Global Skin Friction Diagnostics Based on Surface Mass-Transfer Visualizations

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Objective

To explore the feasibility of global skin friction diagnostic based on surface mass-transfer visualizations

Current State

(1) Global luminescent oil-film skin friction meter

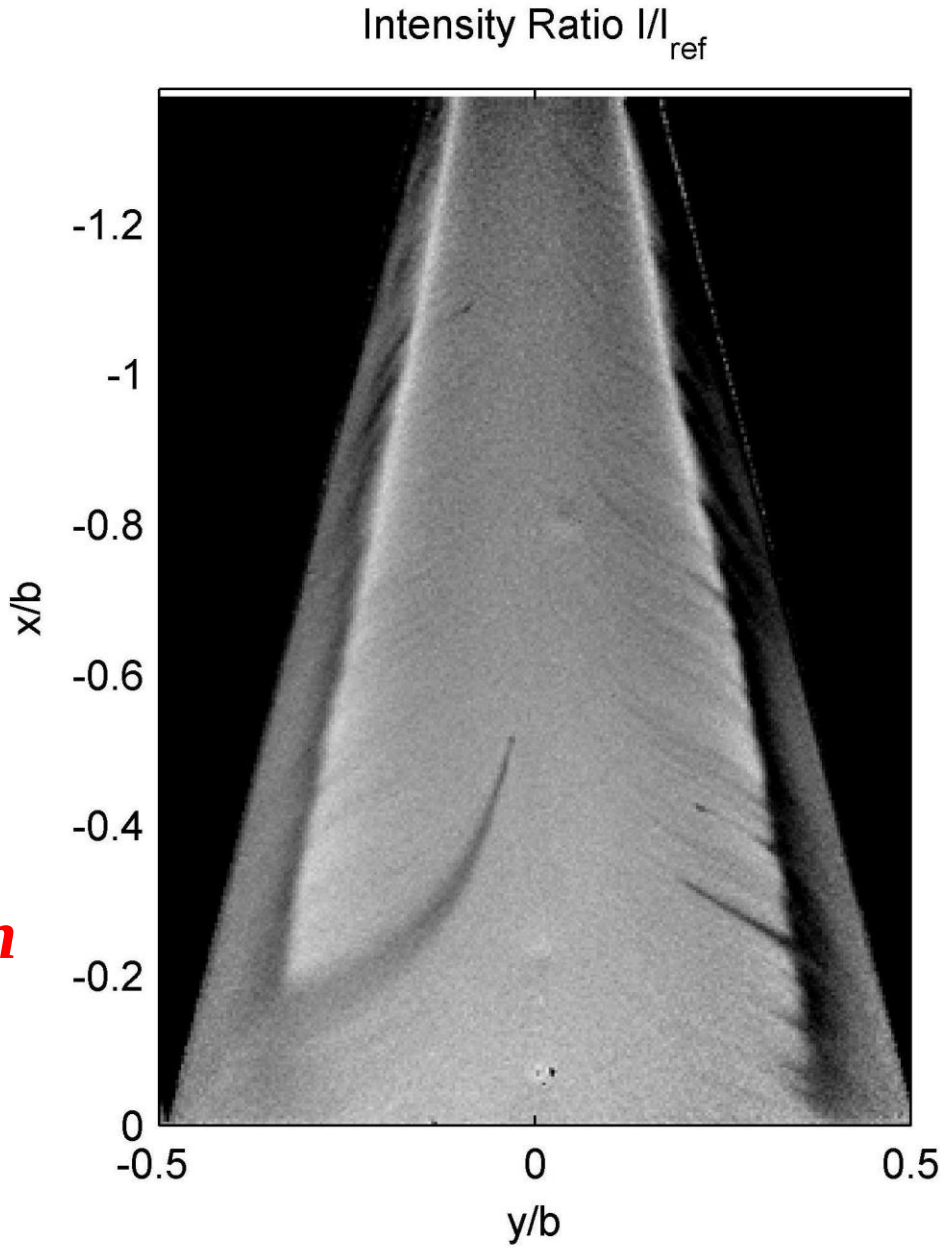
(2) Global skin friction diagnostics based on surface heat-transfer/temperature visualizations

The Specific Question Came from an Image

Pyrene PSP image on a 75-deg delta wing in a large wing tunnel at ONERA (Bouvier, Le Sant & Merienne 2001)

The pattern results from sublimation of Pyrene PSP

<u>Question:</u>
How to extract a skin friction field from this image?



The Issues in Global Skin Friction Diagnostics Based on Mass-Transfer Visualizations

(1) There is no explicit analytical solution for the relation between surface species density, mass flux and skin friction vector.

(2) It was not recognized that it should be solved globally as an inverse problem.

Asymptotic Form of Binary Mass Diffusion Equation at Wall

$$F + \tau_i \, \partial \omega_{1w} / \partial X_i = 0$$

where

$$F = \frac{\mu}{\rho_w D_{12}} \left(-\frac{\partial \dot{m}_{1w}}{\partial t} + D_{12} \frac{\partial^2 \dot{m}_{1w}}{\partial X_i \partial X_i} \right)$$

Relevant Quantities:

τ_i ***Skin friction vector (to be determined)***

$\omega_1 = \rho_1 / \rho$ ***Surface density of species 1 (measurable)***

$\dot{m}_{1w} = -D_{12} \rho_w (\partial \omega_1 / \partial X_3)_w$ ***Surface mass flux (measurable)***

Snapshot Solution in a Short Interval or Window

$$\langle F \rangle_t + \tau_i \, \partial \omega_{1w,s} / \partial X_i = 0$$

where

$$\langle F \rangle_t = \frac{\mu}{\rho_w D_{12} \Delta T} \left(-\dot{m}_{1w,s} + D_{12} \Delta T \frac{\partial^2 \dot{m}_{1w,s}}{\partial X_i \partial X_i} \right)$$

Projection onto Image Plane

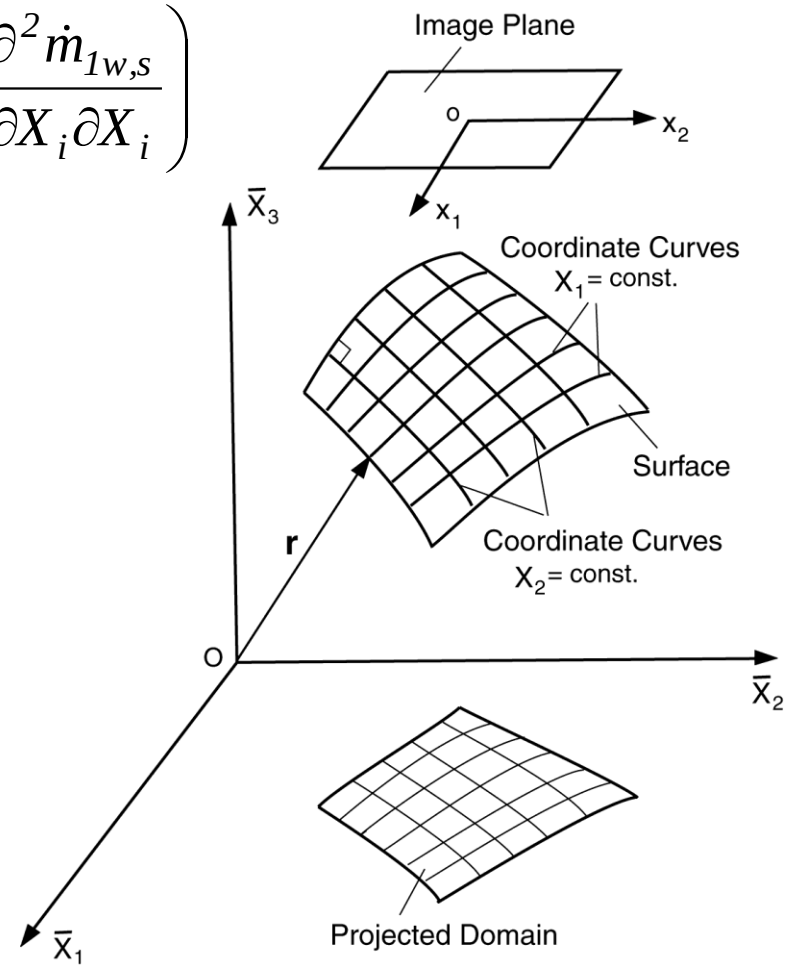
Projected skin friction vector

$$\hat{\tau}_j \propto h_{ji} \, \tau_i$$

where

$$h_{ji} = \partial F_j / \partial X_i$$

define the directions of the coordinate curves on a surface



Generic Optical Flow Equation for Skin Friction in Mass-Transfer Visualizations

$$G + \hat{\tau}_j \, \partial g / \partial x_j = 0$$

PSP Visualization

$g = I_{ref} / I$	$G = g - I_{ref} / I_{00} + \varepsilon_0$

Sublimation Visualization with Changing Density

$g = I / I_{ref}$	$G = g - 1 + \varepsilon_1 + \varepsilon_2$

Sublimation Visualization with Changing Thickness

$g = I / I_{ref}$	$G = -g + 1 + \varepsilon_3$

Variational Formulation

The functional with a smoothness constraint:

$$J(\hat{\boldsymbol{\tau}}) = \int_{\Omega} \left(G + \hat{\boldsymbol{\tau}} \bullet \nabla g \right)^2 dx_1\, dx_2 + \alpha \int_{\Omega} \left(\left| \nabla \hat{\tau}_1 \right|^2 + \left| \nabla \hat{\tau}_2 \right|^2 \right) dx_1\, dx_2$$

The Euler-Lagrange equations:

$$\left[G + \hat{\boldsymbol{\tau}} \bullet \nabla g \right] \nabla g - \alpha \nabla^2 \hat{\boldsymbol{\tau}} = 0$$

where the Neumann condition $\partial \hat{\boldsymbol{\tau}} / \partial n = 0$

If g ***&*** G ***are measured and known,***

$\hat{\boldsymbol{\tau}} = (\hat{\tau}_1, \hat{\tau}_2)$ ***can be obtained by solving the E-L equation.***

Uncertainty Analysis and Intrinsic Limitation

The relative error in skin friction calculation:

$$\frac{(\delta\hat{\tau})_N}{\|\hat{\tau}_0\|} = -\frac{\delta G}{\|\nabla g_0\|\|\hat{\tau}_0\|} - \left(\frac{\hat{\tau}_0}{\|\hat{\tau}_0\|}\right)\bullet \delta \boldsymbol{N}_T + \frac{\alpha}{\|\nabla g_0\|^2}\nabla^2\left[\frac{(\delta\hat{\tau})_N}{\|\hat{\tau}_0\|}\right]$$

Consequences:

(1) When $\|\nabla g_0\| \to 0$ **the error blows up** $(\delta\hat{\tau})_N / \|\hat{\tau}_0\| \to \infty$

which imposes an intrinsic limitation on this method

(2) The Lagrange multiplier α **must be as small as possible.**

Unsteady Measurements with Fast PSP Visualization

Superposition

$$\hat{\tau}_j = \hat{\tau}_{j,s} + \hat{\tau}'_j$$

Quasi-steady solution:

$$G_1 + \hat{\tau}_{j,s}\, \partial g_s / \partial x_j = 0$$

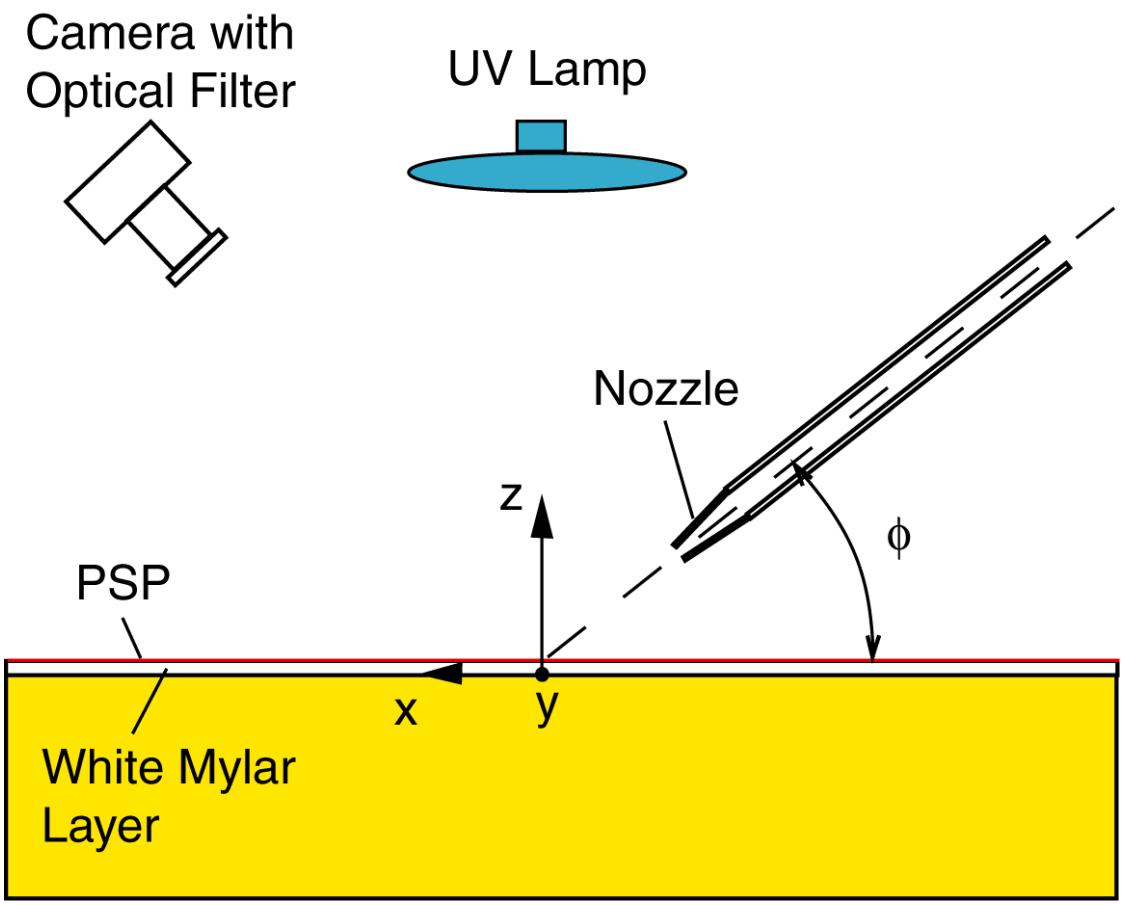
where $G_1 = g_s - g_{00} + \langle \varepsilon \rangle_t$

Variation for unsteady effect:

$$G_2 + \hat{\tau}'_j\, \partial g_s / \partial x_j = 0$$

where $G_2 = \Delta g_{k+1} - \Delta g_k + \hat{\tau}_{j,s} \partial(\Delta g_{k+1} / 2) / \partial x_j$

Circular Impinging Nitrogen Jet Visualized with PSP



- PSP: Ru(phen) in GE RTV 118
- UV for illumination
- CCD camera with long-pass filter
- 75 microns Mylar

$$D = 2\ mm$$

$$U_o = 50\ m/s$$

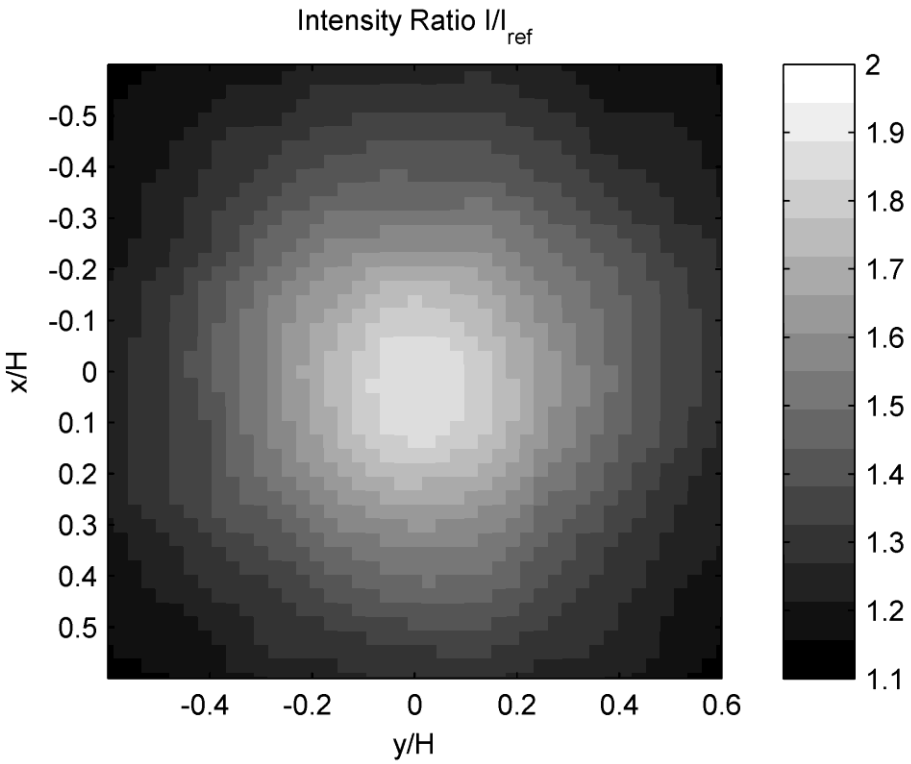
$$Re_D = U_o D / \nu = 6.4 \times 10^3$$

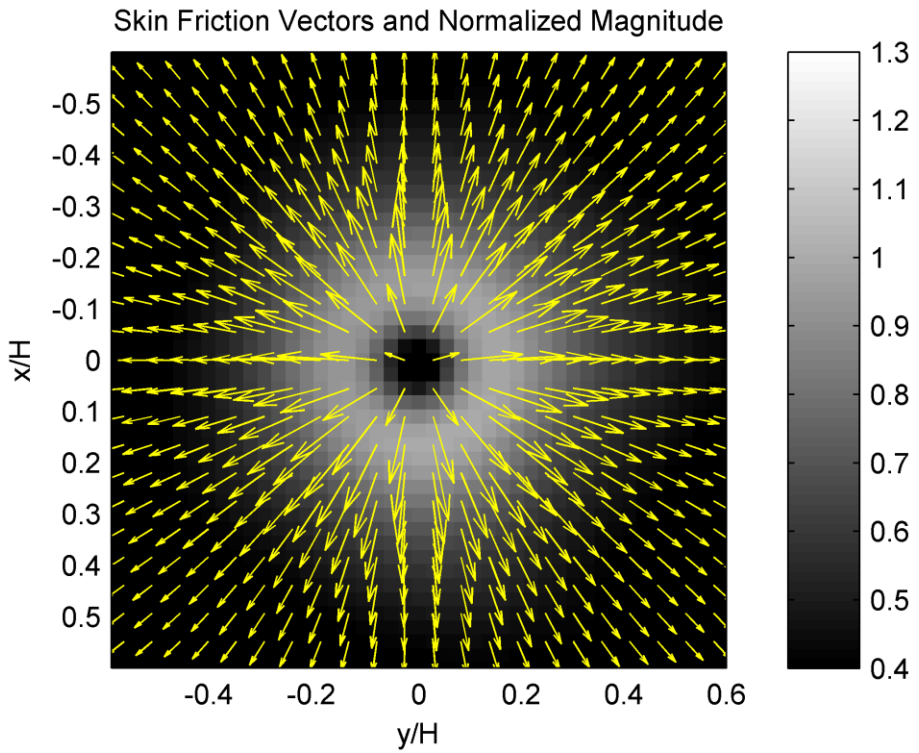
$$H / D = 6$$

Normal Impinging Nitrogen Jet

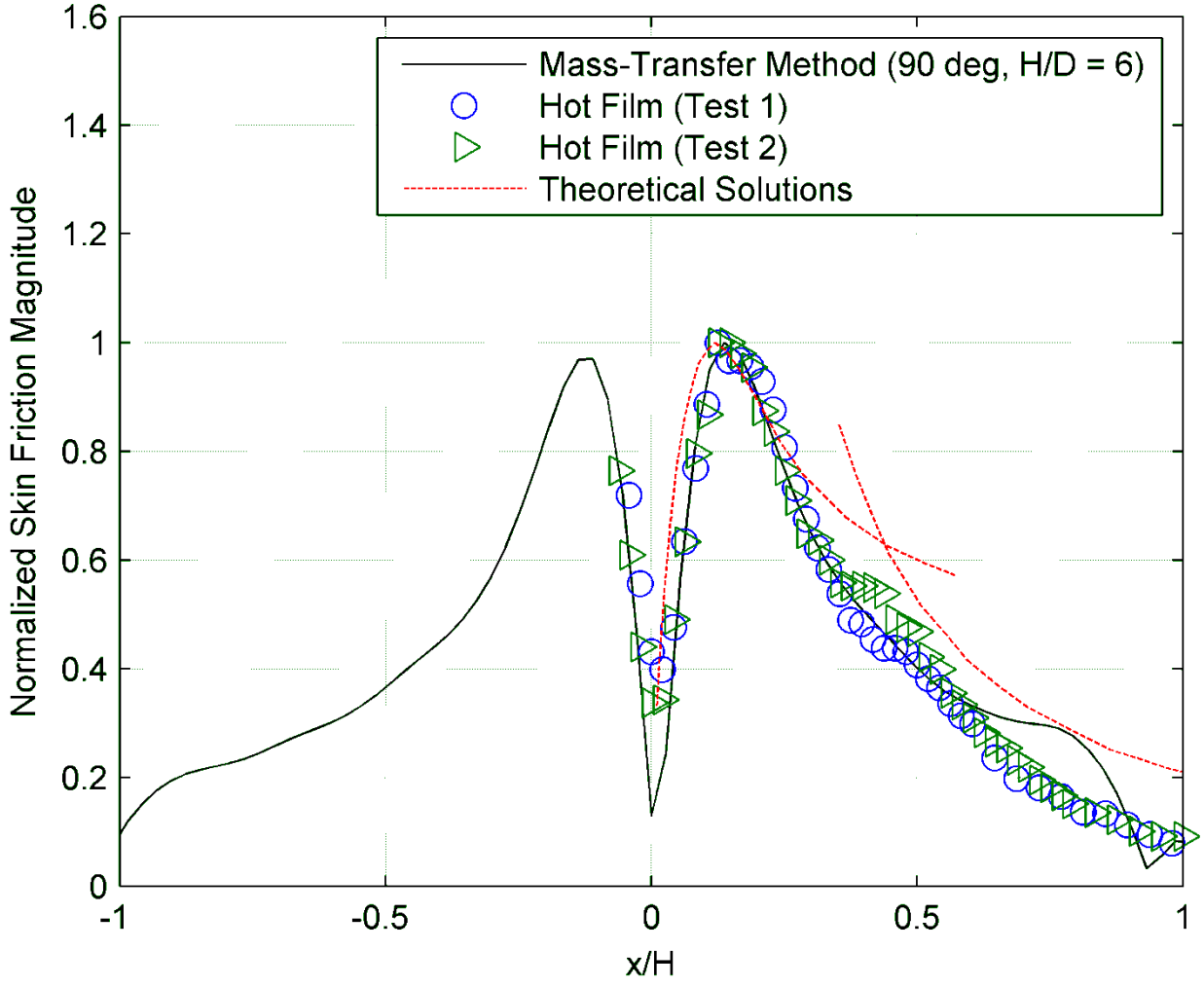
Normalized PSP Intensity Distribution

Normalized skin friction field



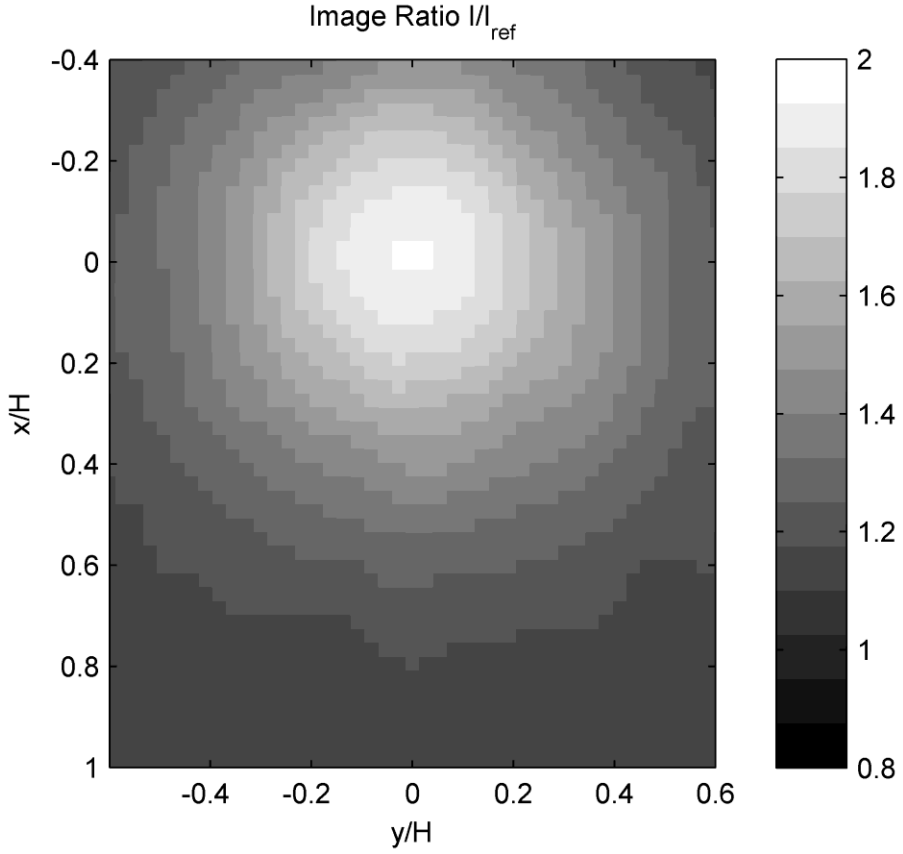


Transverse Distributions of Skin Friction Magnitude for Normal Impinging Jet

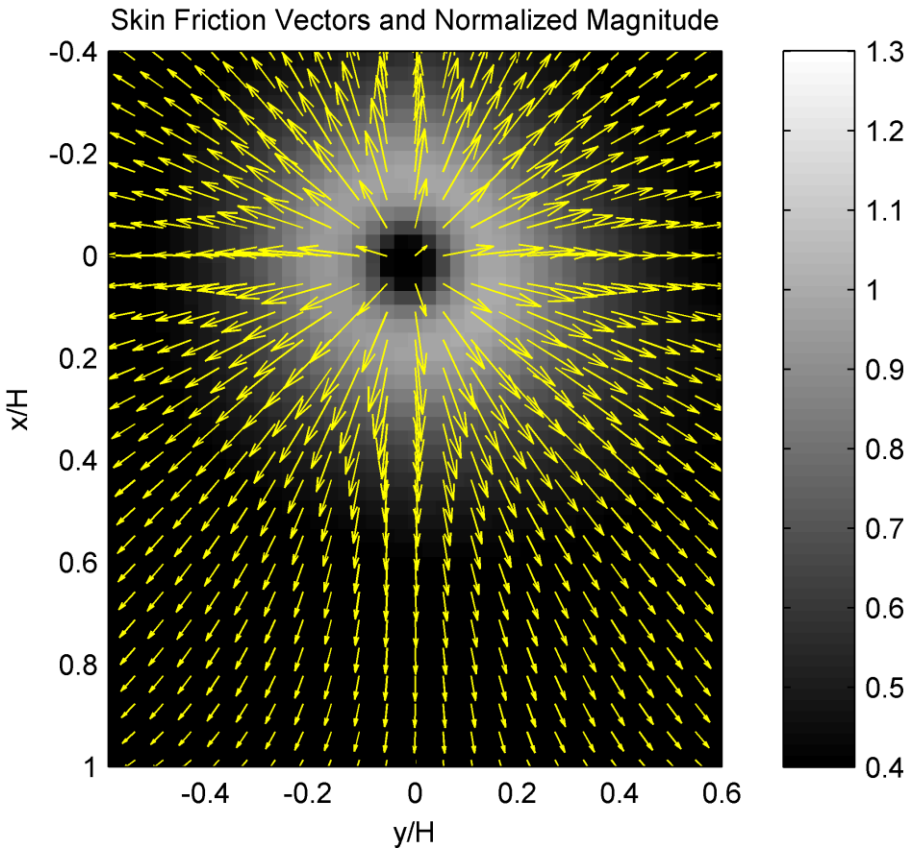


75-deg Oblique Impinging Jet

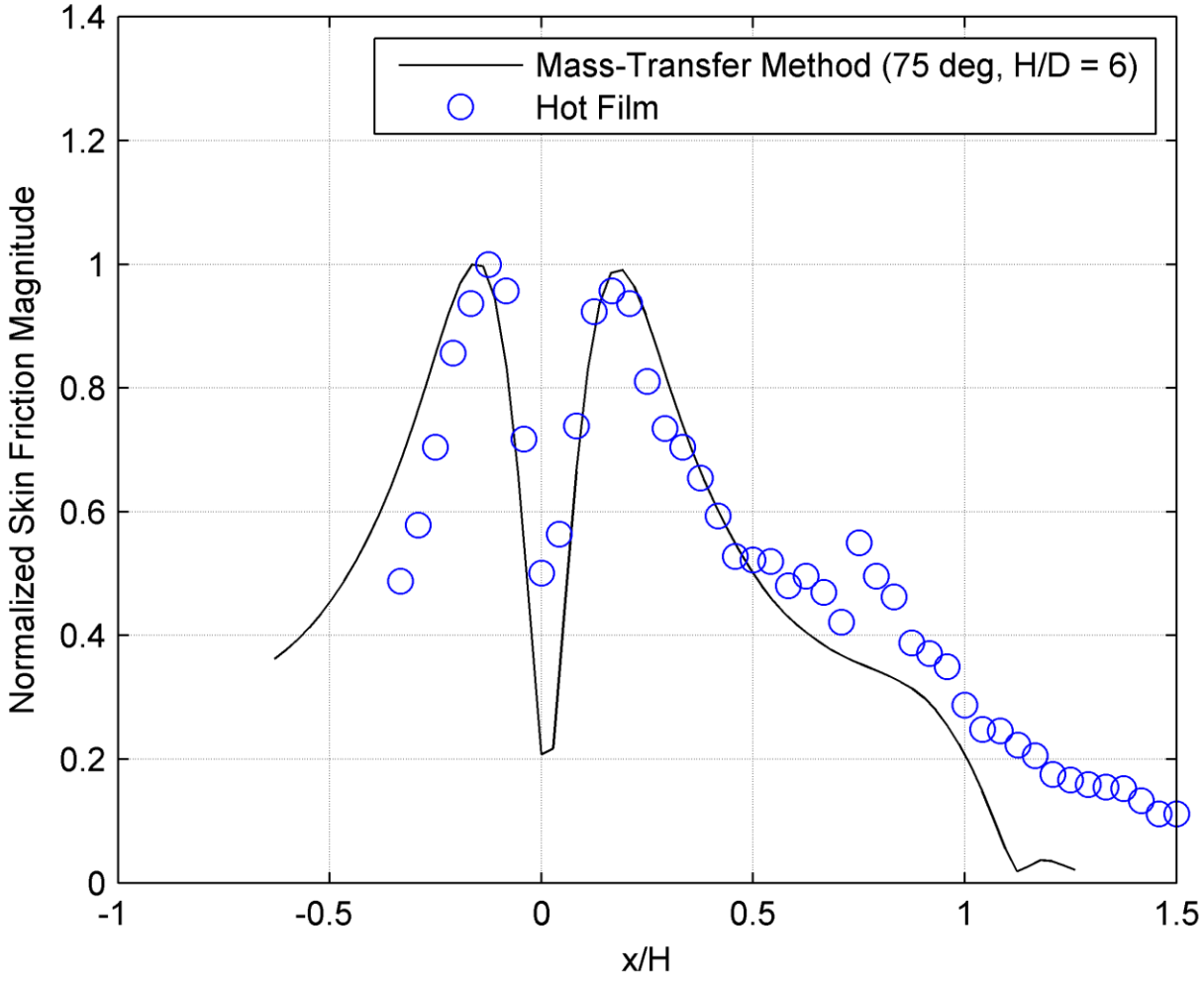
Normalized PSP Intensity Distribution



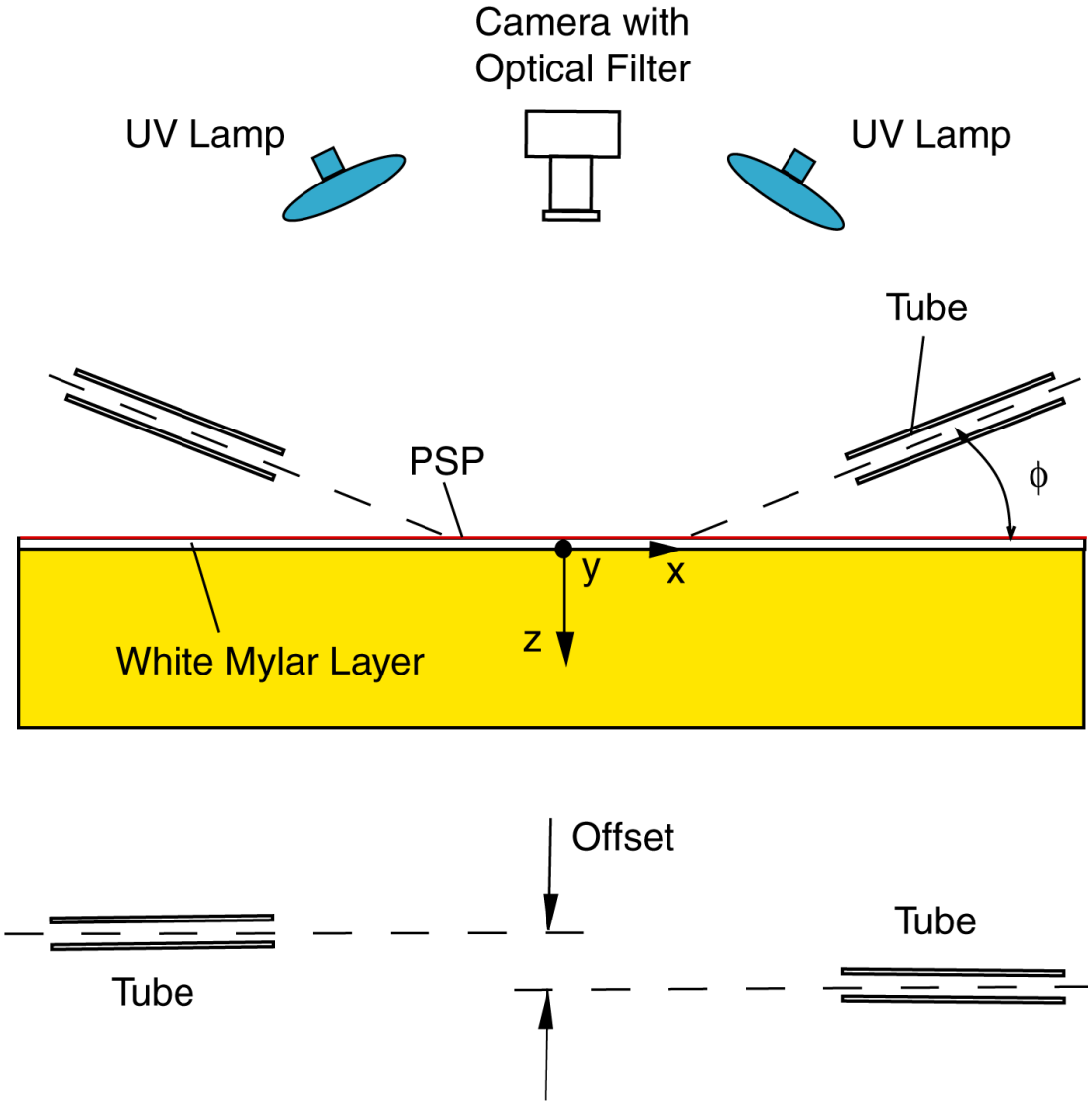
Normalized skin friction field



Transverse Distributions of Skin Friction Magnitude for 75-dge Oblique Impinging Jet



Dual Colliding Impinging Nitrogen Jets Visualized with PSP



- PSP: Ru(phen) in GE RTV 118
- UV for illumination
- CCD camera with long-pass filter
- 75 microns Mylar

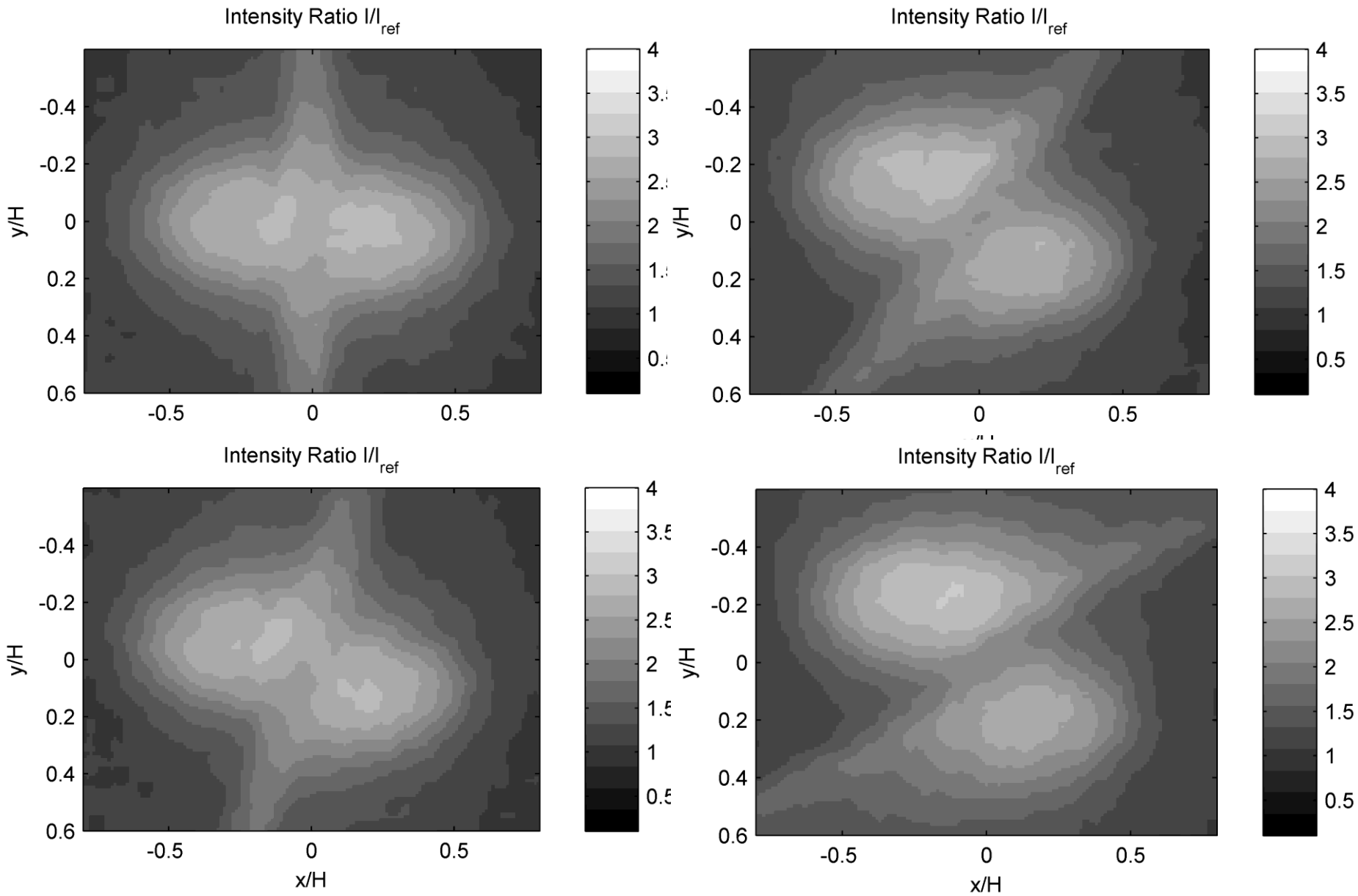
$$D = 5.18\,mm$$

$$\phi = 30^o$$

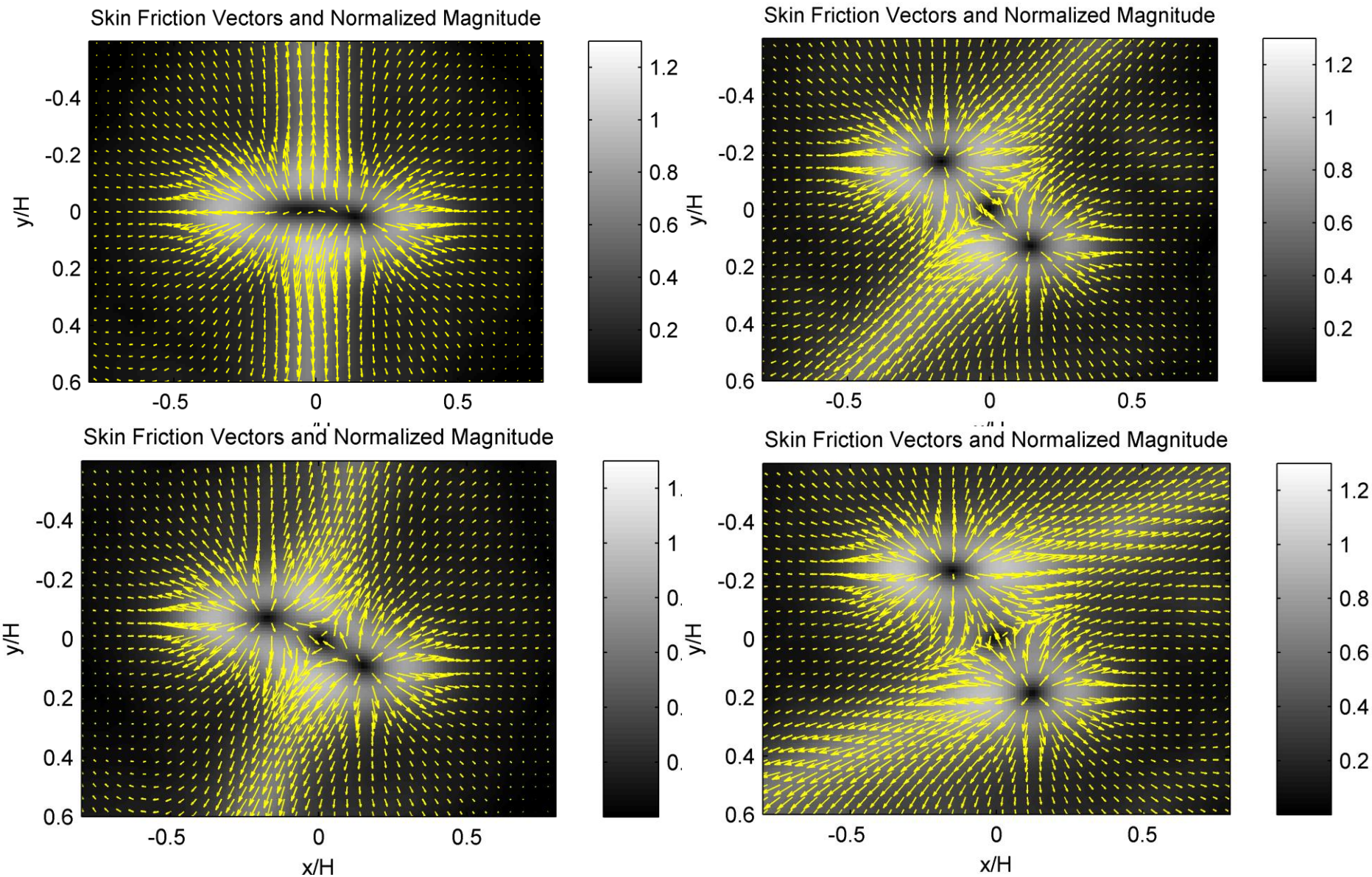
$$H = 29.5\,mm$$

$$U = 4.14\ m/s$$

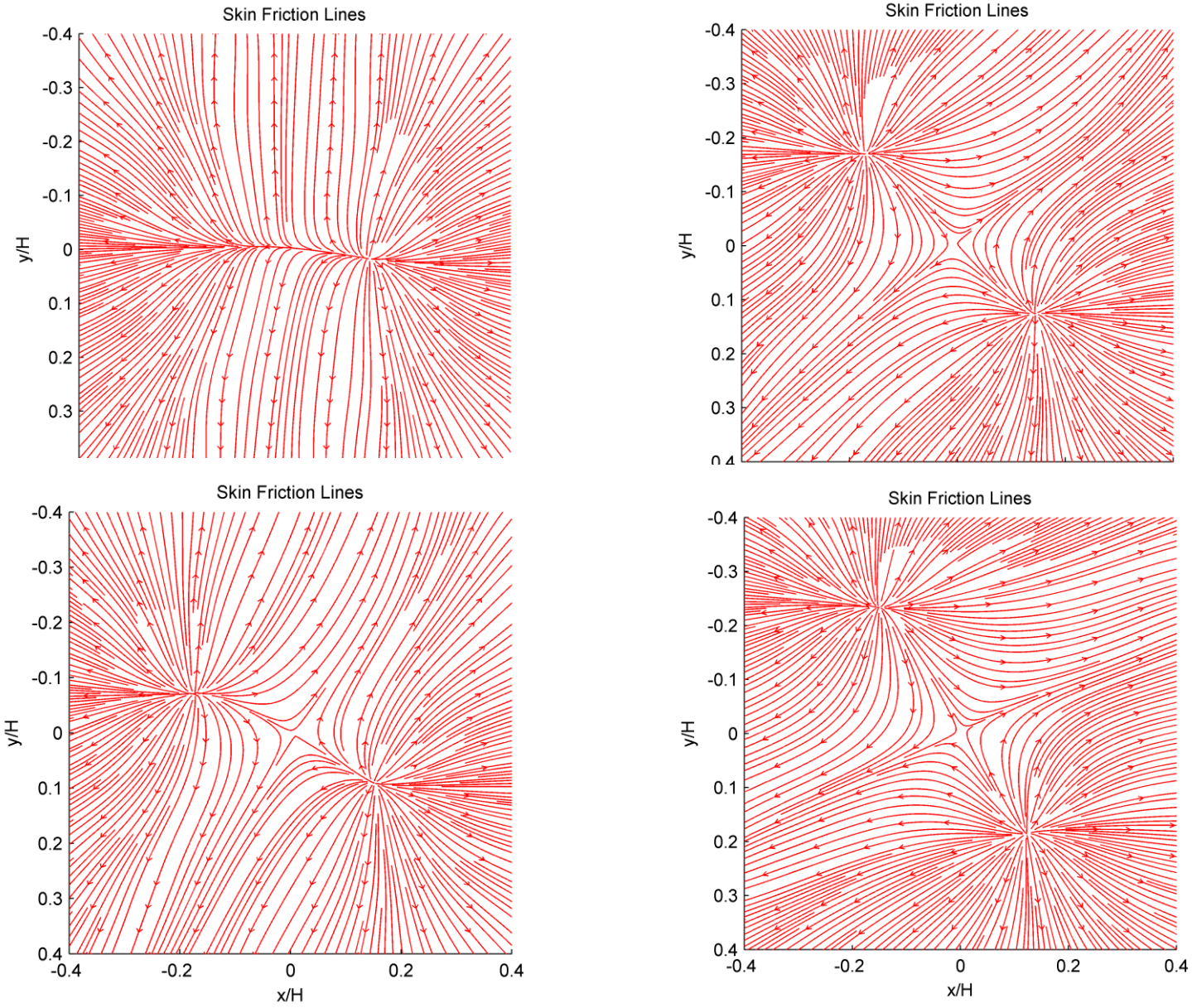
PSP Intensity Images at Different Offsets



Skin Friction Vector and Magnitude Fields

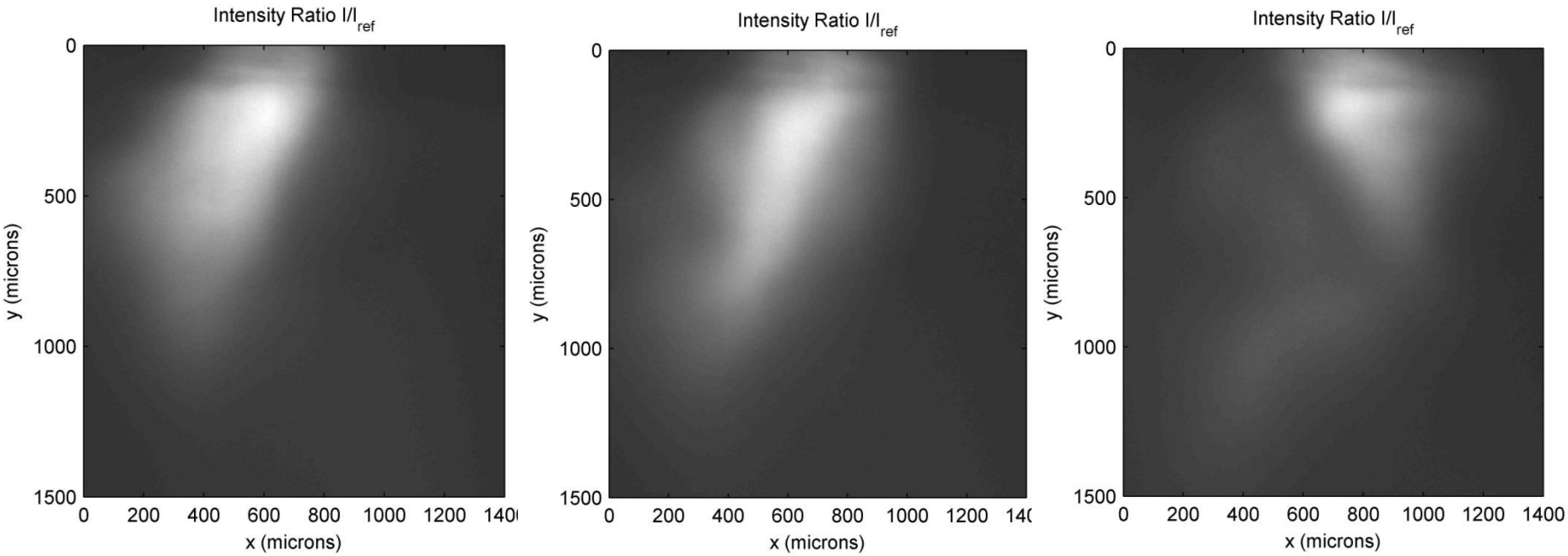


Skin Friction Lines



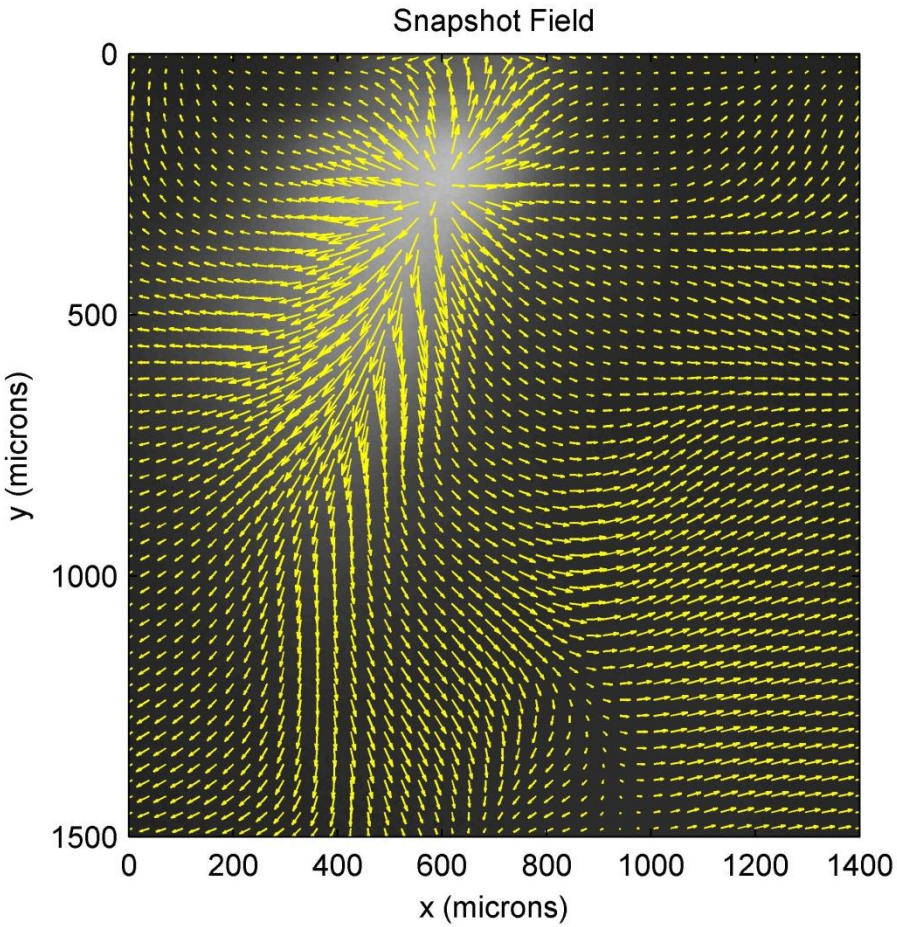
Oscillating Impinging Nitrogen Jets at 9.4 kHz Visualized with Fast PSP (Gregory et al. 2007)

0 μs **20 μs** **40 μs**

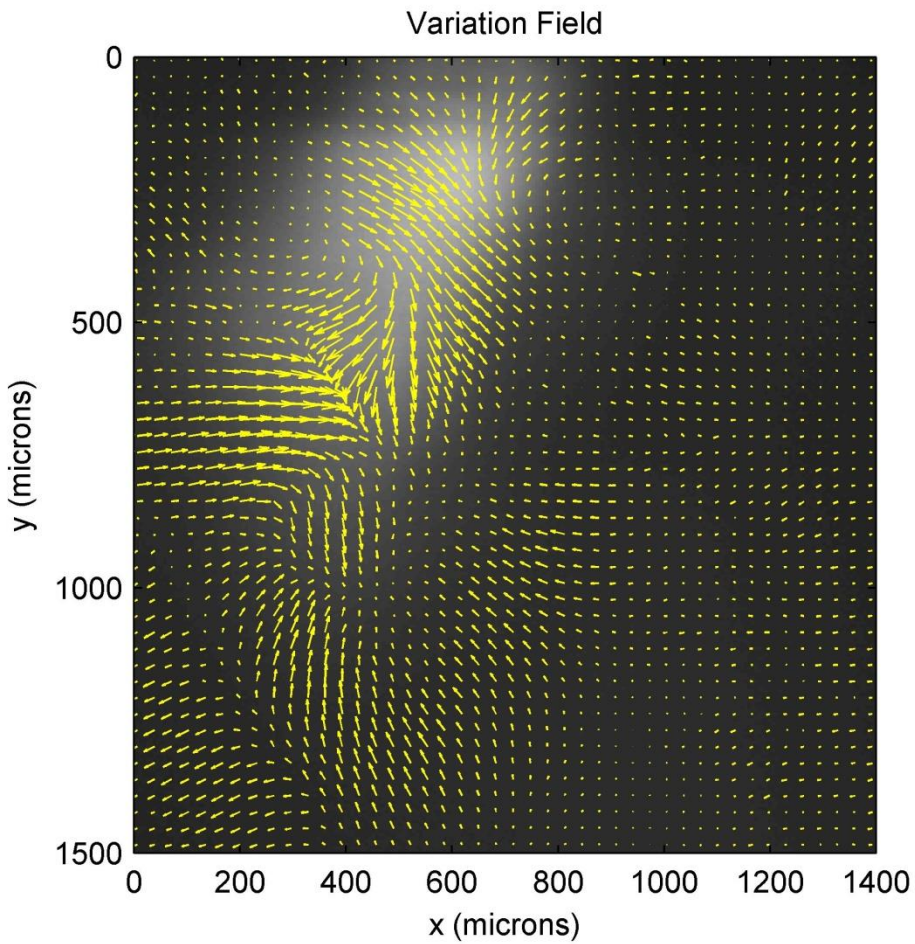


Quasi-Steady and Variation Fields at 0 μs

Quasi-steady field

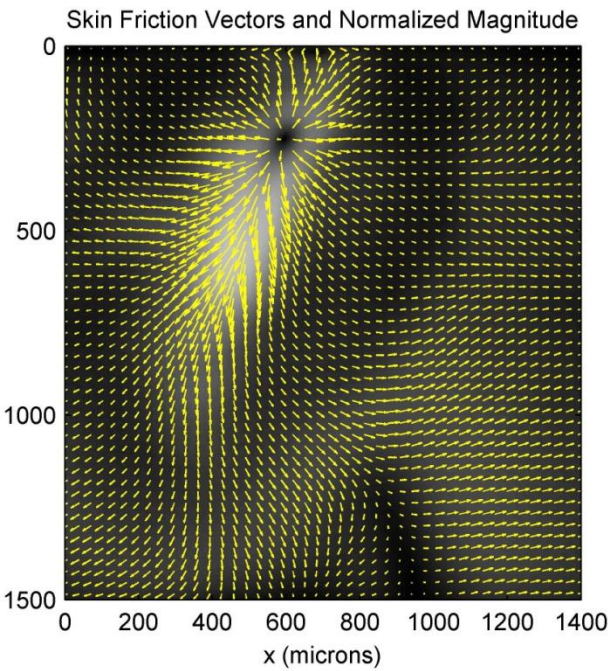


Variation field associated with unsteady effect (~ 10%)

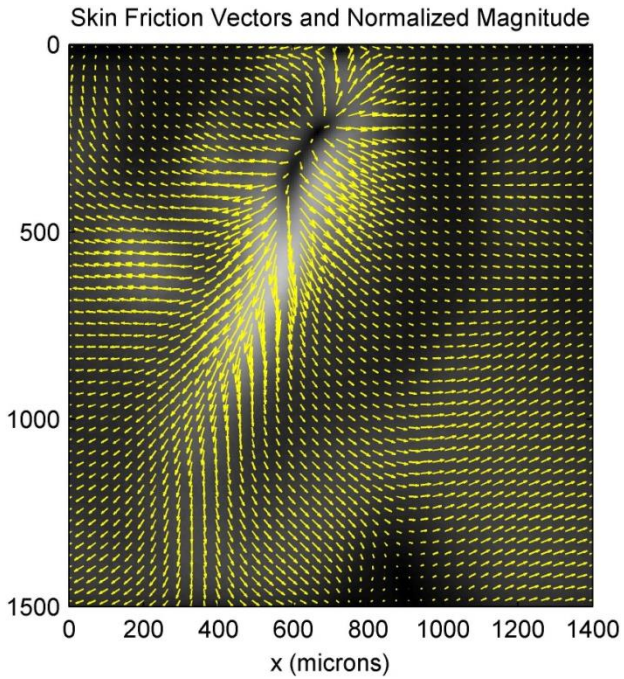


Unsteady Skin Friction Fields Reconstructed by Superposition of Quasi-Steady and Variation Fields

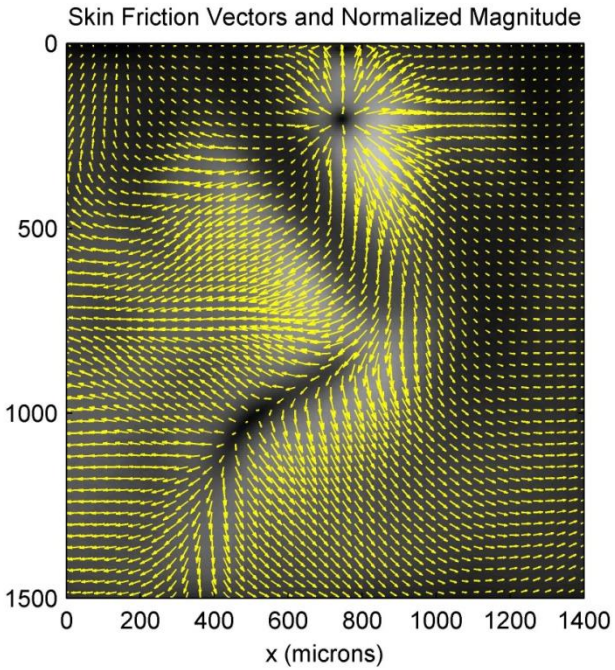
0 μs



20 μs

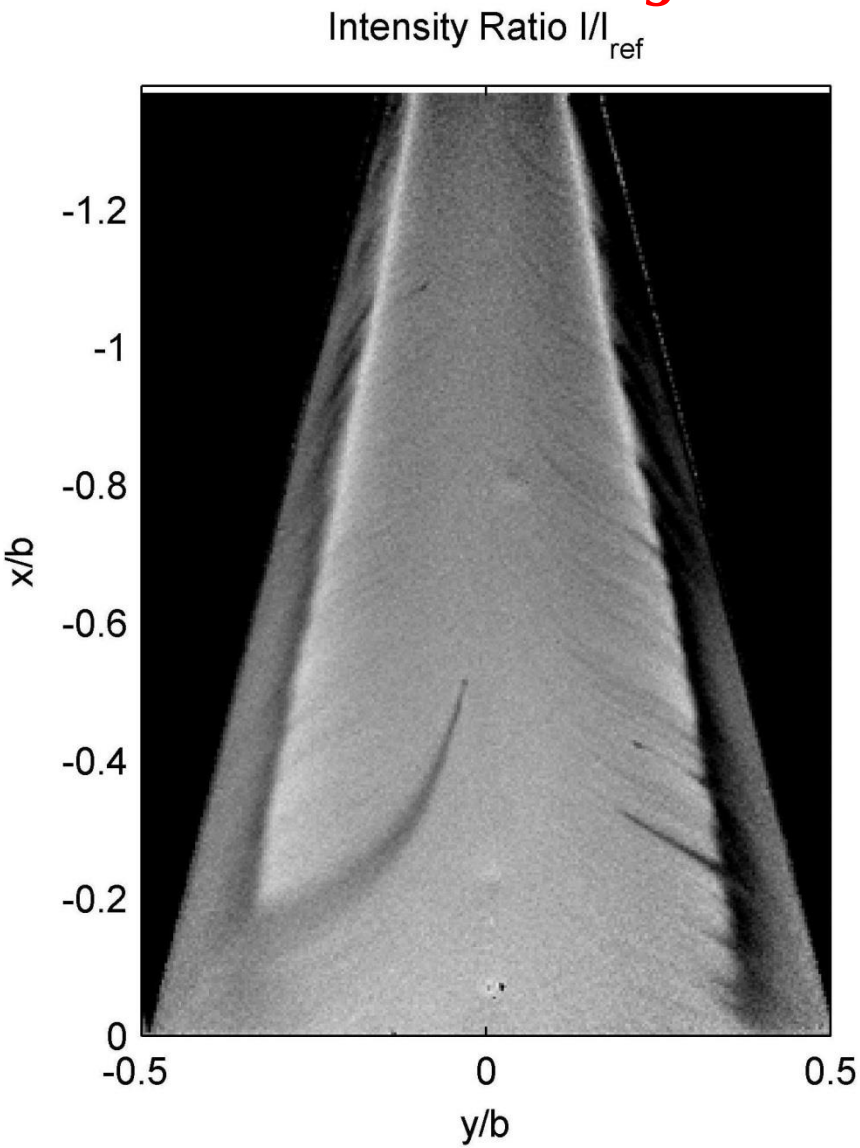


40 μs

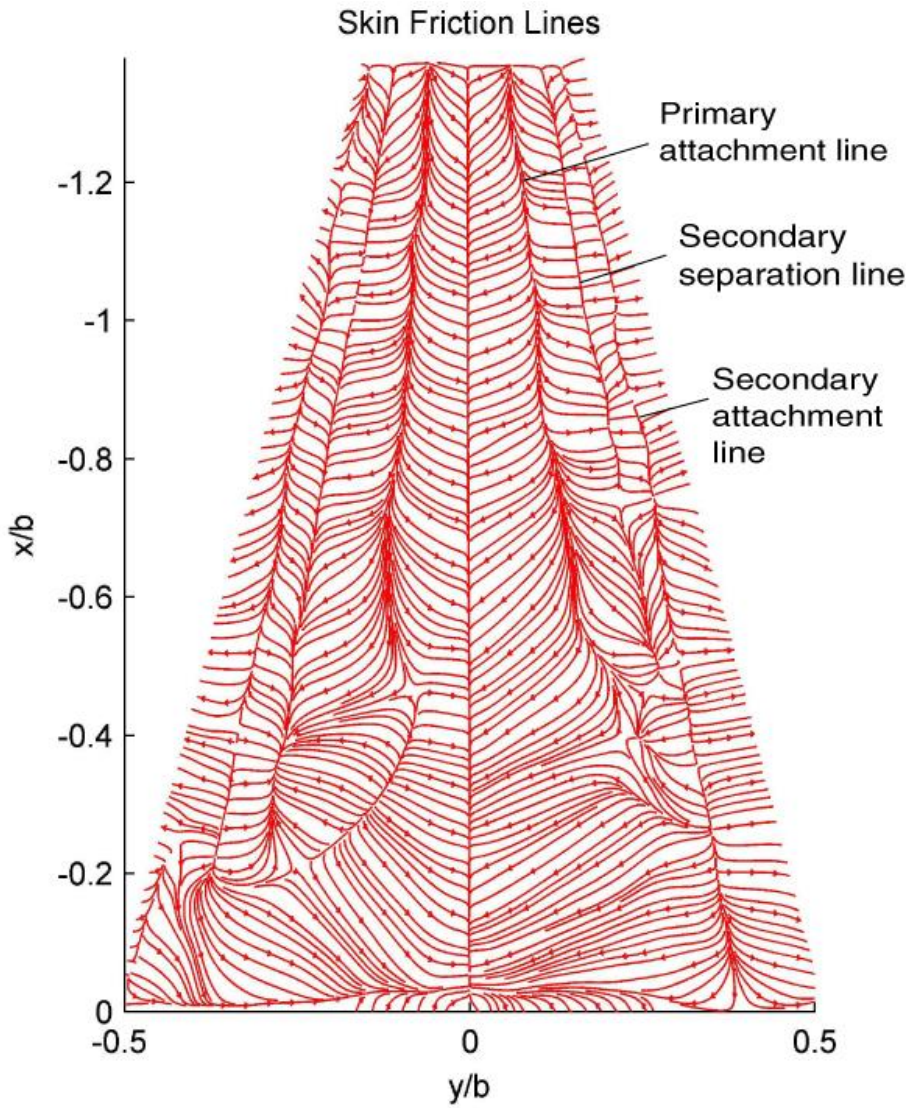


Sublimation Visualization with Pyrene PSP on a 75-deg Delta Wing (ONERA)

Sublimation image



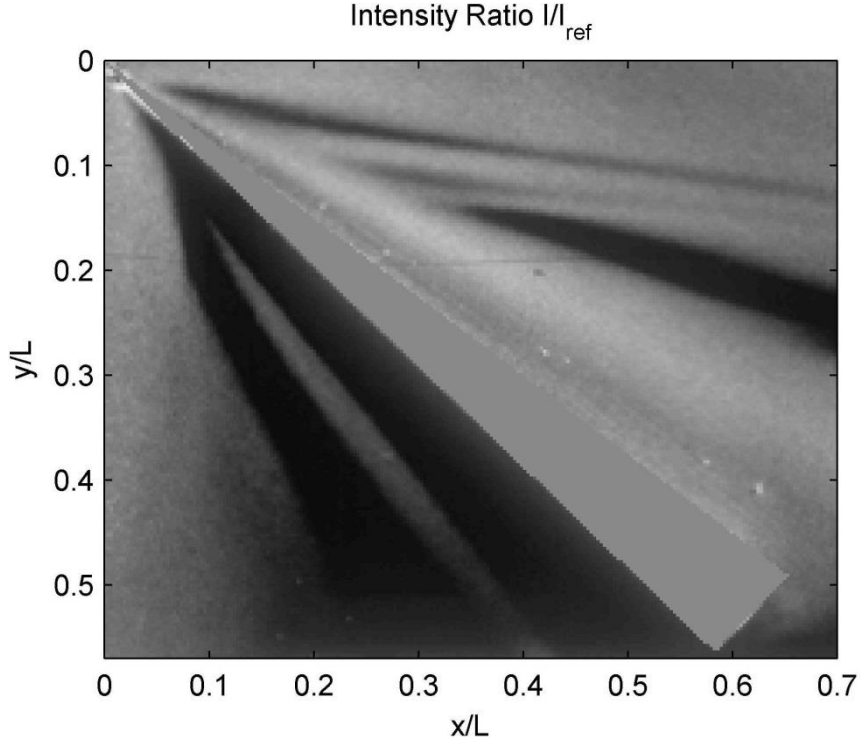
Extracted skin friction field



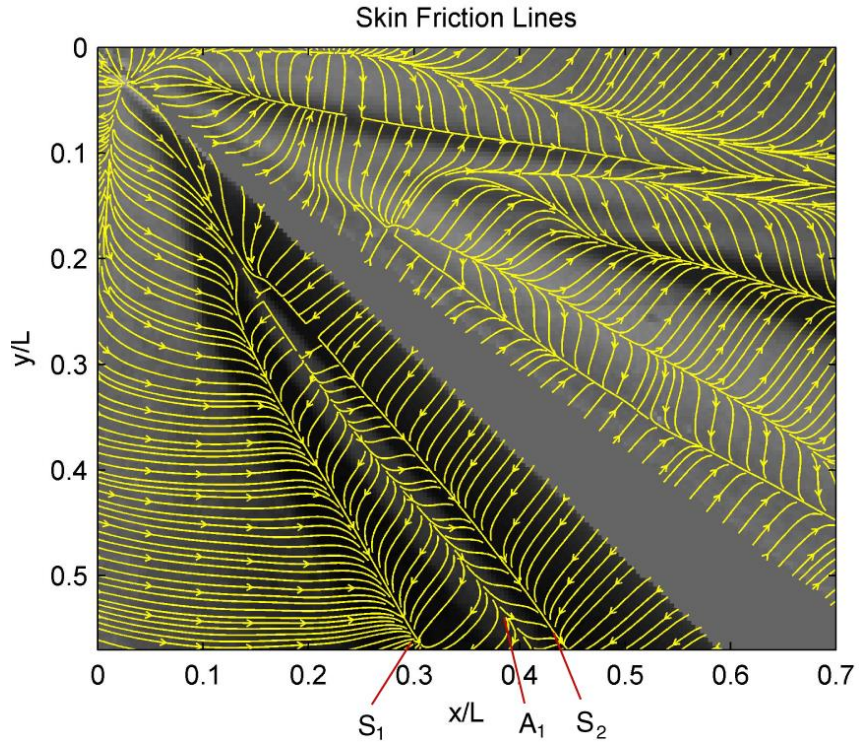
Sublimation Visualization with Acenaphthene in Shock-BL Interaction at Mach 6 (VKI)

(S. Zemsch 1996, M. Carbonaro 1994)

Sublimation image



Extracted skin friction field



Conclusions

- ***Global skin friction diagnostics is feasible based on surface mass-transfer visualizations.***
  In particular, it is possible for unsteady skin friction diagnostics with fast PSP.

- ***The intrinsic limitation is that this method has large error when the intensity gradient is zero.***

- ***It is incorporated into the unified framework of physics-based optical flow method for global velocity and skin friction diagnostics.***