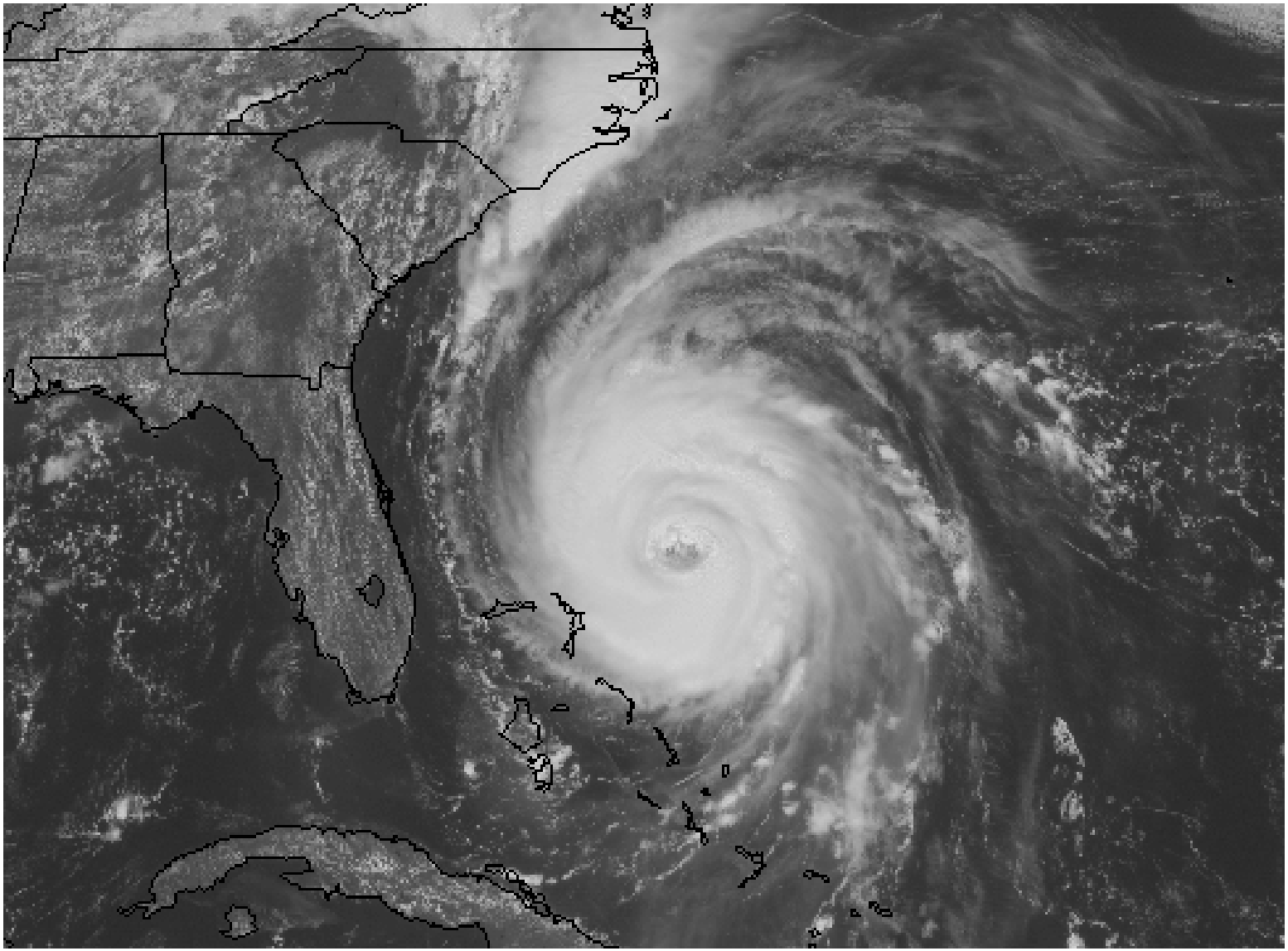
流动显示
Flow visualizations

高南

- “眼见为实”
- “seeing is believing”
- “有图有真相”

Hurricane Fran, 1996



流体力学中的几种线

- 流线
- 迹线
- 脉线
- 时间线

流动显示方法

- 投入示踪粒子
  - 烟，雾
  - 氢气泡
- 表面流动
  - 油流
- 压敏材料
  - PSP，压敏液晶
- 超声速流动显示
  - 纹影等

直接混入示踪粒子

选择示踪粒子

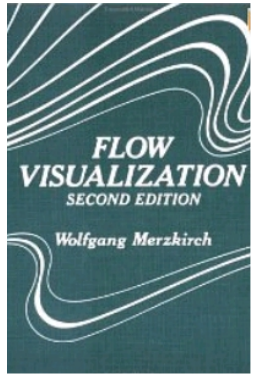
Table 3. Seeding particles in gas flows.

Material	d_p (μm)	Laser	Pulse energy, pulse time	Light sheet w (mm)	Light sheet t (mm)	Reference
TiO_2 ($m = 2.6$, $\rho = 3500$ kg m^{-3})	<1	Nd:YAG	10 mJ, 20 ns	15	0.3	Reuss *et al* (1989)
TiO_2, ZrO_2	0.7–1	Nd:YAG	110 mJ, 12 ns			Paone *et al* (1996)
Al_2O_3 ($m = 1.76$,	0.3	Nd:YAG	400 mJ		0.2	Muniz *et al* (1996)
$\rho = 3970$ kg m^{-3})	3	Nd:YAG	9 mJ, 6 ns			Anderson *et al* (1996)
	0.8	Ruby	20 ns	150	$\simeq$1	Krothapalli *et al* (1996)
Polycrystalline	30	Nd:YAG	135 mJ, 6 ns			Grant *et al* (1994)
Glass	30	Ruby	30 mJ, 30 ns			Schmidt and Löffler (1993)
Oil smoke	1	Ruby	5 J			Stewart *et al* (1996)
Corn oil	1–2	Nd:YAG	100 mJ			Jakobsen *et al* (1994)
Oil	1–2	Nd:YAG	120 mJ		0.4	Westerweel *et al* (1993)
Olive oil ($m = 1.47$, $\rho = 970$ kg m^{-3})	1.06	Nd:YAG	70 mJ, 16 ns	200	0.5	Höcker and Kompenhans (1991) Fischer (1994) Raffel *et al* (1996)

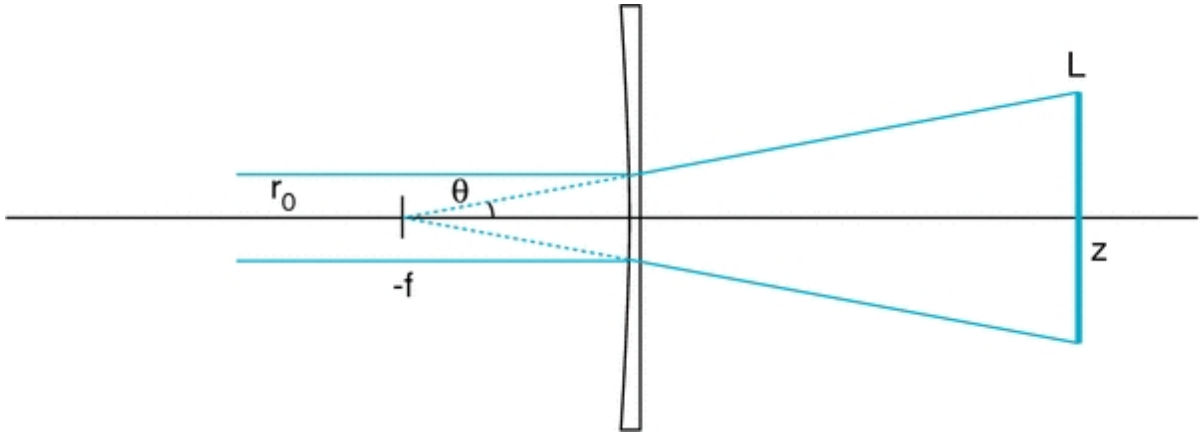
Table 4. Seeding particles in liquid flows.

Material	d_p (μm)	Laser	CW power or energy, time	Light sheet		Reference
				w (mm)	t (mm)	
TiO_2	3	Nd:YAG				Longmire and Alahyari (1994)
Al_2O_3	9.5	Ruby	2 J, 30 ns	100	0.8	Liu *et al* (1991)
Conifer pollen	50–60	Ar ion	1-2 W			Westergaard *et al* (1993)
(ρ = 1000 kg m^{-3})						McCluskey *et al* (1995)
						Gallagher and McEwan (1996)
Polymer	30	Ar ion	0.5–5 W		0.5	Draad and Westerweel (1996)
(ρ = 1030 kg m^{-3})						McCluskey *et al* (1996)
Phosphorescent polymer	80	Ar ion	5 W		1	Willert and Gharib (1991)
Fluorescent	50	Nd:YAG				Hart (1996)
	20	Cu vapour	45 W		1	Roth *et al* (1995)
Polystyrene	500					Khoo *et al* (1992)
(ρ = 1050 kg m^{-3})	15	Ruby	25 mJ, 20 ns			Zhang *et al* (1996)
Thermoplastic	6	Nd:YAG		50	2	Hassan *et al* (1994)
(ρ = 1020 kg m^{-3})						
Reflective	60	Ar ion	18 W			Grant *et al* (1992)
(ρ = 1010 kg m^{-3})	30	Ar ion	12–18 W	200		Grant and Wang (1994)
Metallic coated	4	Ar ion	2 W		2	Magness *et al* (1993)
	14	Ar ion			1	Johari *et al* (1996)
Microspheres	$<$30	Ar ion				Graham and Soria (1994)
(ρ = 700 kg m^{-3})						
H_2 bubbles		Ar ion	1 W		0.3	Dieter *et al* (1994)

Fig. 2.18 Unsteady flow around an elliptic body oscillating at a frequency of 0.17 Hz. The fluid is water and the tracer particles are lycopodium; Reynolds number = 3300. (Courtesy M. Coutanceau, University of Poitiers, France.)



光源



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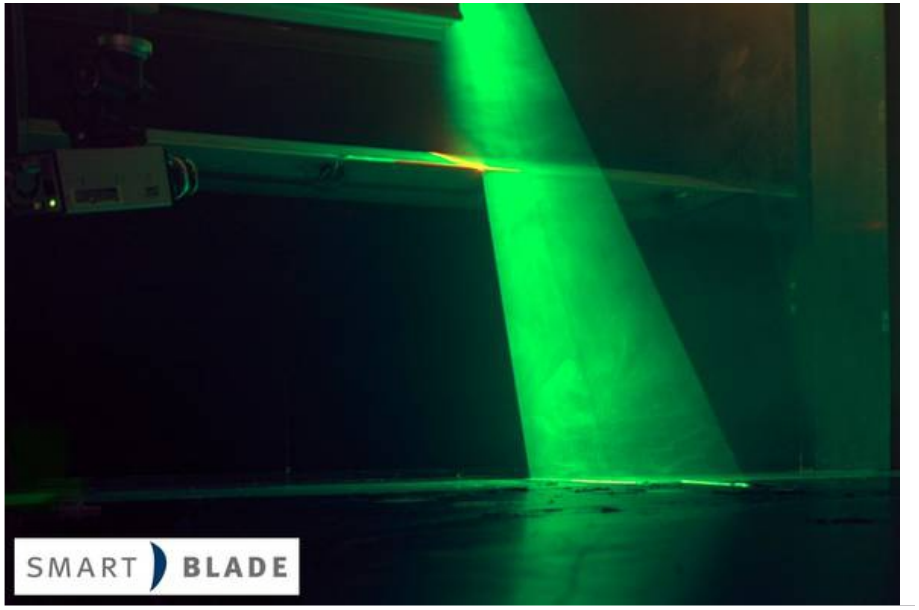
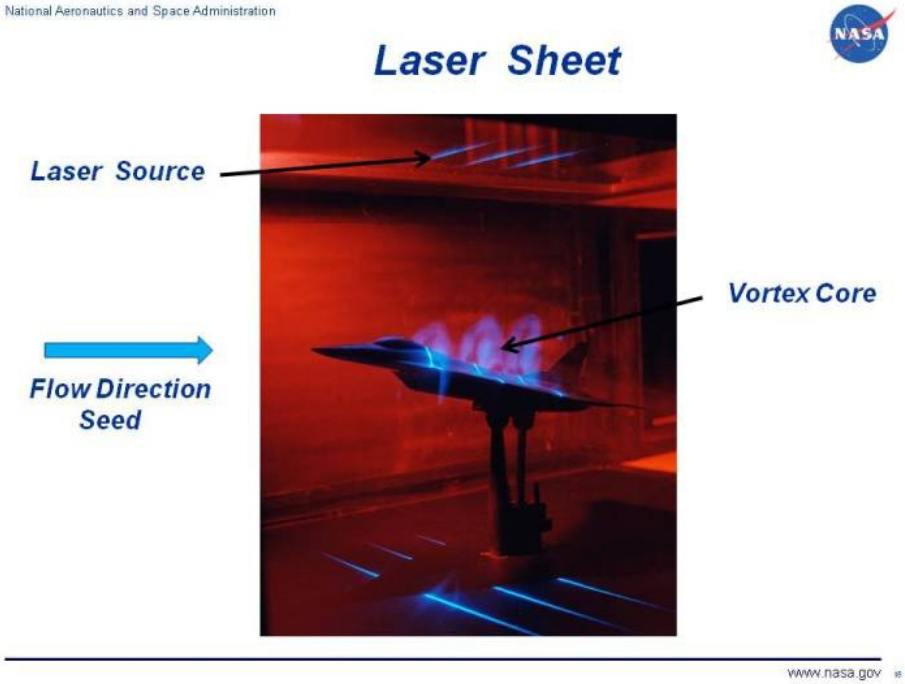
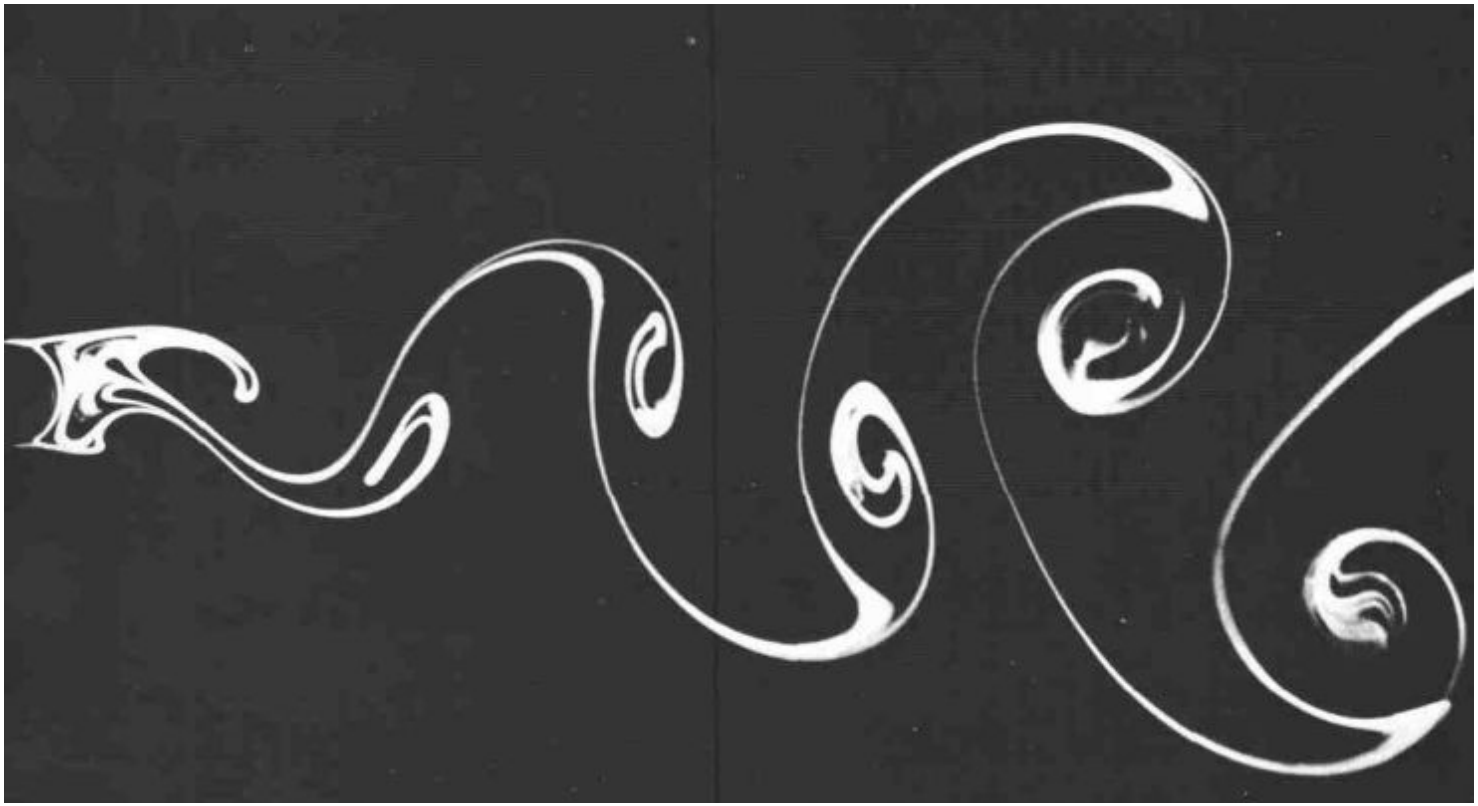


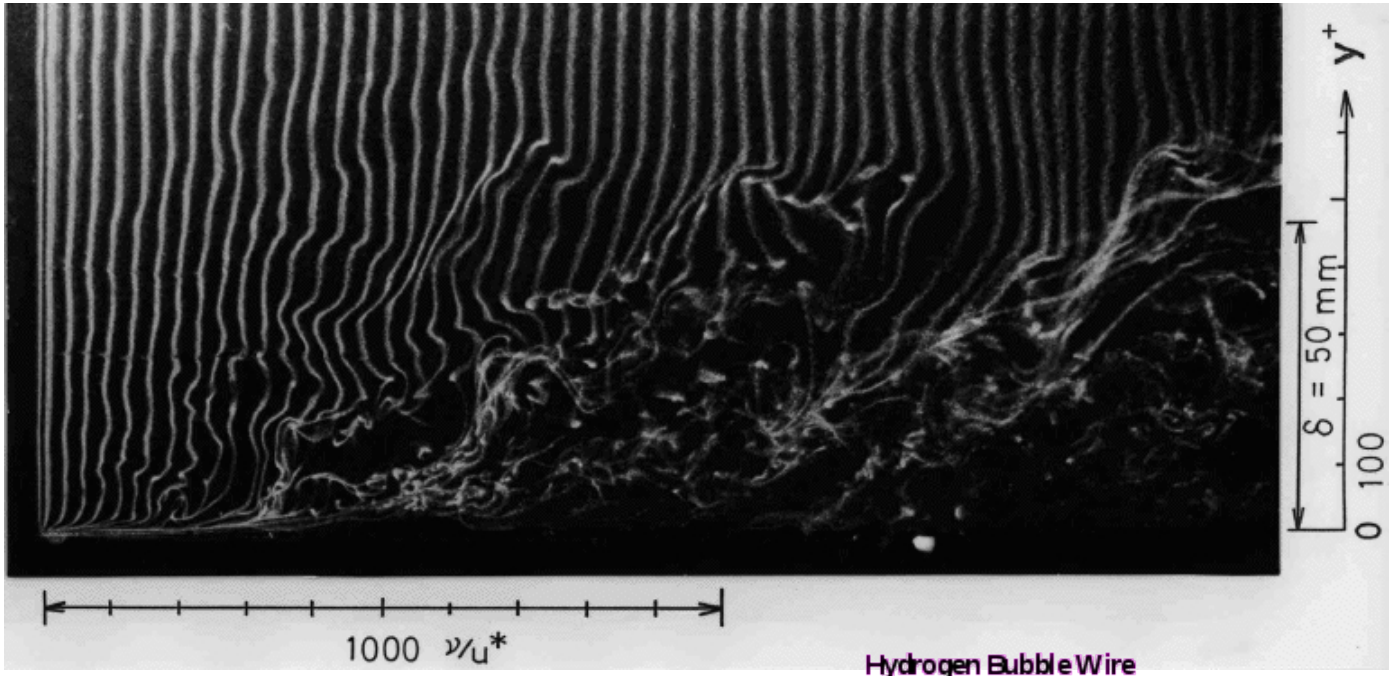


注入示踪粒子

- 圆柱表面注入荧光液体（罗丹明）
- 使用532nm激光照射,诱导590nm荧光



氢气泡



Hydrogen Bubble Wire

V=0 to 100 volts
I = 0 to .5 amp

Frame

Electrolysis of Water
Forms Hydrogen Bubbles
on Small Diameter Wire

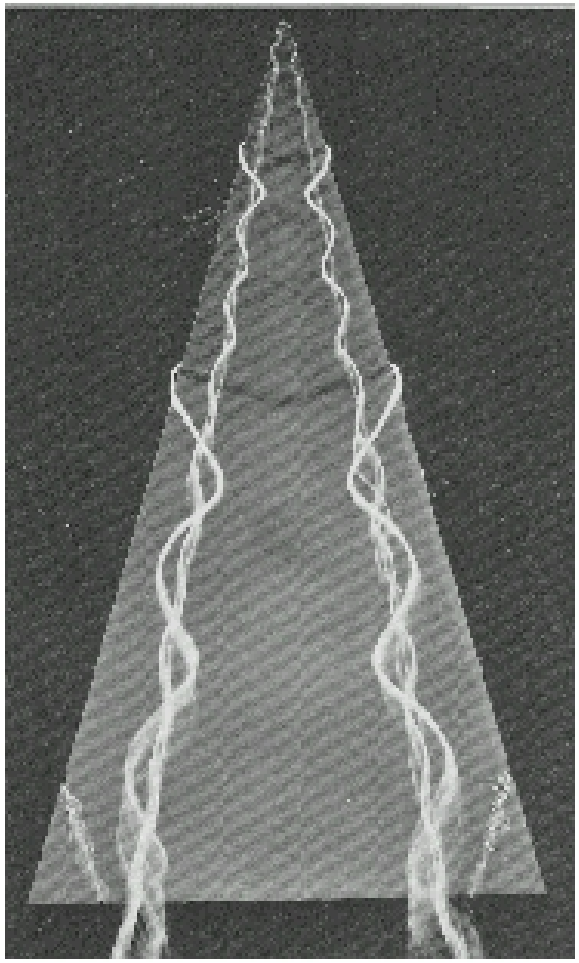
Water must be conductive
Hard water (Lafayette) is
conductive but calcium
deposits on wire
Can add Sodium Sulfate to
adjust the conductivity

Bubble Wire (~.001" dia.)
Platinum – expensive & weak
Tungsten – high strength
Steel – stainless does not corrode
Aluminum - weak

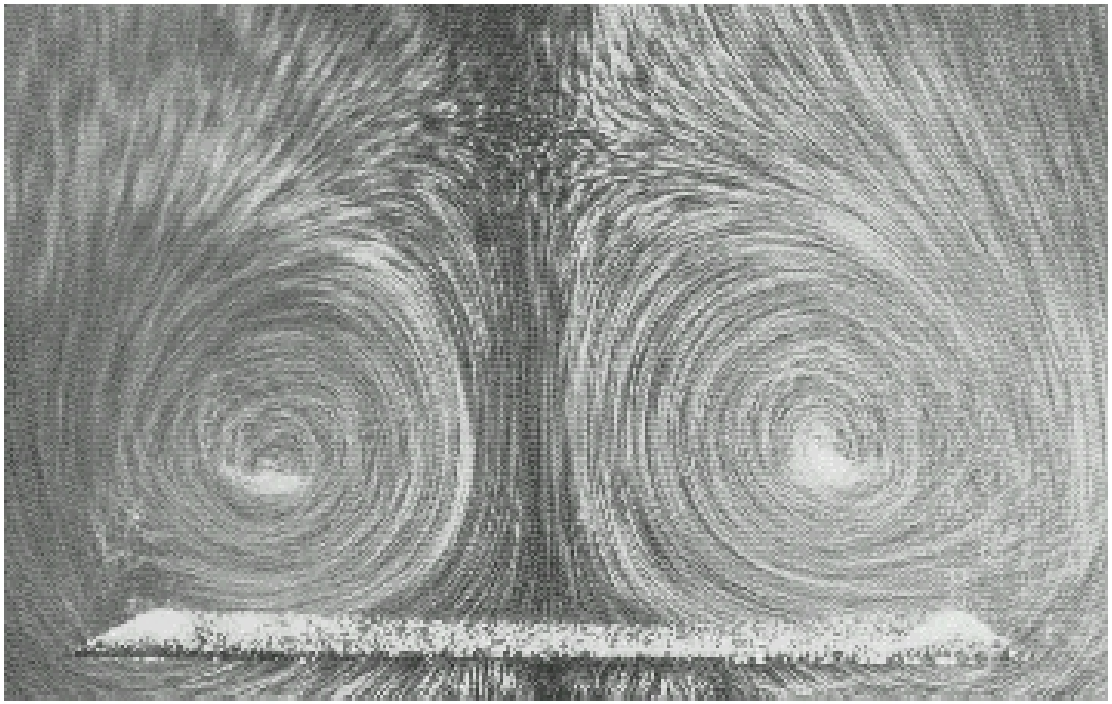
Bectrode
(somewhere
in flow tank)

Lighting is Critical –
Forward Scatter when possible

Delta Wing Vortex Top & Back Views



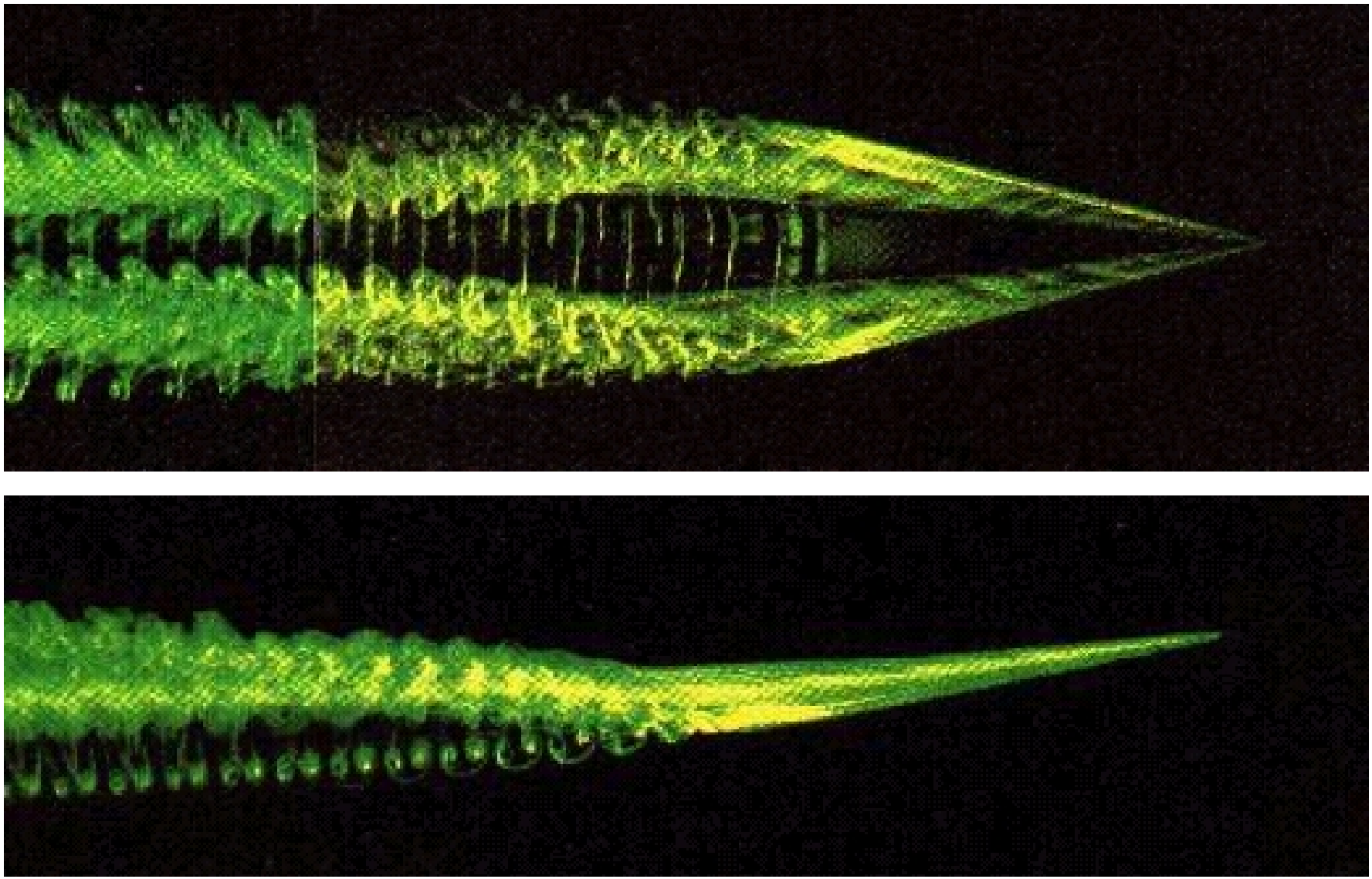
Top view



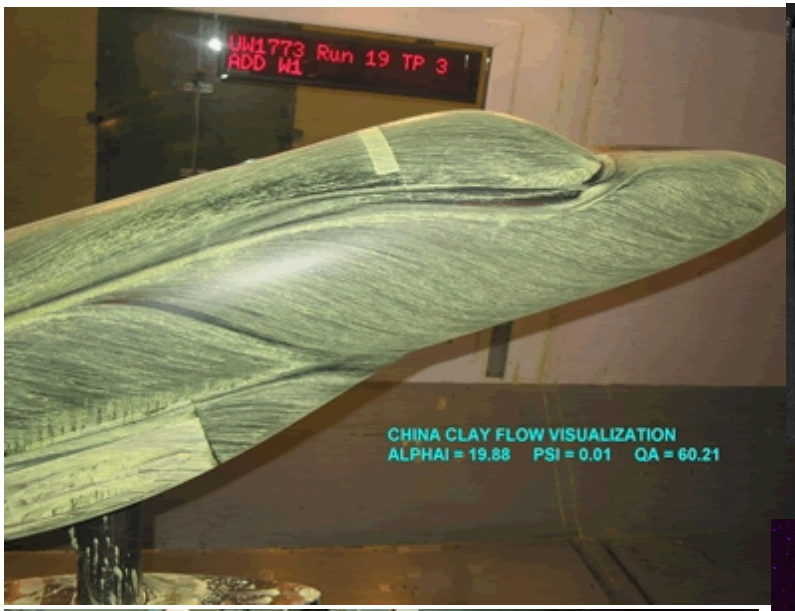
Cross section view

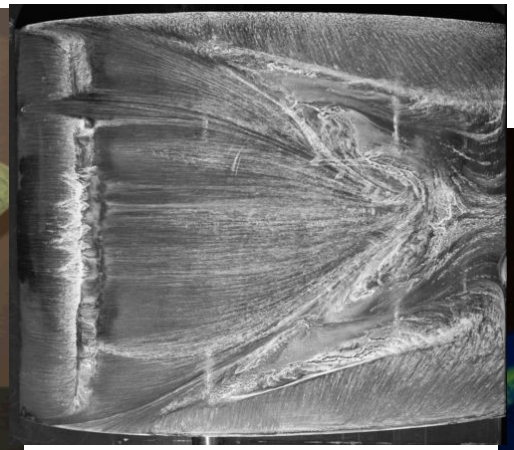
Photos courtesy of Van Dyke "An Album of Fluid Motion"

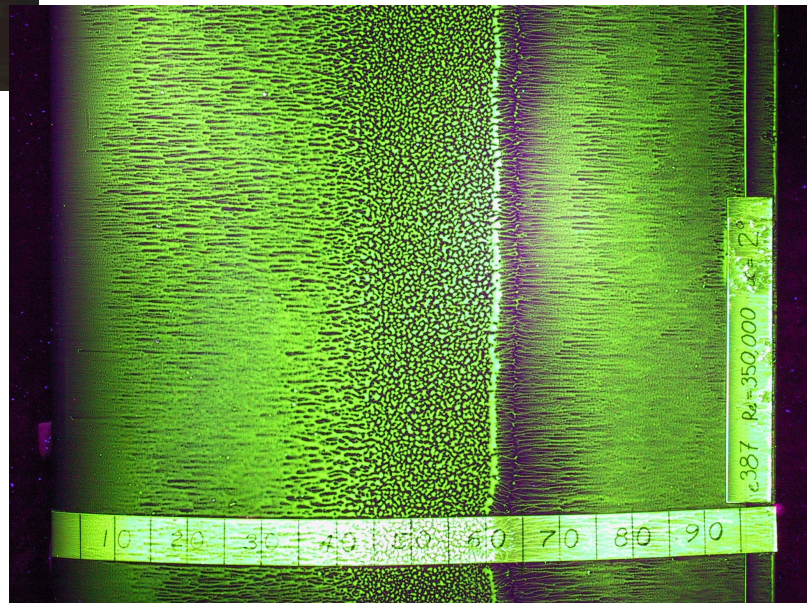
Delta Wing Vortex Top & Side Views



表面油流


UW1773 Run 19 TP 3
ADD W1
CHINA CLAY FLOW VISUALIZATION
ALPHAI = 19.88 PSI = 0.01 QA = 60.21





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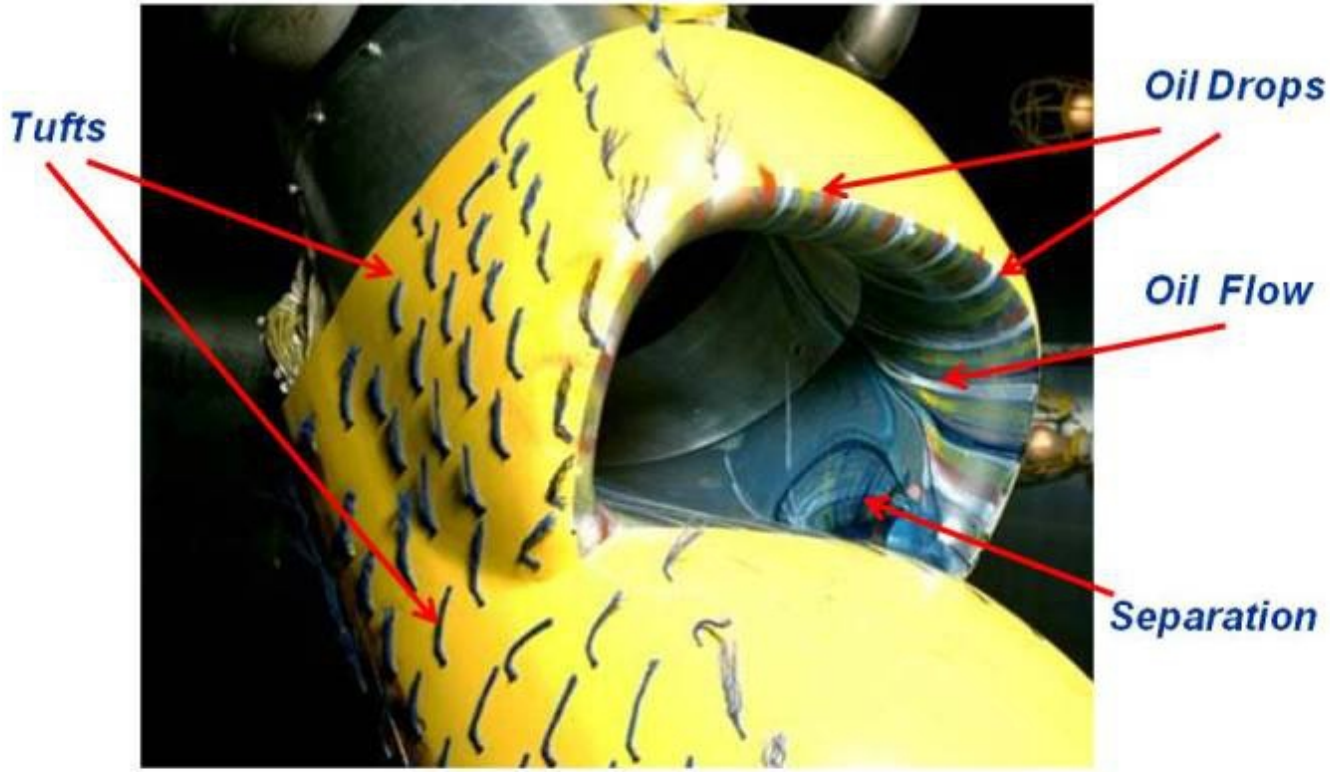
Surface Oil Flow



http://www.grc.nasa.gov/WWW/k-12/airplane/tunvoil.html

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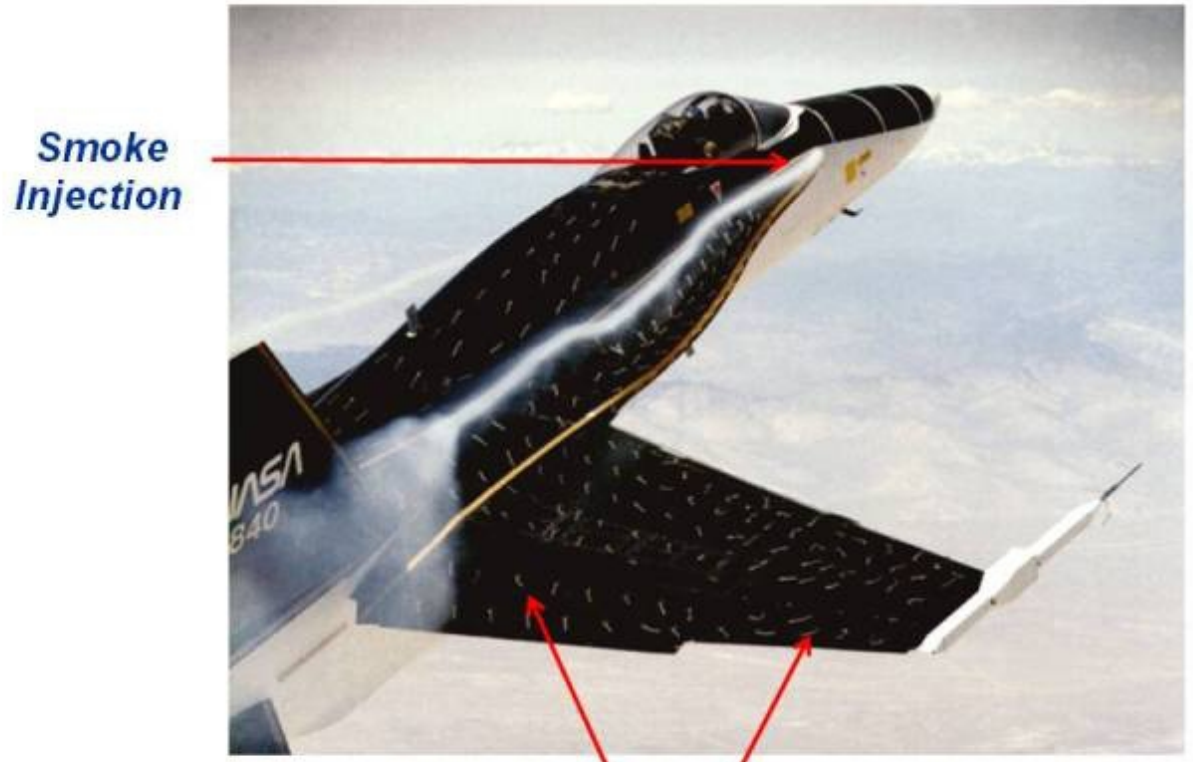
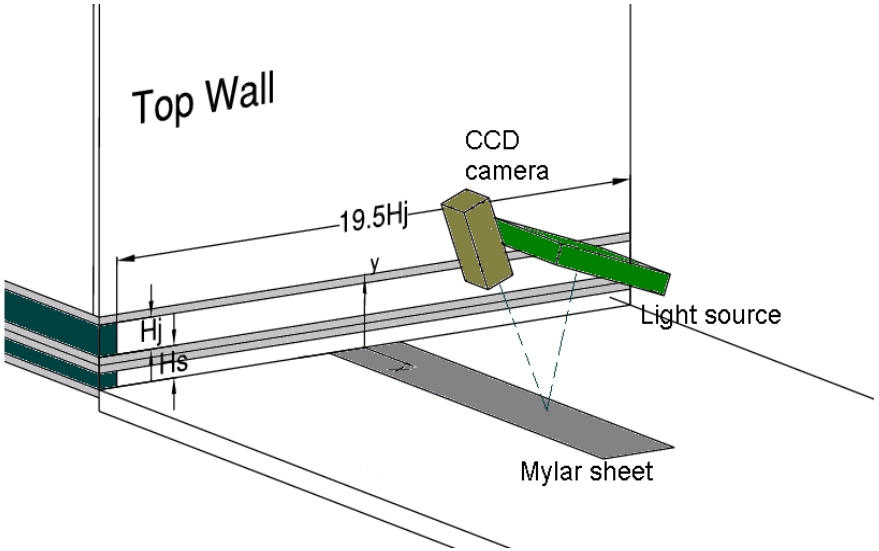
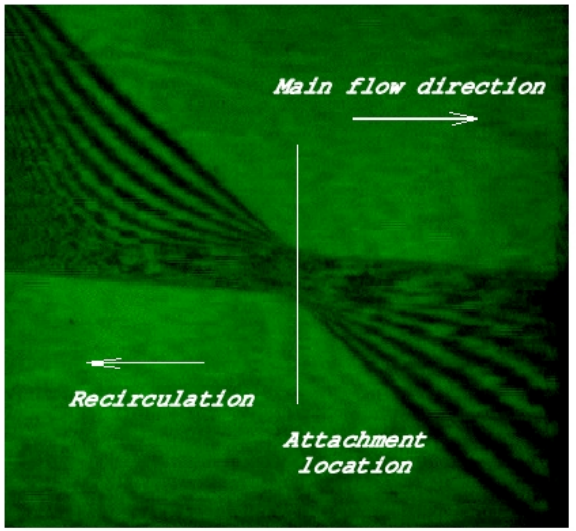
Smoke and Tufts



http://www.grc.nasa.gov/WWW/k-12/airplane/tunvsmoke.html

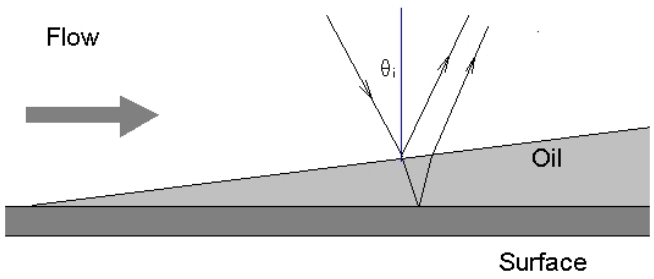
Skin friction measurements thin-oil-film interferometry





- Mylar sheet (Monokote Industries) , 91cm x 13 cm
- Dow Corning 200 Fluids, 20cs, applied in a line ~45 degrees
- Edmunds Scientific single wave length light source, wave length 546nm
- Pulnix CCD camera, Matrox Meteor II frame grabber, triggered by computer signal
- Light and camera on a traversing mechanism, 9 positions, 75mm x 75 mm each
- Jet temperature and dynamic head monitored

Skin friction analysis



Oil film equation:

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}\left(\frac{\tau_w h^2}{2\mu}\right) = 0$$

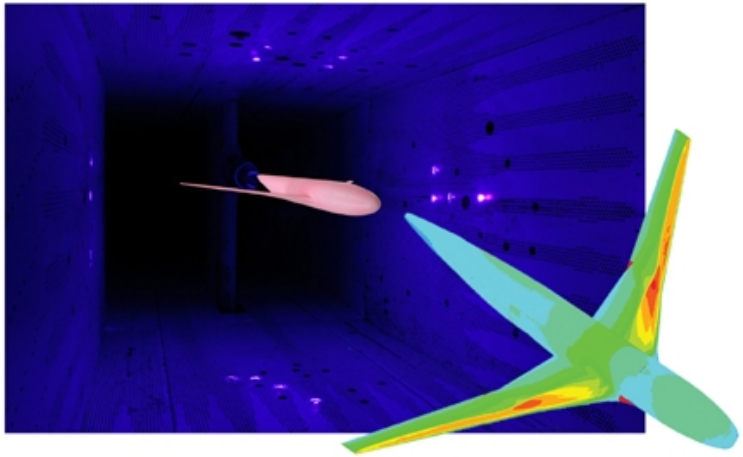
Solution:

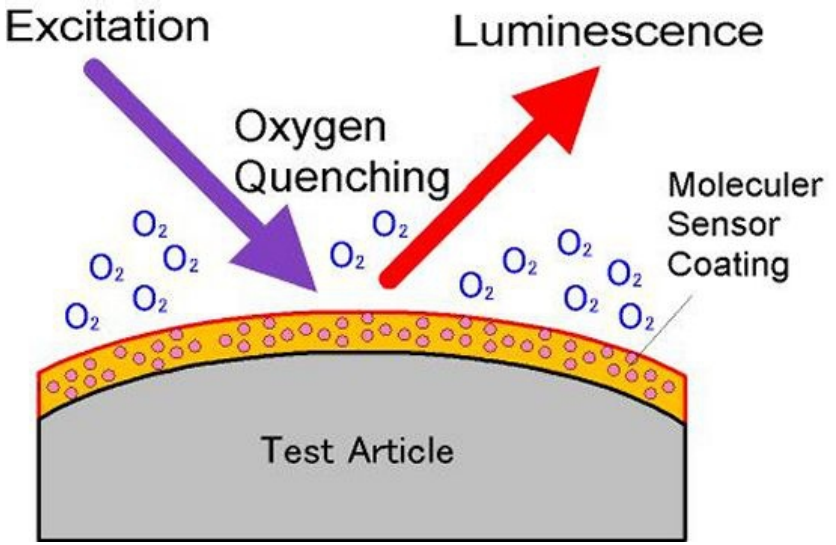
$$C_{fx} = \frac{x/h}{\int_0^t (q_\infty/\mu)\,dt}$$

$$h = \frac{\lambda\phi}{4\pi}\left(\frac{1}{\sqrt{n_f^2 - n_a^2 \sin^2\theta_i}}\right)$$

- Naughton, J.W. and Sheplak, M., Progress in Aerospace Sciences, 38, pp.515-570, 2002
- Naughton, J.W., Viken, S., and Greenblatt, D., to appear AIAA Journal, 2006

PSP 压敏涂料




Excitation
Luminescence
Oxygen
Quenching
Moleculer
Sensor
Coating
O2
Test Article

纹影

Optical Techniques for Flow Visualization

- Shadowgraph $\frac{\partial^2 \rho}{\partial x^2} + \frac{\partial^2 \rho}{\partial y^2}$
- Schlieren $\frac{\partial \rho}{\partial y}$ gradients perpendicular to knife edge
- Interferometer $\Delta\rho$

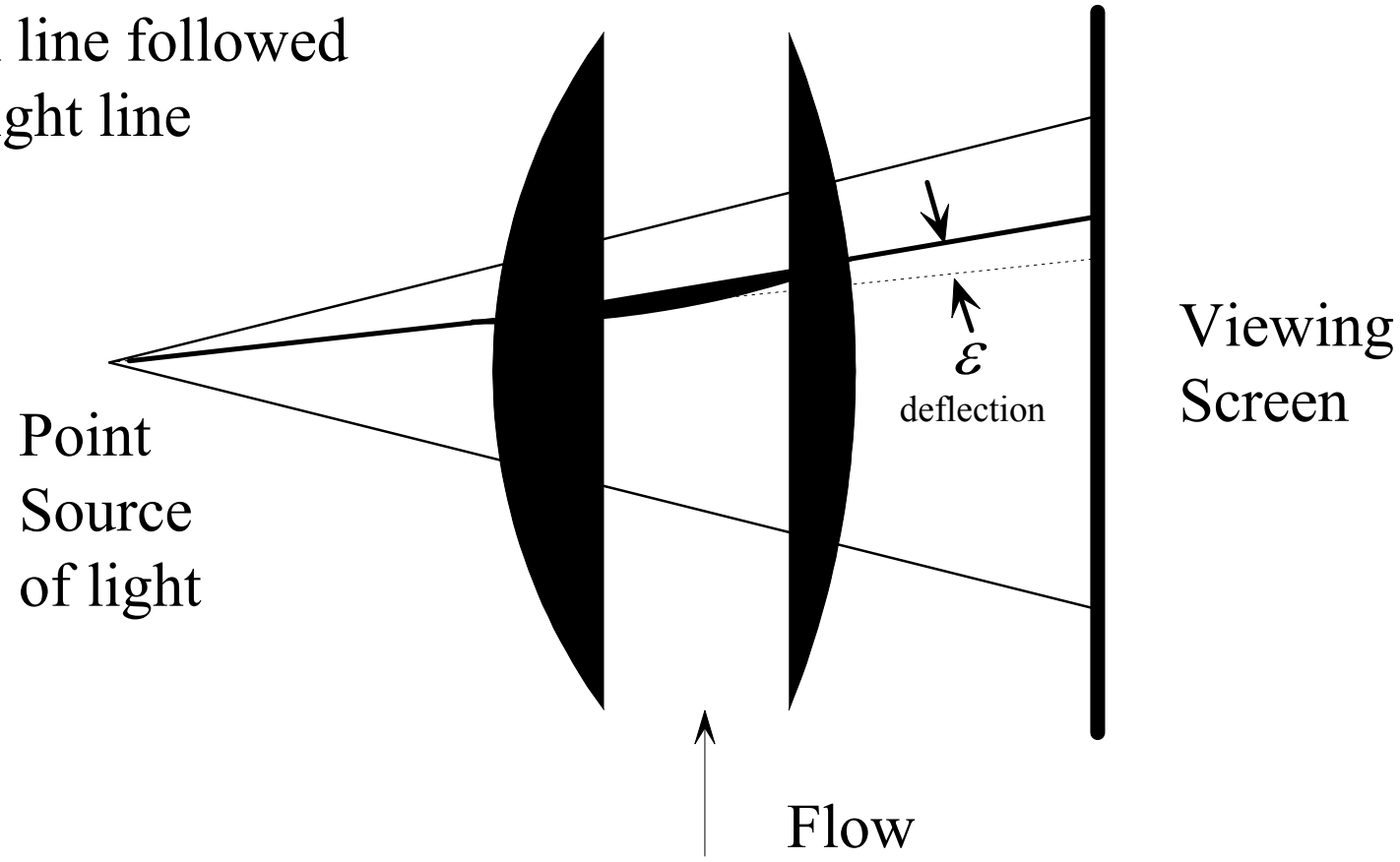
All depend of the fact that the speed of light and therefore the index of refraction varies with the density.
The index of refraction is approximately

$$\eta = \eta(\rho) = 1 + \beta \frac{\rho}{\rho_{ref}}$$

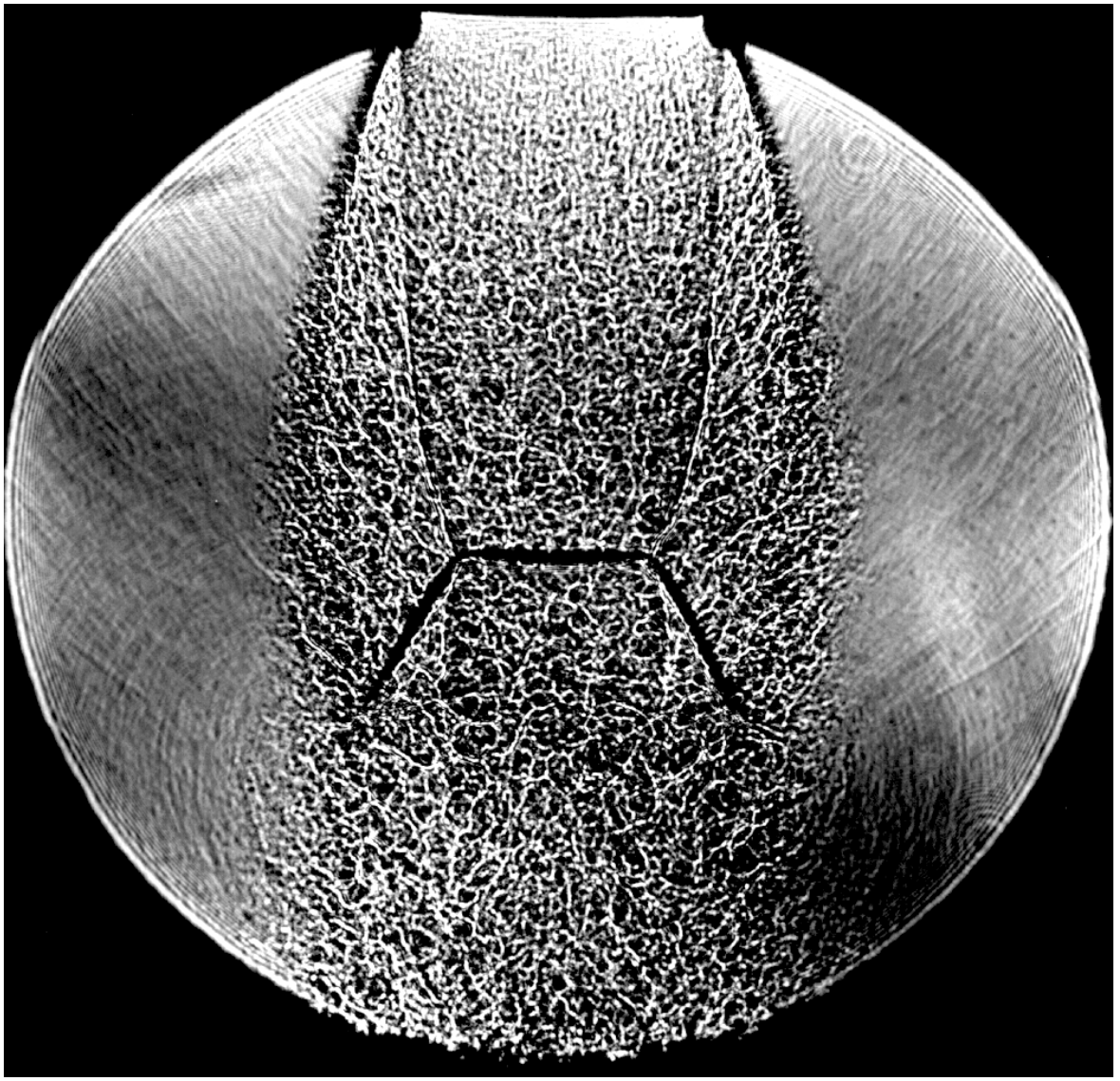
$$\beta = .000292 \quad \text{for air}$$

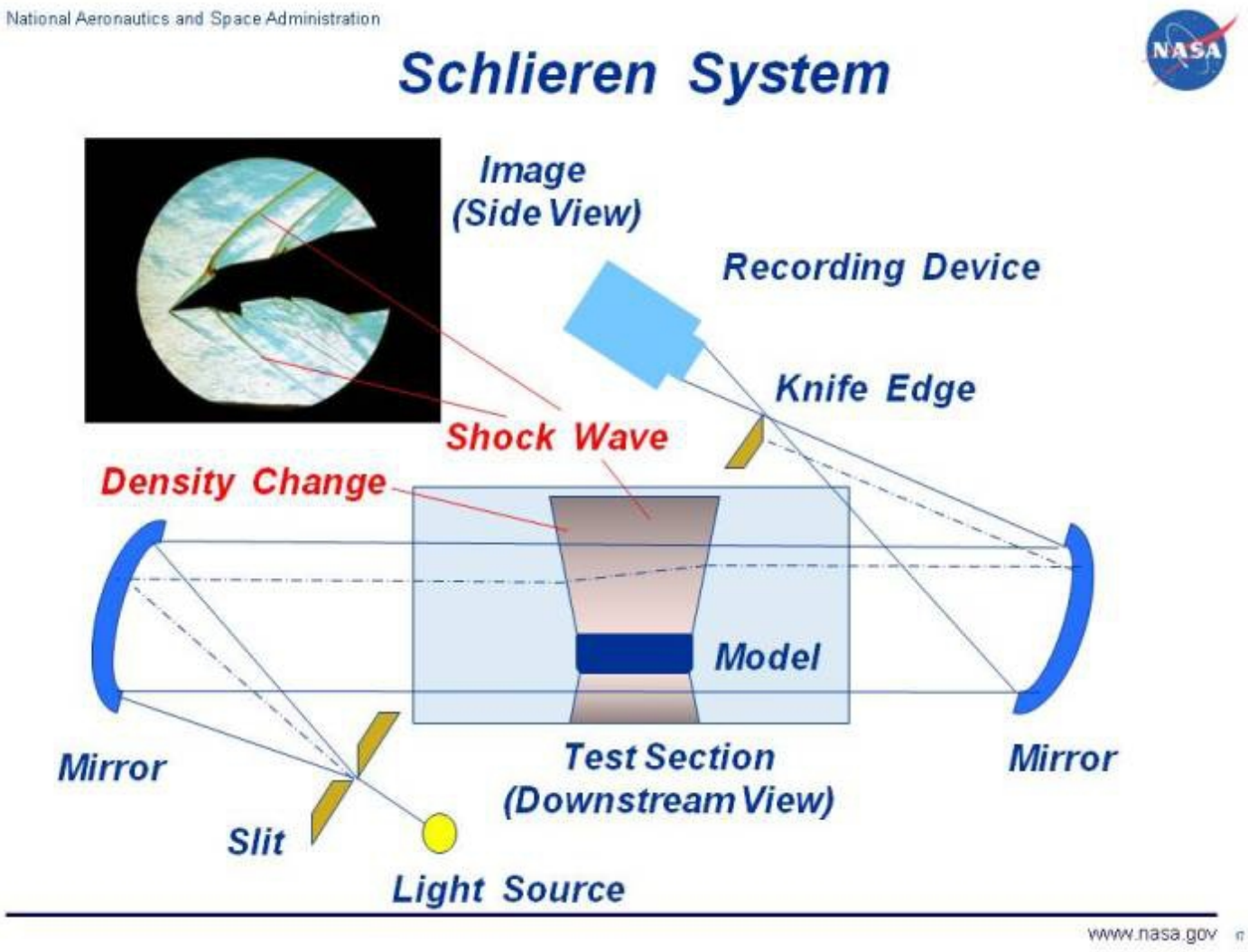
Shadowgraph

Shocks appear as
a dark line followed
by a light line



Shadowgraph





http://www.grc.nasa.gov/WWW/k-12/airplane/tunvschlrn.html