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Physical property measurement of primary reference fuels and blends using a droplet generator and strobed imaging

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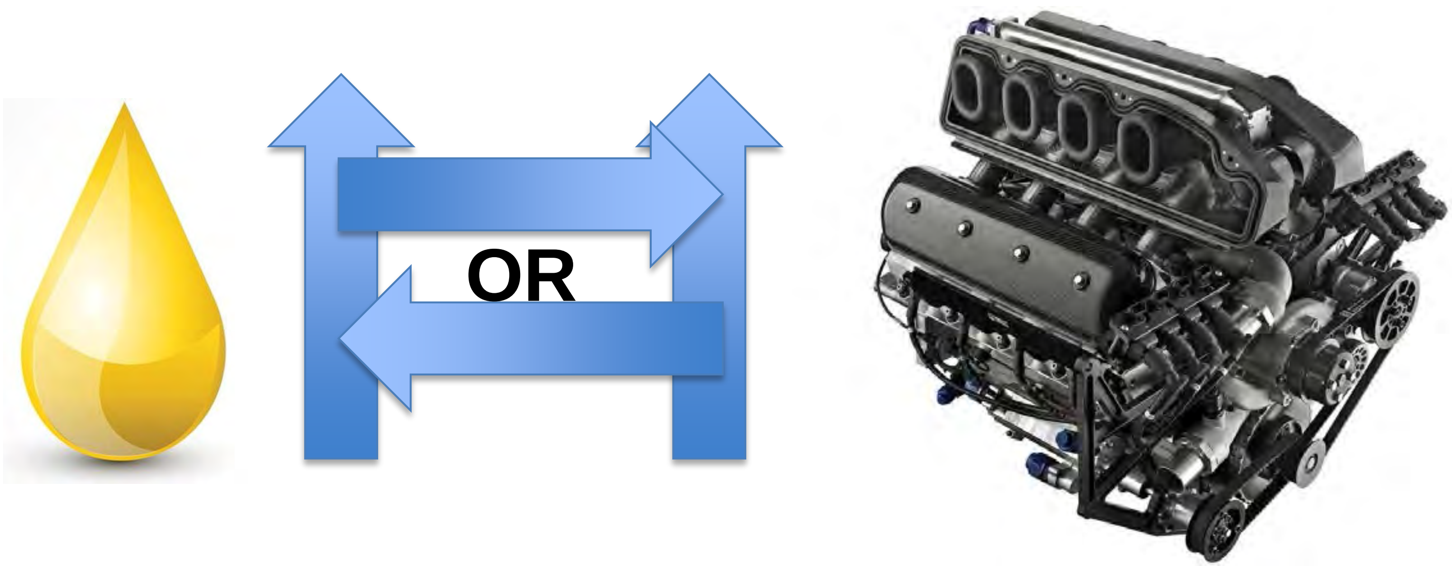
Motivation

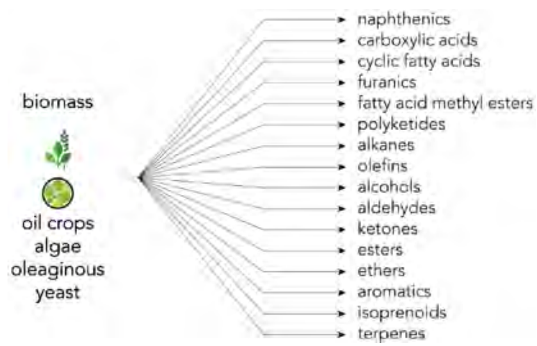
- Department of Energy Co-Optima initiative
  - "*Accelerate the introduction of affordable, scalable, and sustainable high performance fuels for use in high-efficiency, low-emission engines*"
    - Do we optimize fuels for advanced engines?
    - Do we optimize engines for emerging fuels?
    - How about we Co-optimize!

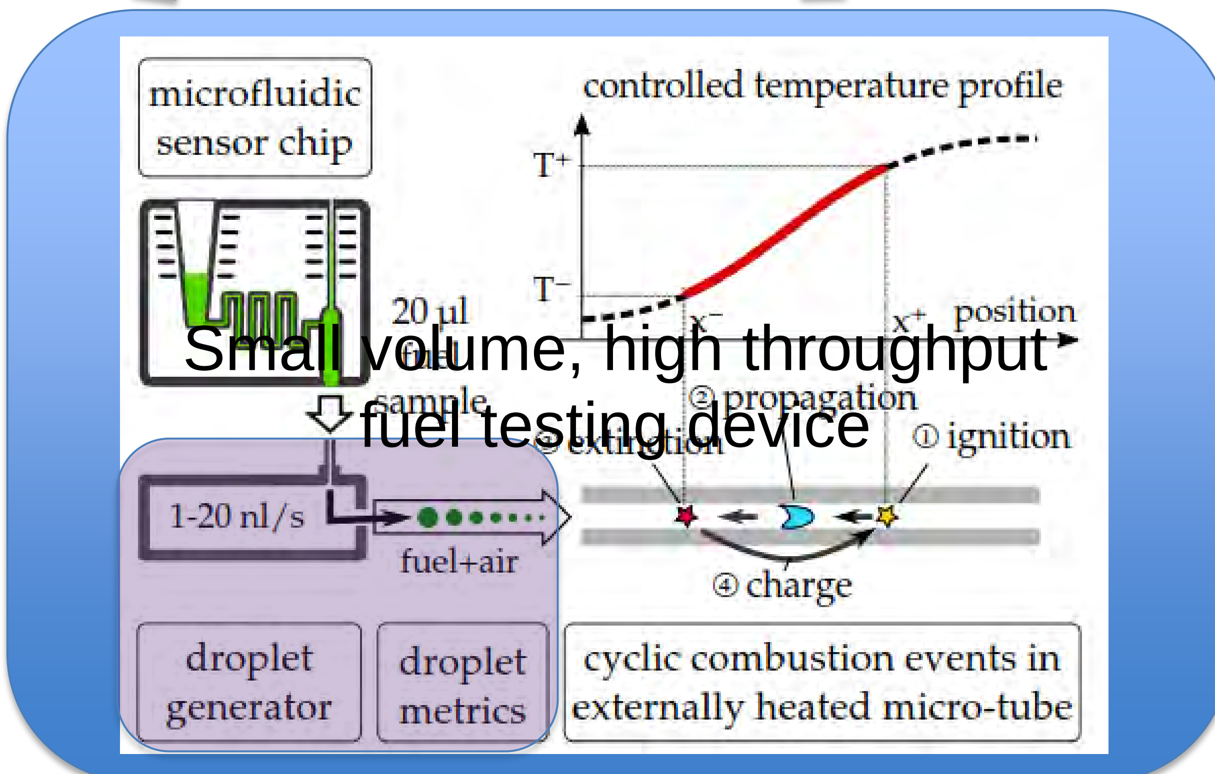


µL-Fuel Ignition Tester ⇔ Micro-FIT

Small volumes of fuel (20µl)

Many hundreds of pure fuels and blends





Physical properties

Combustion metrics

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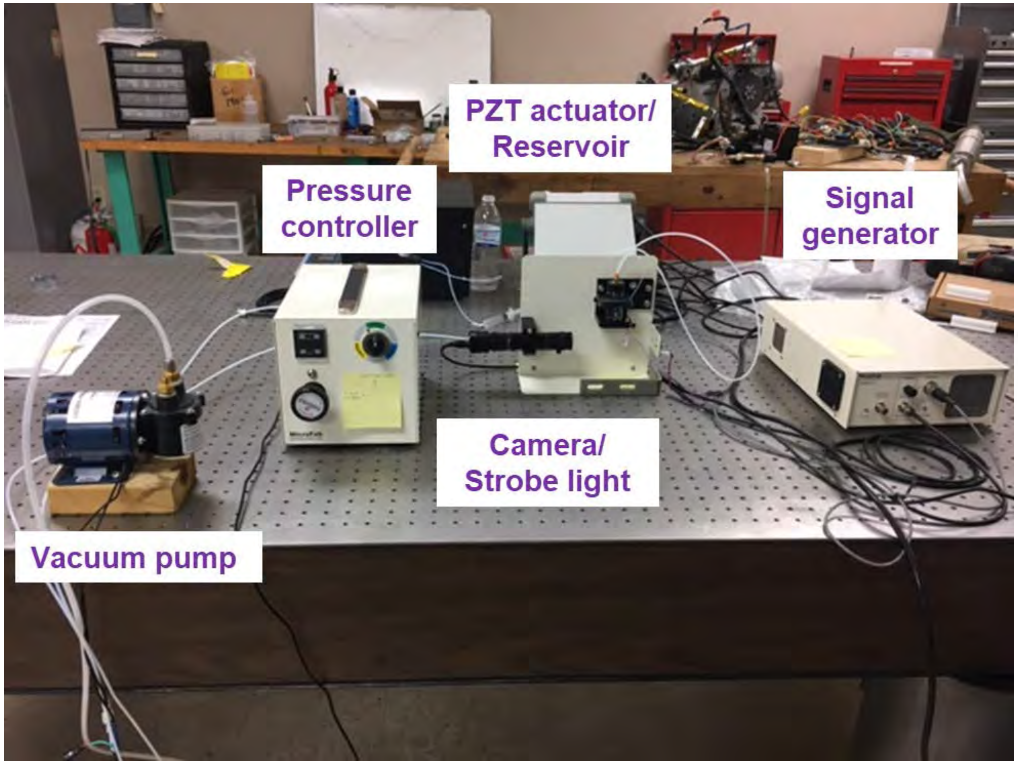
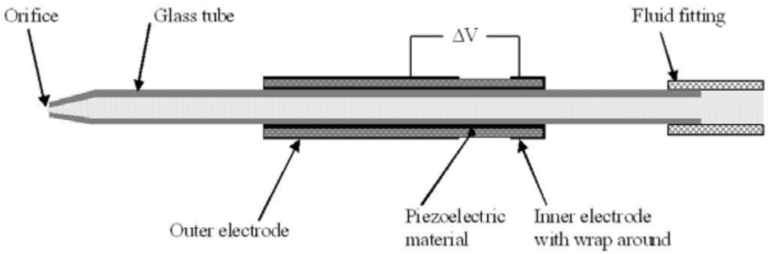
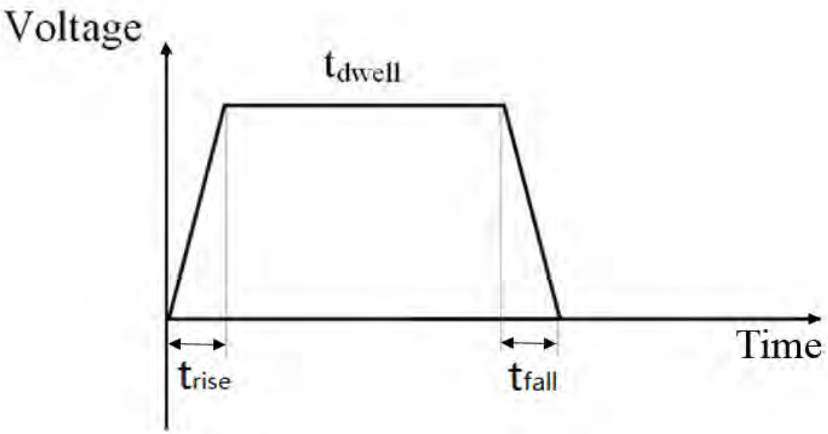
Fuel delivery



Piezo-electric droplet generator



PZT actuator



Applied waveform

 http://www.microfab.com/assemblies

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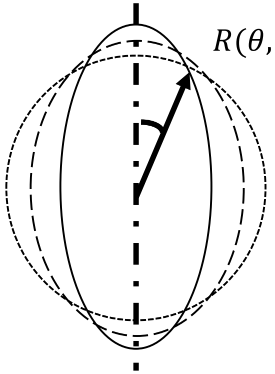
Property measurement

- **Droplet shape oscillations**
  - For an isolated liquid drop undergoing small amplitude axisymmetric oscillation, drop shape $R(\theta, t)$ can be described by[1,2],



$$R(\theta, t) = R_0 + \sum_{n=2}^{\infty} a_n(t) P_n(cos\theta)$$

Where θ is the polar angle, R_0 is the initial radius, P_n are Legendre polynomials and $a_n(t)$ are time-dependent surface mode amplitude coefficients given by,

$$a_n(t) = e^{-\beta_n t} cos\left(\sqrt{\omega_n^2 - \beta_n^2}\, t\right) \text{ where,}$$

$$\omega_n^2 = n(n-1)(n+1)\frac{\sigma}{\rho R_0^3} \text{ and } \beta_n = (n-1)(2n+1)\frac{\mu}{\rho R_0^2}$$

- Measuring the decay rate β_n, gives **viscosity** μ
- Measuring the eigenfrequency ω_n, gives **surface tension** σ

[1]Staat, H. J. et al. (2017). Ultrafast imaging method to measure surface tension and viscosity of inkjet-printed droplets in flight. *Experiments in fluids*, 58(1), 2.
[2]Lamb H (1932) *Hydrodynamics*. Cambridge University Press, Cambridge

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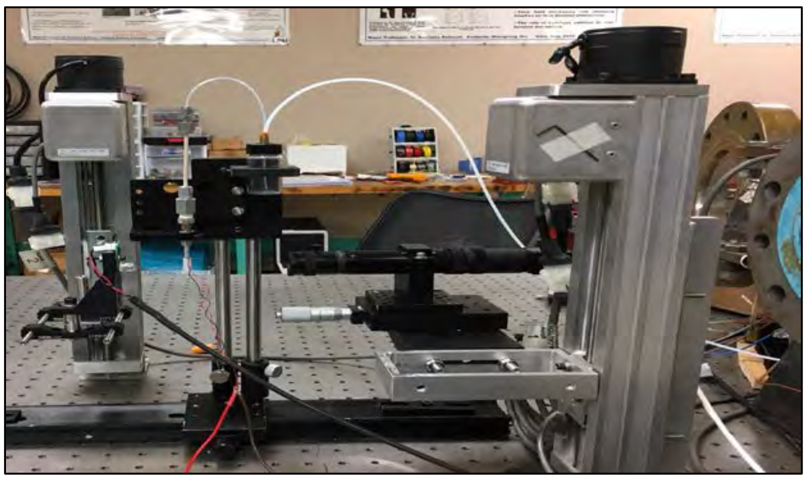
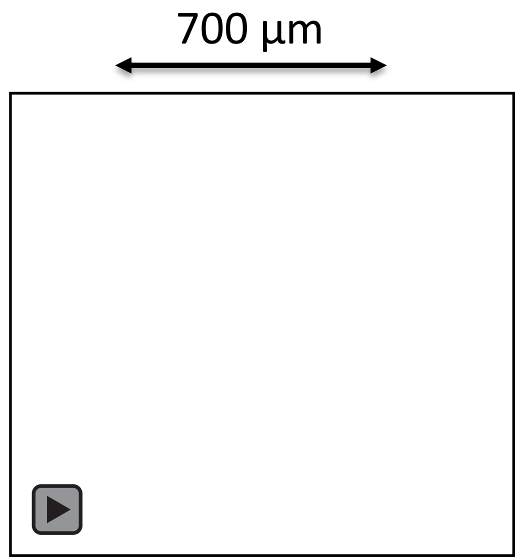
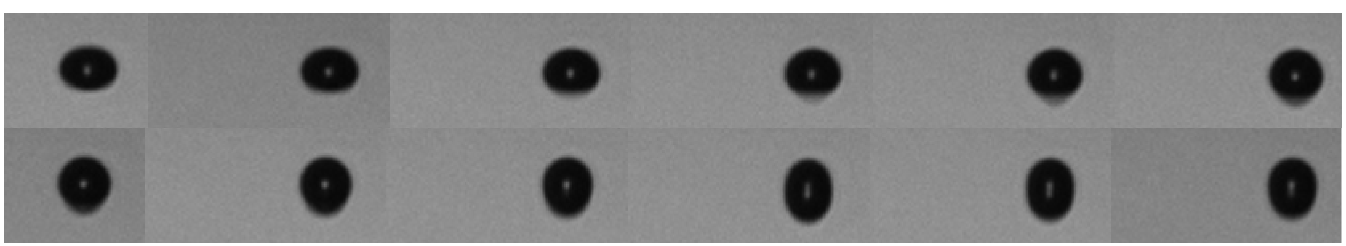
Experiment

- **Droplet generation at 1 atm pressure and 20^0C**
  - Nozzle diameter = 30 µm
  - Droplet imaged using strobe imaging 1 µs apart
  - Camera & optics resolution ~ 2-3 µm/pixel





Water droplets
- ~50 µm
- ~1—2 m/s



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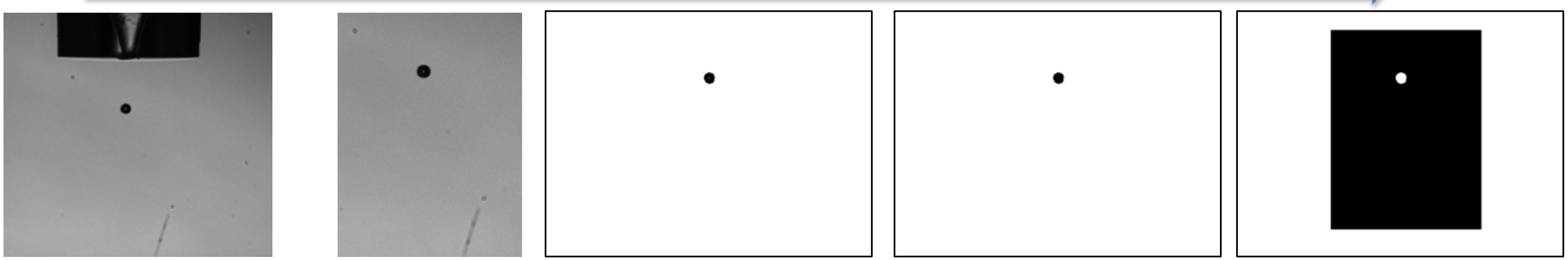
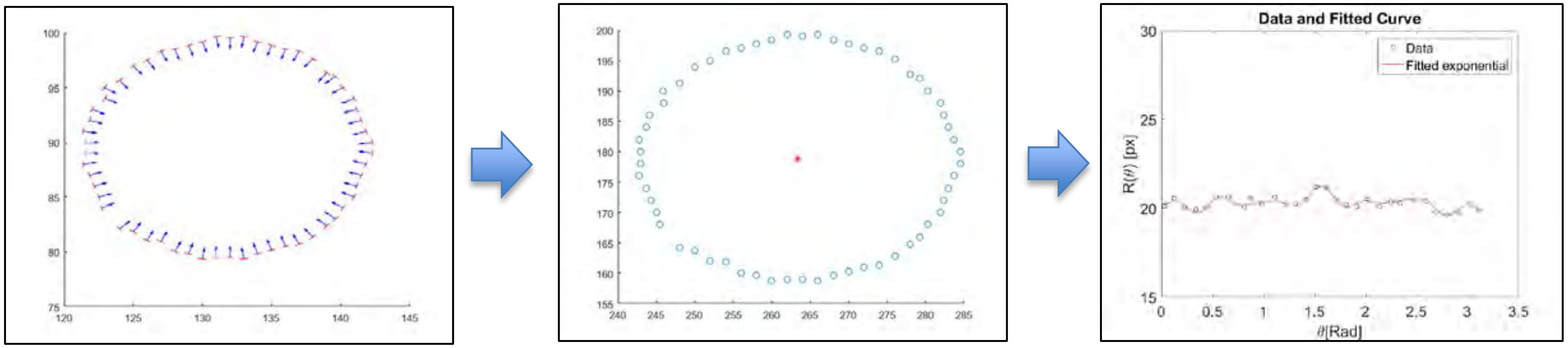
Co-Optimization of Fuels & Engines

Data processing

1. Image batch cropping and processing
2. Droplet edge detection using "Subpixel edge location[1]"
3. Co-ordinates of droplet centroid (MATLAB function)
4. Droplet radius calculated as function of polar angle at each location/time





[1]Trujillo-Pino, A., Krissian, K., Alemán-Flores, M., & Santana-Cedrés, D. (2013). Accurate subpixel edge location based on partial area effect. Image and Vision Computing, 31(1), 72-90.

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Data processing

5. Least-square curve fitting to solve for $a_2(t)$ – time-dependent surface mode amplitude coefficients, n is the mode number, P_n are Legendre polynomials

$$R(\theta, t) = R_0 + \sum_{n=2}^{\infty} a_n(t) P_n(cos\theta)$$

6. $a_0(t) = R_0$, where R_0 is the equilibrium radius
7. Use $a_2(t)$ to find the decay rate β_n
8. Perform Discrete Fourier Transform (DFT) to get eigen-frequency of the shape mode f_2
9. Compute viscosity and surface tension

Test cases

- Primary reference fuels:
  - *Iso*-octane: Octane rating of 100 → Most resistant to auto-ignition
  - *n*-heptane: Octane rating of 0 → Least resistant to auto-ignition

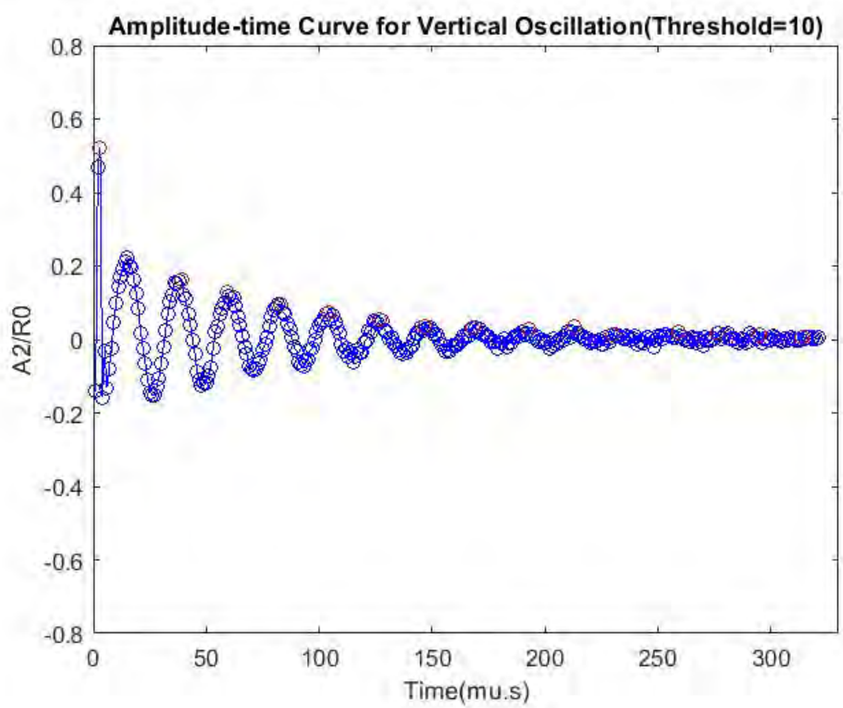
Test Conditions

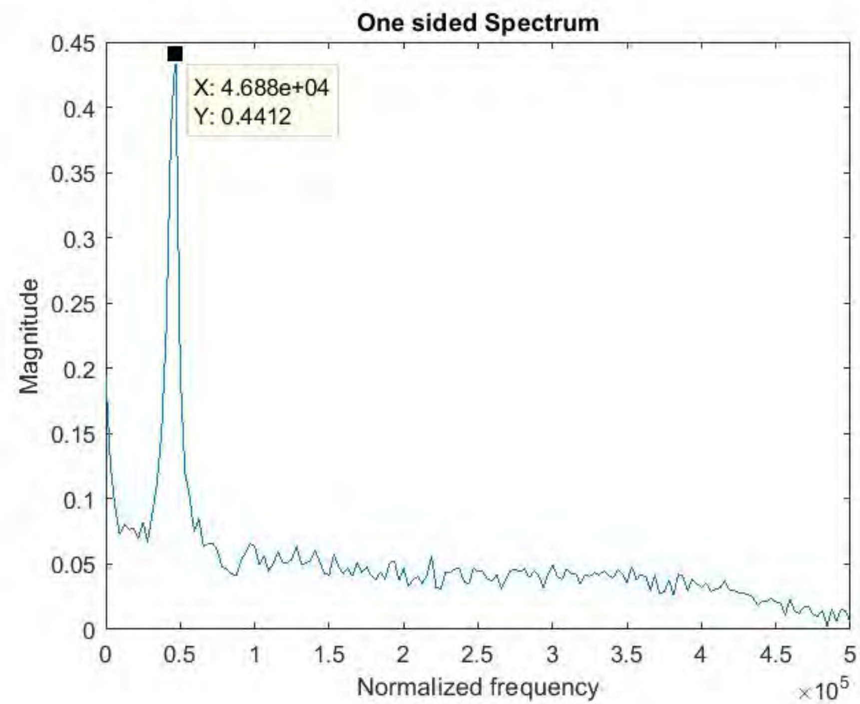
Ambient temperature = 20°C
Pressure = 1 atm
Droplet generation at 720Hz
Applied voltage = 33-34 V
Dwell time = 27-32 µs
Rise time = 5 µs
Fall time = 5 µs
Back pressure = -0.3 in. Hg

Case	*Iso*-octane	*n*-heptane
1	100	0
2	75	25
3	50	50
4	25	75
5	0	100

Results

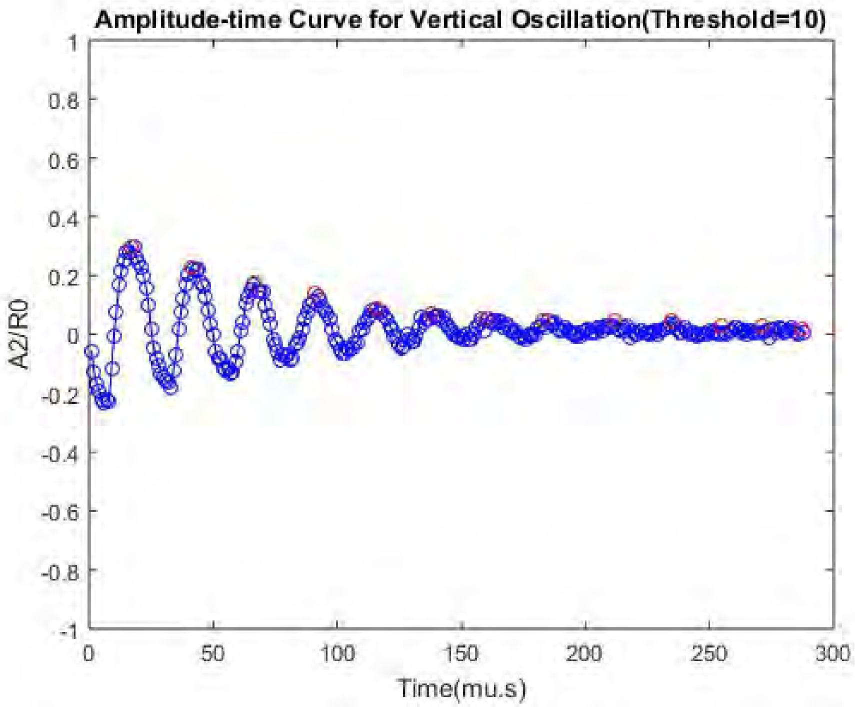
100% - *Iso*-octane

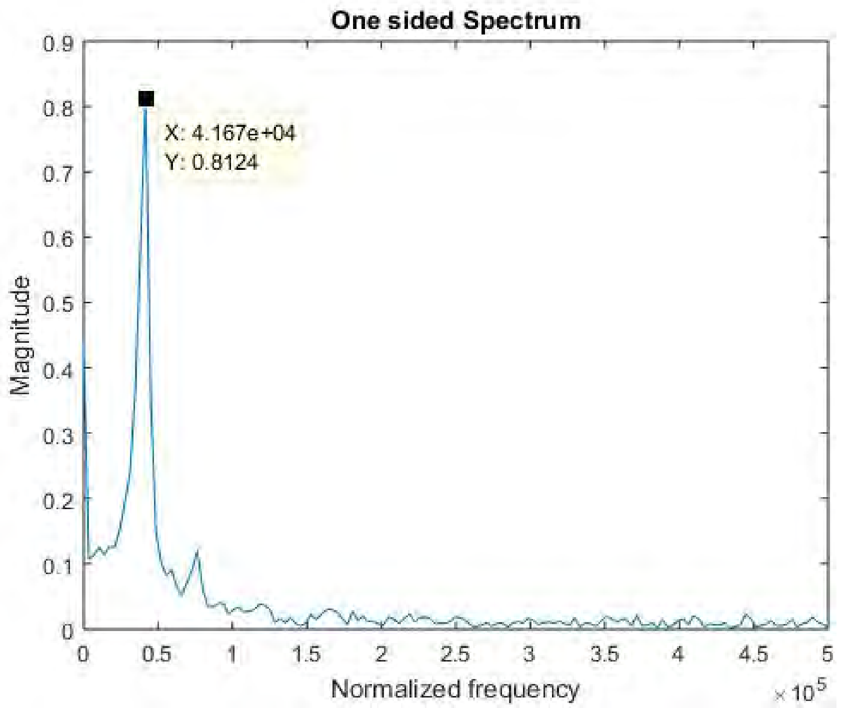




Results

100% - *n*-heptane





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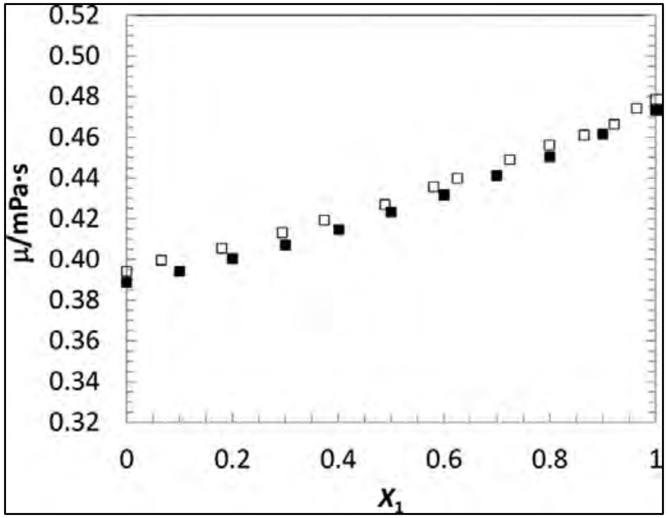
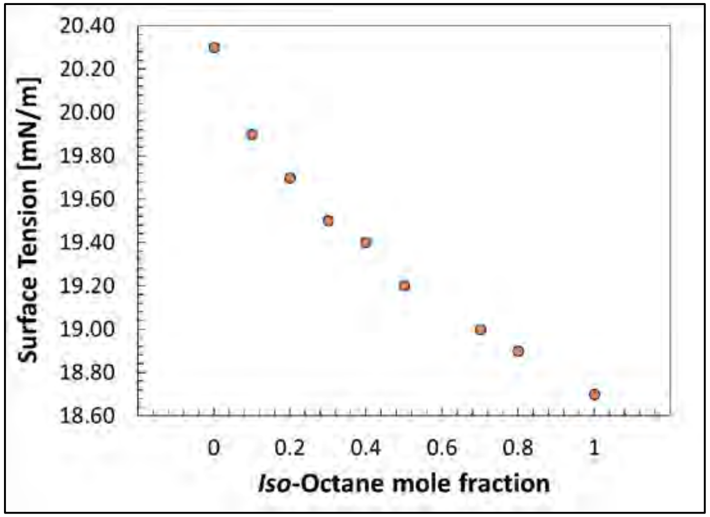
Correlations for properties of PRF blends

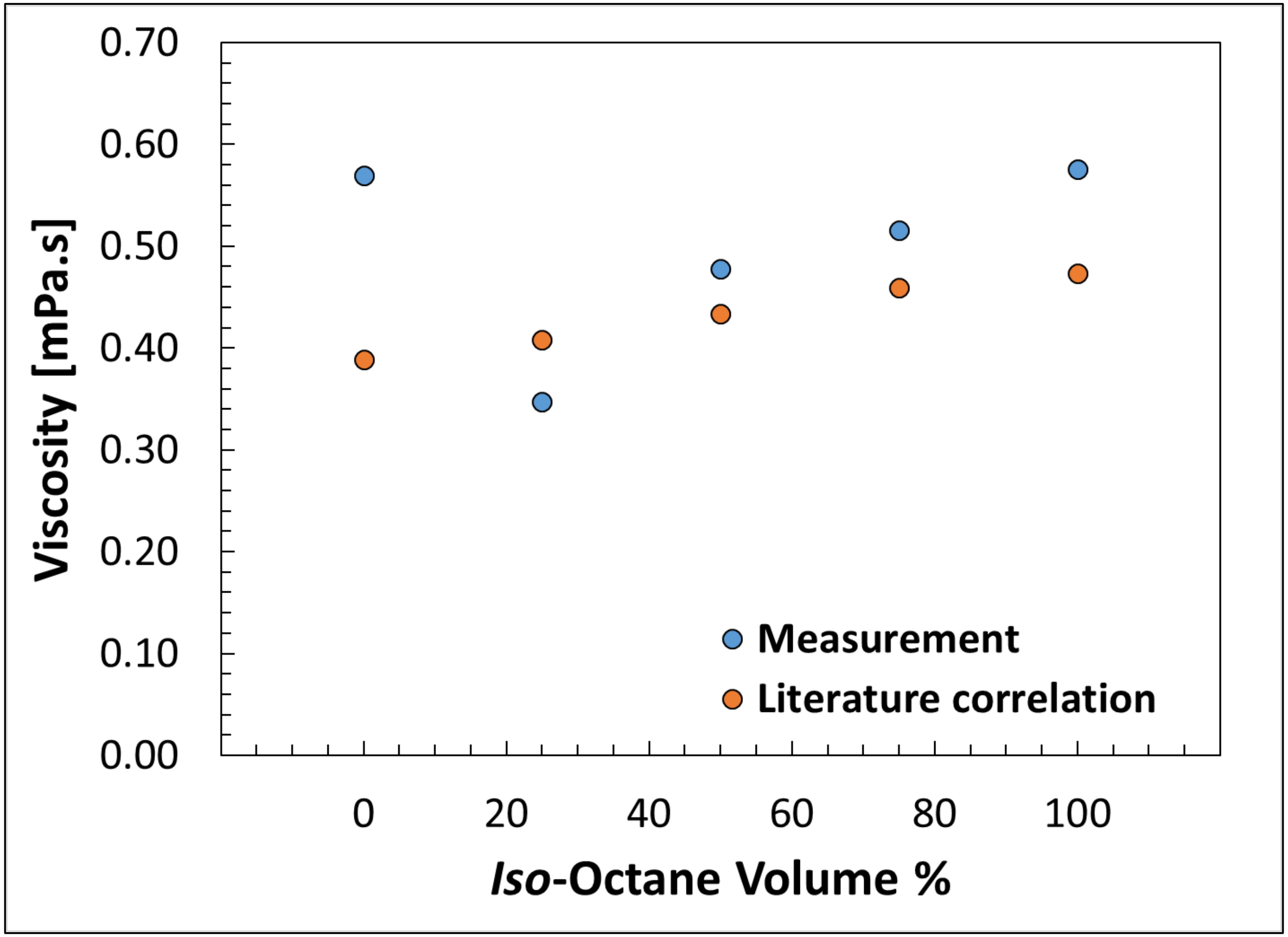




- $\rho_{mixture} = AX_1^2 + BX_1 + C$
- $\nu_{mixture} = X_1^3 ln\nu_1 + 3X_1^2X_2\nu_{1,2} + 3X_1X_2^2 ln\nu_{2,1} + X_2^3 ln\nu_2 - ln\left(X_1 + \frac{X_2M_2}{M_1}\right) + 3X_1^2X_2 ln\left(\frac{1}{3}\left(2 + \frac{M_2}{M_1}\right)\right) + 3X_1X_2^2 ln\left(\frac{1}{3}\left(1 + 2\frac{M_2}{M_1}\right)\right) + X_2^3 \ln(\frac{M_2}{M_1})$
- $\mu_{mixture} = \nu_{mixture} * \rho_{mixture}$
- X_1, X_2 are mole fraction, ν_1, ν_2 are pure component viscosities, M_1, M_2 are molecular masses

[1]Dianne J. Luning Prak; Jim S. Cowart; Paul C. Trulove; J. Chem. Eng. Data 2014, 59, 3842-3851

Mixture viscosity



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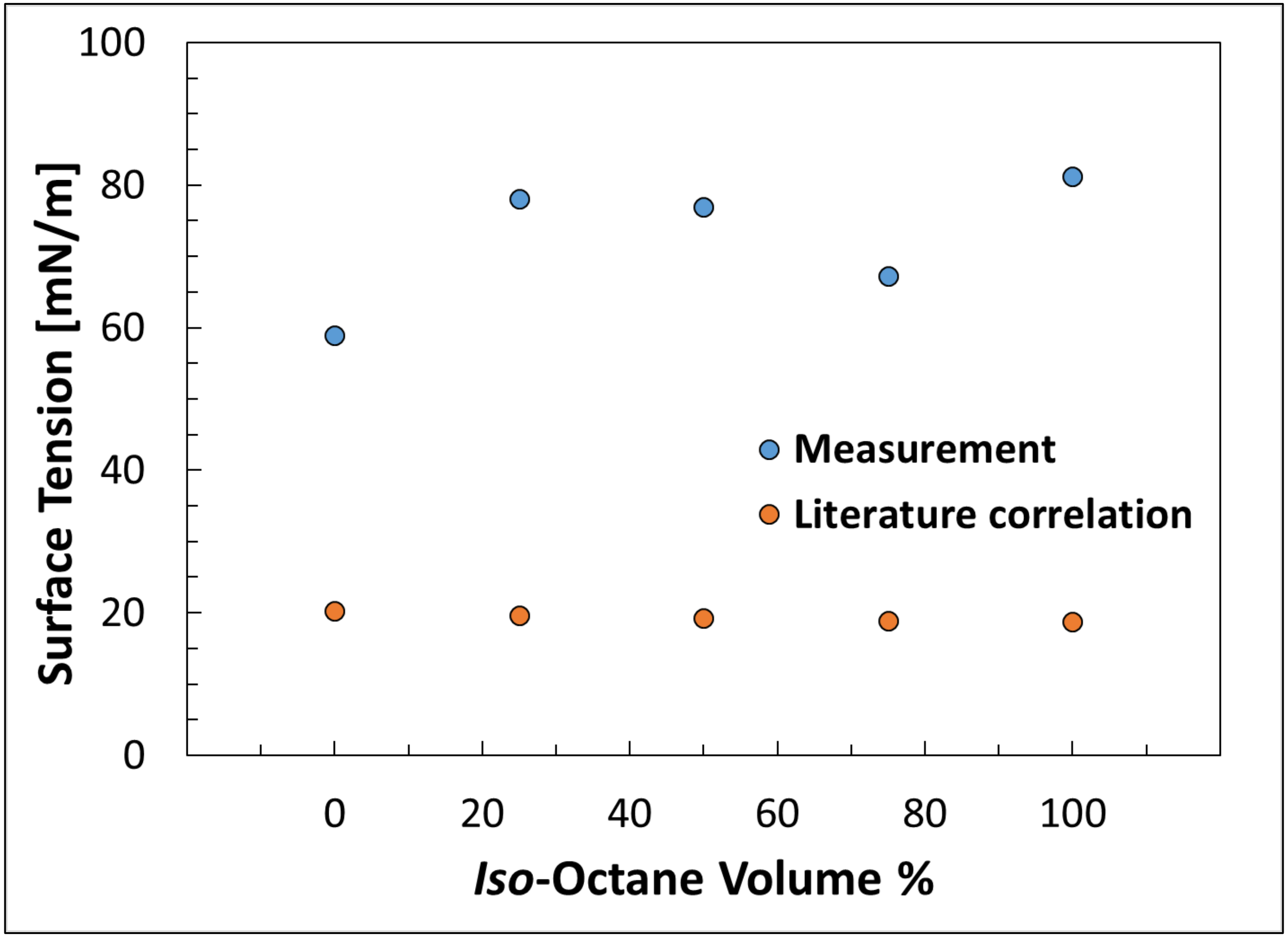
Mixture surface tension



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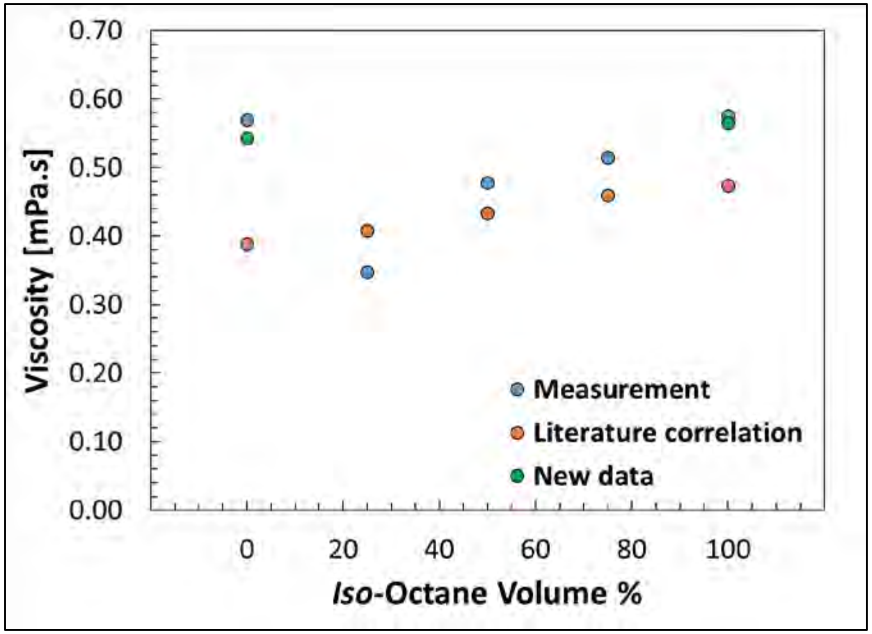
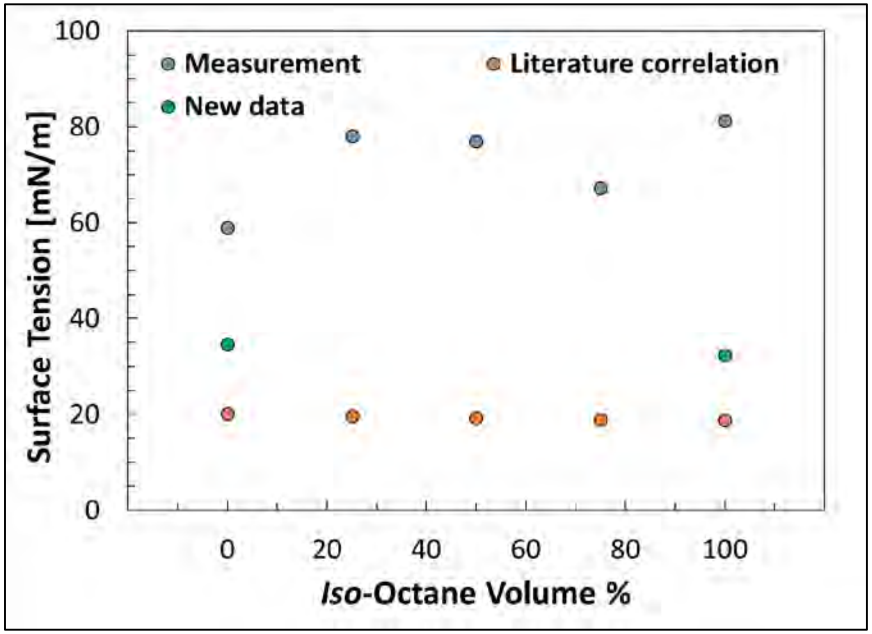
Updated results

- Switching method between fuels was not proper. Fuel samples were likely not of expected concentration.
- System is air purged between samples for 2 minutes to ensure complete removal of previous fuel sample.





	Dynamic Viscosity(mPa.S)	Surface Tension (mN/m)
Pure Iso-octane	0.565	32.37
Pure n-heptane	0.5428	34.62

Error sources

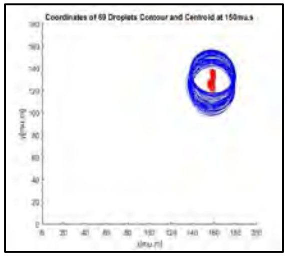
- Uncertainty in droplet size

$$R(\theta,t) = R_0 + \sum_{n=2}^{\infty} a_n(t)P_n(cos\theta)$$

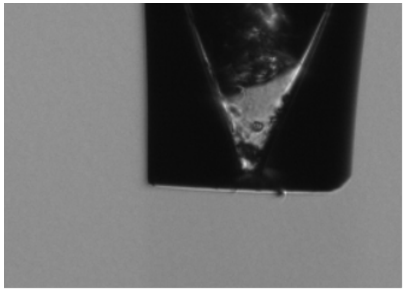
- Droplet motion during flight

		Units
Strobe exposure	5	µs
Droplet velocity	1.2	m/s
Distance traveled	6	µm

- Non-repeatability of setup

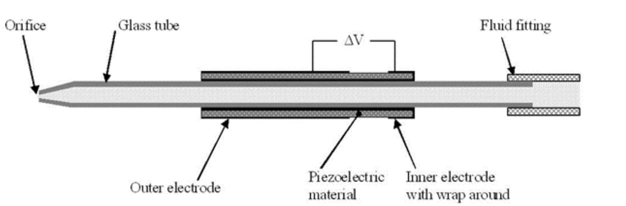


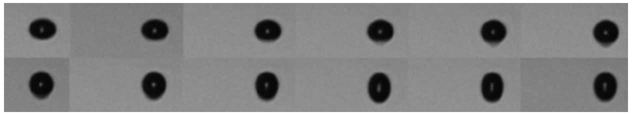
- Possible debris in fuel sample

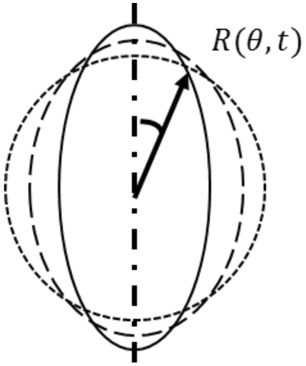


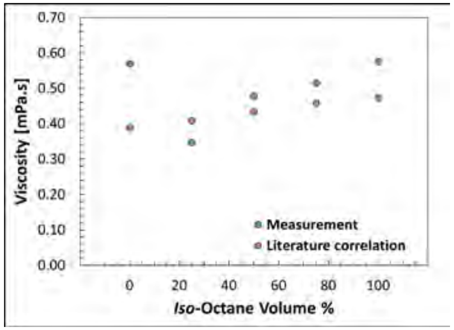
Conclusions

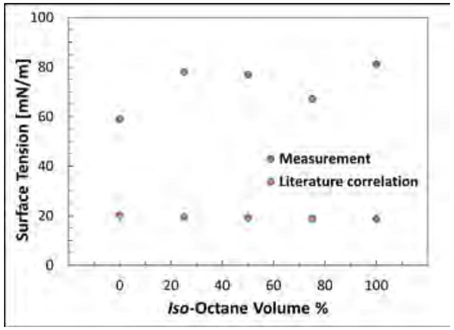
- A micro-liter fuel delivery apparatus using a piezo-electric droplet generator is used to measure physical properties – surface tension and viscosity.
- Fuel physical properties are estimated using droplet shape oscillations.
- Initial results for viscosity and surface tension are encouraging.
- Current efforts focus on reducing errors by:
    - Better synchronization between camera & strobe
    - Replacement of strobe by high powered short duration laser pulse











Acknowledgement

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Questions?