Lecture 26: Molecular Tagging Techniques Part - 03

Dr. Hui HU

Martin C. Jischke Professor and Director

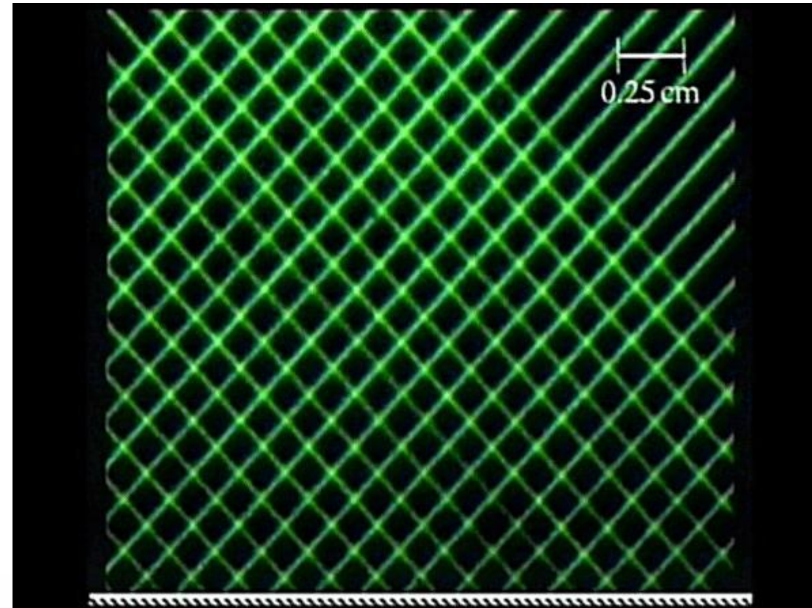
Advanced Flow Diagnostics and Experimental Aerodynamics Laboratory

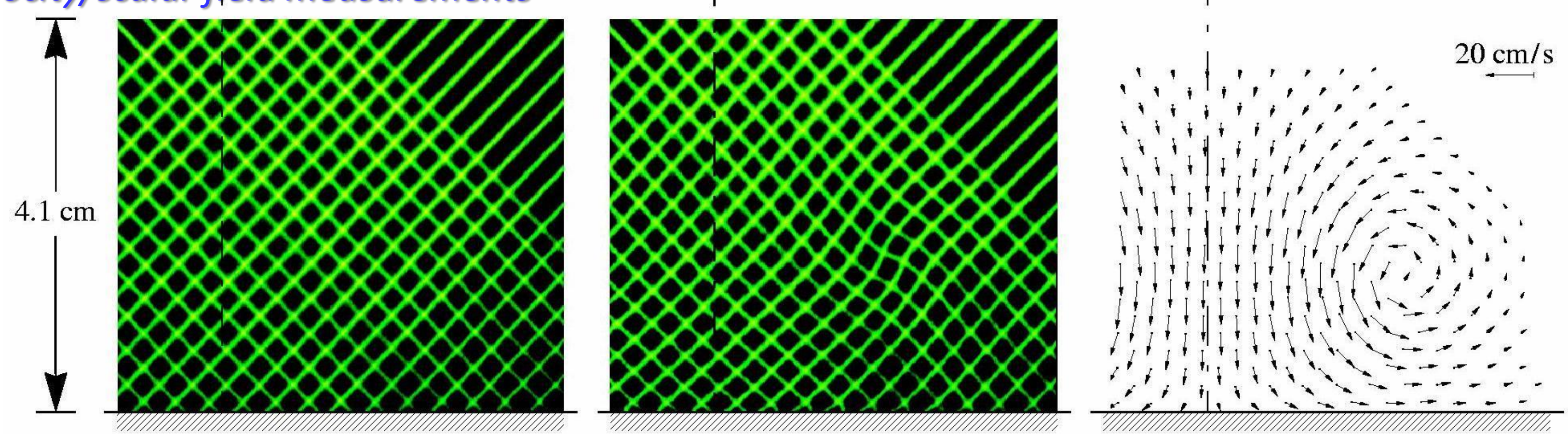
Department of Aerospace Engineering, Iowa State University
2251 Howe Hall, Ames, IA 50011-2271
Email: huhui@iastate.edu

 Copyright © by Dr. Hui Hu @ Iowa State University. All Rights Reserved!

❑ Molecular Tagging Velocimetry (MTV): General Description

- *Whole field, non-intrusive, optical diagnostic technique*
- *Use special chemical molecules premixed in fluid flows as long lifetime tracers*
- *A pulsed laser is used to "tag" small regions of interest*
- *Tagged regions are imaged twice with pre-set time delay*
- *The displacement vectors of the tagged regions provide the estimate of the velocity vectors of the fluid flow.*
- *Line (1-d), Grid (2-d), Stereoscopic (3-d) MTV*
- *Flow visualization and quantitative measurements*
- *Scalar field measurements, simultaneous velocity/scalar field measurements*





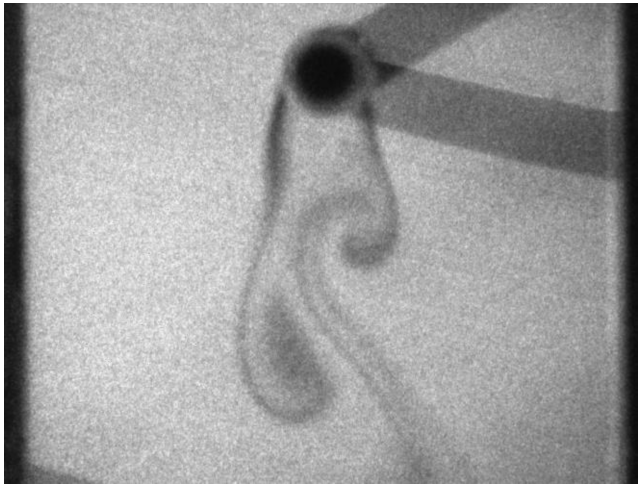
Tagged regions imaged right after the laser pulse

Tagged regions imaged 8 ms later

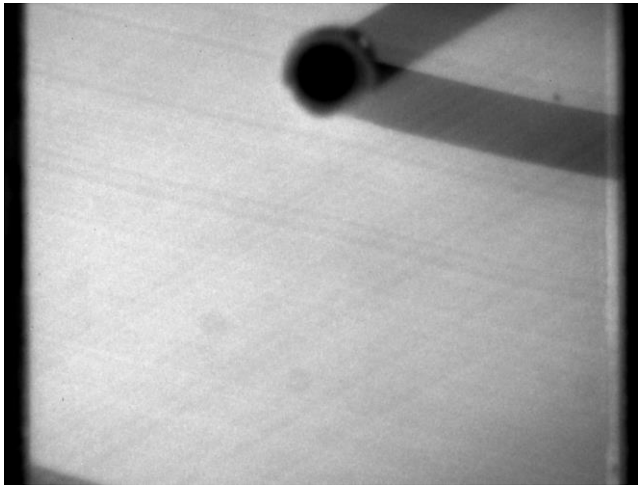
The velocity field derived using a spatial correlation procedure

❑ Molecular Tagging Thermometry (MTT) results

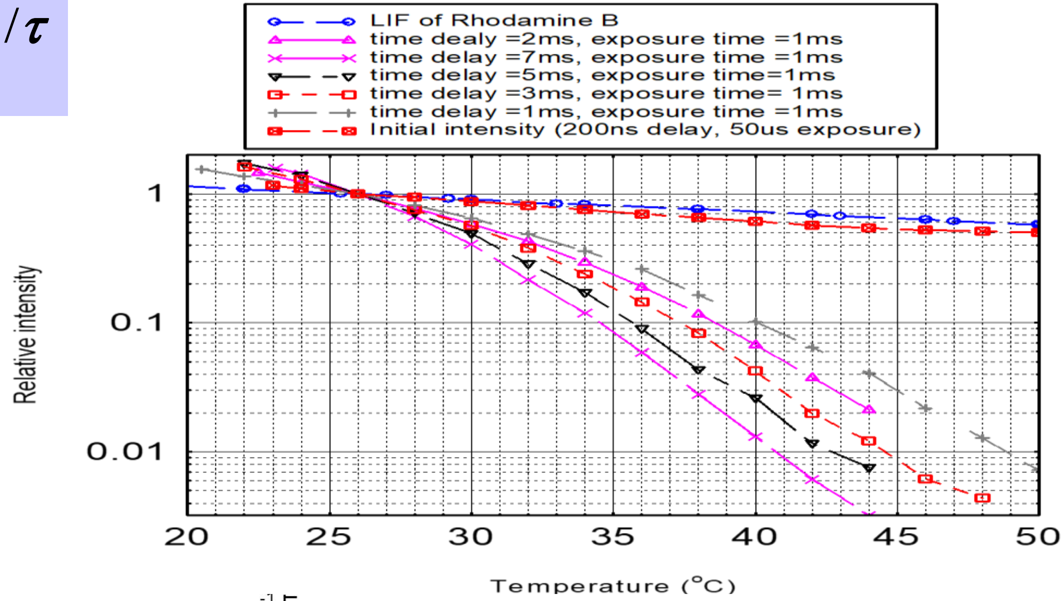
$$I_{em} = I_o e^{-t/\tau} = I_i C \varepsilon \Phi_p e^{-t/\tau}$$

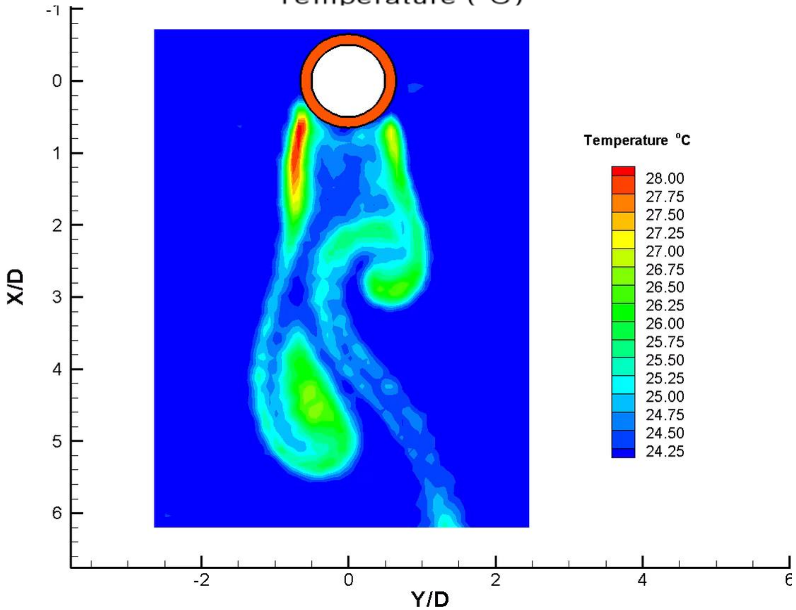


a. 7ms after laser pulse, exposure time



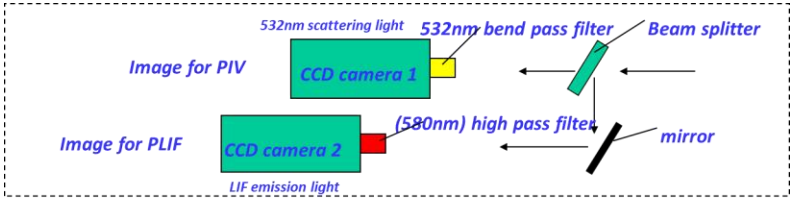
b. Background

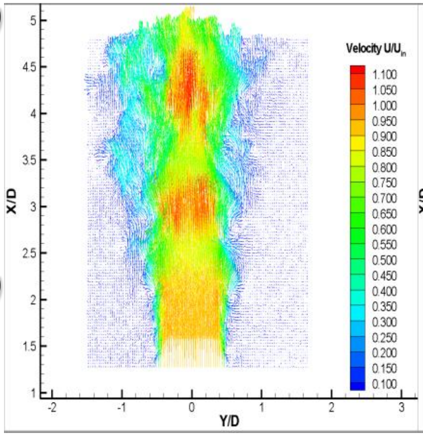


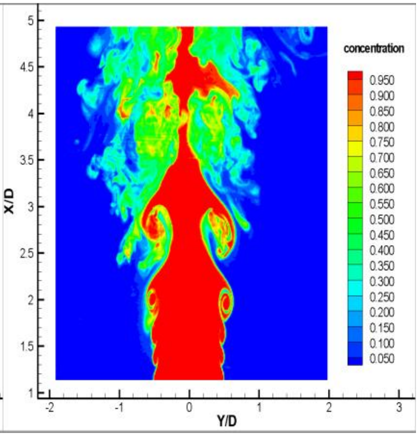


❑ Simultaneous Flow Velocity and temperature Measurements

- *Velocity and temperature* are two *most important variables* in studies of thermo-fluids problems.
- *Development of novel experimental techniques capable of simultaneously measuring whole-field velocity and temperature distributions is very important and essential for either optimum design of various heat-exchange devices or the development and validation of fundamental physical models.*
- *Existing techniques for simultaneous flow velocity and temperature measurements:*
    - *Intrusive, point measurements:*
        - *Cold-wire sensor mounted on an X-wire probes*
            - *Antonia et al. (1975) & Chevray and Tutu (1978)*
    - *Non-intrusive, point measurements:*
        - *LDV + vibrational Raman scattering: Dibble et al. (1984)*
        - *LDV + LIF: Lemoine et al. (1999)*
    - *Non-intrusive, whole-field measurements:*
        - *Combined PIV-PLIF technique:*
            - *PIV for velocity measurements + Planar LIF for temperature measurements:*
                - *Sakakibara et al. (1997), and Grissino et al. (1999)*
        - *Digital particle Image Velocmetry/Therometry (DPIV/T) technique:*
            - *Using Theromochromic Liquid Crystal (TLC) tracers for both velocity and temperature measurements.*
                - *Dabiri and Gharib (1991), and Park et al. (2001)*







❑ Molecular Tagging Velocimetry & Thermometry (MTV&T): Why!!?

- *The limitations of the particle-based techniques (LDV, PIV and DPIV/T):*
  - *They measure the velocity or temperature of tracer particles, other than the velocity or temperature of working fluid directly.*
    - *Flow tracking issues (particle size, density mismatch, …)*
    - *Seeding issues (particles don't always go where you need them)*
    - *Thermal response of the tracer particles for temperature measurements.*

- *The objective of the present study is to develop a novel molecule-based flow diagnostic technique, named Molecular Tagging Velocimetry and Thermometry (MTV&T), for the simultaneous whole-field mapping of velocity and temperature fields in fluid flows.*

- *The Advantages of molecule-based technique:*
  - *Molecular tracers can usually be dissolved in the working fluids, which move exactly with the same velocity as the local fluid molecules. The ambiguities related to the tracking issues of diagnostic tracers for the velocity measurements can be solved.*
  - *The size of the molecular tracers are much smaller than the particle tracers, the issues related to the thermal response of particle tracers for temperature measurements can be significantly mitigate, and perhaps even eliminate.*

❑ Molecular Tagging Velocimetry & Thermometry (MTV&T): How!!?

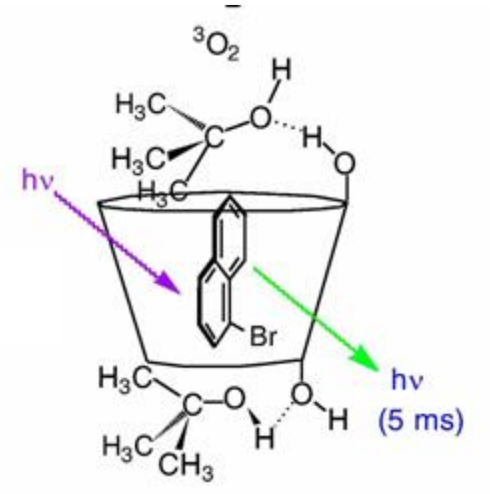
- *Instead of using tiny particles, specially-designed molecules are used as tracers for both flow velocity and temperature measurements.*
- *A pulsed laser is used to "tag" the tracer molecules in the regions of interest.*
- *The tagged molecules can be turned into long-lived glowing tracers upon the pulsed laser excitation.*
- *The movements of the tagged molecules are imaged at two successive times within the photoluminescence lifetime of the tracer molecules after the same laser excitation pulse.*
- *The measured Lagrangian displacement of the tagged molecules between the two image acquisitions provides the estimate of the flow velocity vector.*
- *The simultaneous temperature measurement is achieved by taking advantage of the temperature dependence of photoluminescence lifetime, which is estimated from the intensity ratio of the tagged molecules in the two images.*

	Particle-based technique (PIV)	*Molecular-tagging technique*
Diagnostic tracer	*tiny particles (~μm)*	*molecules (~nm)*
Illumination laser pulse for each frame of measurement	*2 pulse*	*1 pulse*
Imaging photo source	*scattering light (same wavelength as illumination laser)*	*photoluminescence emission (fluorescence/phosphorescence)*
Measured flow variables	*velocity*	*multiple flow variables (velocity and temperature)*

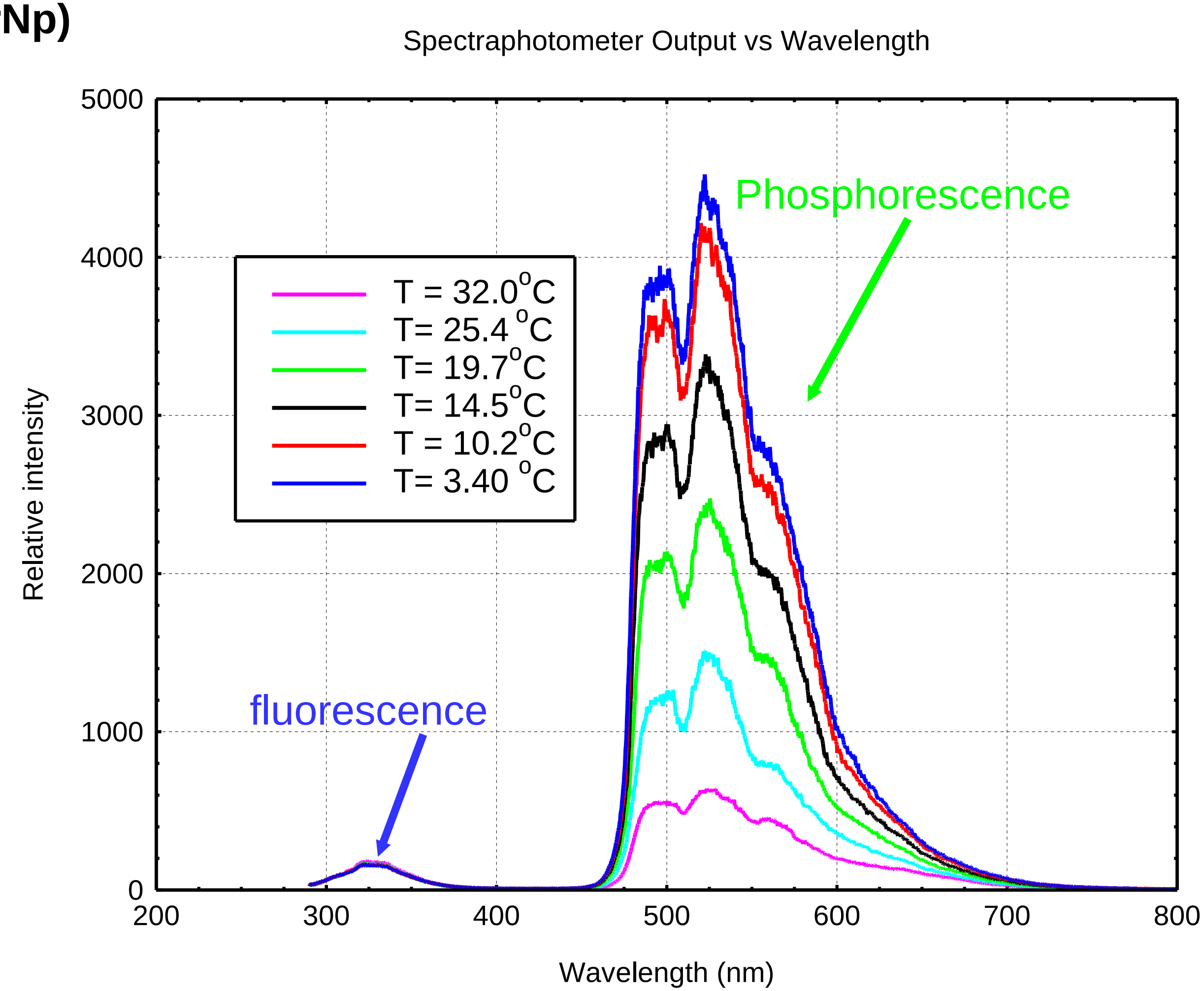
Long Lifetime Phosphorescent Molecular Tracers

Phosphorescent triplex (1-BrNp • Gβ-CD • ROH)

1. Bromonaphthalene (1-BrNp)
2. Cyclodextrin (Gβ-CD)
3. Alcohols (ROH)



Phosphorescence emission lifetime is about 5 ms at room temperature



Copyright © by Dr. Hui Hu @ Iowa State University. All Rights Reserved!

❑ Molecular Tagging Thermometry (MTT) technique

- According to quantum theory, the phosphorescence emission intensity can be expressed as:

$$I_{em} = I_o e^{-t/\tau} = \frac{I_i C \varepsilon \Phi_p}{\tau} e^{-t/\tau}$$

I_i : the local incident laser intensity C : concentration of phosphorescence dye

ε : the absorption coefficient Φ_p: phosphorescence quantum yield, temperature-dependant

τ : phosphorescence lifetime, which refers to the time when the intensity drops to 37% (i.e. 1/e) of the initial intensity (I_0), temperature-dependant.

- Thomson and Maynes (2001) demonstrated the possibility of temperature measurement by mapping the phosphorescence intensity of the 1-BrNp·Gβ-CD·ROH supramolecules. The spatial and temporal variations of the incident laser intensity would have to be corrected for separately to extract quantitative temperature data from the phosphorescence images by using this method.

- A novel method, named lifetime-based thermometry technique (Hu and Koochesfahani 2003), is used in the present study for the quantitative temperature mapping of fluid flows.

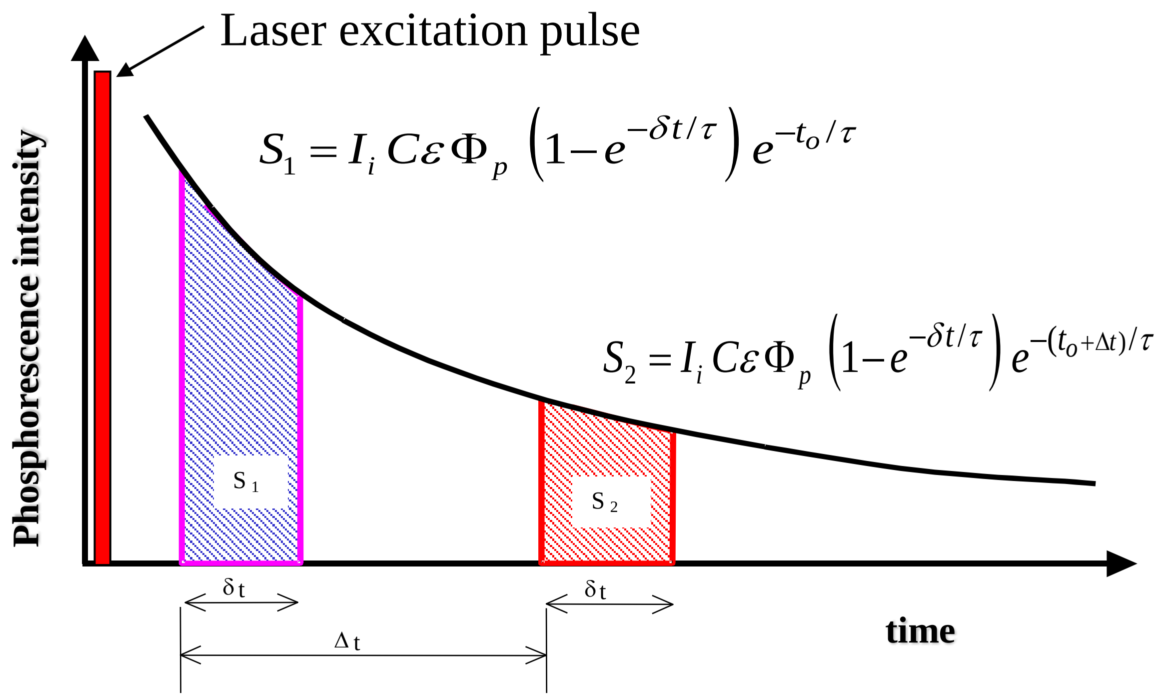
Copyright © by Dr. Hui Hu @ Iowa State University. All Rights Reserved!

❑ Lifetime-based Molecular Tagging Thermometry (MTT) Technique

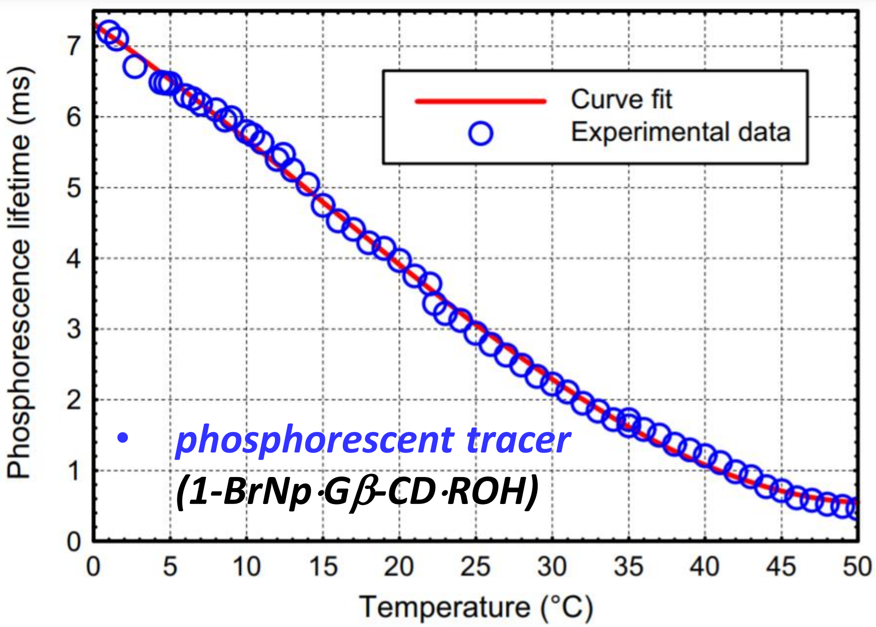
- ***Lifetime imaging technique:***

$$\frac{S_2}{S_1} = e^{-\Delta t/\tau} \quad \Rightarrow \quad \tau = \frac{\Delta t}{\ln(S_2/S_1)} \quad \overset{\tau = \tau(T)}{\Rightarrow} \quad T = T(x, y)$$

- ***Phosphorescence lifetime of tagged molecules can be calculated on a pixel-by-pixel basis.***
- ***It is a ratiometric method, which can eliminate the effect of the incident laser intensity for the temperature measurement.***



❑ Lifetime-based Molecular Tagging Thermometry (MTT) Technique



- *phosphorescent tracer* *(1-BrNp·Gβ-CD·ROH)*

- ***Phosphorescence Lifetime vs. Temperature***

Advantages of lifetime-based Thermometry:

- ***High temperature sensitivity:***
  - ***About 5.0% per °C at 20 °C .***
  - ***About 20.0% per °C at 50 °C .***
  - ***Much higher than commonly used LIF dye (Rhodamine B, ~ 2.0% per °C).***
- ***Ratiometric method:***
  - ***It can eliminate the effect of the non-uniformity of incident laser intensity and the dye concentration on the temperature measurement.***

- ***Simultaneous velocity and temperature measurements:***
  - ***A pulsed Laser is used to "tag" tracer molecules premixed in fluid flows.***
  - ***The movements of the tagged tracer molecules are imaged twice after the same laser pulse.***
  - ***The displacements of the tagged molecules between two interrogations is used to derive velocity vectors.***
  - ***The intensity ratio of the two images is used to derive fluid temperature distribution.***
  - ***It allows the simultaneous quantification of velocity and temperature fields by using the same phosphorescent tracer (1-BrNp·Gβ-CD·ROH) and same optical and equipment setup.***

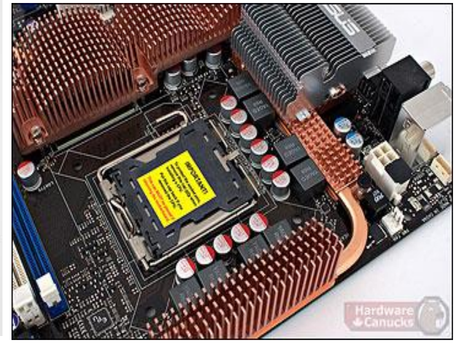
❑ Thermal Effects on the Wake Instability Behind Heated Cylinder

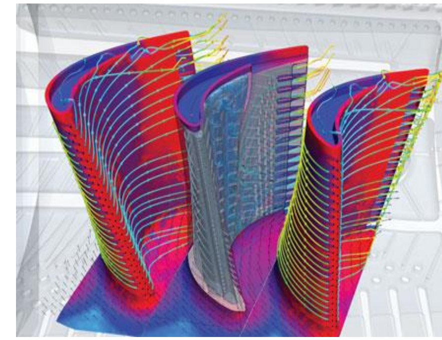
incoming flow

heated cylinder $T_w > T_\infty$

Buoyancy force

Gravity direction

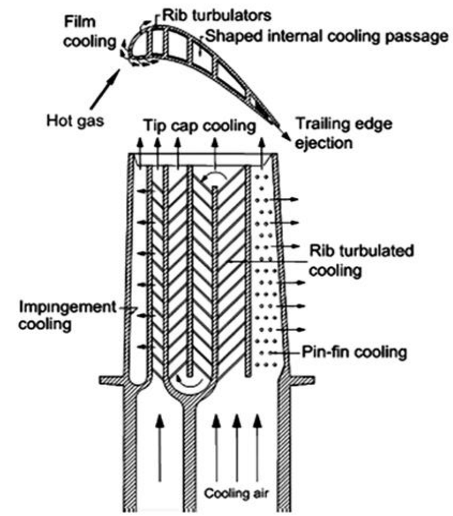




$$Re_D = \frac{UD}{\nu} = \frac{\text{inertial force}}{\text{viscous force}}$$

$$Gr_D = \frac{g\beta(T_s - T_\infty)D^3}{\nu^2} = \frac{\text{buoyancy force}}{\text{viscous force}}$$

$$Ri_D = \frac{Gr_D}{Re_D^2} \propto \frac{\textit{buoyancy force}}{\textit{inertial force}}$$

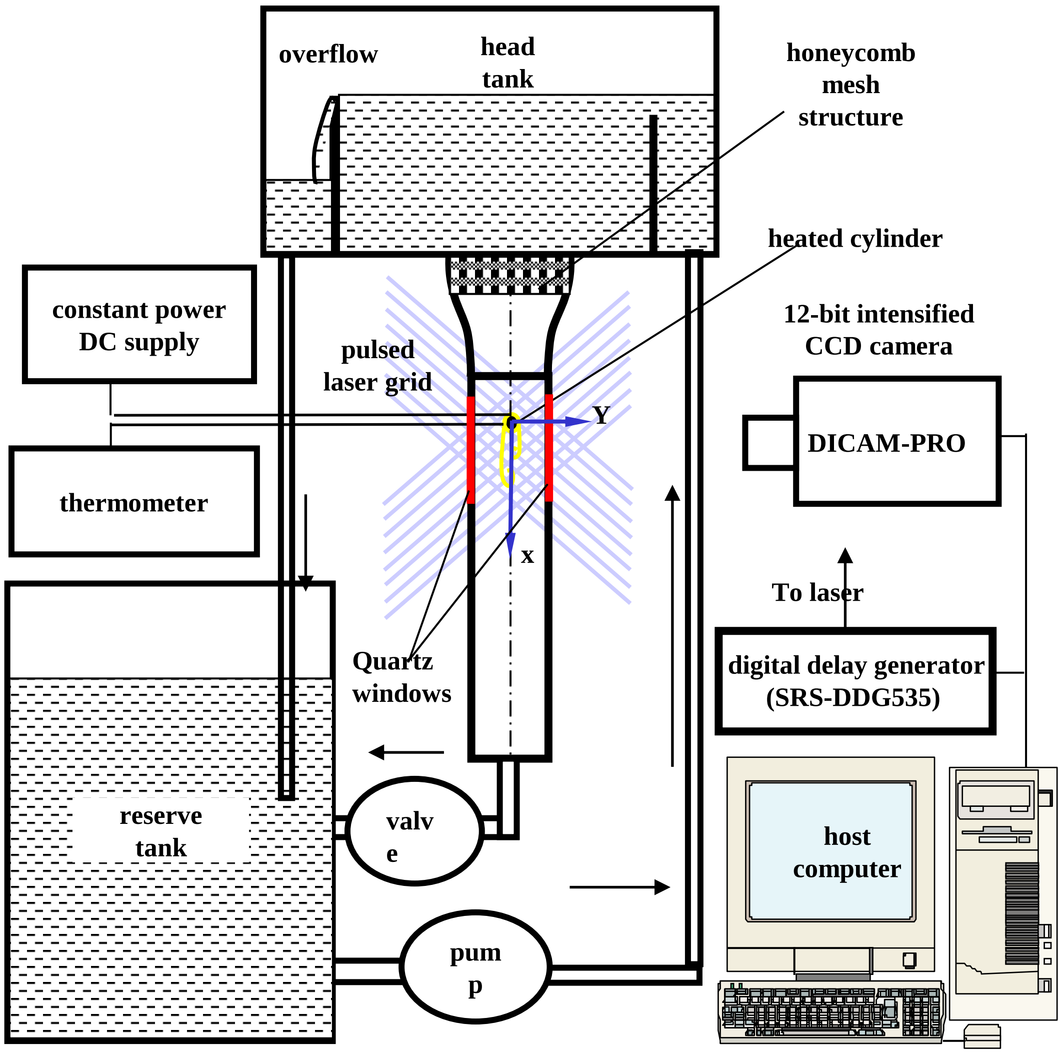


Present study:

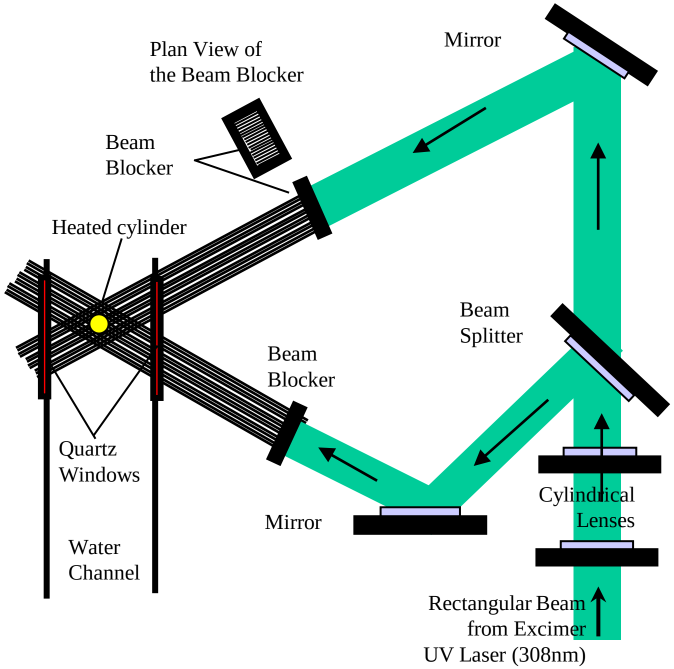
- ❑ ***In coming flow condition is fixed:*** ***(T_{fluid} = 24.0 ℃ , U_{in}=2.6cm/s, Re=130)***
- ❑ ***Cylinder temperature is changing (Tw):*** ***24.0 ℃ ~ 83.0 ℃***
- ❑ ***Richardson numbers (Ri_D):*** ***0.00 ~ 1.05***
- ❑ ***Heat transfer regime:*** ***forced convection ~ mixed convection***

- **Hu H, Koochesfahani MM,** "Thermal Effects on the Wake of a Heated Circular Cylinder Operating in Mixed Convection Regime", *Journal of Fluid Mechanics,* Vol.685, pp235-270, 2011.

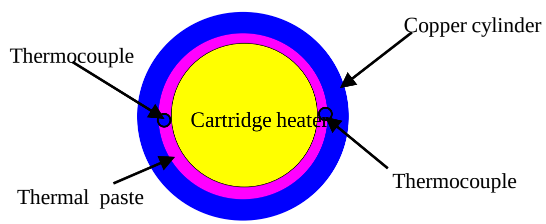
❑ Experimental Setup for MTV&T Measurements



Experimental setup



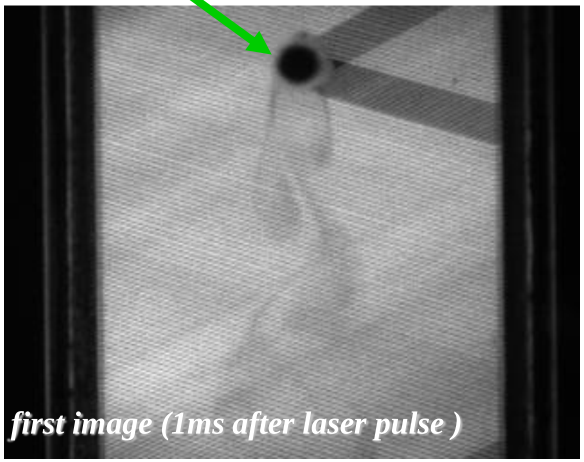
Optical setup

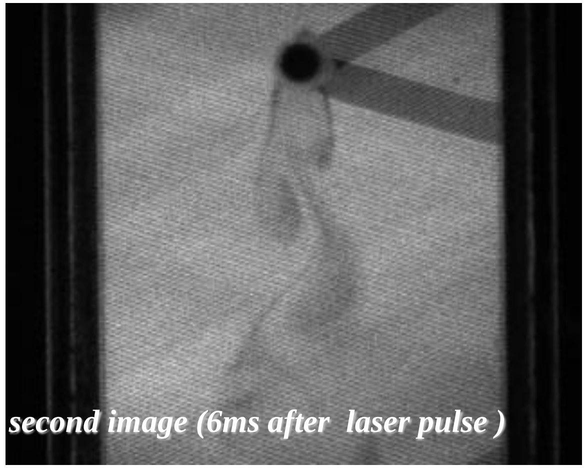


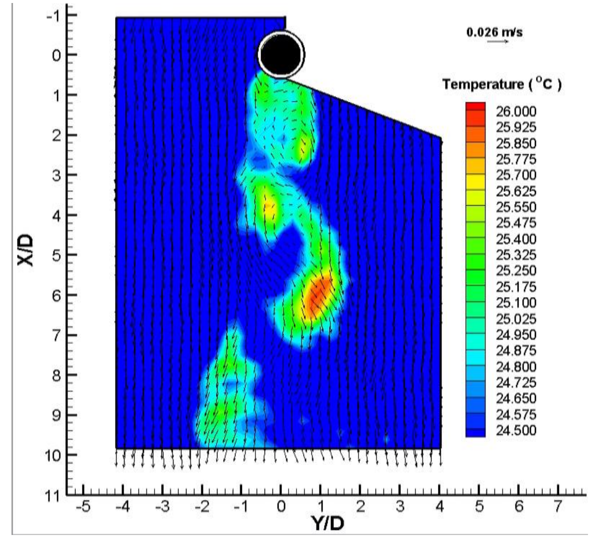
Heated cylinder

❑ SIMULTANEOUS MEASUREMENTS OF VELOCITY & TEMPERATURE FIELDS

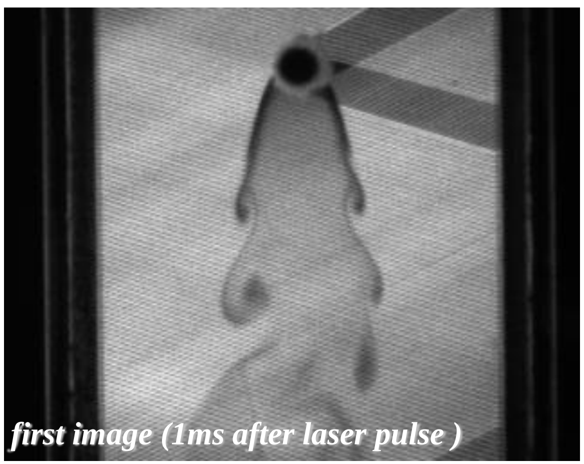
heated cylinder

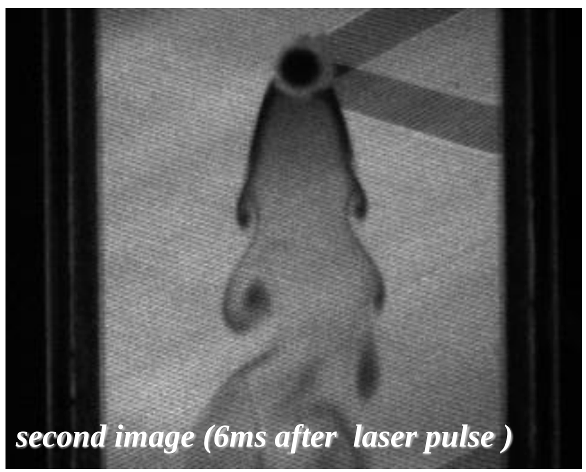


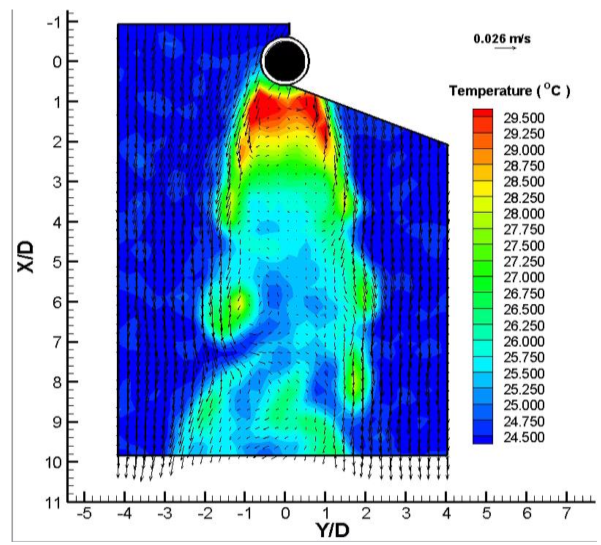




A: T_{fluid} = 24.0 ℃; $T_{cylinder}$ = 35.0 ℃; Re=130; Gr=3300; Ri=0.19; St=0.157



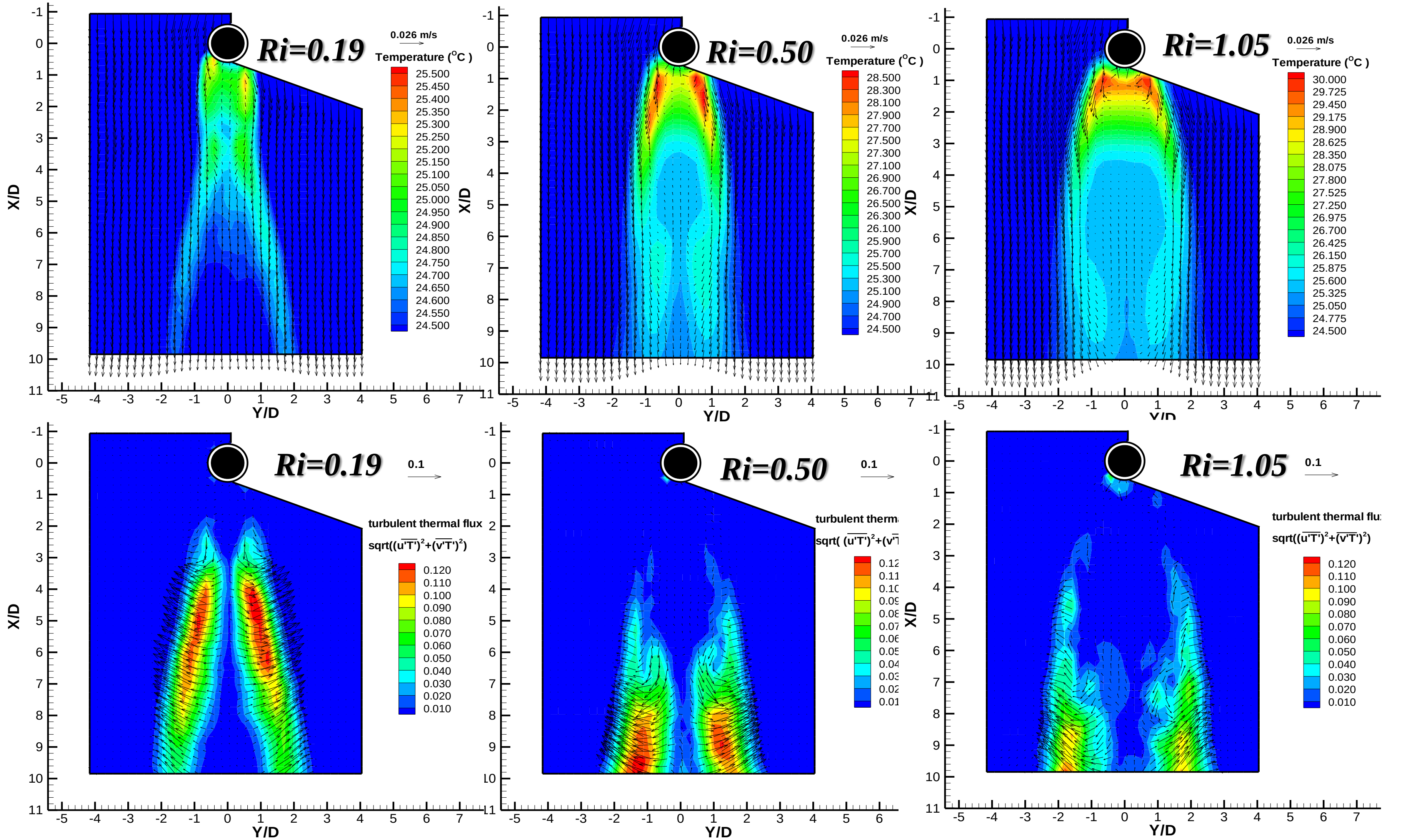




B: T_{fluid} = 24.0 ℃ , $T_{cylinder}$ = 83.0 ℃; Re=130; Gr=18200; Ri=1.05; Str=0.103

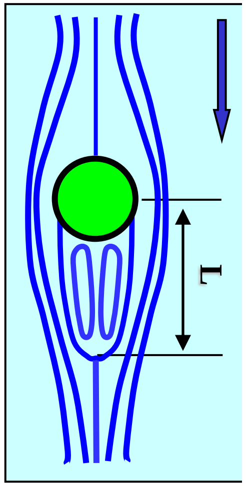
(Hu and Koochesfahani. JFM, Vol.685, pp235-270, 2011)

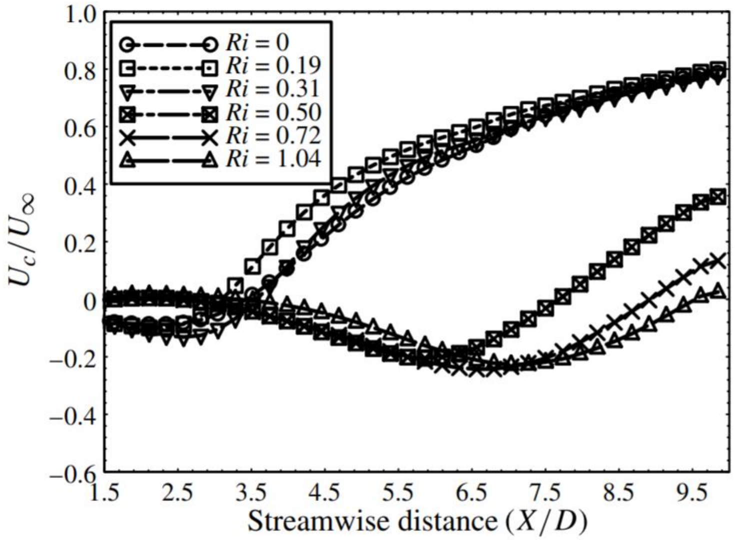
❑ Ensemble-averaged MTV&T Measurement Results

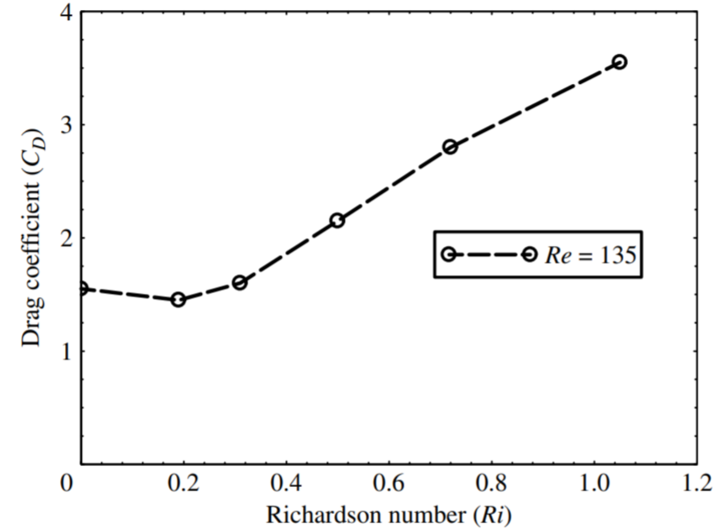


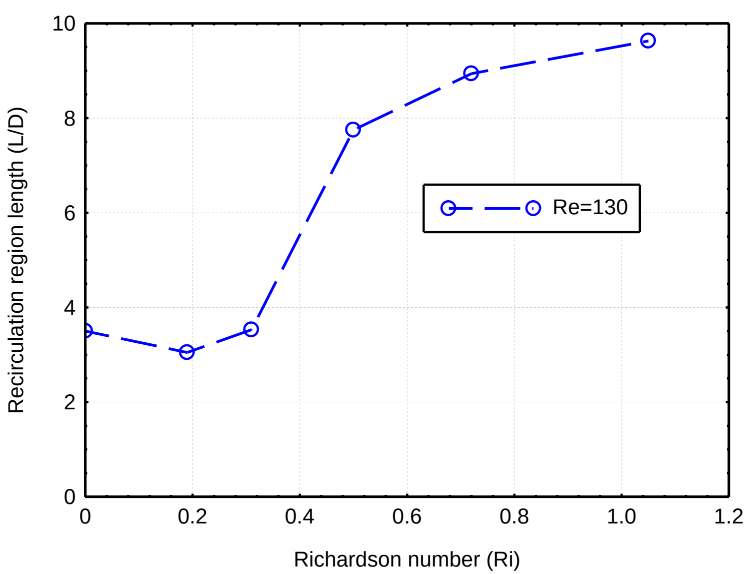
- ***Hu H, Koochesfahani MM,*** *"Molecular Tagging Velocimetry and Thermometry (MTV&T) Technique and Its Application to the Wake of a Heated Circular Cylinder", Measurement Science and Technology, Vol. 17, No. 6, pp1269-1281, 2006 (* ***2007 Best Paper Award, Measurement Science and Technology, IOP Publishing)***

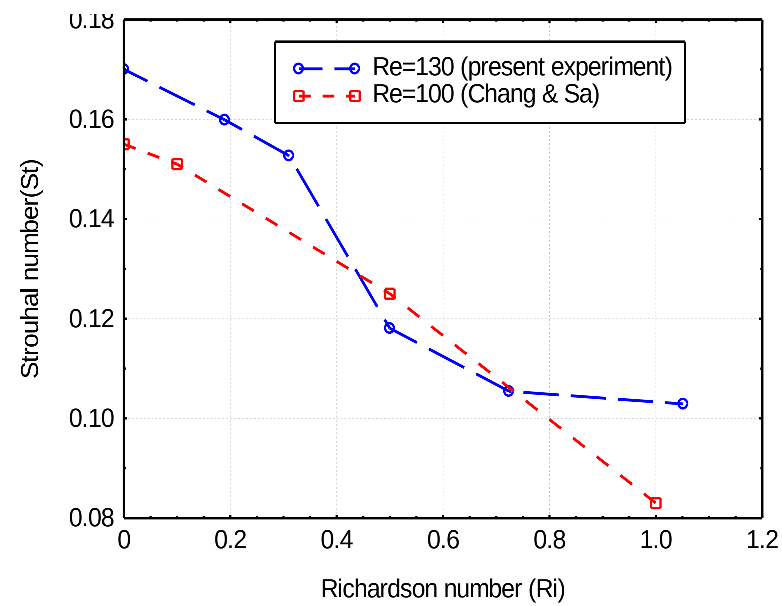
❑ Ensemble-averaged MTV&T Measurement Results





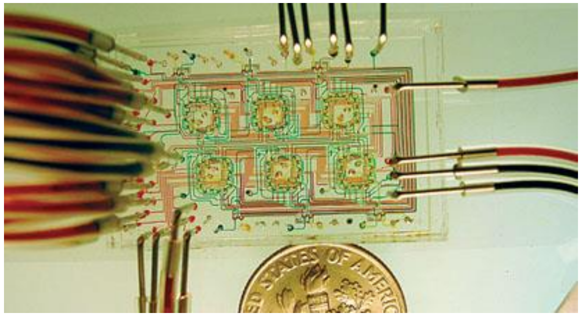




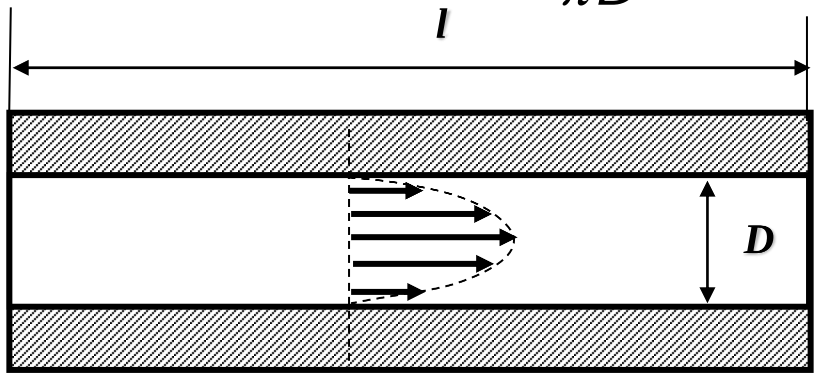


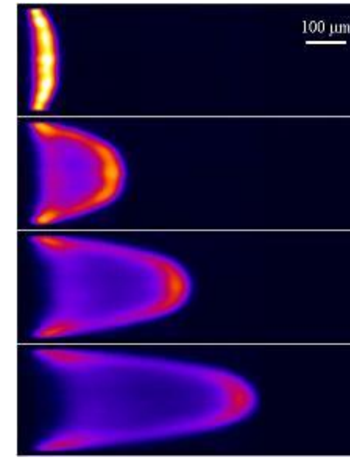
- *Recirculation region length vs. Richardson number*
- *Strouhal number vs. Richardson numbe*

❑ Fluid Transportation inside Micro-channels



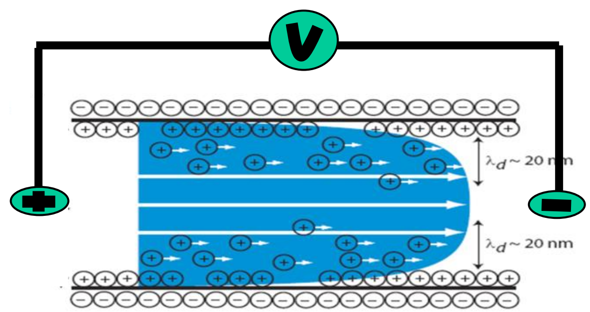
$$\Delta p = P_2 - P_1 = \frac{128 \mu l Q}{\pi D^4}$$



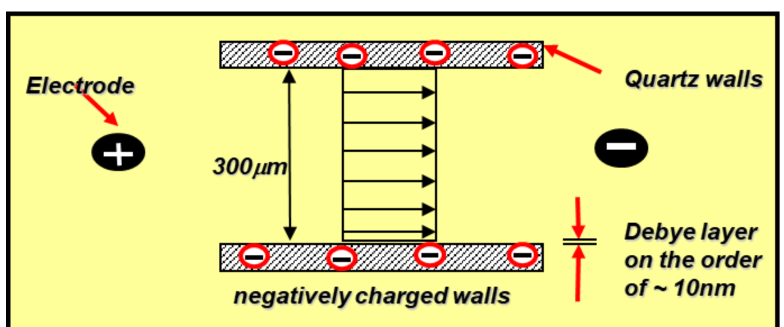


- ***Pressure-driven flows inside microchannels:***

- ***Electro-Osmotic Flow (EOF) inside microchannels:***



$$V_{eof} = \frac{\varepsilon_r \varepsilon_o \zeta V}{\mu L}$$



ε_o : *the permittivity of vacuum*
ε_r : *the relative permittivity*
ζ : *the zeta potential*
V : *the applied voltage*
μ: *liquid viscosity*
L : *the length over which the voltage is applied*

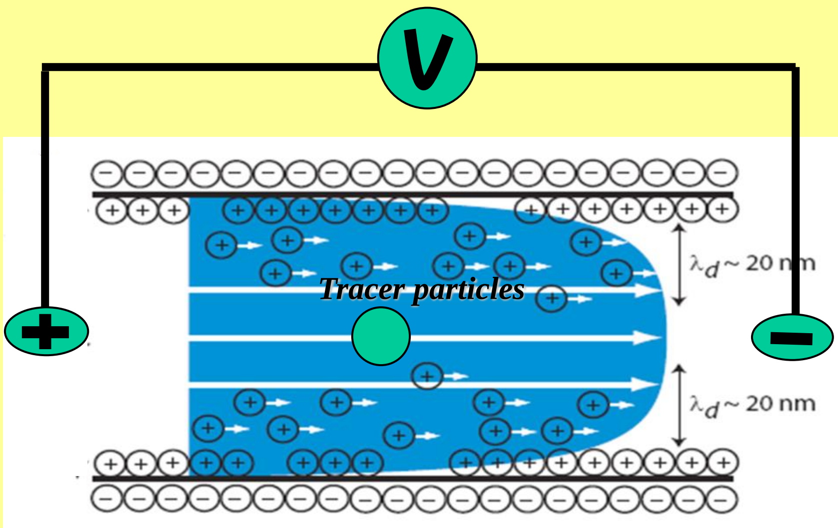
In-Situ Velocity Measurements of EOF inside Microchannels

μ-PIV images

μ-PIV

- *Tracer particles used for μ-PIV measurements usually have their own charge characteristics.*

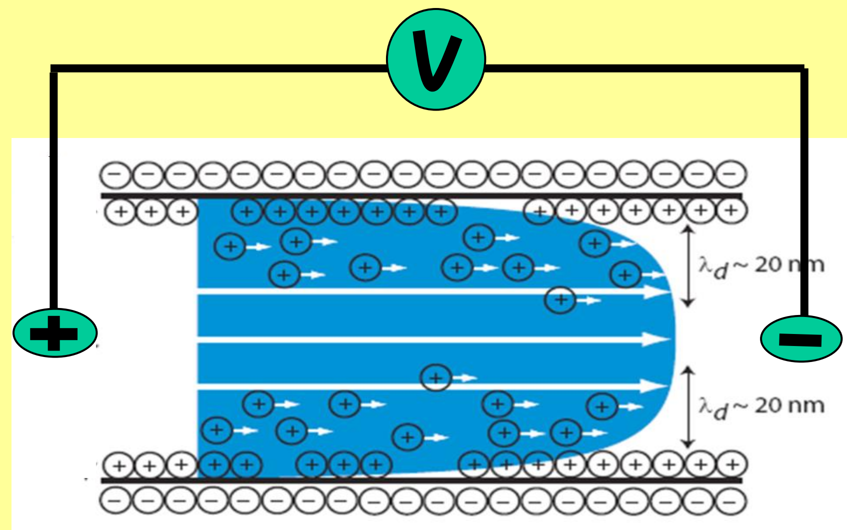
$$U_{measured} = U_{EOF} + U_{electrophoresis}$$



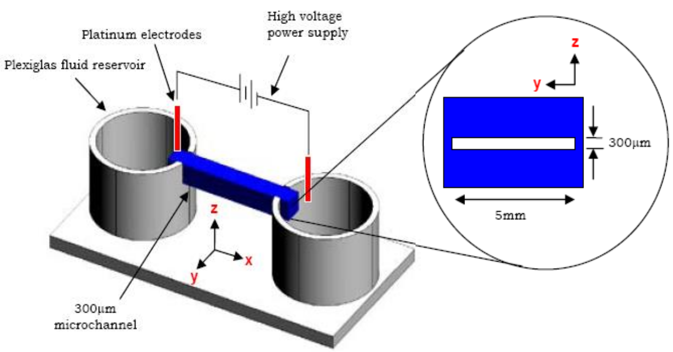
Molecular Tagging techniques

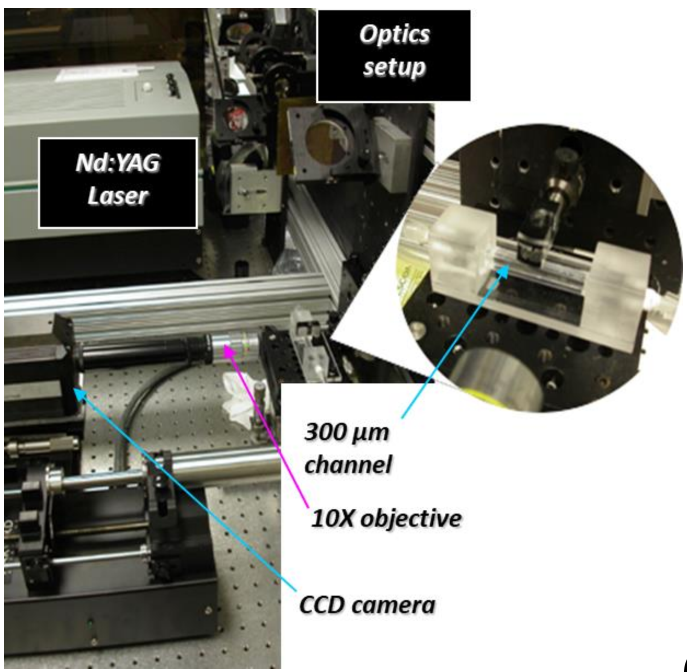
- ***Lum et al. (2005) measured the electrophoretic mobility of MTV triplex and found that the molecule of MTV triplex is neutrally charged.***

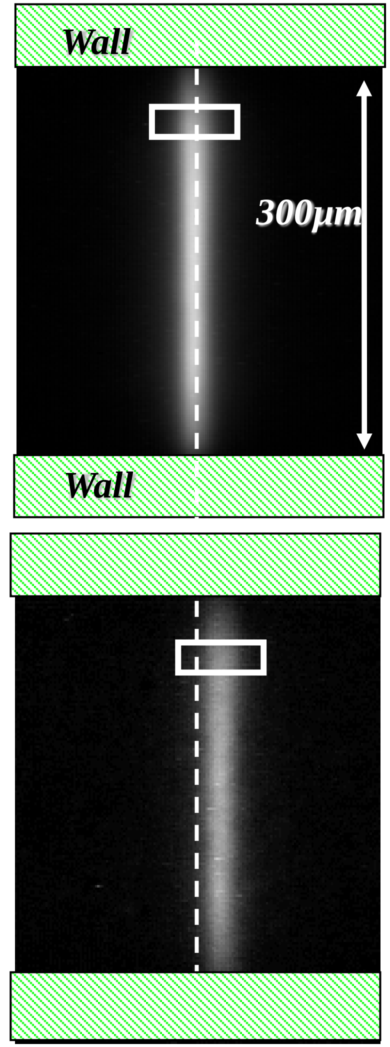
$$U_{measured} = U_{EOF}$$



❑ MTV&T Measurements of EOF in Micro channel



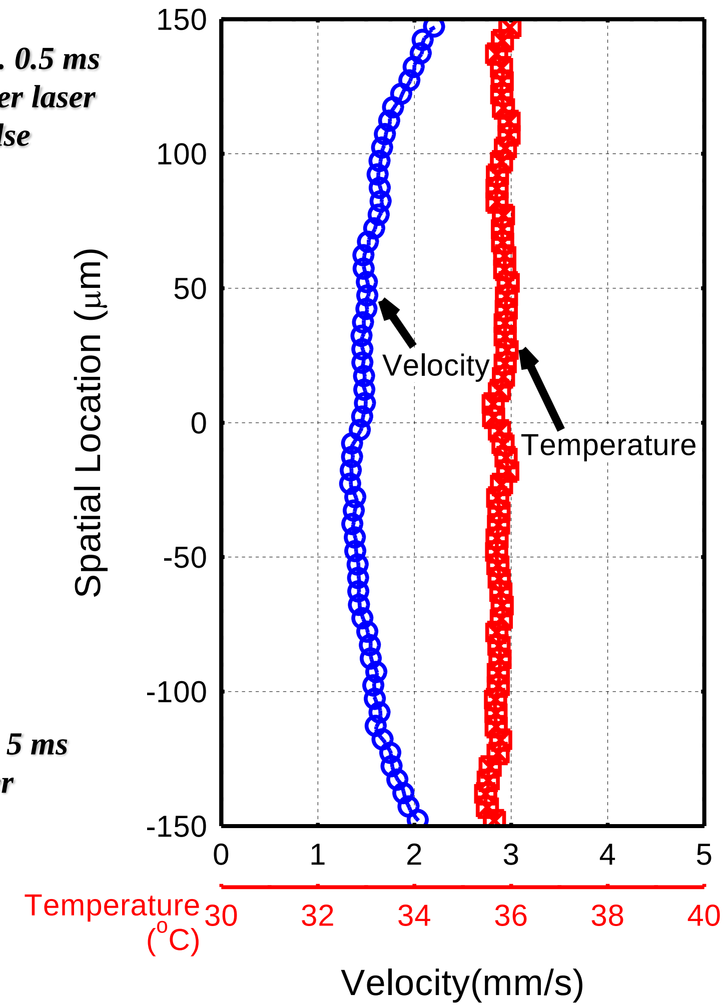




(a). 0.5 ms after laser pulse

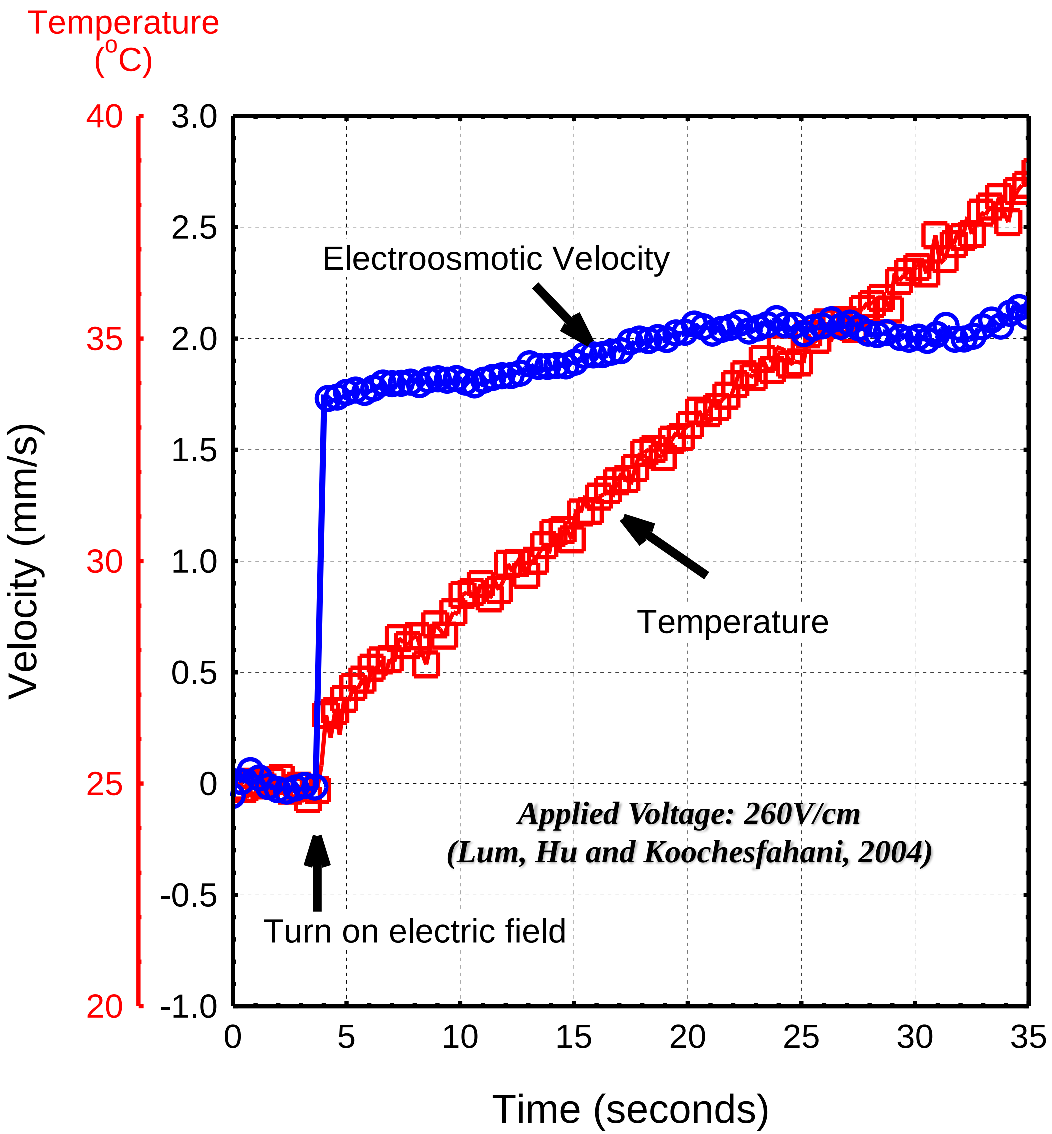
(b). 5 ms later

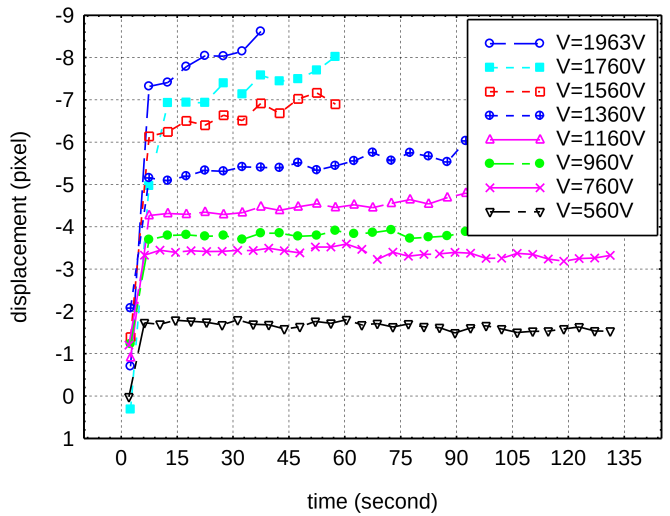
(Lum, Hu and Koochesfahani, 2004)

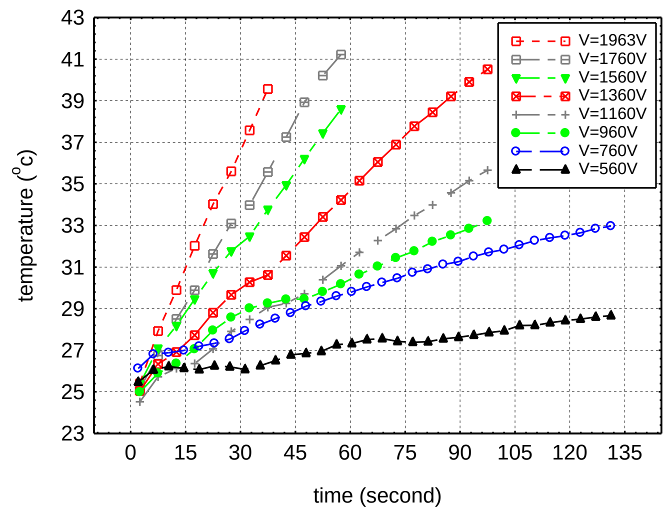


(c). Instantaneous velocity and temperature profiles

❑ Dynamic Response of EOF Flow inside the Microchannel





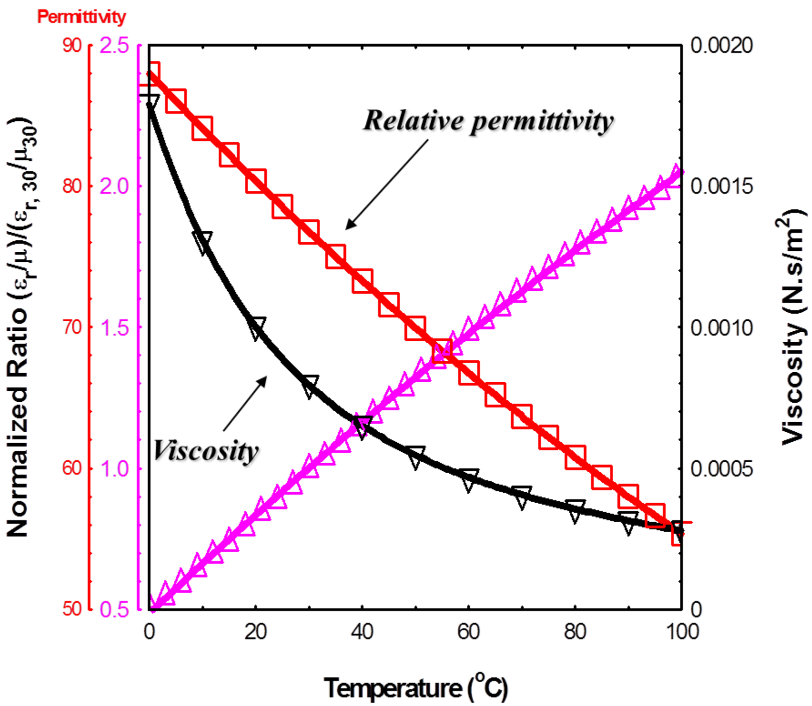


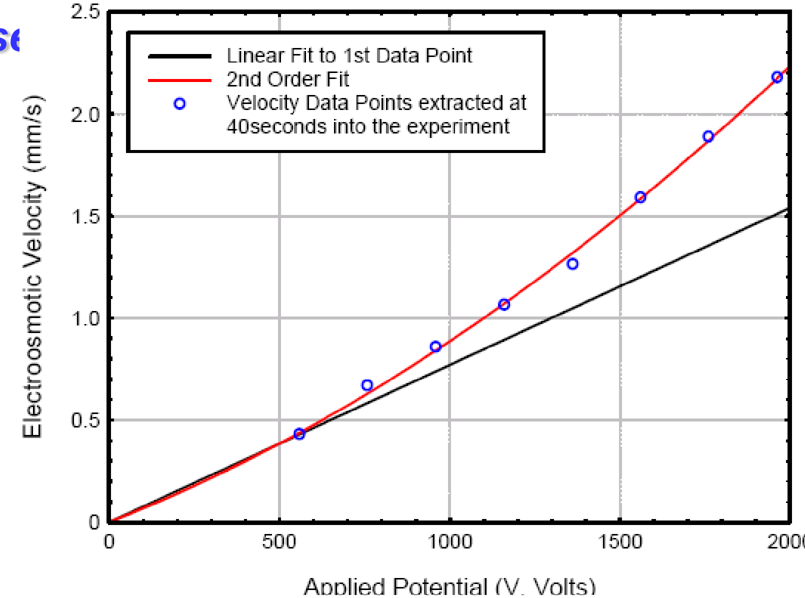
Velocity results at difference applied electrical voltage

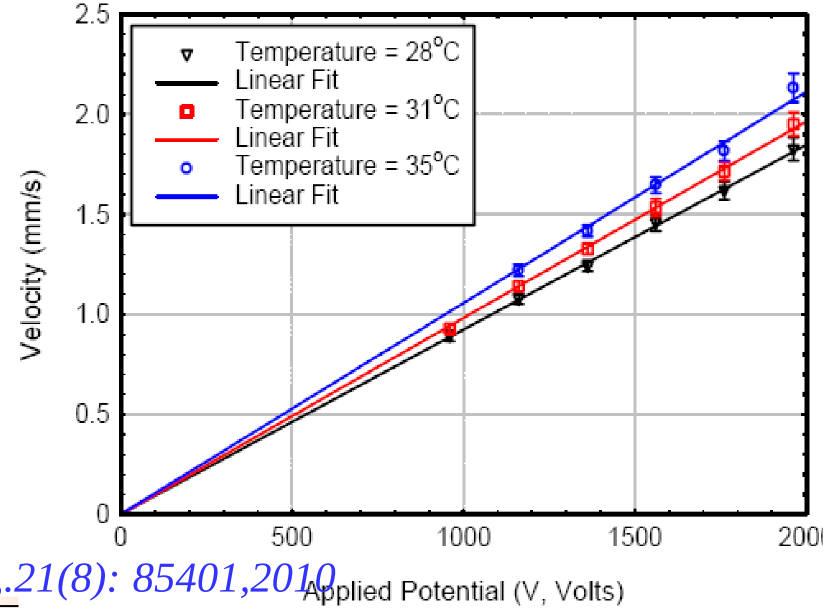
❑ Change in Viscosity and Permittivity due to Joule Heating

- *Change of viscosity and permittivity with increase in temperature results in a net increase in EOF velocity with increasing temperature*

$$U = \frac{\varepsilon_r(T)\varepsilon_o \zeta E}{\mu(T)}$$



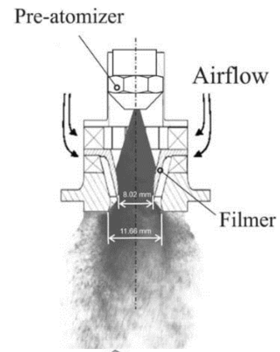


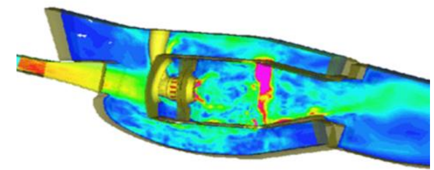


- *Hu et al. , Measurement Science & Technology,.21(8): 85401,2010*

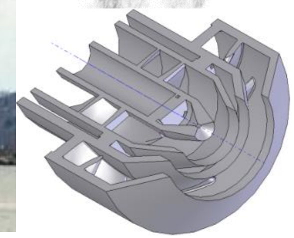
❑ Characterization of Liquid Fuel Spray Flow of Gas Turbines (Funded by UTAS and Honeywell)

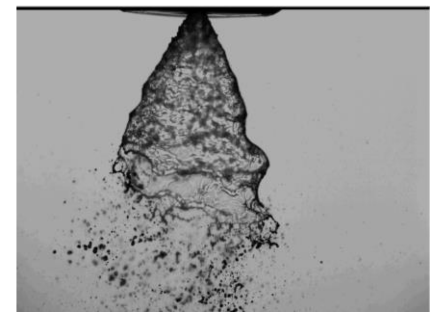
- ***Breaking up process or atomization of liquid fuel into droplets in the form of a fine spray plays a pivotal role in improving energy efficiency and suppressing pollutant formation for gas turbine engines.***

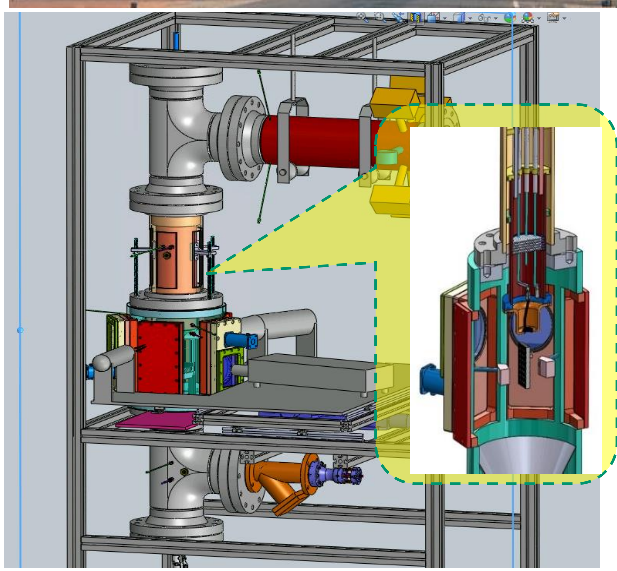




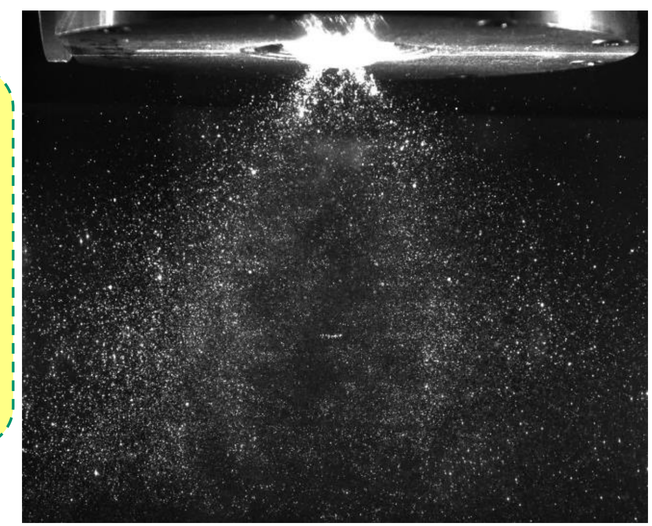
- ***Air blast fuel injector/atomizer***

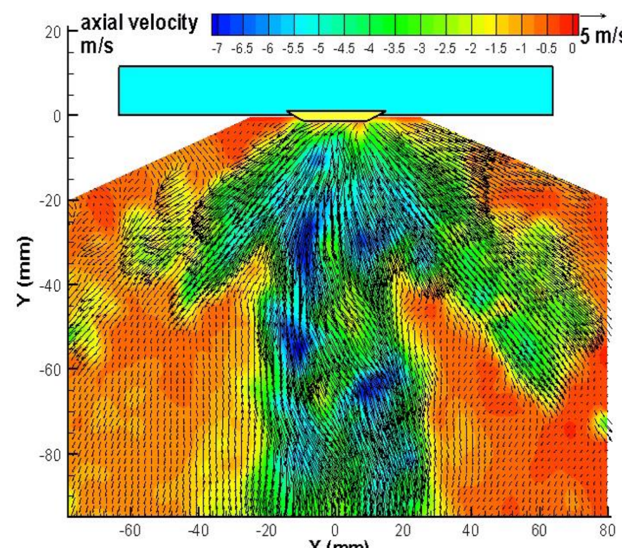






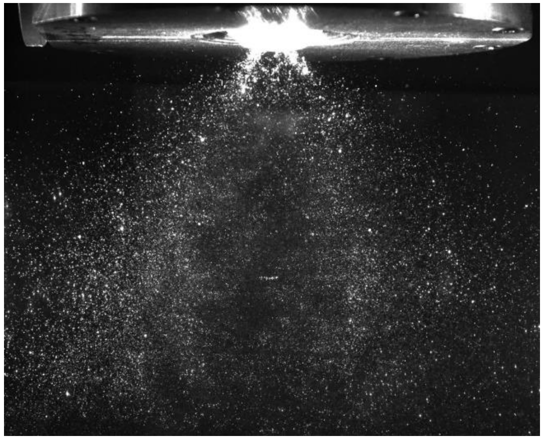
High-pressure fuel spray test rig (~250psi, i.e., 15atm) @ Iowa State

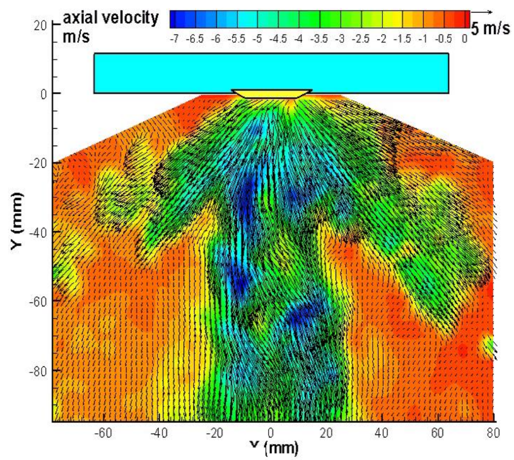


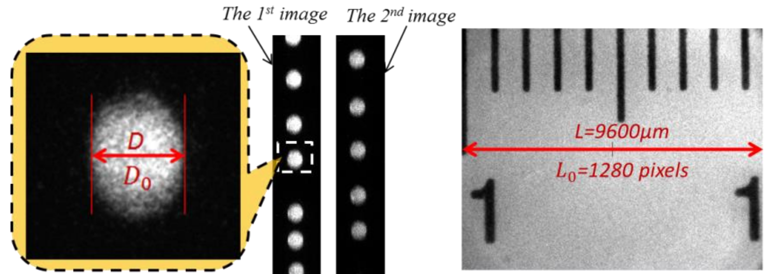


PIV measurements of liquid fuel spray flows

Simultaneous Measurements of Droplet Size, Velocity, and Temperature of In-flight Droplets





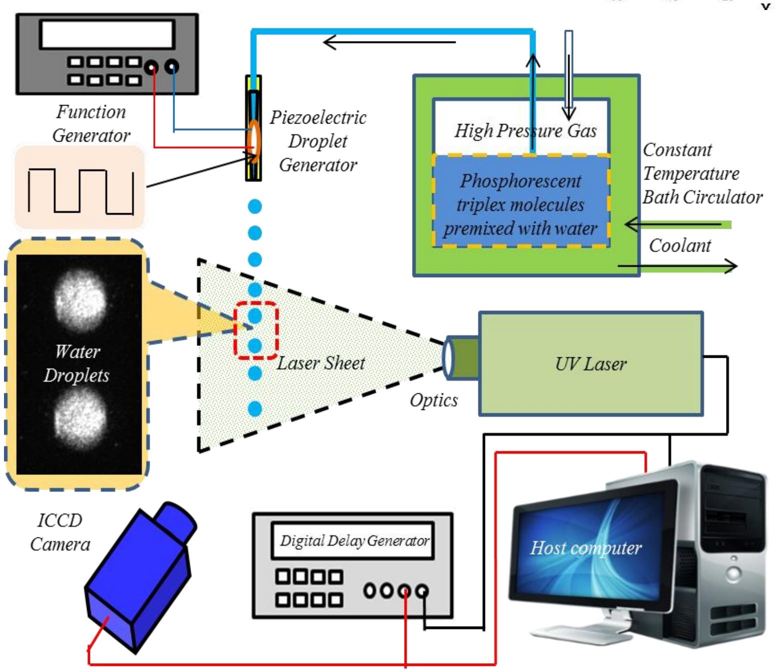


(a). Acquired phosphorescence image pair of the in-flight droplets

(b). Scale ratio between the image plane and the object plane

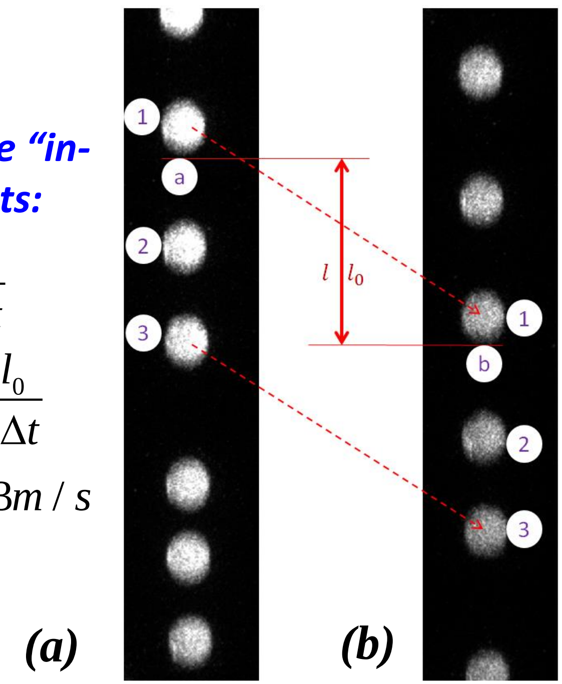
- ***Size of the "in-flight" droplets:***

$$D = D_0 \frac{L}{L_0}$$



- ***Velocity of the "in-flight" droplets:***

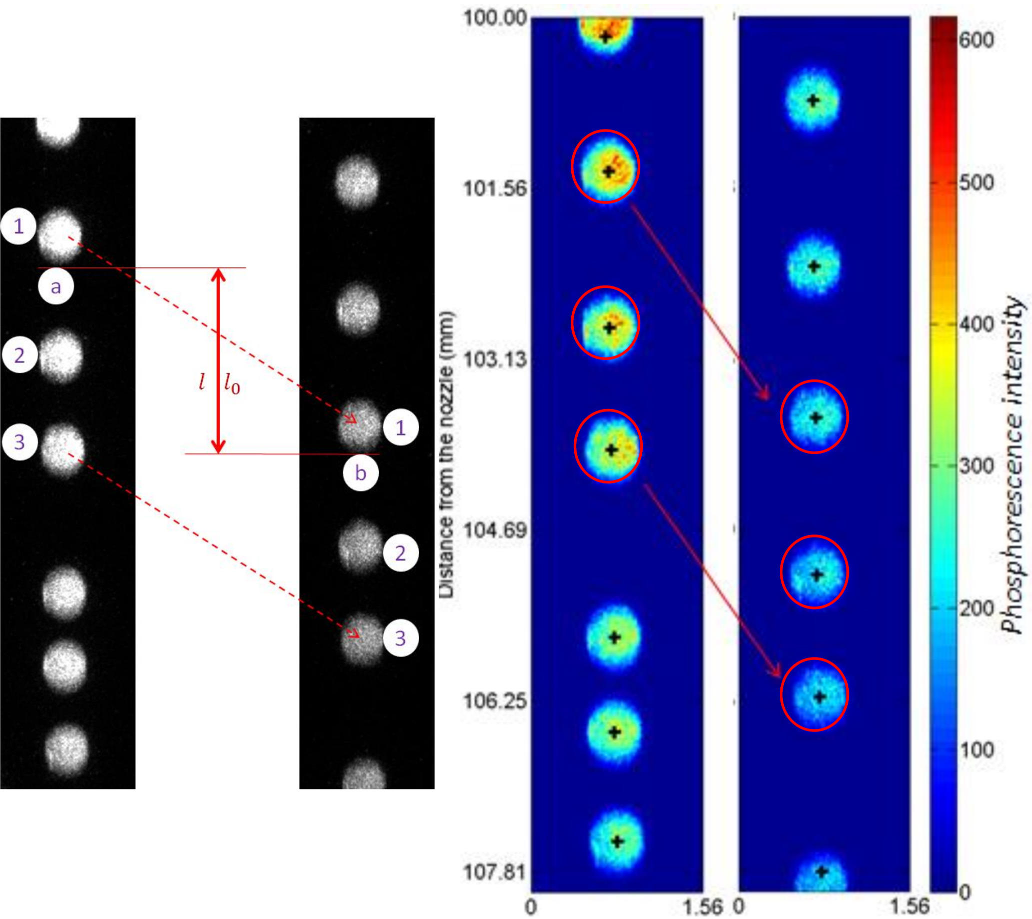
$$V = \frac{l}{\Delta t} = \frac{L l_0}{L_0 \Delta t} = 2.3 m/s$$



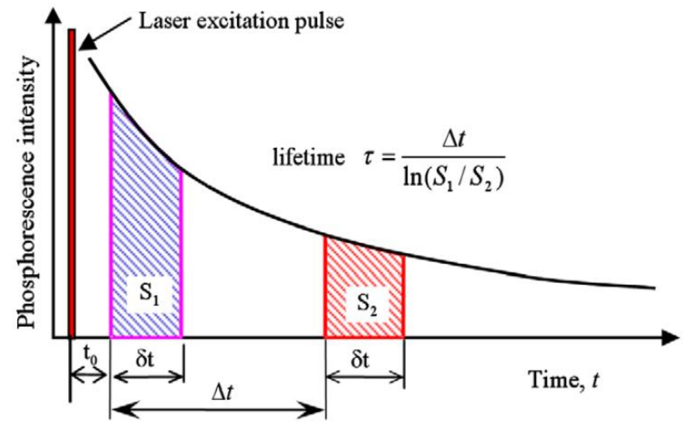
- ***HX. Li, F. Chen and H. Hu,*** *"Simultaneous Measurements of Droplet Size, Flying Velocity and Transient Temperature of In-Flight Droplets by Using a Molecular Tagging Technique",* ***Experiments in Fluids****, 56:194(14 pages), 2015,*

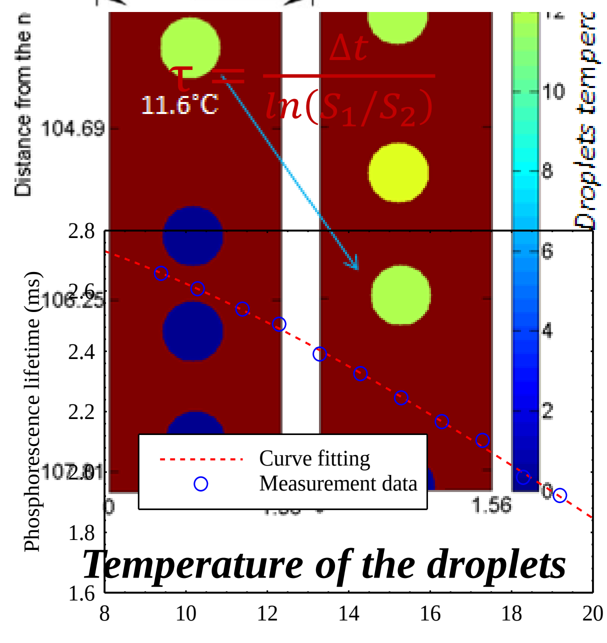
❑ Simultaneous Measurements of Droplet Size, Velocity, and Temperature of In-flight Droplets

- ***Temperature measurements of in-flight droplets***



(a) (b)



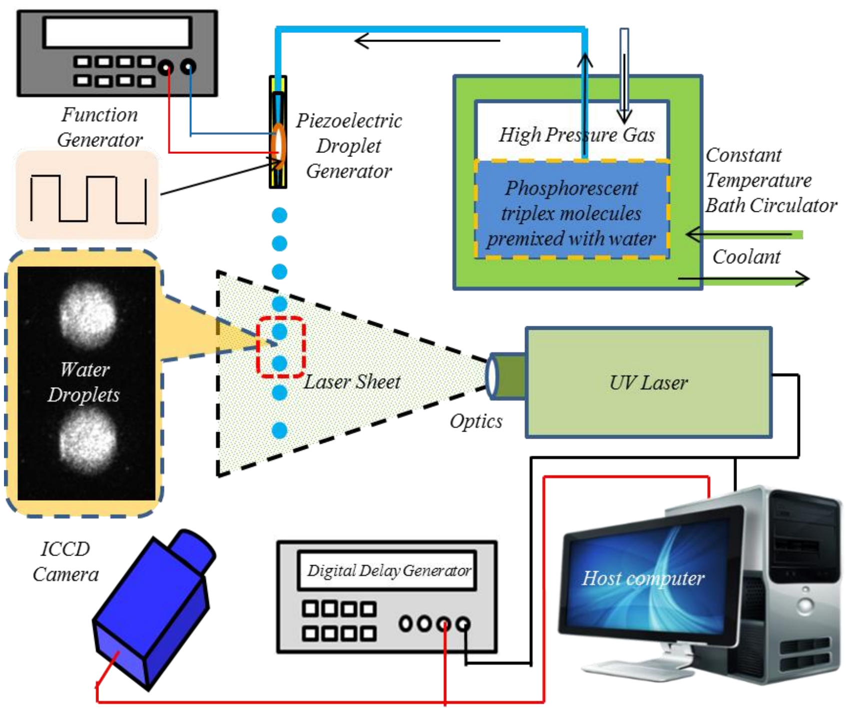


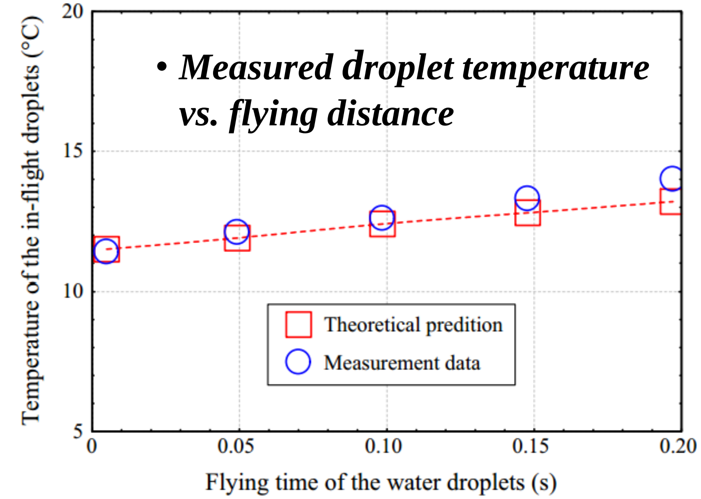
- *(a) Droplet phosphorescence imaged 0.5ms after the laser pulse.*
- *(b) The same droplet phosphorescence imaged 1.1ms after first image.*

- ***HX. Li, F. Chen and H. Hu,** "Simultaneous Measurements of Droplet Size, Flying Velocity and Transient Temperature of In-Flight Droplets by Using a Molecular Tagging Technique", **Experiments in Fluids**, 56:194(14 pages), 2015,*

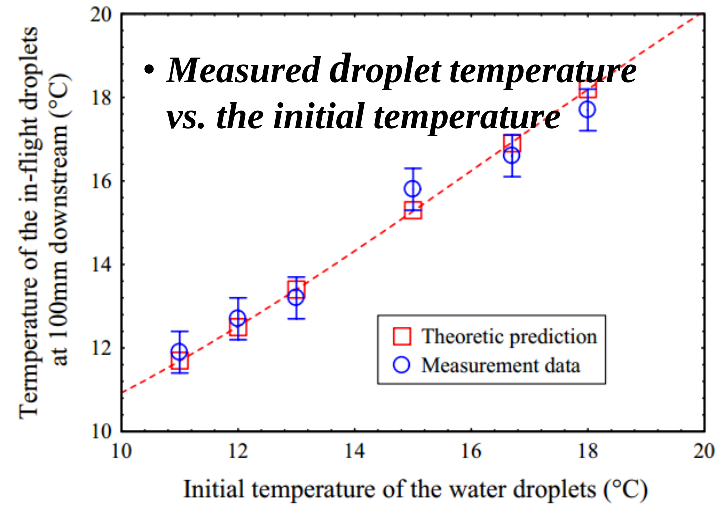
Simultaneous Measurements of Droplet Size, Flaying Velocity, and Temperature of In-flight Droplets

- ***D* = 450μm,**
- ***V* ≈ 2.3m/s,**
- **T_e = 22℃,**
- **T_i = 11.0℃.**



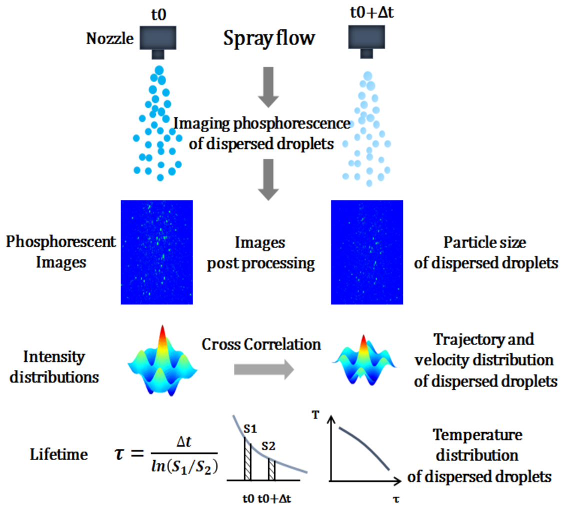


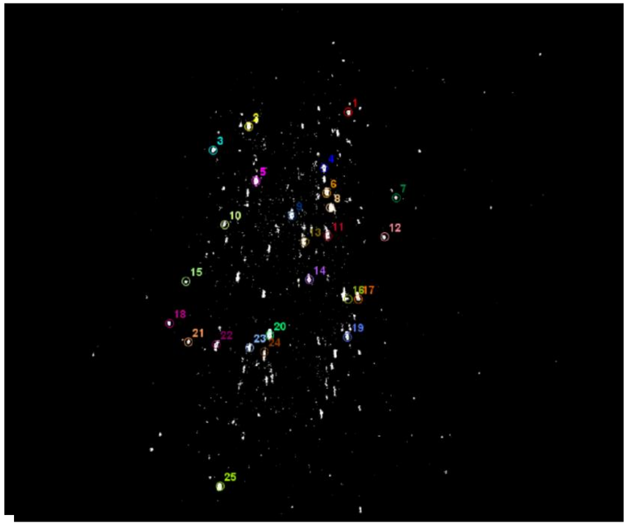
- ***Discrepancies: -0.2°C~0.8°C***

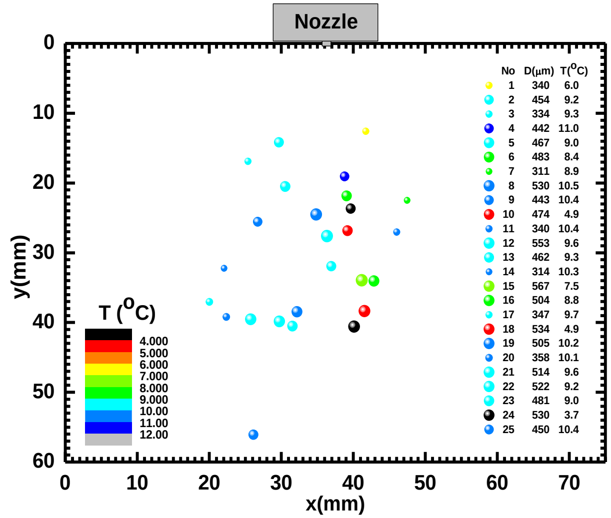


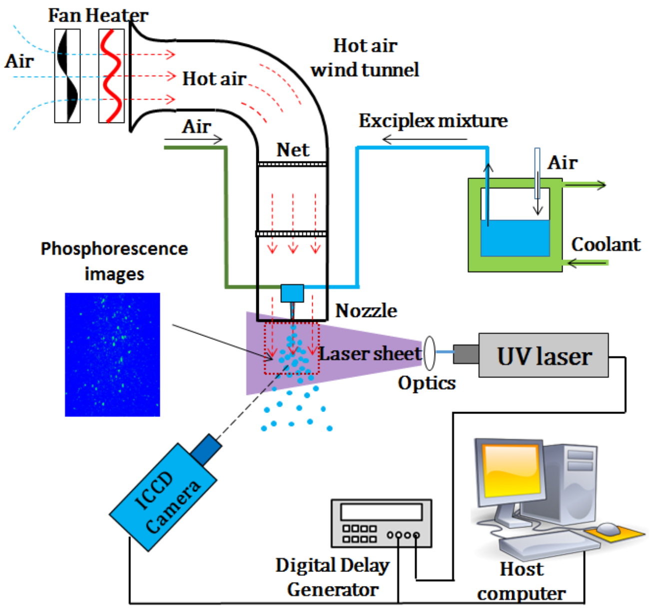
- ***HX. Li, F. Chen and H. Hu,*** *"Simultaneous Measurements of Droplet Size, Flying Velocity and Transient Temperature of In-Flight Droplets by Using a Molecular Tagging Technique", Experiments in Fluids, 56:194(14 pages), 2015,*

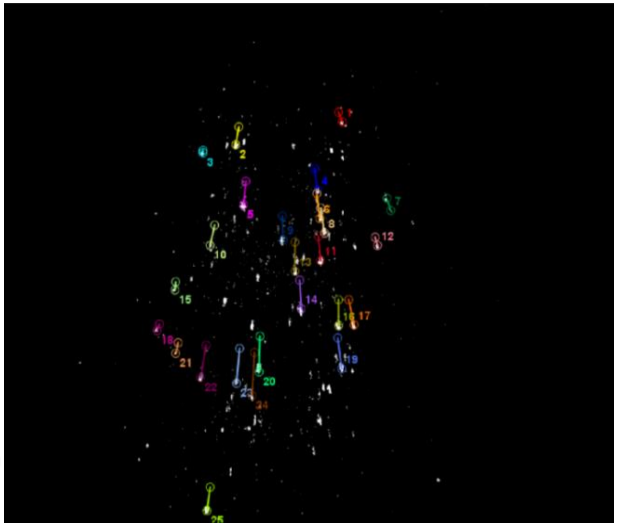
❑ Simultaneous Measurements of Droplet Size, Velocity, and Temperature of In-flight Droplets

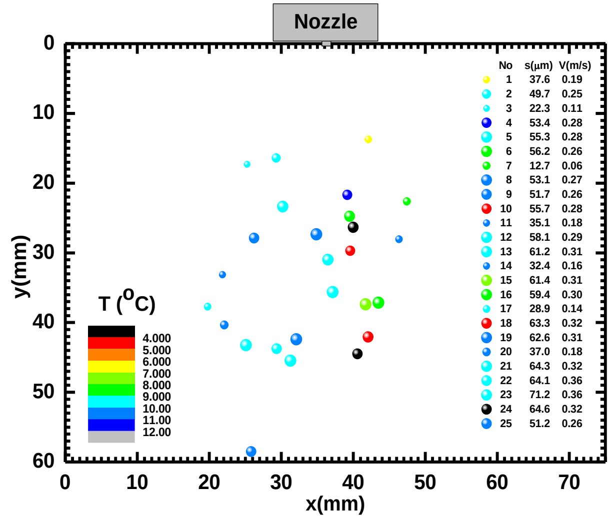












❑ Introduction: Aircraft Icing and Anti-/De-Icing

- ***Aircraft icing, including aero-engine icing,*** ***is recognized as a significant hazard to aircraft operations in cold weather.***
- ***Aircraft icing remains as an important unsolved problem*** ***at the top of the National Transportation Safety Board's most wanted list of aviation safety improvements.***

- *Aircraft inflight icing*

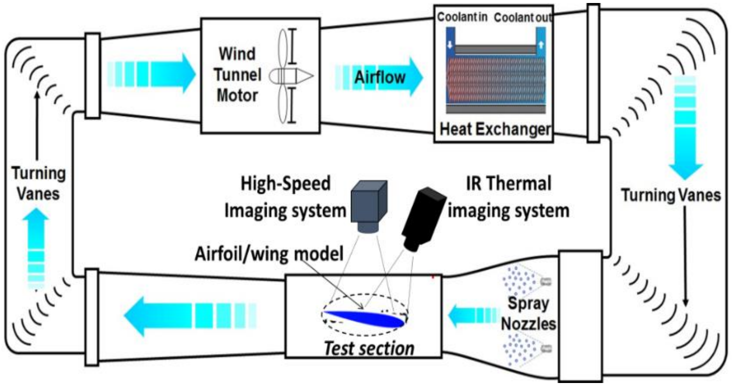
- *Aircraft de-icing at airport*

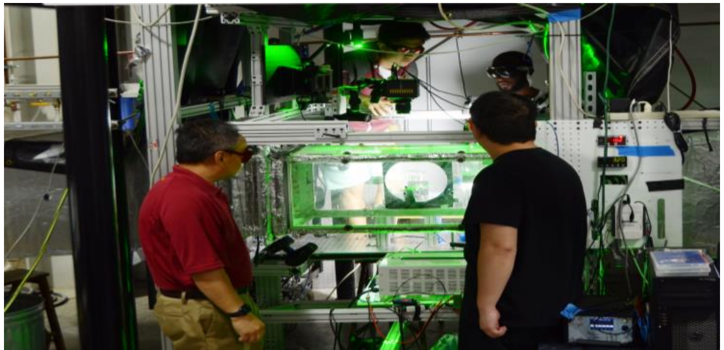
- *Aero-engine inflight icing*

- *Various deadly aircraft crashes due to icing*

❑ Icing Research Tunnel @ Iowa State University (ISU-IRT)

Iowa State University Icing Research Tunnel



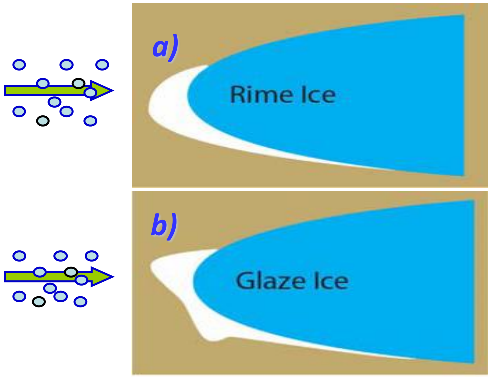


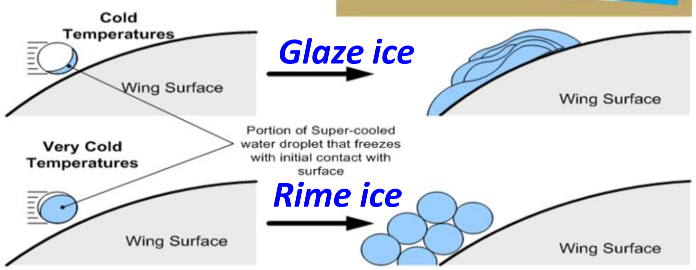
- *ISU Icing Research Tunnel (ISU-IRT), donated by Collins Aerospace System in 2008, is a newly refurbished, research-grade, multi-functional icing research tunnel.*
- *The working parameters of ISU-IRT include:*
  - *Test section:* 0.4m × 0.4m×2.0m
  - *Airflow velocity:* V_∞ = 5 ~ 100 m/s;
  - *Temperature:* T_∞ = - 25 °C ~ 20 °C;
  - *Droplet size:* $D_{droplet}$ = 10 ~ 100 μm;
  - *Liquid Water Content:* LWC = 0.1 ~ 10 g/m³
- *The large LWC range allows ISU-IRT to be run over a wide range of conditions (i.e., from dry rime to wet glaze icing).*
- *Received ~ $10.0M funding on icing related research since 2008 years from NASA, NSF, DoE, NAVY, GE, P&W, Collins, UTAS, GA, Avangrid, DuPont…*

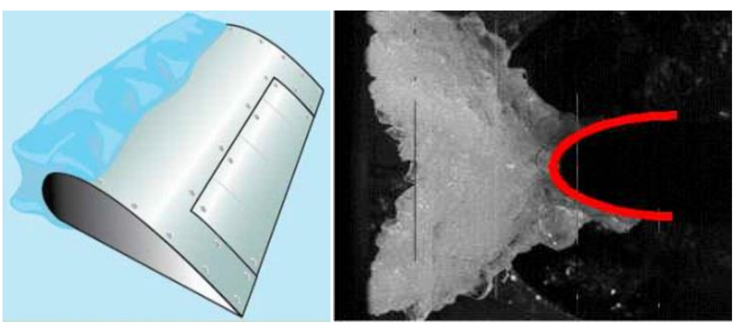
❑ Impact Icing Phenomena: Rime Icing and Glaze Icing

- *Icing is a very complex, multiphase flow problem coupled with heat transfer & phase changing.*

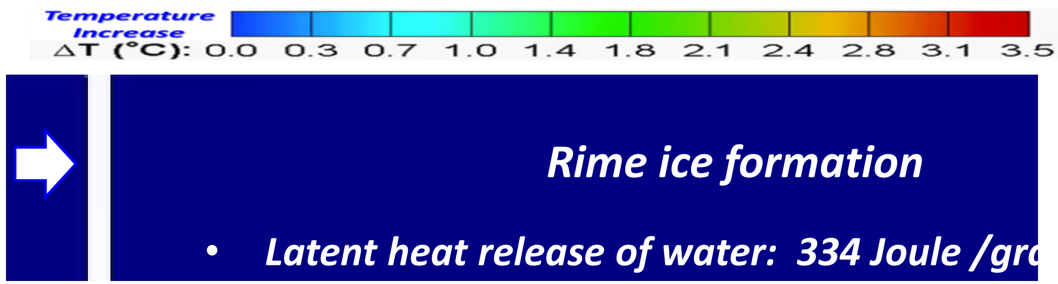
*Incoming airflow with airborne **supercooled water droplets***

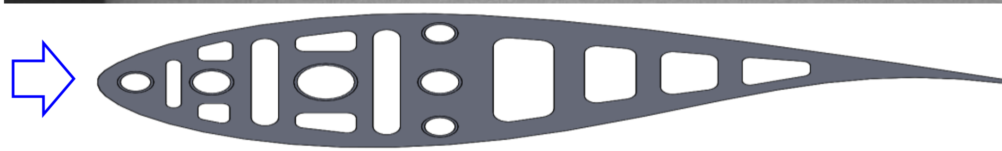


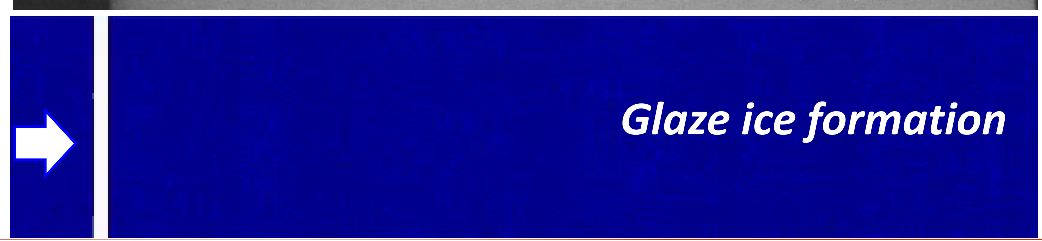




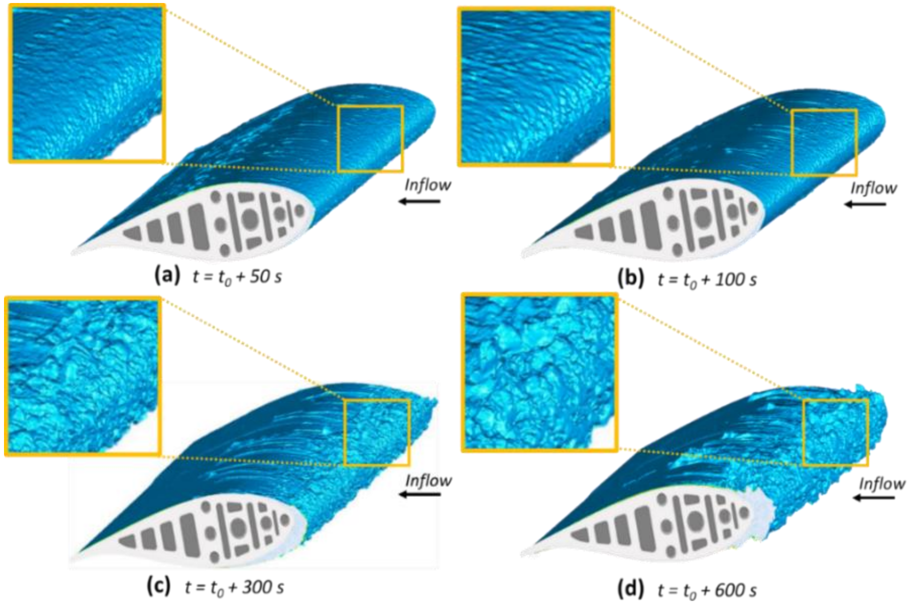
- ***Glaze ice is the most dangerous type of ice.***
- ***It can form much more complicated ice shapes, and will be much more difficult to remove once built up.***



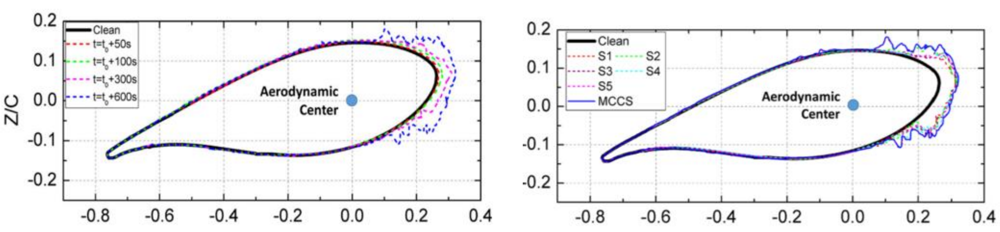




❑ PIV Measurements: Icing-Induced Aerodynamic Performance Degradation

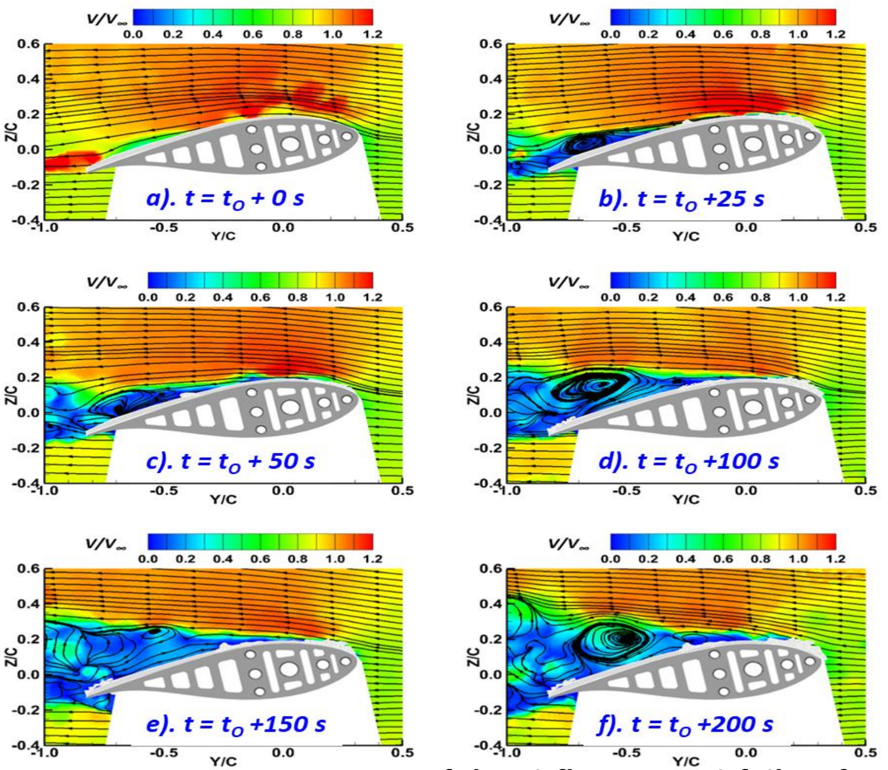


- **Quantifications of 3D shapes of the iced airfoil mod**

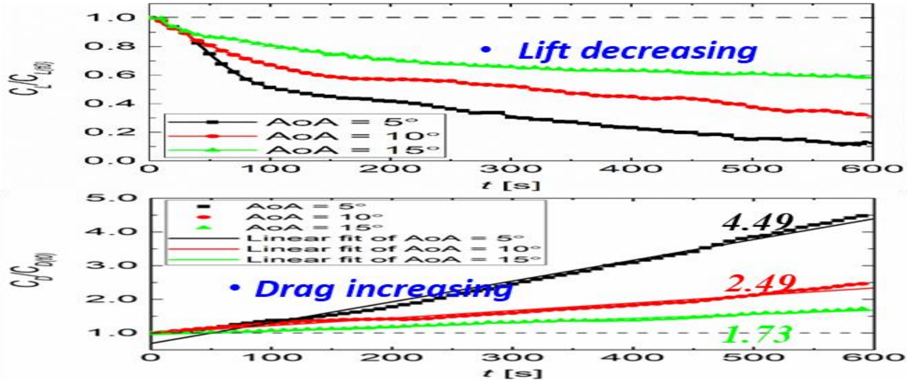


- *Gao et al., Renewable Energy, 133(4), 663-675, 2019.*

- $T_\infty = -5.0\ ^oc$; $V_\infty = 40.0\ m/s$; $LWC = 1.1\ g/m^3$, $AOA = 10^0$

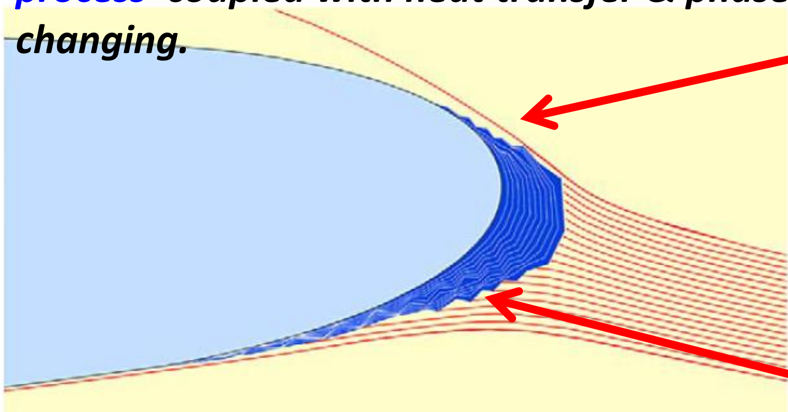


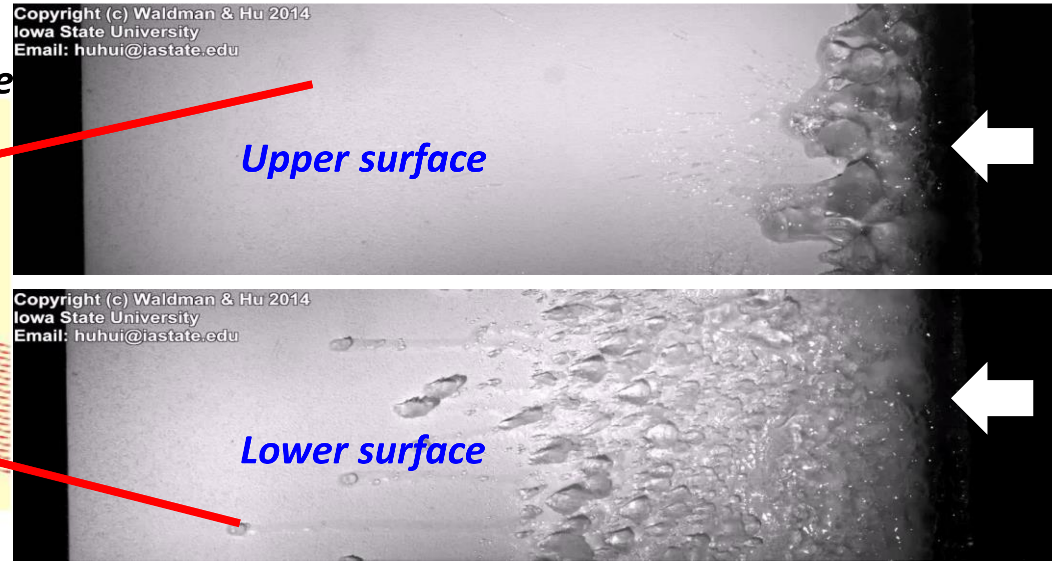
- **PIV measurements of the airflow over airfoil surface**



❑ Icing Physics: Unsteady Heat & Mass Transfer during Icing Process

- *Icing is a very **complex, multiphase flow process** coupled with heat transfer & phase changing.*



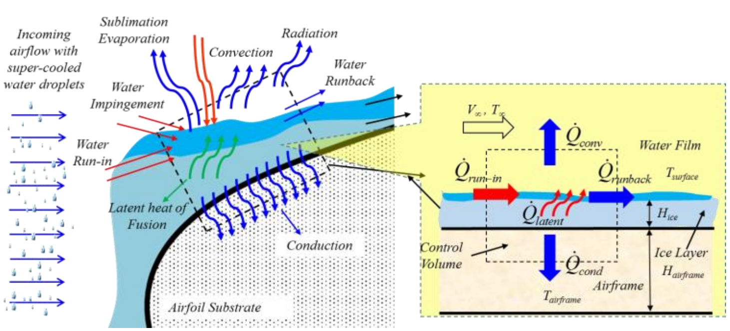


$$\dot{E}_{in} - \dot{E}_{out} = \frac{dE_{st}}{dt} \equiv \dot{E}_{st}$$

$$\dot{E}_{in} = \dot{Q}_{adh} + \dot{Q}_{kin} \qquad \dot{E}_{st} = \left(\dot{Q}_{latent} + \dot{Q}_{ss}\right)$$

$$\dot{E}_{out} = \dot{Q}_{conv} + \dot{Q}_{sub/evp} + \dot{Q}_{cond}$$

$$\left[\dot{Q}_{adh} + \dot{Q}_{kin}\right] - \left[\dot{Q}_{conv} + \dot{Q}_{sub/evp} + \dot{Q}_{cond}\right] = \left(\dot{Q}_{latent} + \dot{Q}_{ss}\right)$$



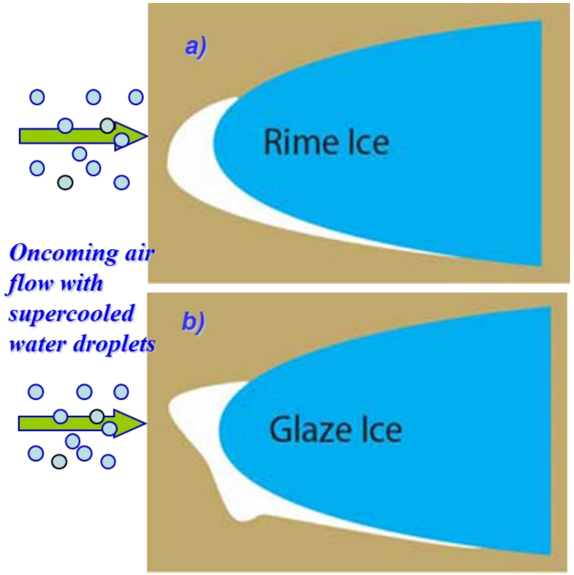
- ***Adiabatic heating:*** ***The heat introduced by air friction on the object is from a viscous adiabatic heat which occurs inside the boundary layer.***
  (Fortin et al., 2006) $\dot{Q}_{adh} = h_{cv}\cdot(T_{rec} - T_\infty)\cdot A$ $\quad T_{rec} = T_\infty + r\cdot\frac{T_\infty}{T_e}\cdot\frac{U_e^2}{2\cdot Cp_{air}}$ $\quad r = \sqrt{Pr}$ $\quad Pr = \frac{Cp_{air}\cdot\mu_{air}}{k_{air}}$
- ***Kinetic energy:*** ***associated with the droplets impacting onto the airfoil surface.***
  (Myers, 2001) $\dot{Q}_{kin} = \frac{1}{2}\cdot\dot{m}_{imp}\cdot V_{imp}^2$ $\quad \dot{m}_{imp} = LWC\cdot V_{imp}\cdot A$
- ***Evaporation and Sublimation***
  (Dong et al., 2015) $\dot{Q}_{sub/evp} = \dot{m}_{es}\cdot\left[\eta\cdot L_i + (1-\eta)\cdot L_w\right]$;
  - *to be estimated directly. Being negligible terms with small quantities.*

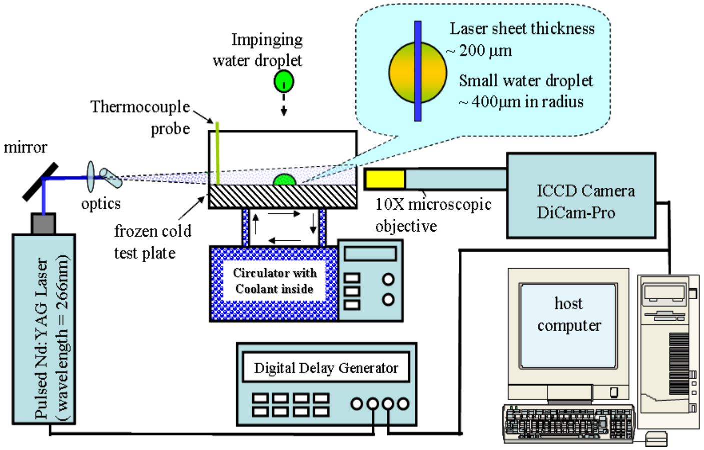
- ***Convective heat transfer*** $\dot{Q}_{conv} = h_{cv}\cdot(T_s - T_\infty)\cdot A$
- ***Conductive heat transfer*** $\dot{Q}_{cond} = \frac{A\cdot(T_s - T_{airfoil})}{R_{tot,cond}}$
  - ***to be evaluated based on the measurements of heat flux sensors and thermocouples***

- ***Latent heat of fusion*** $\dot{Q}_{latent} = \dot{m}_{freeze}\cdot L_s$
- ***Sensible heat*** $\dot{Q}_{ss} = \dot{m}_{freeze}\cdot Cp_i\cdot(T_f - T_s) + (\dot{m}_w - \dot{m}_{freeze})\cdot Cp_w\cdot(T_f - T_s)$
  (Henry et al., 2000)
  - ***To be estimated based on the DIP measurements of accreted ice mass and characteristics of runback surface water flow.***

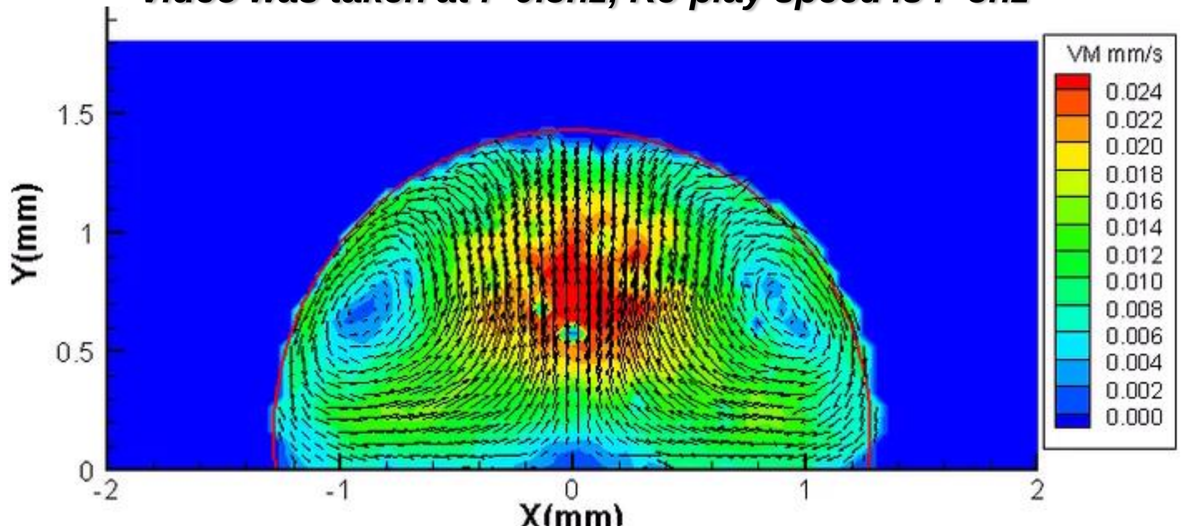
- *Liu & Hu (2018) "An Experimental Investigation on the Unsteady Heat Transfer Process over an Ice Accreting Airfoil Surface", Intel. J. Heat & Mass Transfer, 122, pp707-718.*
- *Li & Hu (2019) "Effects of Thermal Conductivity of Airframe Substrate on the Dynamic Ice Accretion Process", Intl. J. of Heat & Mass Transfer, 131, pp1184-1195.*

❑ Icing Physics: Surface-Tension Induced Marangoni Flow inside Droplets





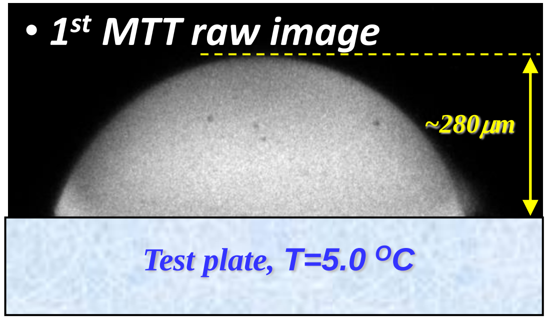
Temperature of Plate, T_{Wall}=21.9 ^{O}C
Video was taken at f=0.5hz; Re-play speed is f=5hz



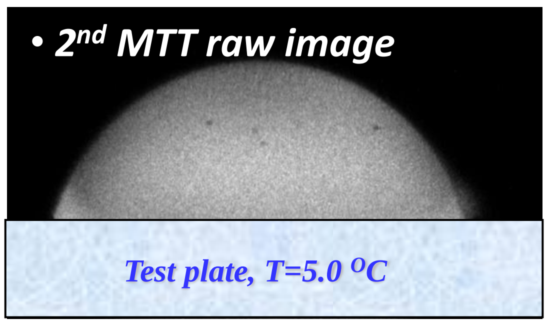
- *(Hu and Jin, Int. J. of Multiphase Flow, Vol. 36, No.8, pp672–681, 2010)*

Unsteady Heat Transfer & Mass Transfer Inside Impinged Droplets

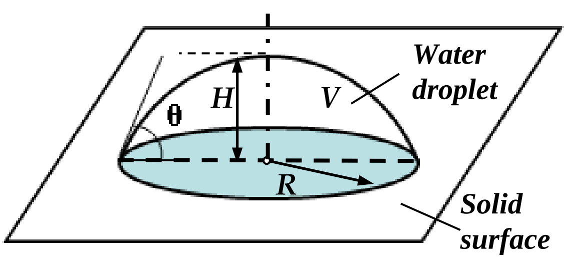
- *Measurements by using a novel Molecular Tagging Thermometry (MTT) Technique (USA Patent No: 2006/0146910)*

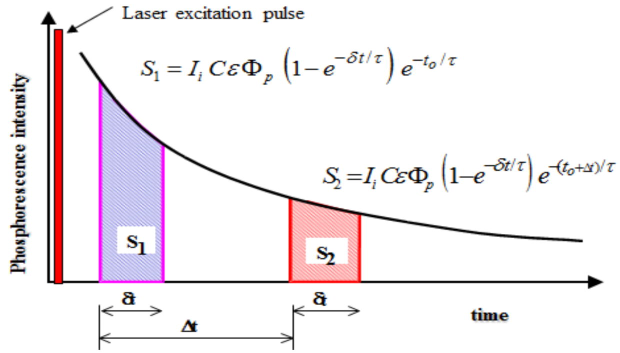


a). The 1st phosphorescence image acquired at 0.5ms after excitation laser pulse



b). The 2nd phosphorescence image acquired at 3.5ms after the same laser pulse

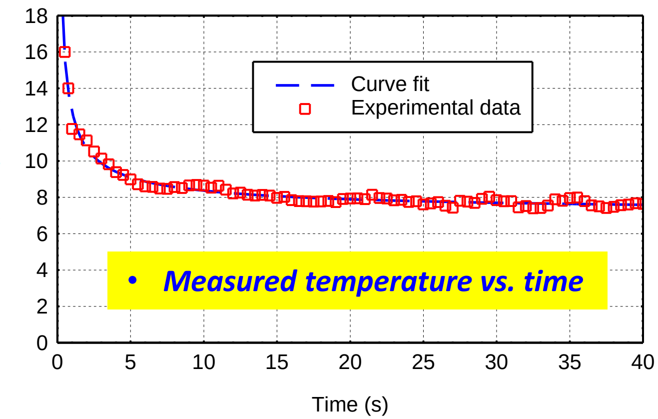


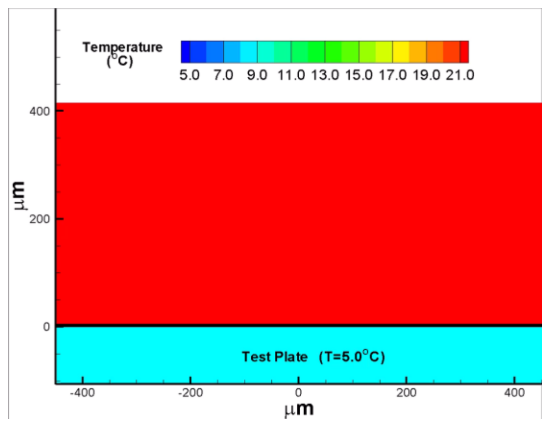


$$S_1 = I_i C \varepsilon \Phi_p \left(1 - e^{-\delta t/\tau}\right) e^{-t_o/\tau}$$

$$S_2 = I_i C \varepsilon \Phi_p \left(1 - e^{-\delta t/\tau}\right) e^{-(t_o+\Delta t)/\tau}$$

- *Time chart for MTT measurements*

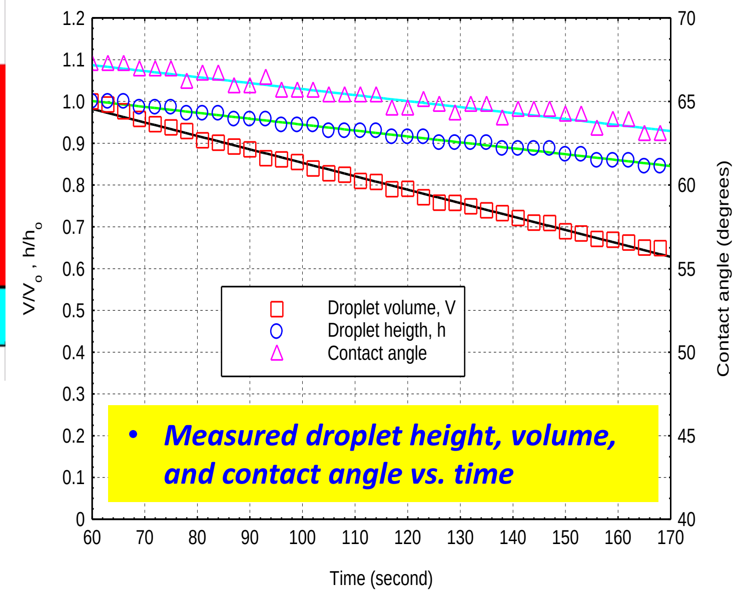




MTT measurement results

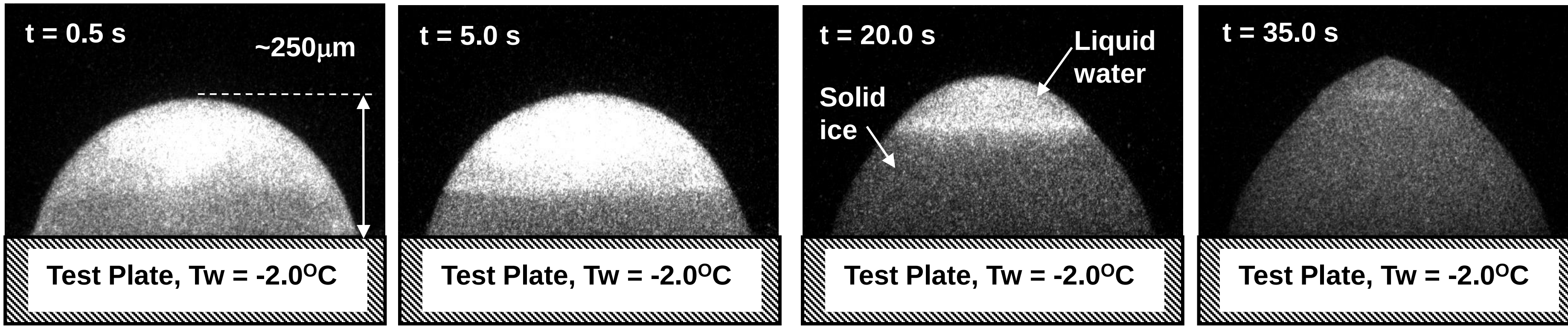
$$\theta = 2\tan^{-1}\left(\frac{H}{R}\right)$$

$$V = \frac{\pi R^3 (1-\cos\theta)^2 (2+\cos\theta)}{3\sin^3\theta}$$

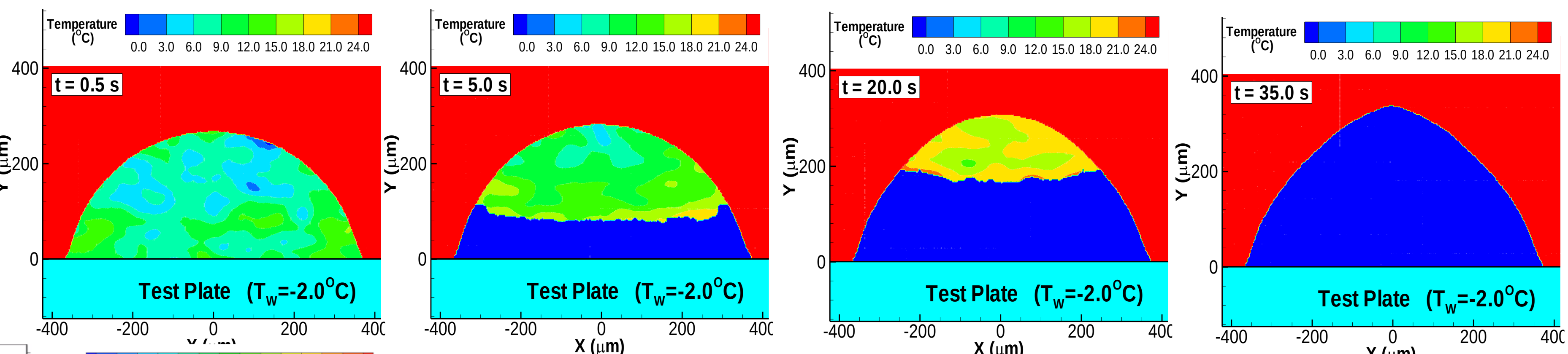


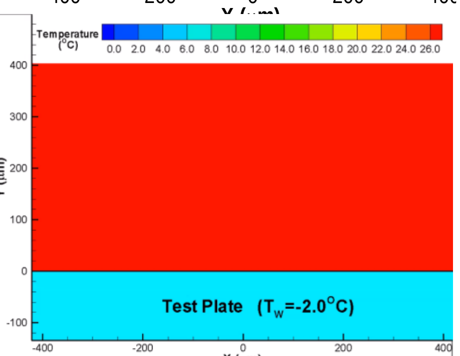
- **Hu H & Huang D,** *"Simultaneous Measurements of Droplet Size and Transient Temperature within Surface Water Droplets", AIAA Journal, Vol.47, No.4, pp813-820, 2009*

❑ Dynamic Phase Changing Process within an Icing Droplet



Instantaneous phosphorescence images



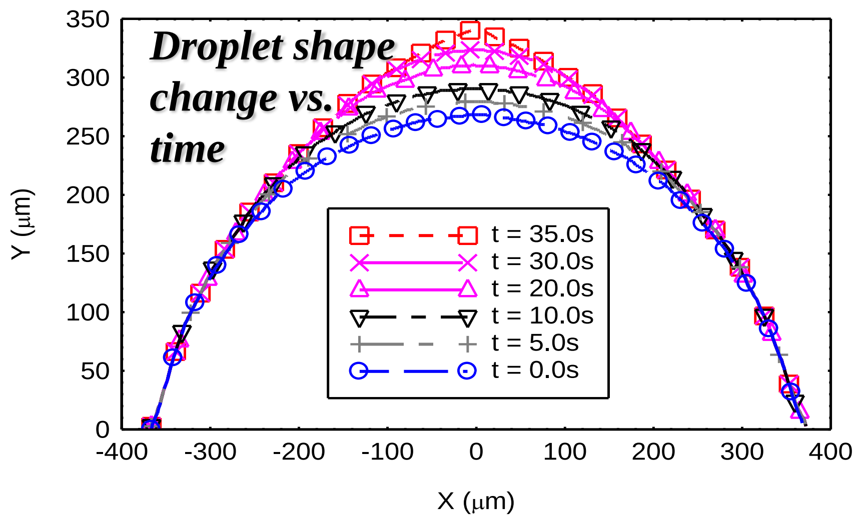


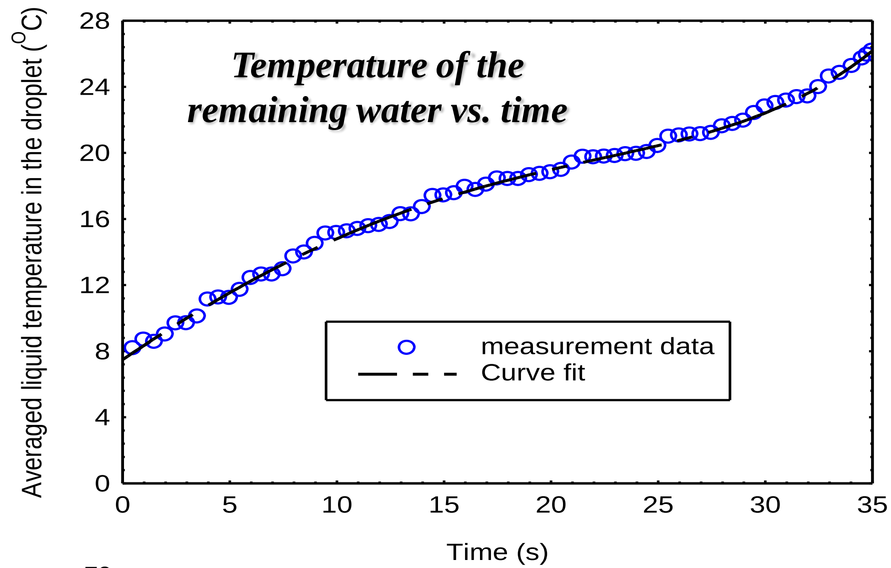
Unsteady heat transfer and phase changing process inside small icing water droplets

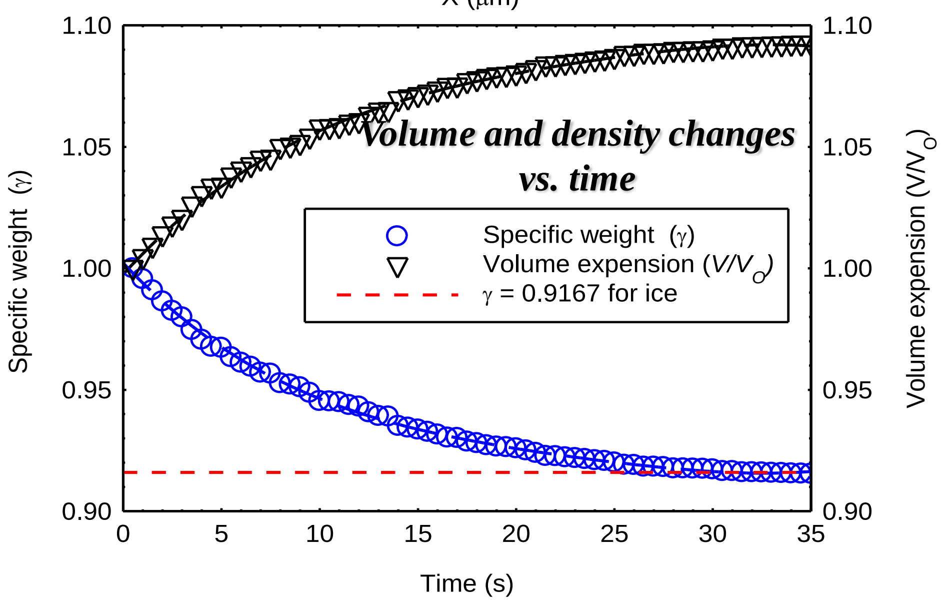
MTT measurement results

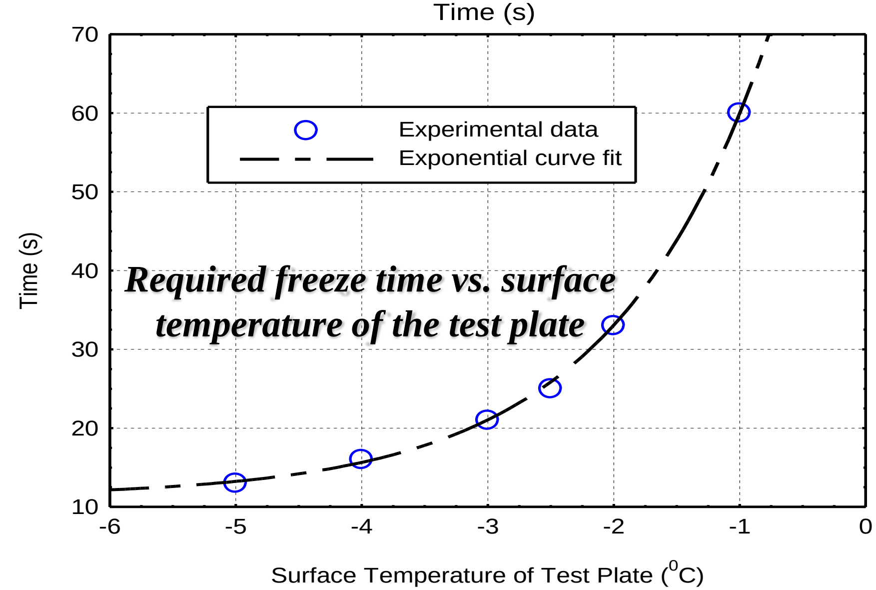
- *(Hu and Jin, International Journal of Multiphase Flow, 36(8):672–681, 2010)*

❑ Dynamic Phase Changing Process within An Icing Droplet









(Hu and Jin, Int. J. of Multiphase Flow, Vol. 36, No.8, pp672–681, 2010)