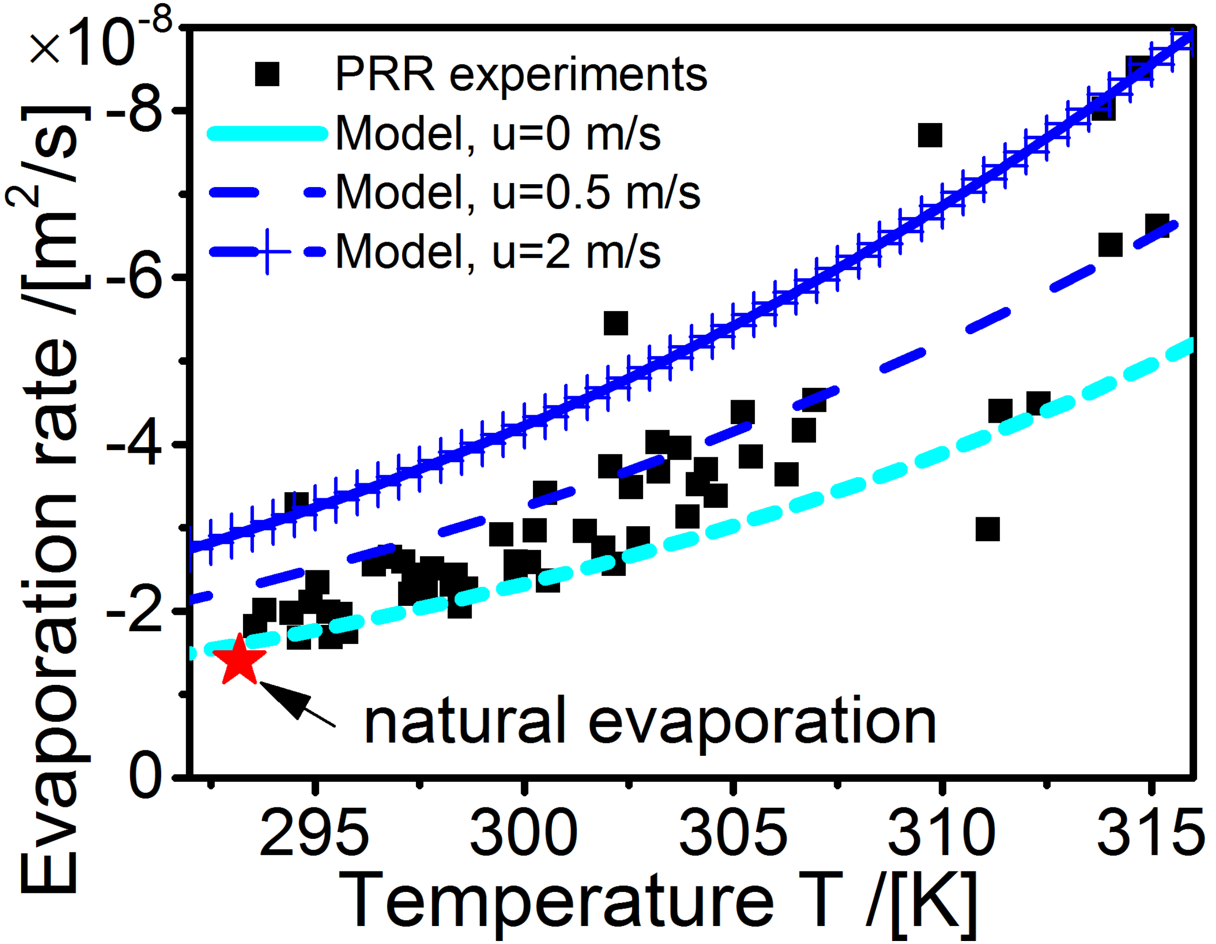
➢ Maxwell and Stefan-Fuchs model

$$k_t = 4D_{\mathrm{v}}\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{l}}}\mathrm{Sh}\ \ln\left(1+B_{\mathrm{M}}\right)$$

Evaporation rate /m²/s	Theory	Experiment
Before spark	-1.36×10^{-8}	-1.28×10^{-8}

After spark: consistent with each other

Local relative velocity varying



Comparison of sixty n-heptane droplets

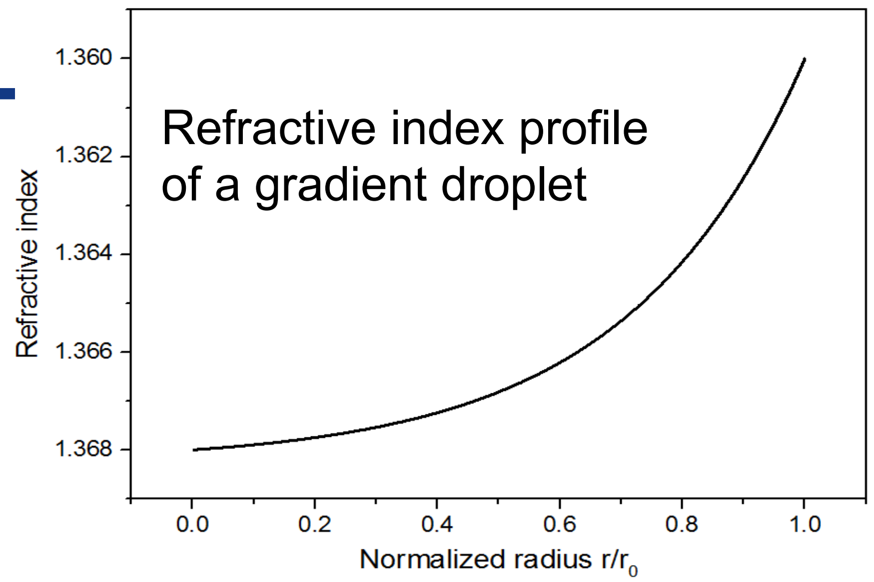
D_v :diffusion coefficient of the vapor
Sh: Sherwood number
B_M: Spalding mass transfer number
ρ_g and ρ_l : densities of the gas surrounding the droplet, and of the droplet's liquid phase, respectively.

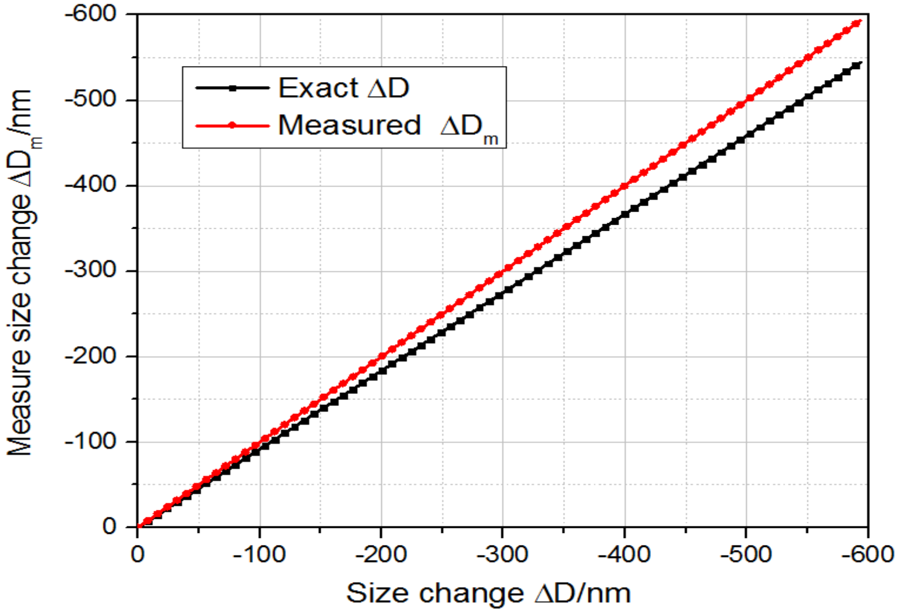
3. Uncertainty analysis

- ☐ **Sources**
- ➢ **Systematic uncertainty:** $1.4^{\circ}C$
  Scattering angle calibration, $0.6^{\circ}C$
  Inversion algorithm: $0.8^{\circ}C$

- ➢ **Droplets inhomogeneity**
  Light is curved inside droplet
  Problem: Optical path unknown
  Inhomogeneity: change or unchange

- ➢ **Evaporation rate uncertainty up to 8-15%**





Comparison of the measured size change with the setting values.

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