Chapter 2
Flow Visualization Techniques

(- the first step to approach the Physics of the nature)

Contents

Design of an experiment (I)

Which quantities are important to measure (both independent and dependent) ?

⇨ Aim of experiment,

⇨ experience

⇨ dimensional analysis

In what range will the measured quantities vary ?

⇨ choice of measuring technique

Which quantities must be controlled ?

⇨ stationary and repeatable

Design of an experiment (II)

What is the required dynamic response of the measuring instrument ?

⇨ any correction or compensation needed?

How long is the measurement time needed?

⇨ given statistical variance for time-mean averaged quantities.

Has the experimental already been performed before ?

Does a theoretical solution exist ?

Moddelling & Similarity

$$\Pi_1 = \Phi(\Pi_2, \Pi_3, \ldots, \Pi_\kappa)$$

model prototype

$$\text{if} \quad \Pi_{2m} = \Pi_{2p}$$

$$\Pi_{3m} = \Pi_{3p}$$

$$\ldots \quad \ldots \quad \ldots$$

$$\Pi_{km} = \Pi_{kp}$$

$$\text{then} \quad \boxed{\Pi_{1m} = \Pi_{1p}}$$

complete similarity !

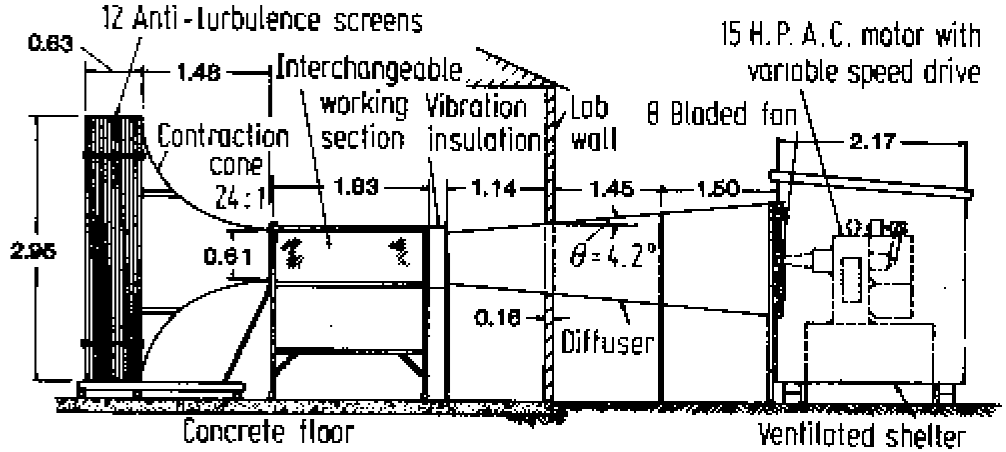
Moddelling & Similarity

In engineering,instead of complete similarity,We consider.

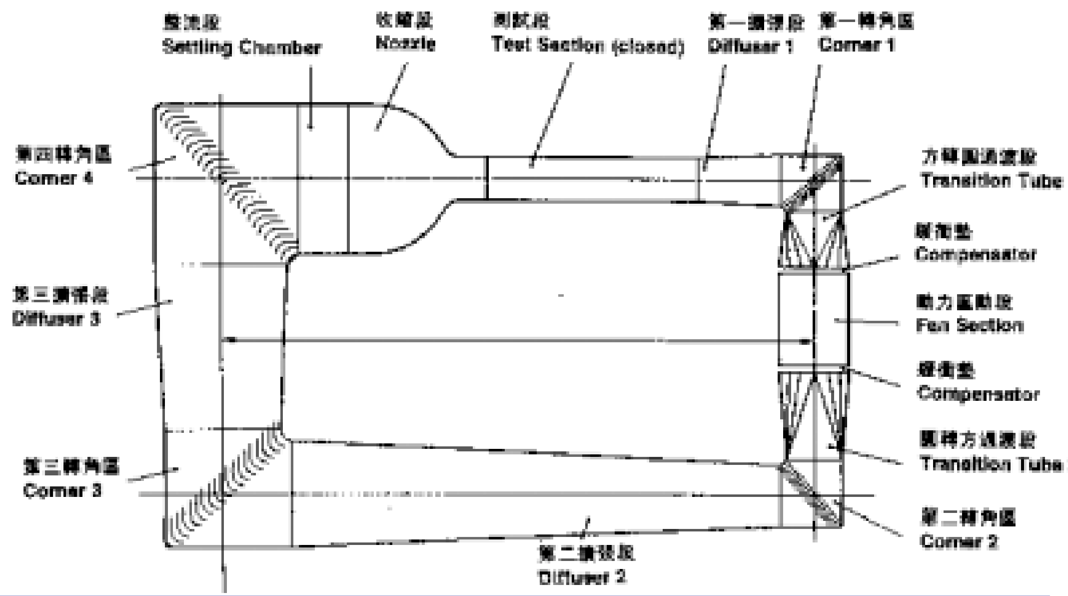
- Geomatric similarity (L-scale)
- Kinematic similarity (L- & t-scale)
- Dynamic similarity (L- & t- & m-scale)
- Thermal similarity

Experimental apparatus (I)

Open Circuit Wind-Tunnel (Open jet or Eiffel type)

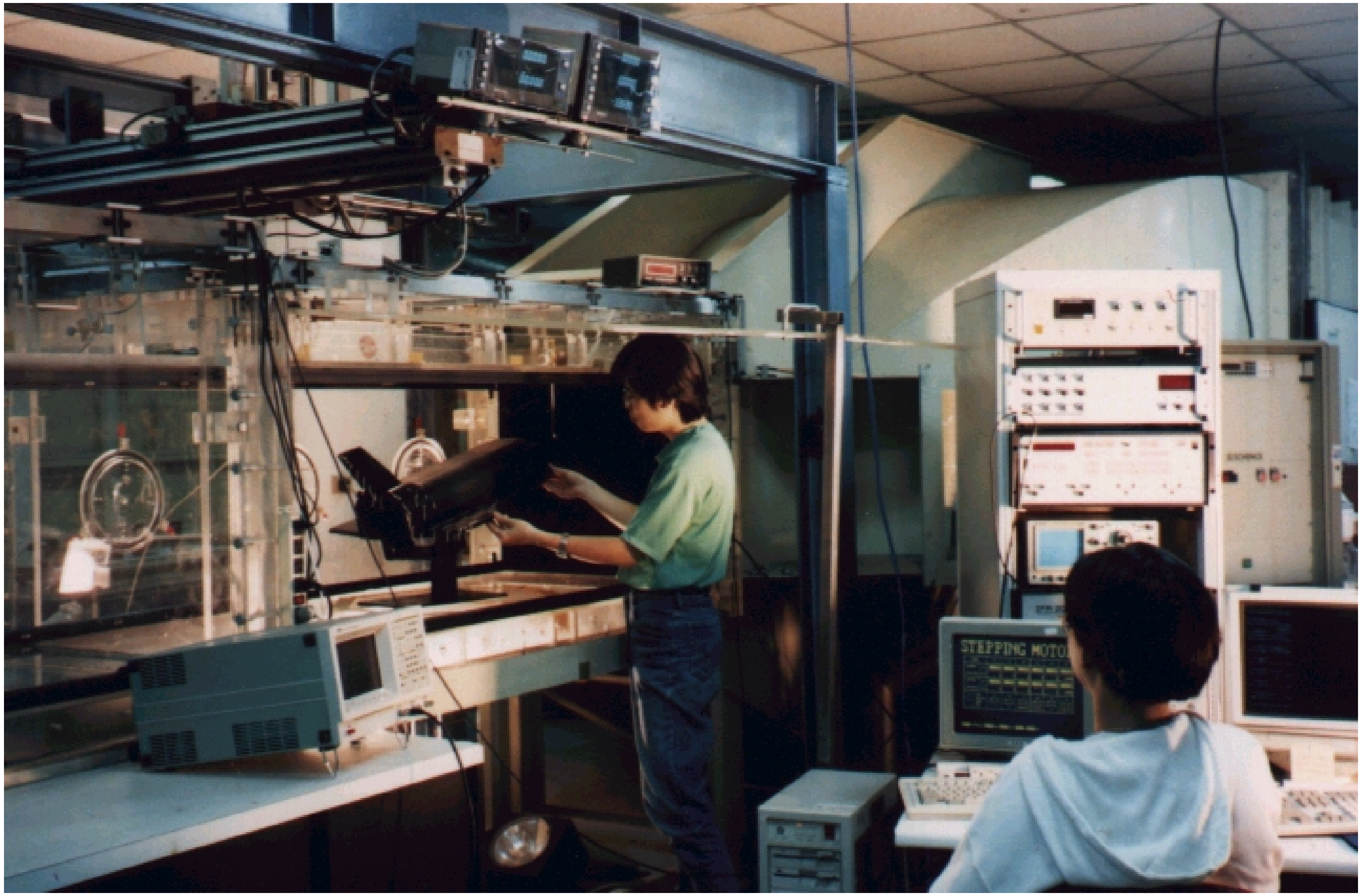


Closed Return Wind Tunnel (Prandtl / Göttingen type)



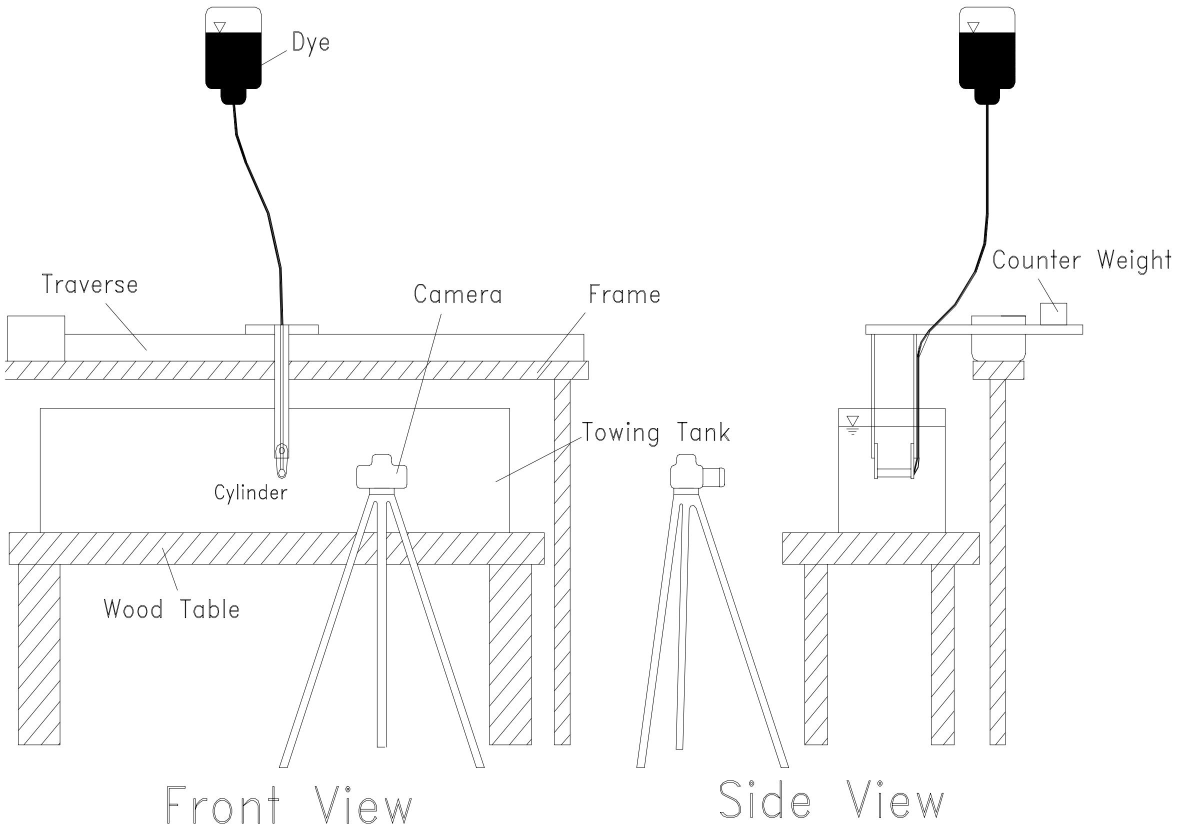
NTU-IAM Low-turbulence Wind-Tunnel

- **Test section: 0.8m x 0.6m x 3.8m; U_{max}:70 m/s**
- **T.I.: ~ 0.05%; Uniformity: < ±0.1%; Angularity：< ±0.1°**



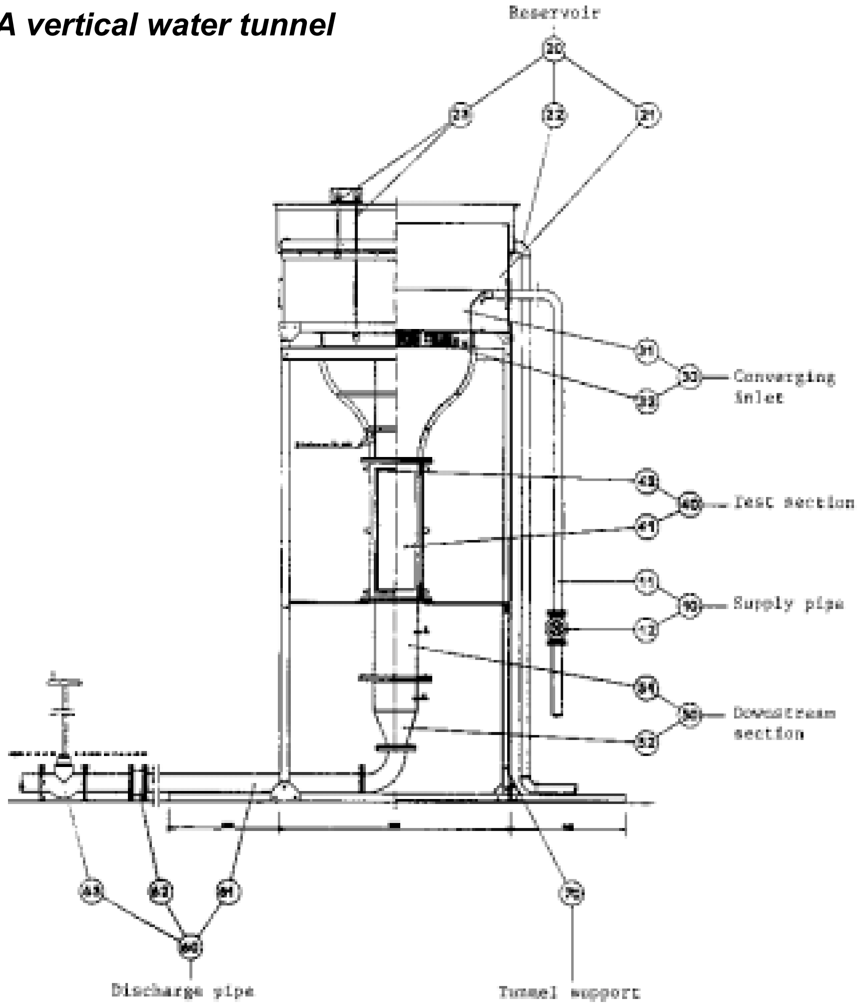
Towing Tank

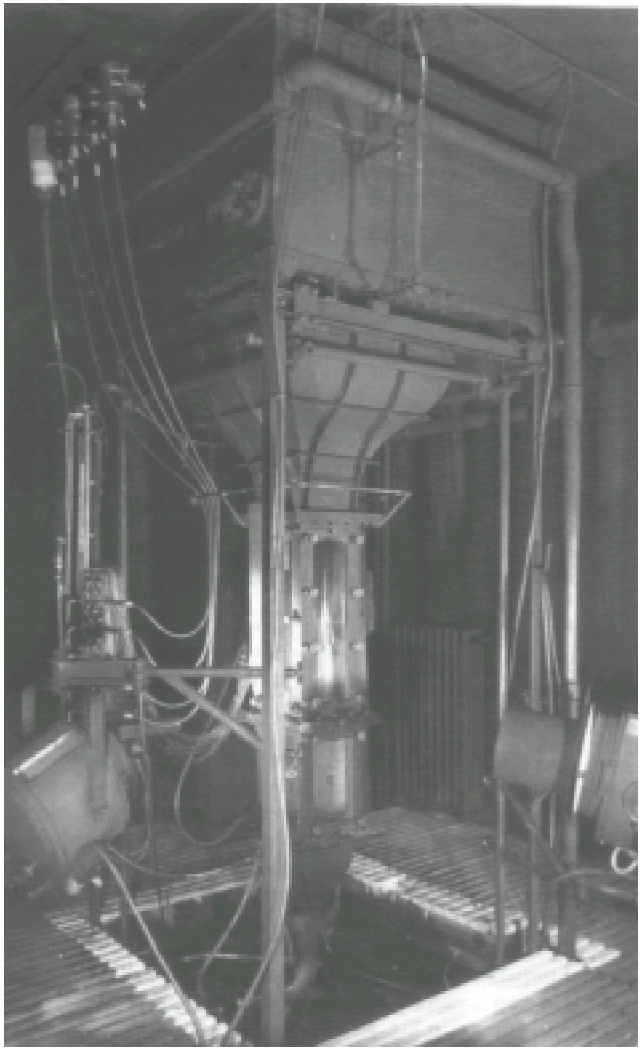
- Test section: 1500 x 455 x 460 mm
- Towing speed: 0.06 ~ 120 cm/s



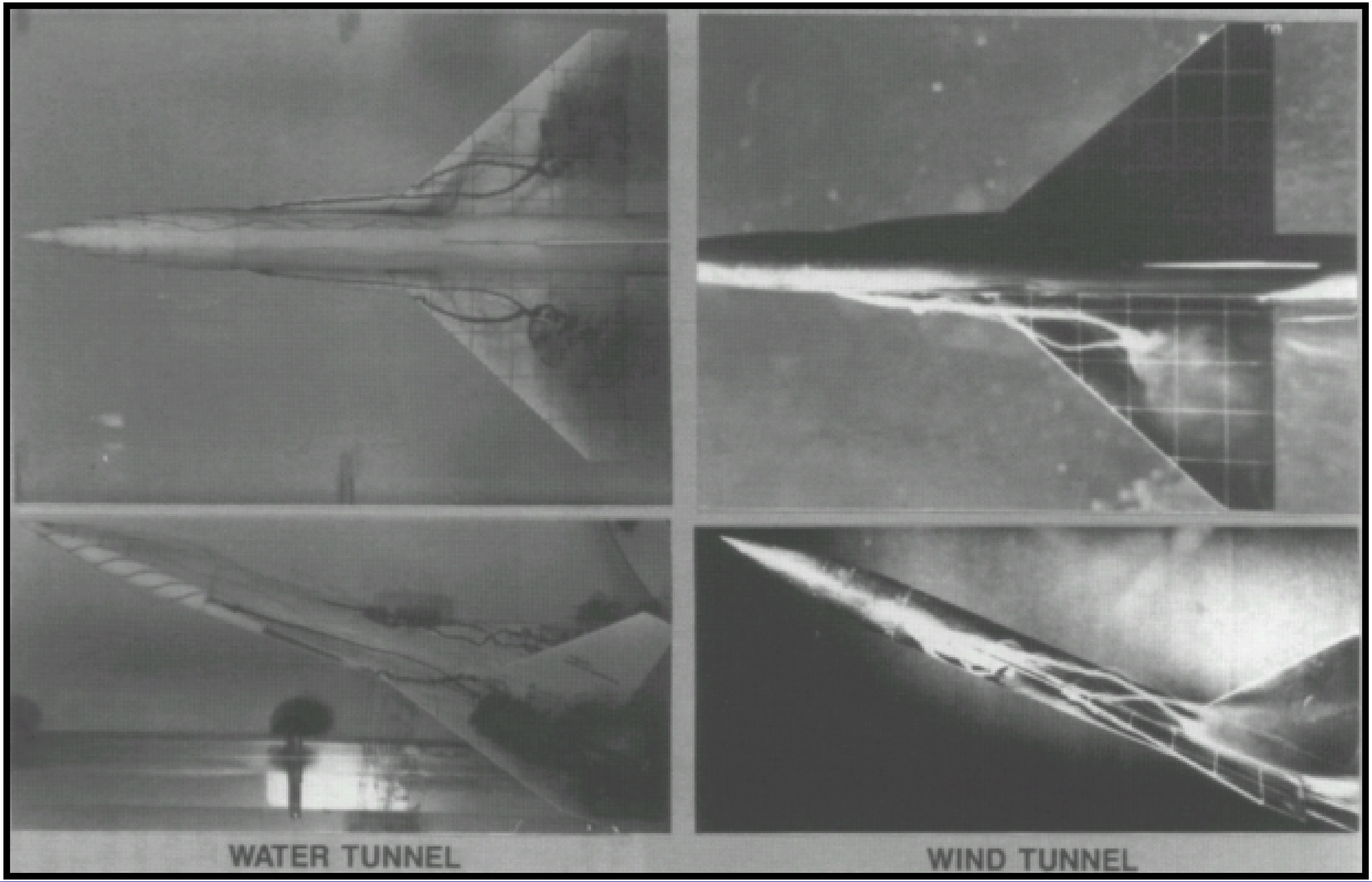
Water tunnel

ONERA vertical water tunnel





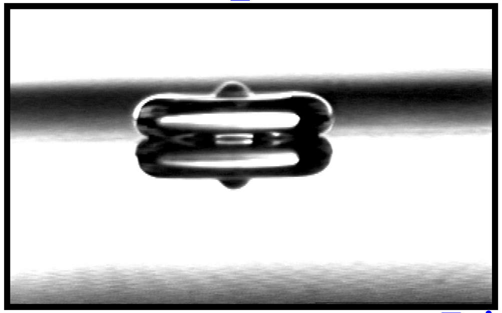
Wind Tunnel or Water tunnel ?

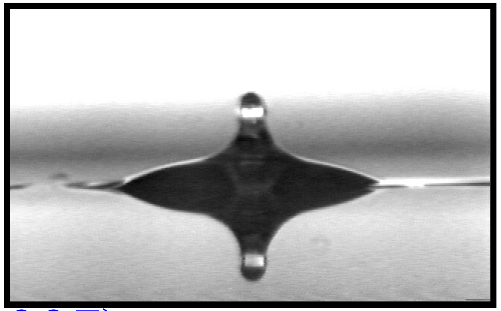


Flow Visualization (I)

- "***Seeing is believing***."
- Flow Visualization is often the ***1st step*** of flow investigation
- Flow Visualization can get a ***overall*** view for the system.
- Flow Visualization may be used for ***steady*** or ***qusi-steady*** or ***unsteady*** flow.
- Flow Visualization could be ***qualitative*** or ***quantitative***.

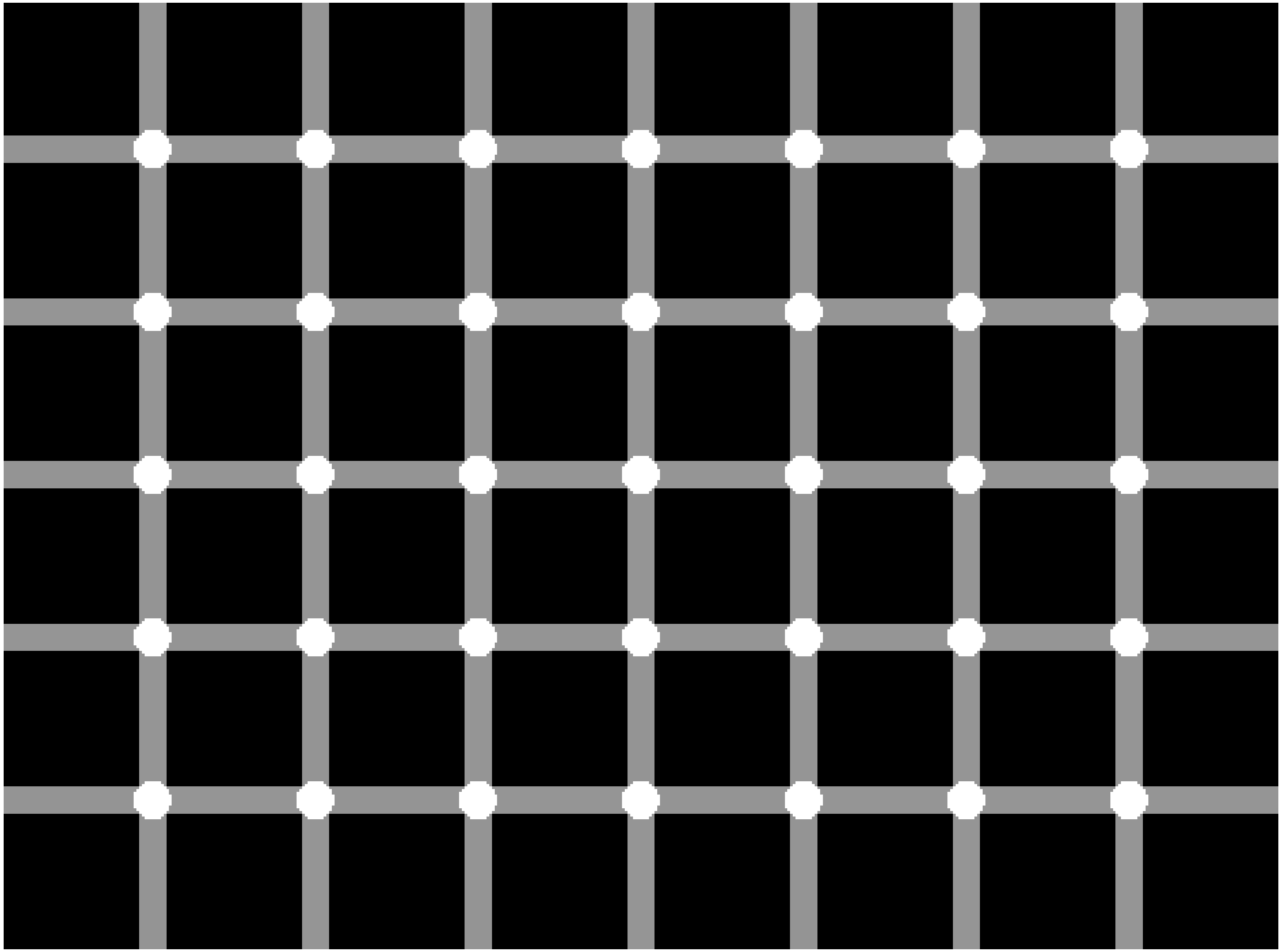
Worthington (1908)



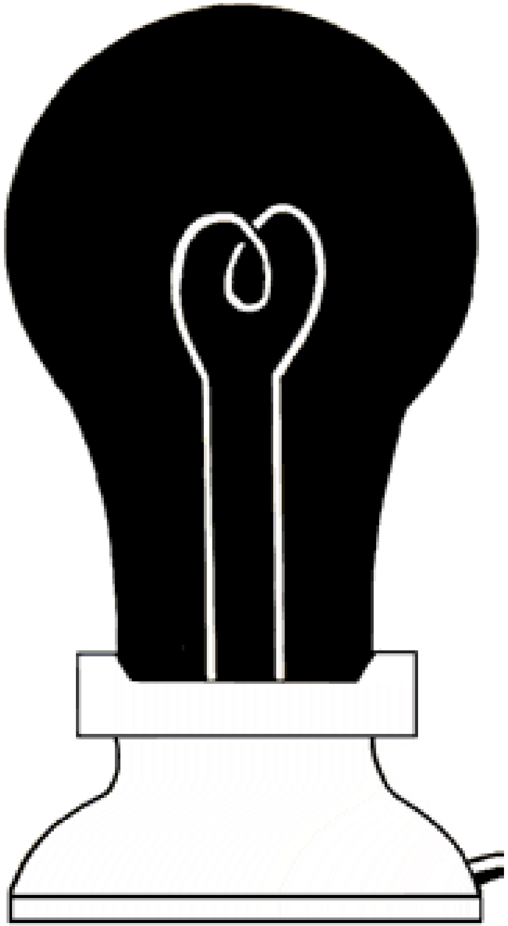


Lin (1997)

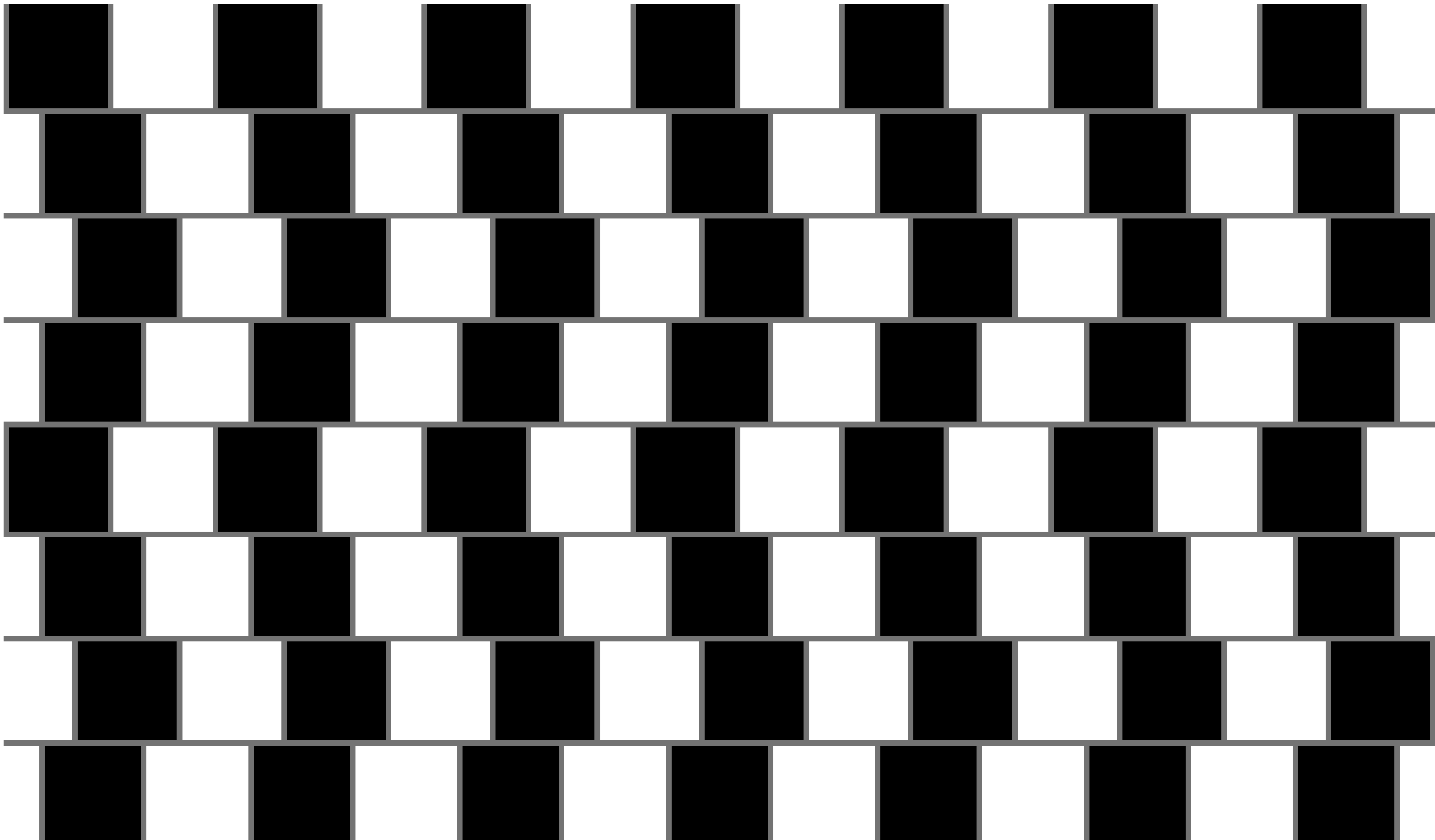
Seeing is believing (I) ?



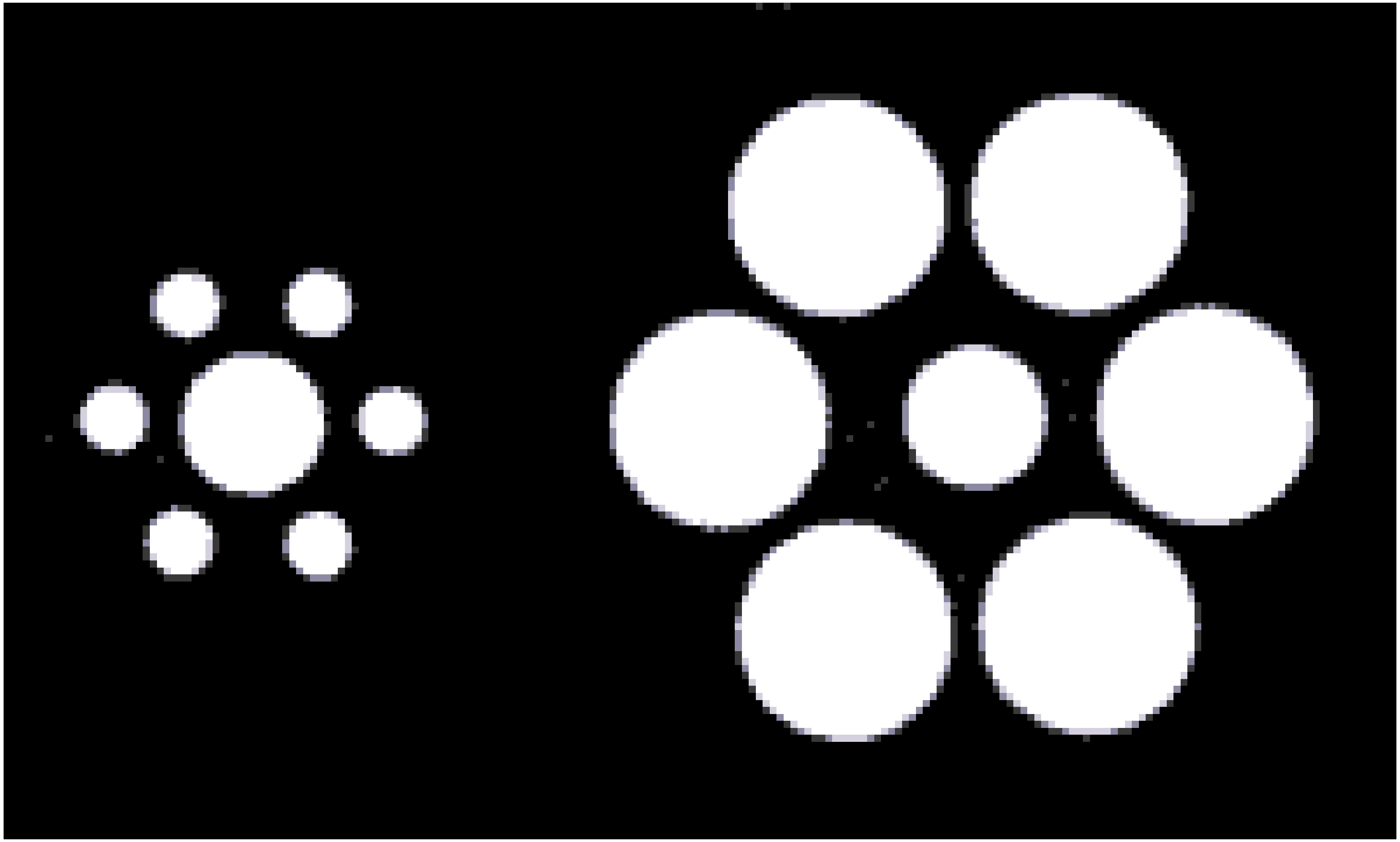
Seeing is believing (Ia) ?



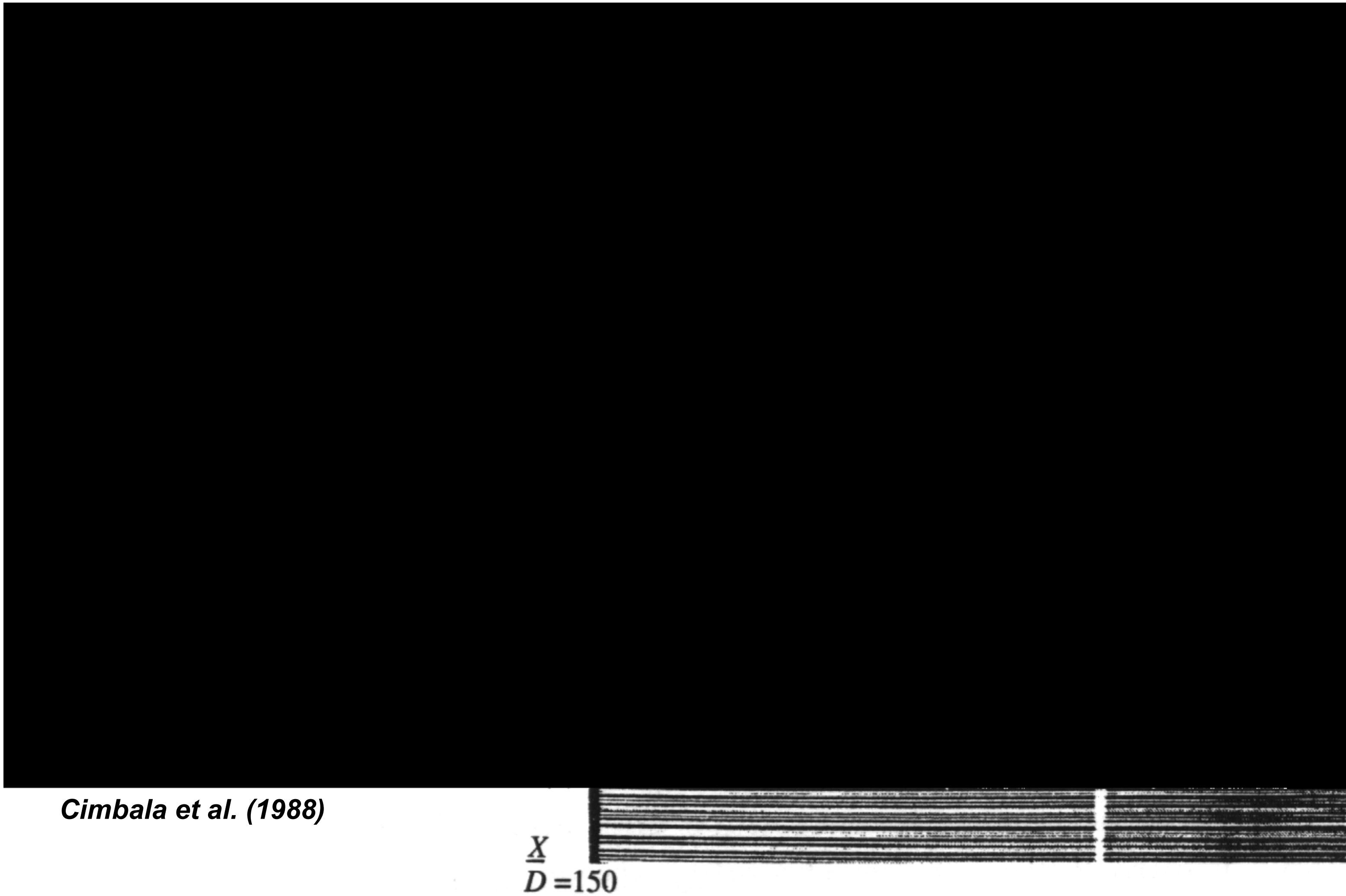
Seeing is believing (II) ?



Seeing is believing (III) ?



Seeing is believing (IV) ?



Cimbala et al. (1988)

Flow Visualization (II)

Elements of Flow Visualization:

- **Light source**：Sun-light , spot light, laser sheet
- **Objects**： seeded particles, Fluid molecules
- **Recording device**：drawings, Camera,Video Cam.,

H. M. the Queen

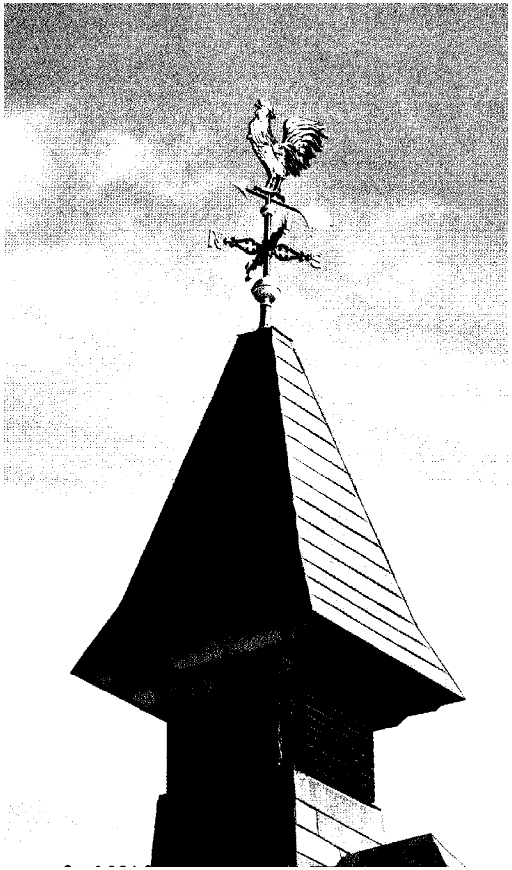
Flow Visualization (III)

Traditional Flow Visualization methods can be classified as :

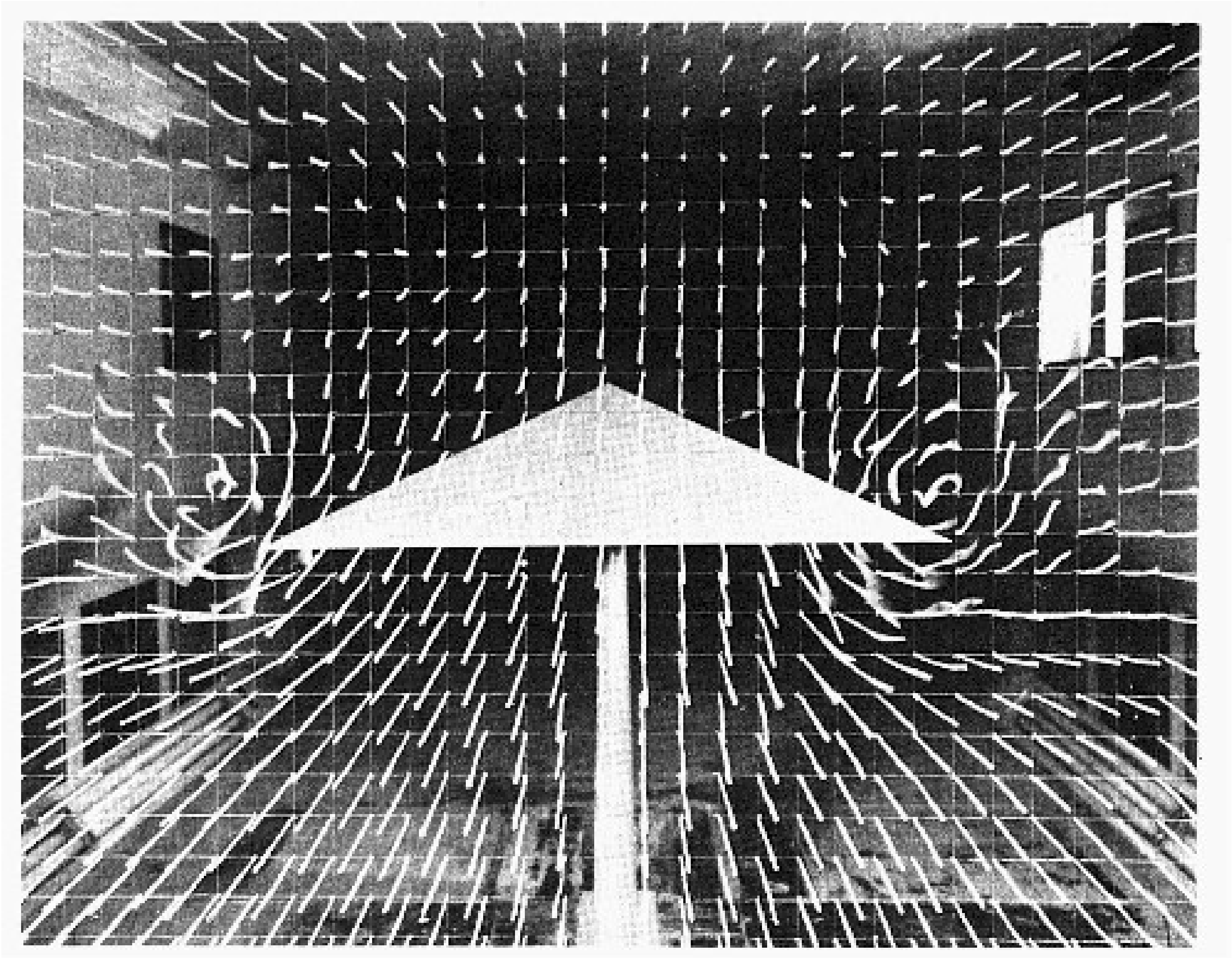
Stationary Probes	**Tracer Methods**
weather vane, tufts	weather ballon
Surface oil film, Liquid crystal paint	Particle tracers (e.g. hydrogen bubbles, smoke etc.), Dye injection
Optical methods (Shadowgraph, Schlieren, Interferometry)	Optical methods (Spark Tracer, LIF,…)

Examples of Flow Visualization Methods

1. Tuft method
2. Fluorescent method
3. Oil film method
4. Dye method
5. Smoke method
6. Hydrogen bubbles method
7. Shadow method
8. Spark Tracer method

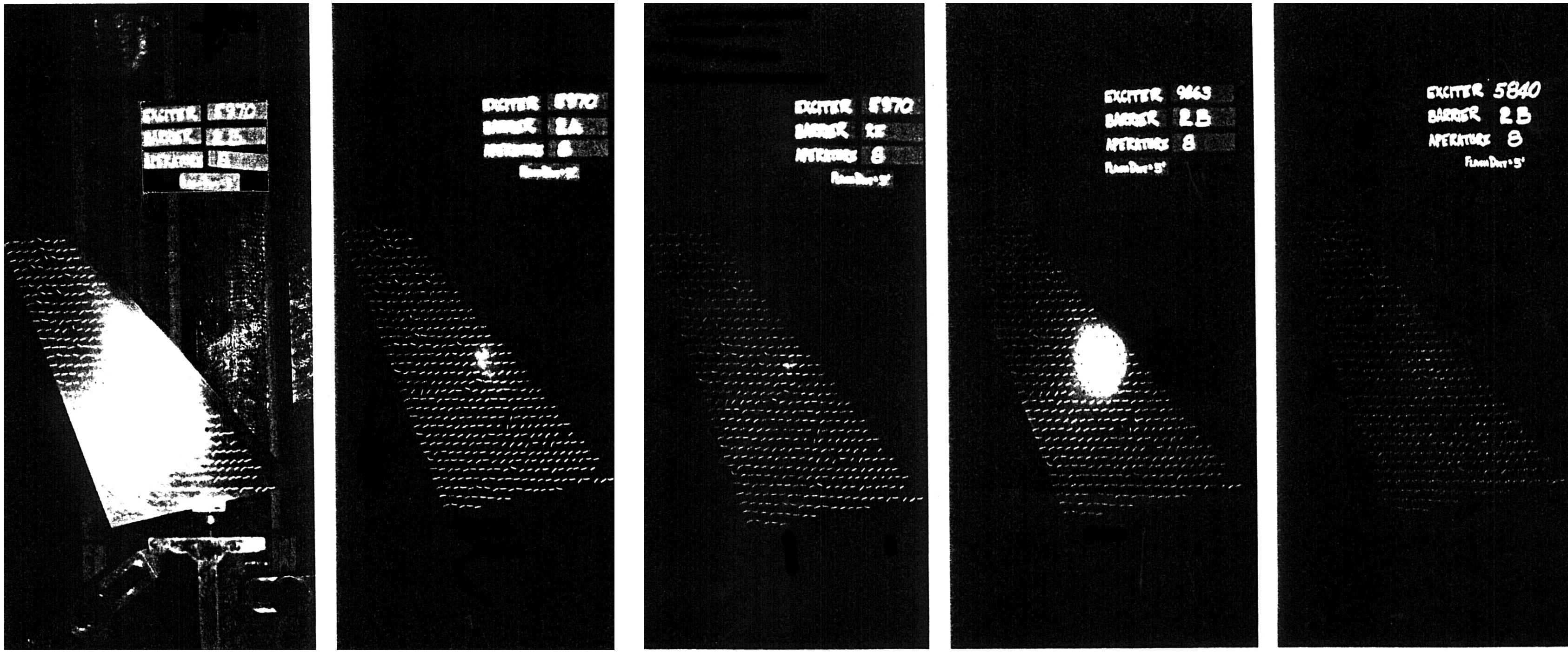


Grid-and-Tuft



(From NASA)

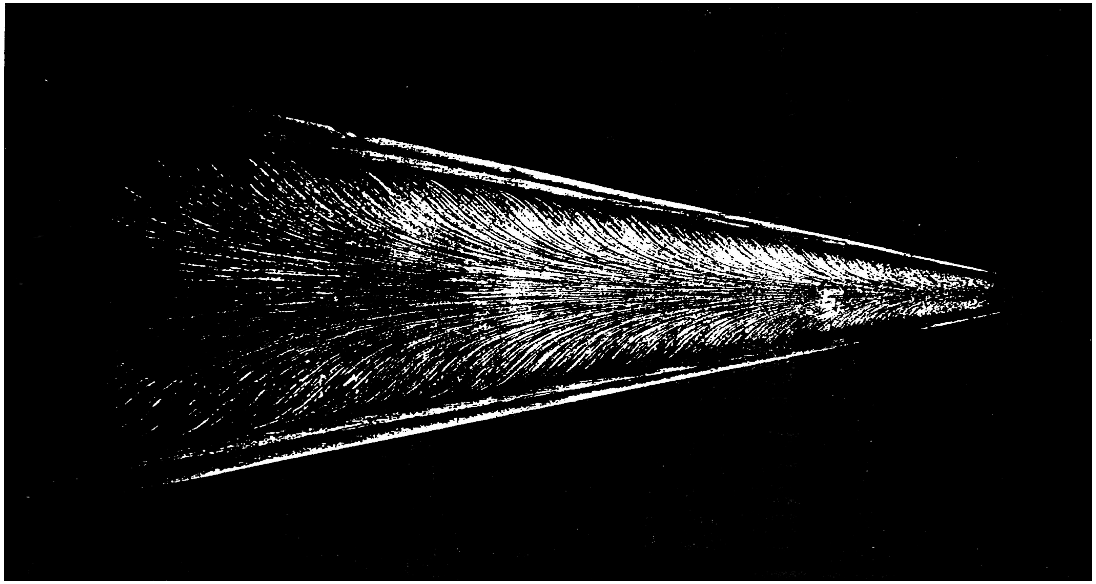
Minituft Visibility



From Crowder (1989)

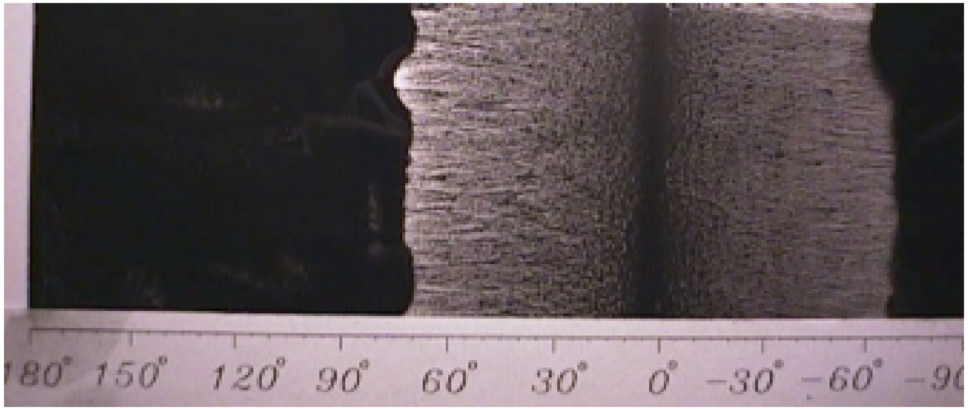
(a) 5970exciter, 2B barrier filters
(b) 5970exciter, 2A barrier filters
(c) 5970exciter, 2E barrier filters
(d) 9863exciter, 2B barrier filters
(e) 5840exciter, 2B barrier filters

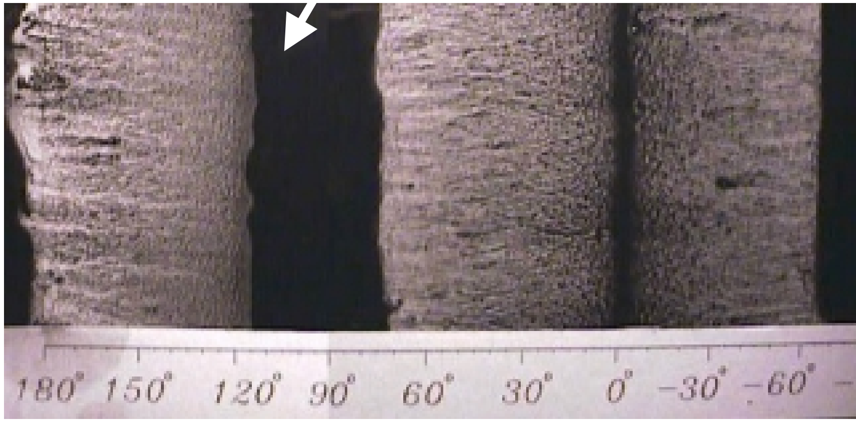
Oil-Film Method



Delta wing
$\alpha = 15°$

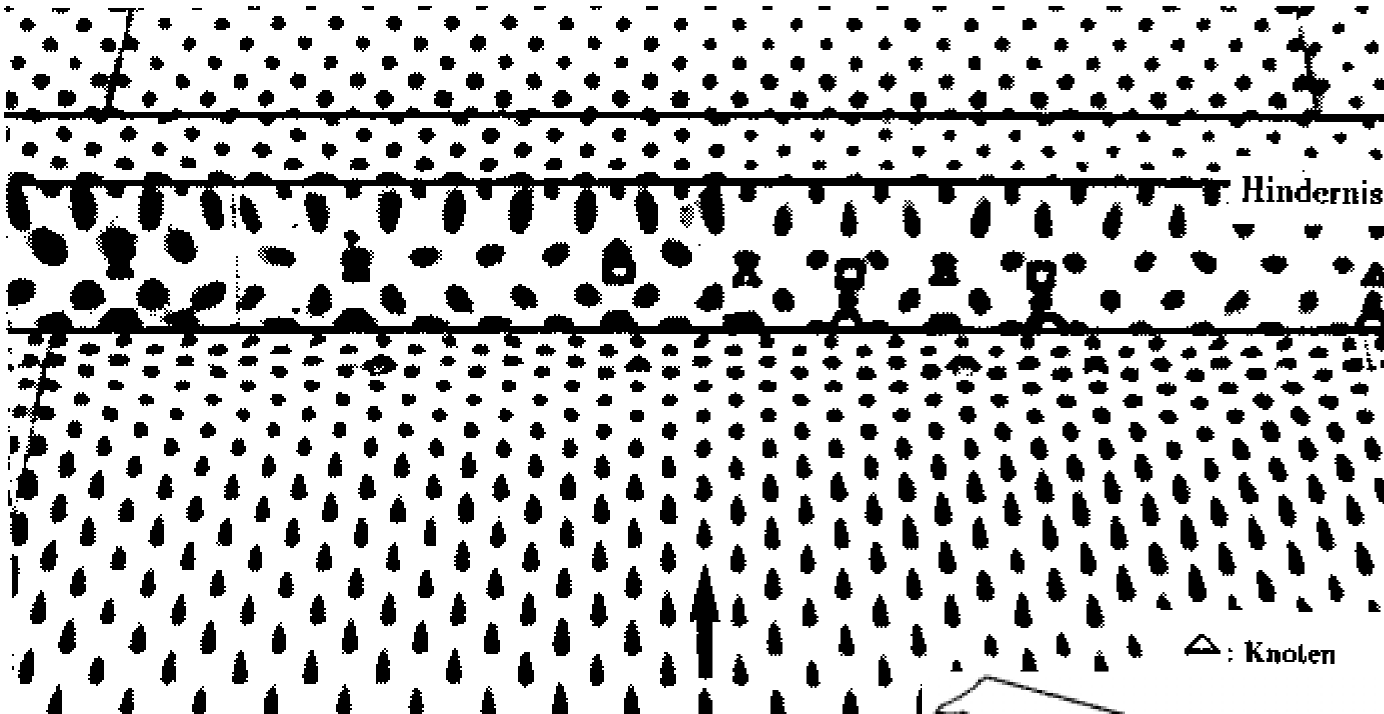
Cylinder Flow
w/ɔ control



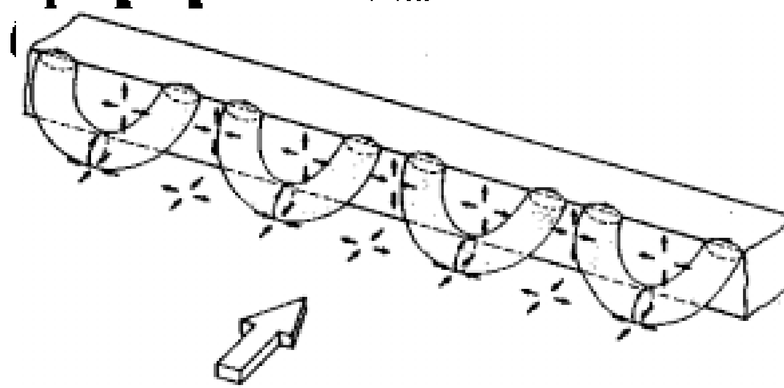


Wang(1997)

Oil-dot Method



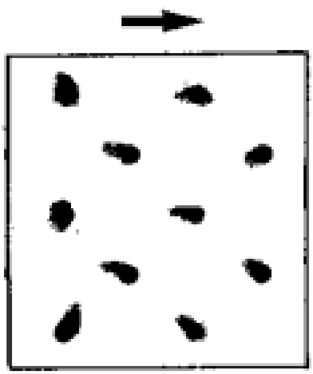
Flow over a square cylinder

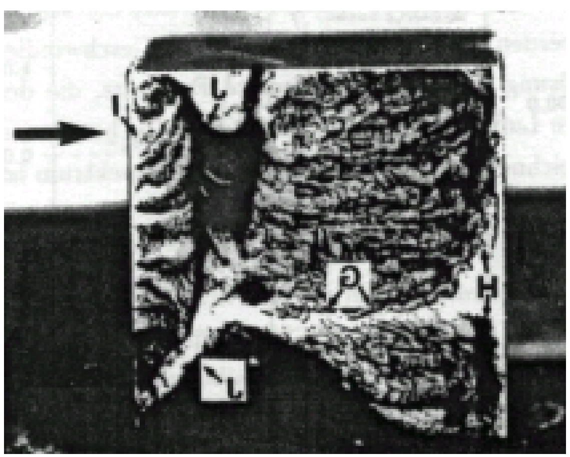


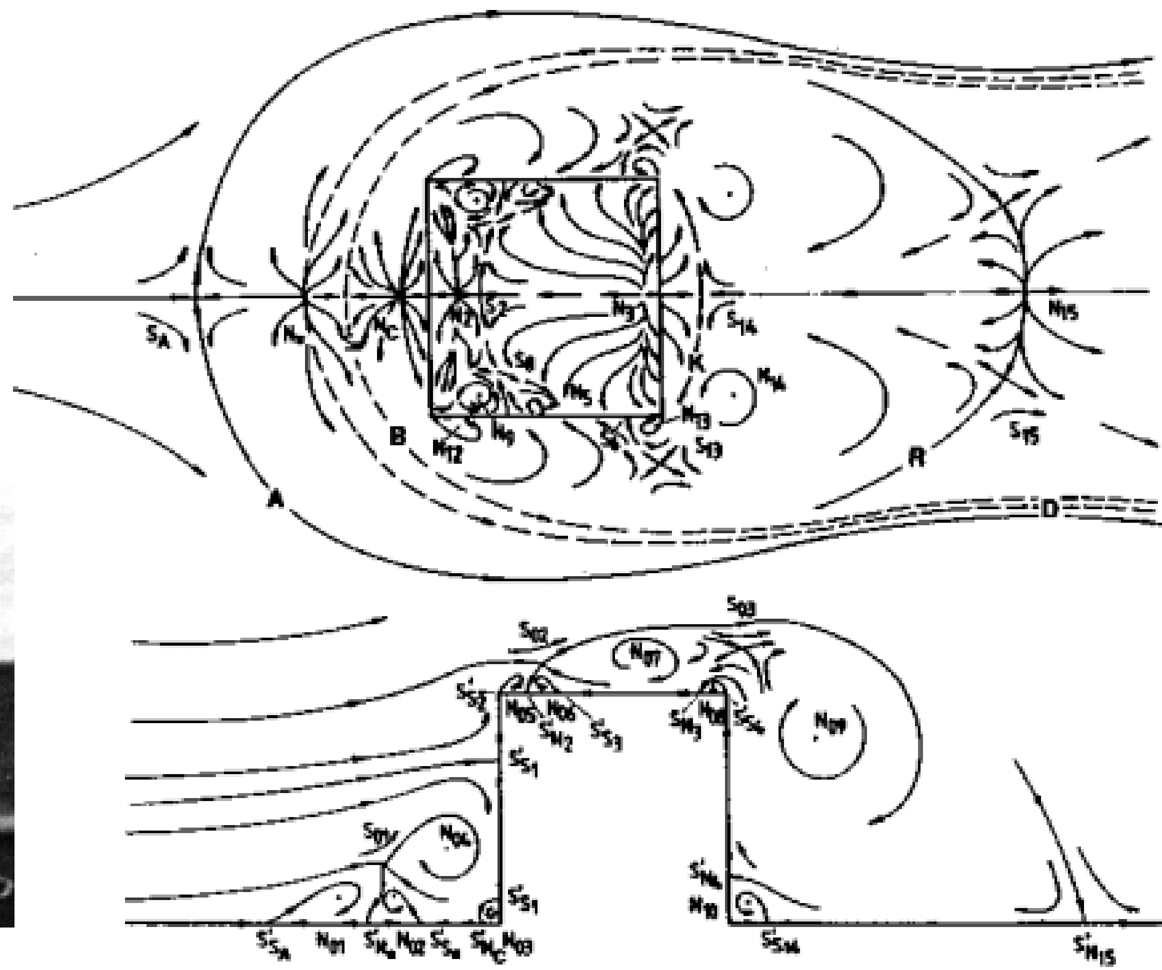
Martinuzzi (1992)

Oil-dot & oil-film Method

Flow over a cube

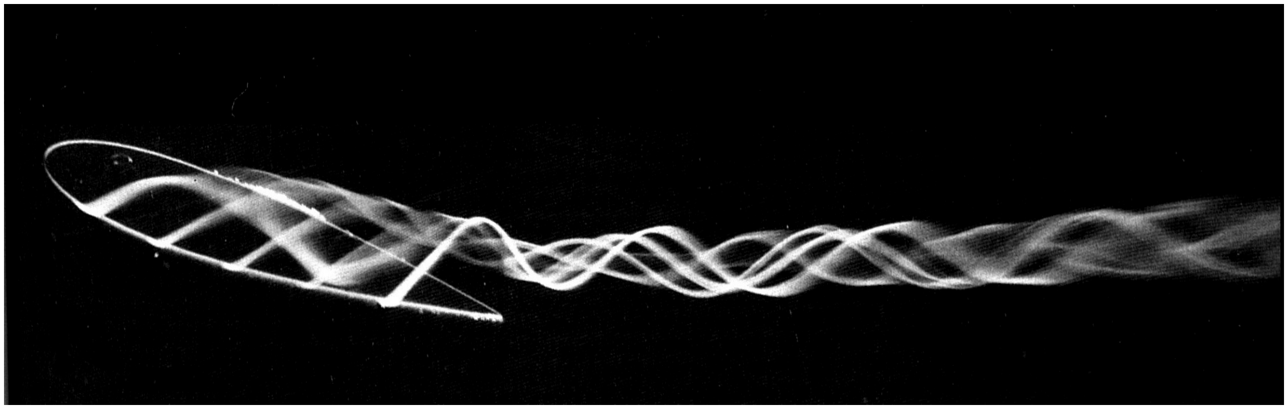




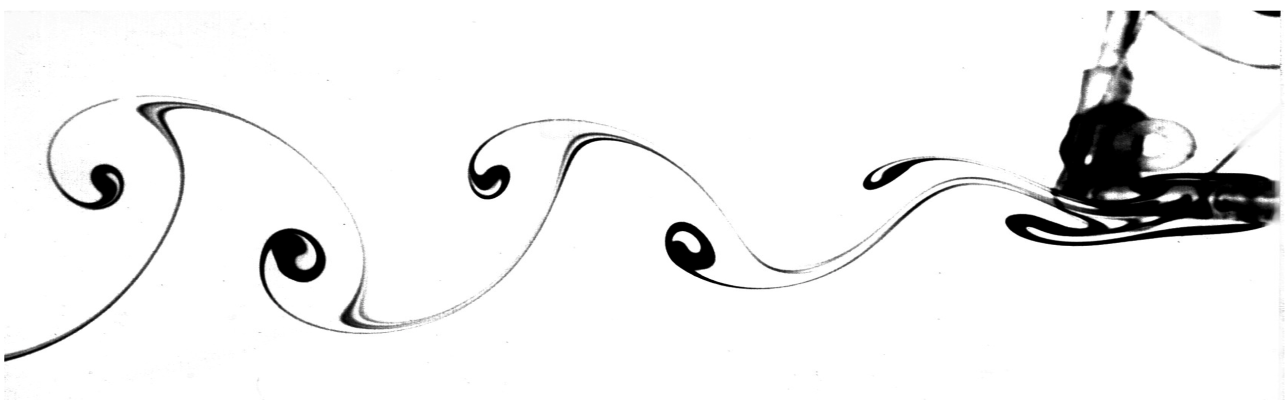


Martinuzzi (1992)

Dye-line method

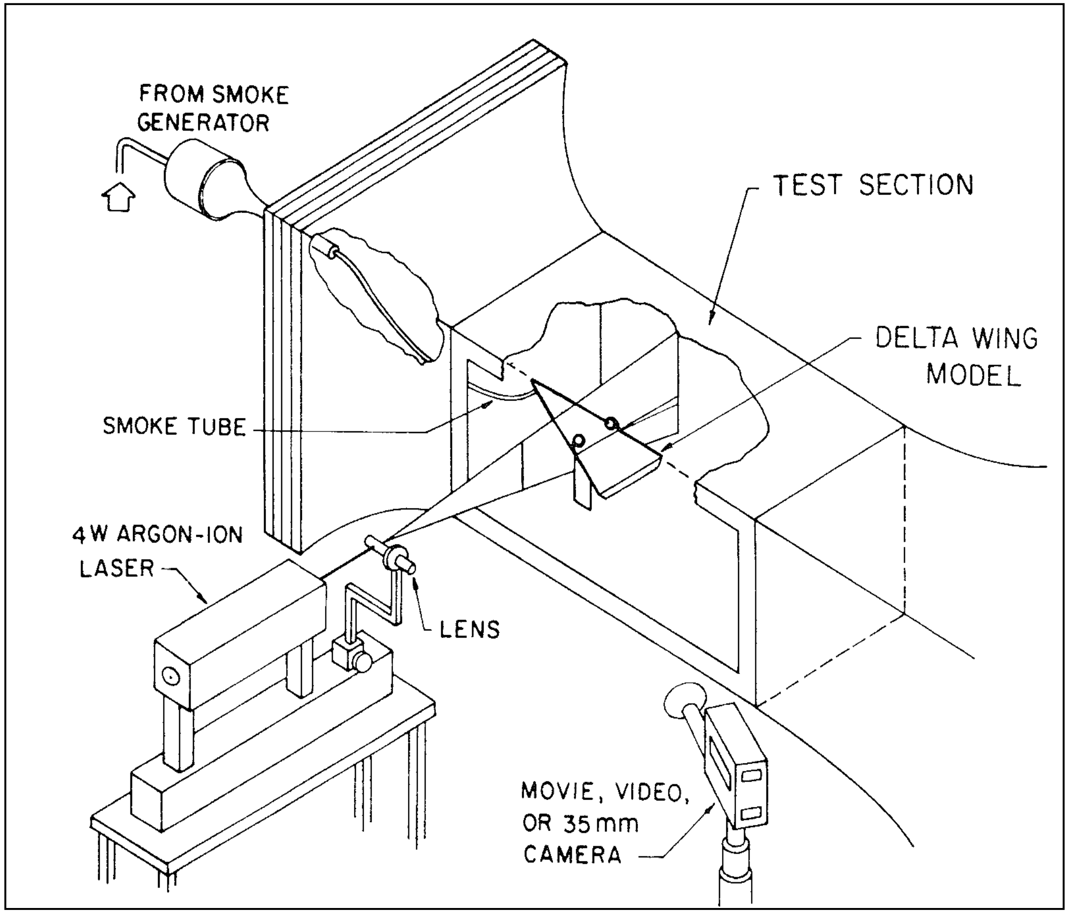


(Werle 1974)



(Wang et al. 1996)

Smoke Method (I)

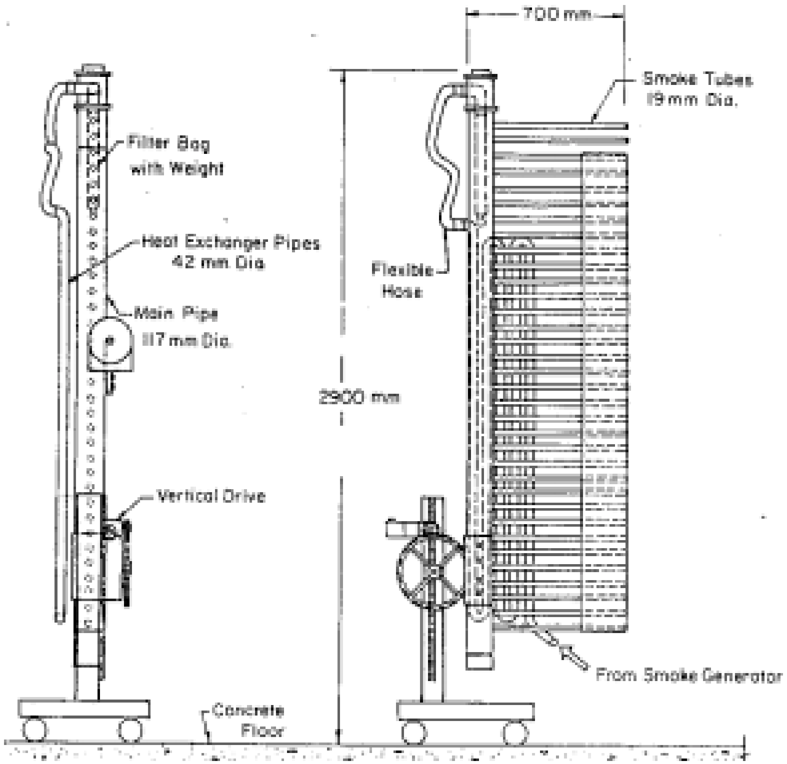


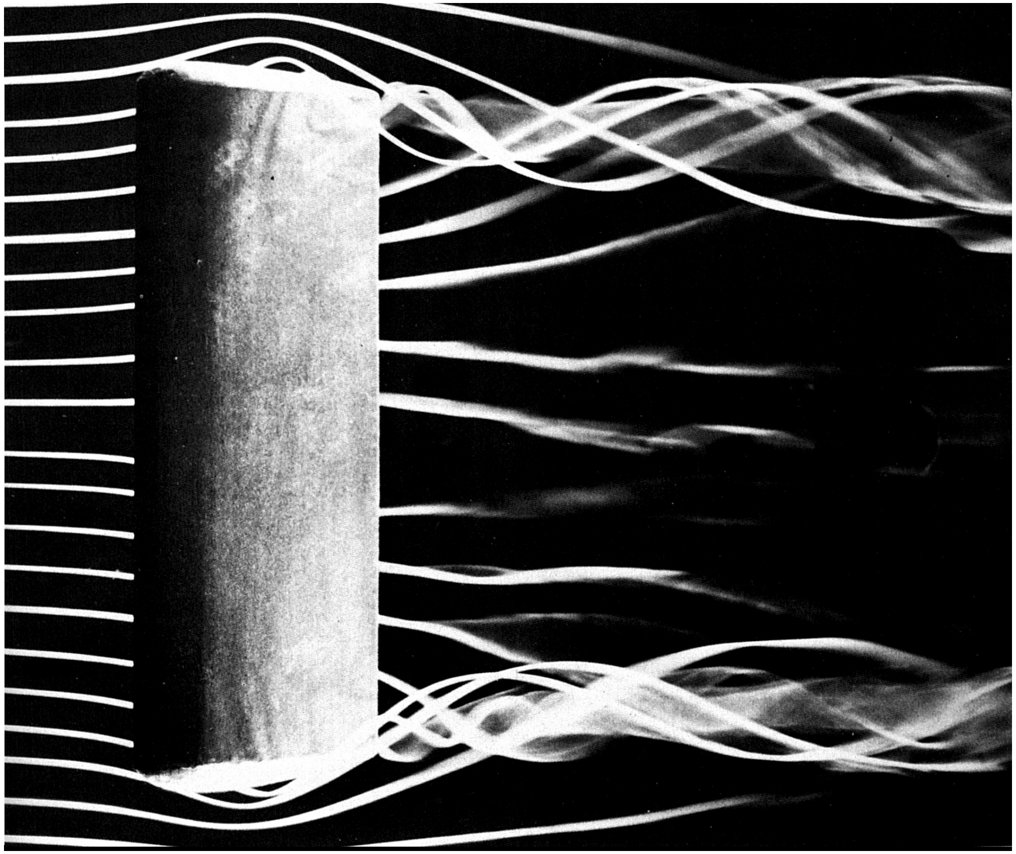
Laser-light sheet

(by R. C. Nelson)

Smoke Method (II)

Smoke tube rakes

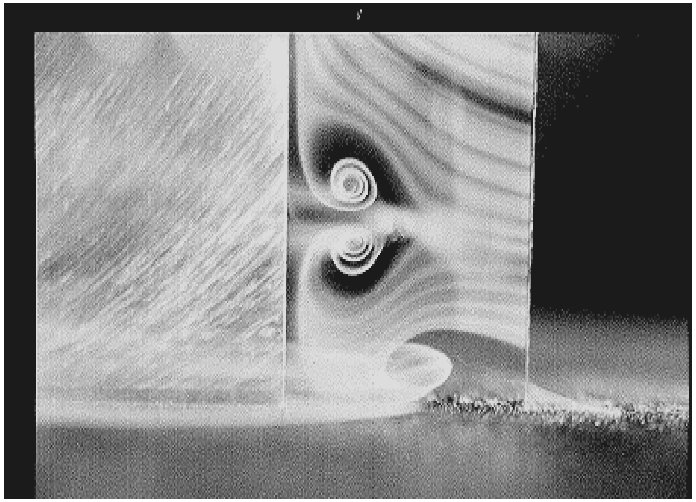




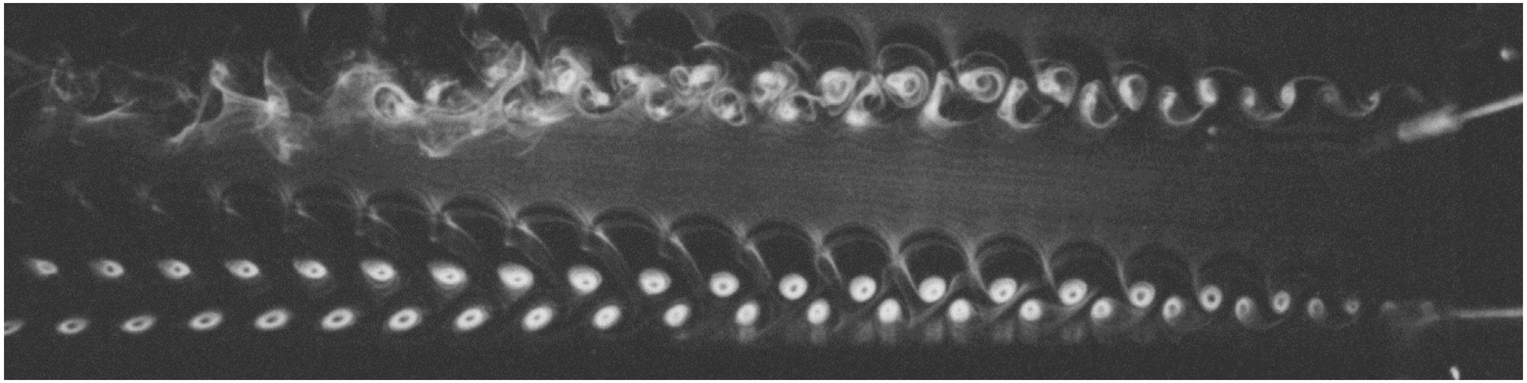
Head (1982)

Smoke Method (III)

Smoke wire

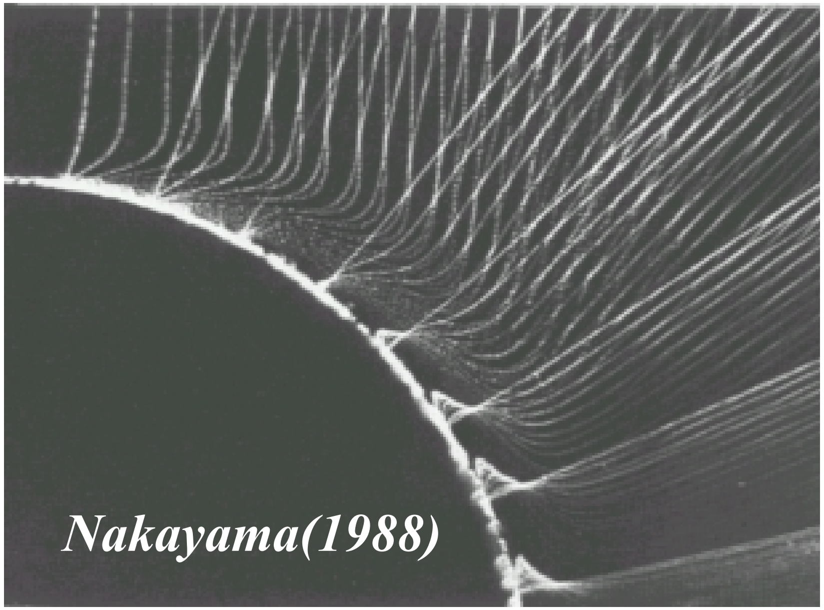


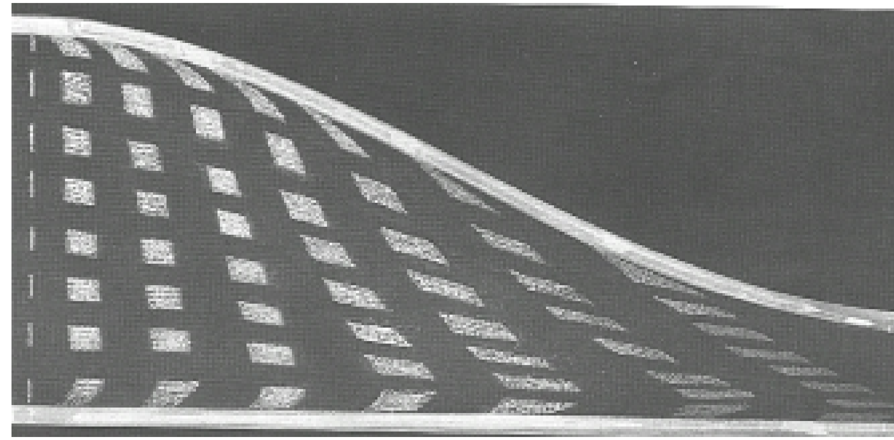
Hwang (1997)

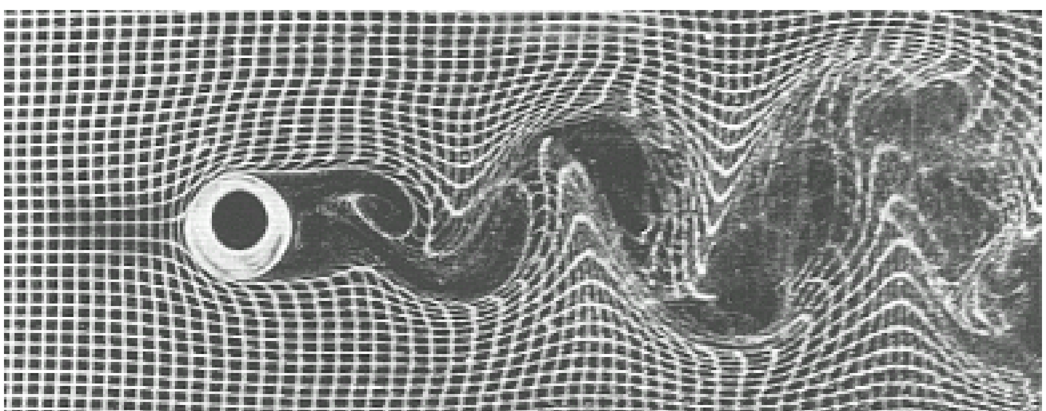


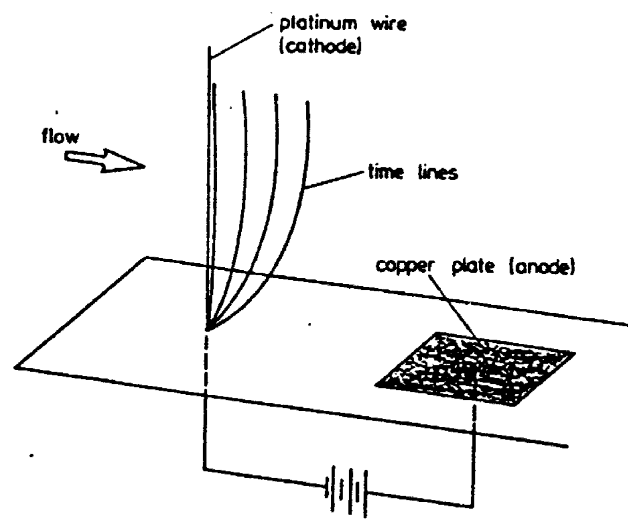
Wang et al. (2000)

Hydrogen Bubbles



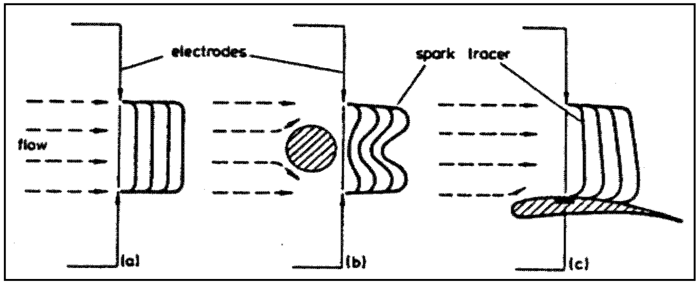


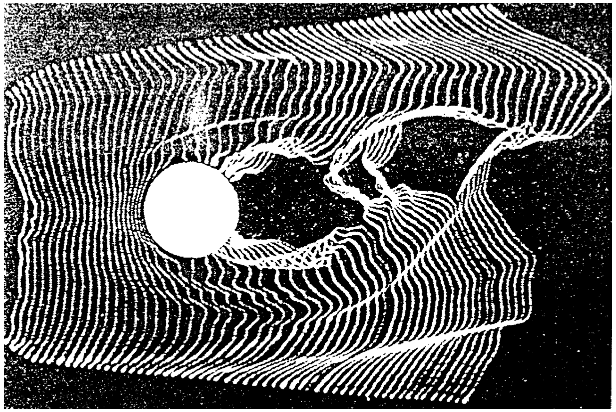




Spark Tracer Technique

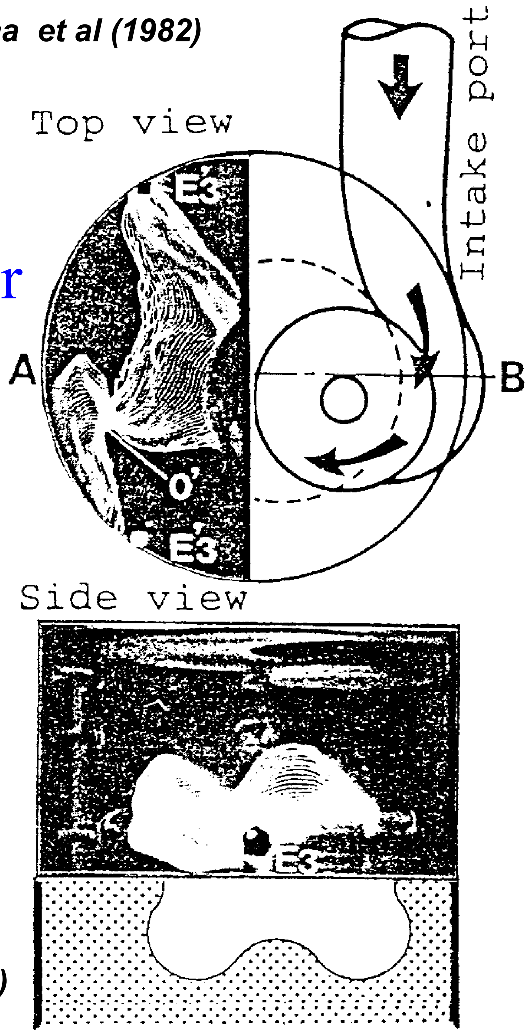
- Application:high speed air flow
- spark duration: ~100 µsec
- Measuring velocity: 1m/s ~ supersonic
- Tracer lighter than working fluid (main error
- source)



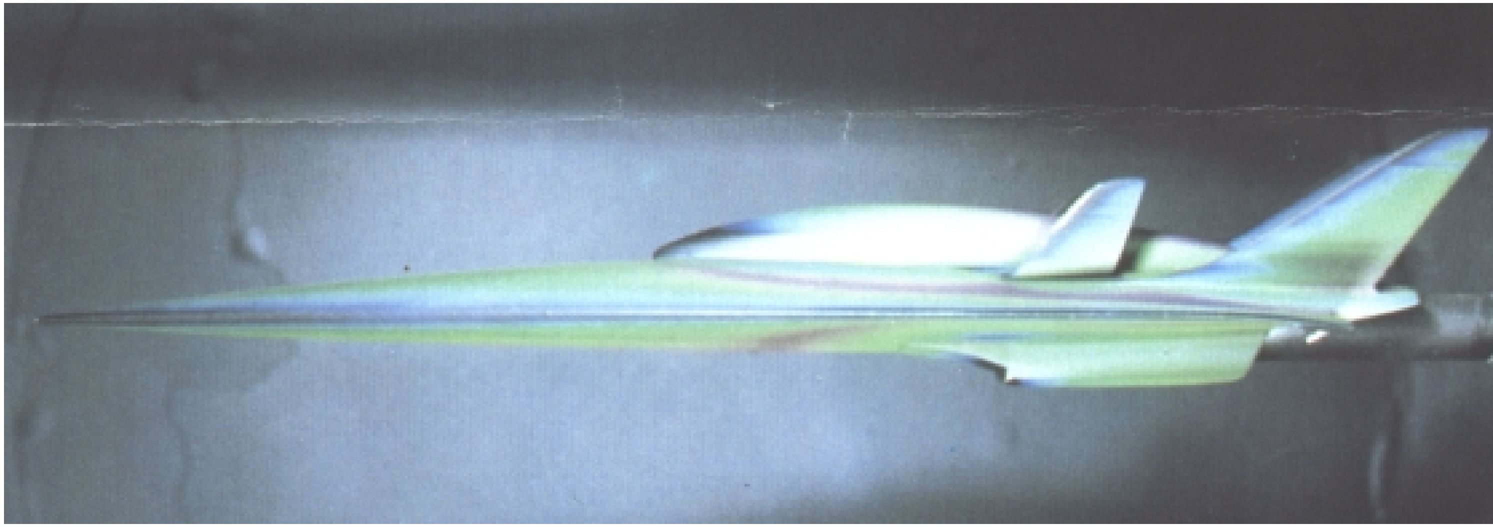


Nakayama et al (1976)

Najiyama et al (1982)



Thermal sensitive liquid crystal paint

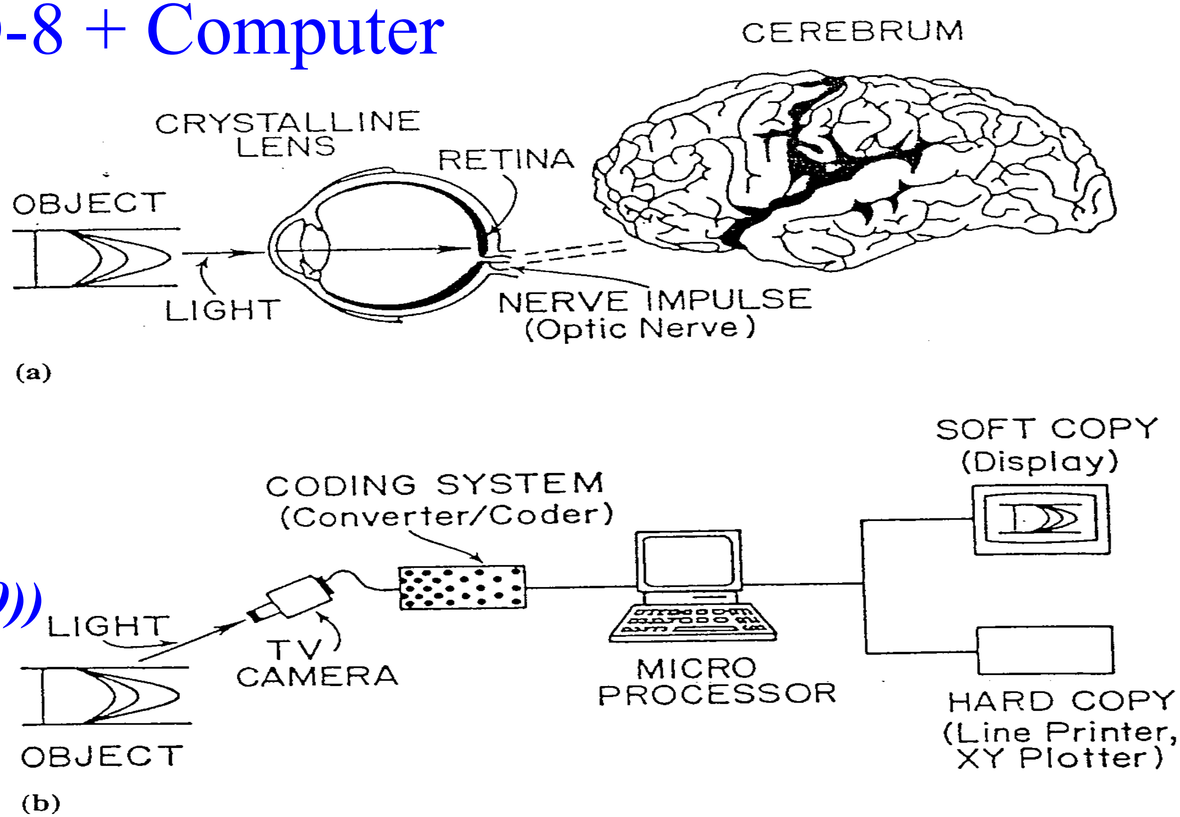


(Sänger, Hypersonic space-shuttle test, source: DLR)

<29° black
30° red
32° yellow
35° green
40° blue
>47° black

Recording Devices

- Pencil & Paper
- Camera + Film + Lens
- CCD, V-8, D-8 + Computer

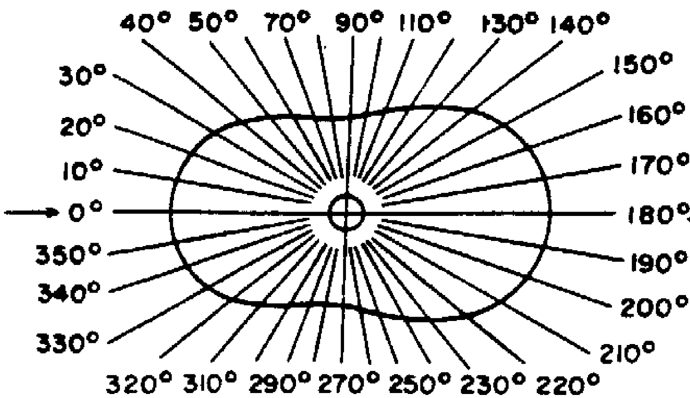


(from Yang(1989))

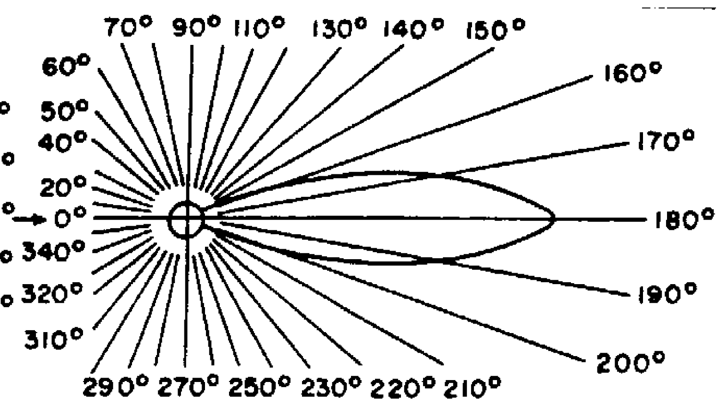
Light scattering phenomena

$$q = \frac{2r_p\pi}{\lambda}$$

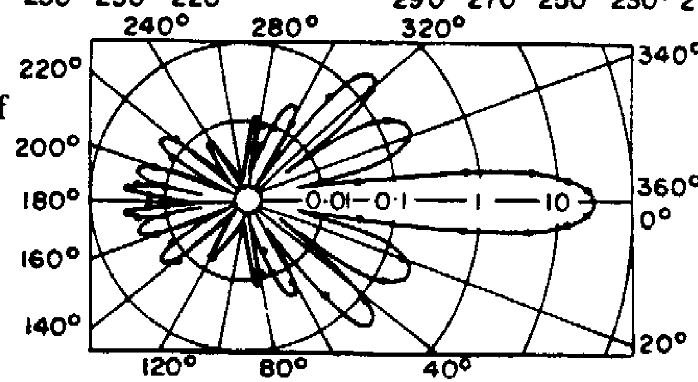
$q << 1$



$q > 1$



The intensity of scattered light depends on the particle size.

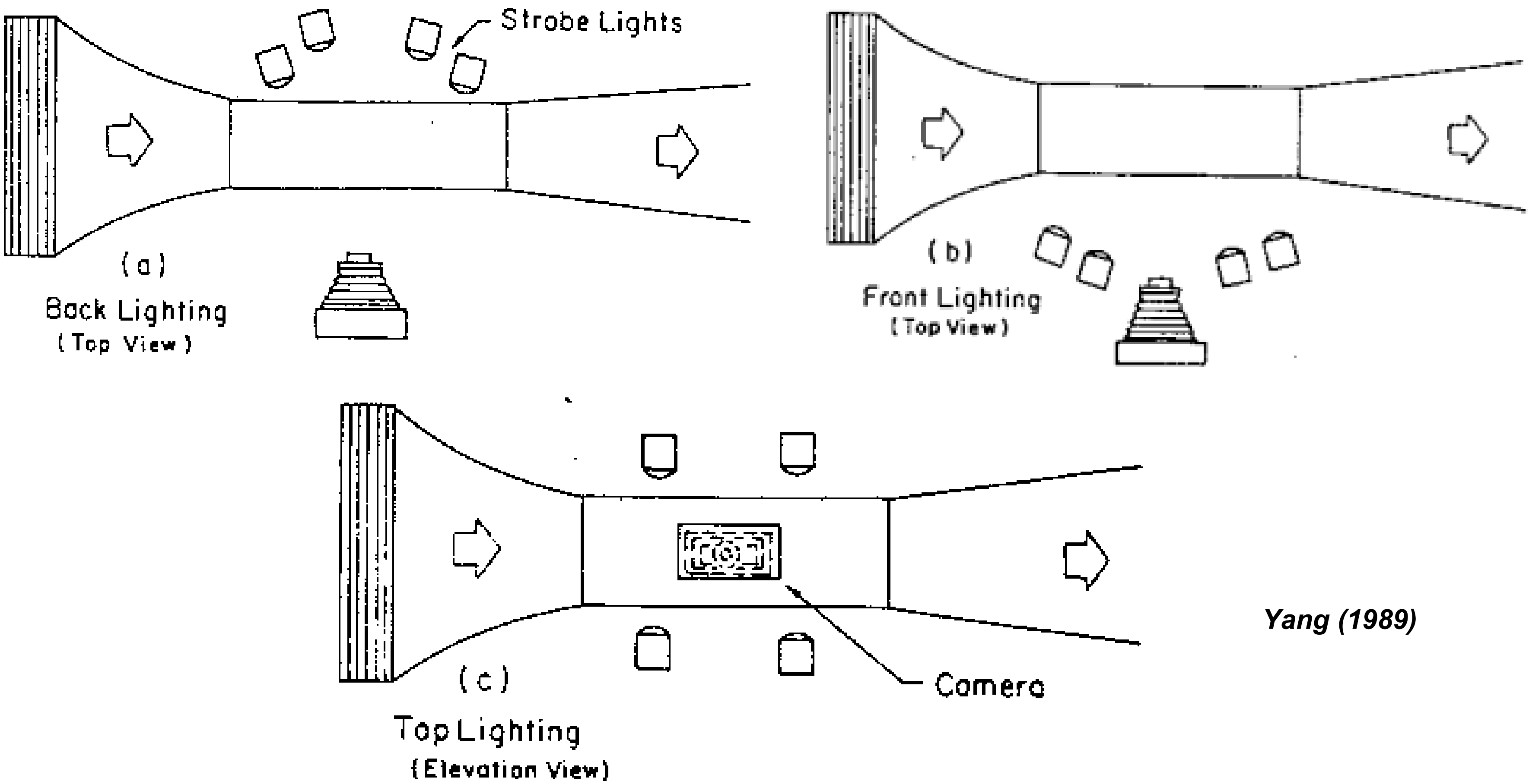


Light intensity variation as function of the direction of observation.

Durst et al.

For a given system, the signal intensity is several orders of magnitude larger in forward scattering arrangement.

Lighting & camera arrangement



Yang (1989)

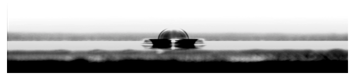
Clear (Freezed) Image

- Correct Forcusing ，Illumination and Exposure time (～ 0.5ms)
- Recording for moving body:
- High Speed Camera ： high time resolution ， low spatial resolution ，high price ， complex operation and maintainence
- CCD (charge-coupled device) Camera ： low time resolution (standard：33ms) ，high space resolution ， low price ， user-friendly.
- To avoid image blur → adjustable shutter speed, using stroboscope or modified by image processing.

Freezed Image of Drop Impact

(a) t=0.00 ms

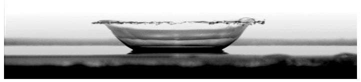
(b) t=0.25ms



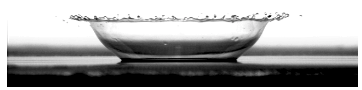
(c) t=0.50ms

(d) t=1.00 ms

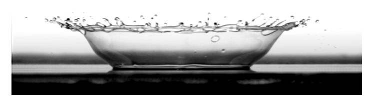
(e) t=2.00ms



(f) t=3.00ms

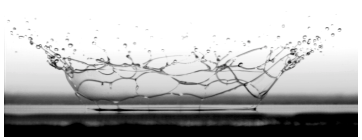


(g) t=4.00 ms



(h) t=5.00ms

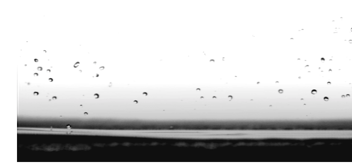
(i) t=6.00ms



(j) t=7.00 ms

(k) t=7.50ms

(l) t=15.00ms



Optical Methods(I)

- Optical methods are especially advantageous because of their ***non-intrusiveness.***
- Principle of optical visualization methods is to make visible the light ray deviations (or wavefront deformations) due to the ***refractive index heterogeneities*** in a medium.
- Commonly used methods are ***Shadowgraphy, Schlieren*** and ***Interferometry.***

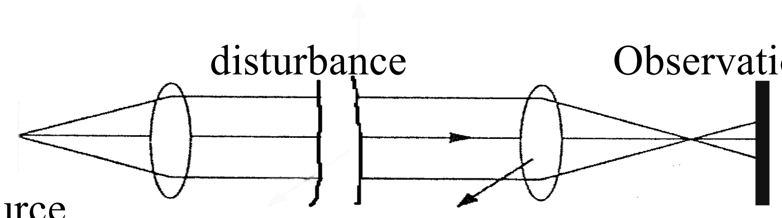
Optical Methods (II)

- Optical techniques are all integral method and give no information about local condition
- The investigated flow medium must be ***transparent.***

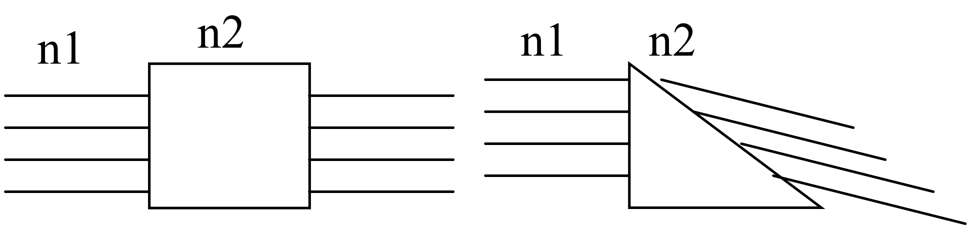
Method	Measuring Quantity	Remarks
Shadowgraphy	Second Derivative of Density	Simplest
Schlieren	Density Gradient	Suitable for large density gradient
Iinterferometry	Density difference	Most complex and expensive

Shadowgraph Method

- **Configuration:**



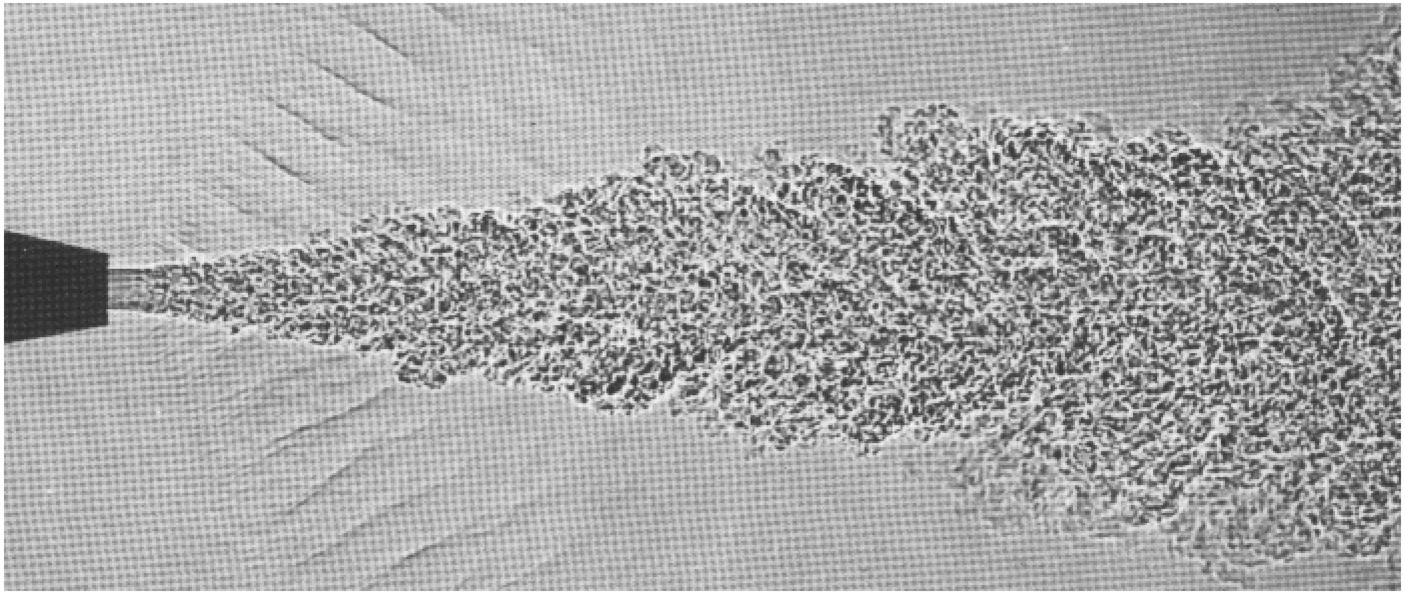
- **The Shadowgraph can be understood by considering the three following situations:**



$$\frac{\partial \rho}{\partial y} = 0 \qquad \frac{\partial \rho}{\partial y} = const \qquad \frac{\partial^2 \rho}{\partial^2 y} \neq 0$$

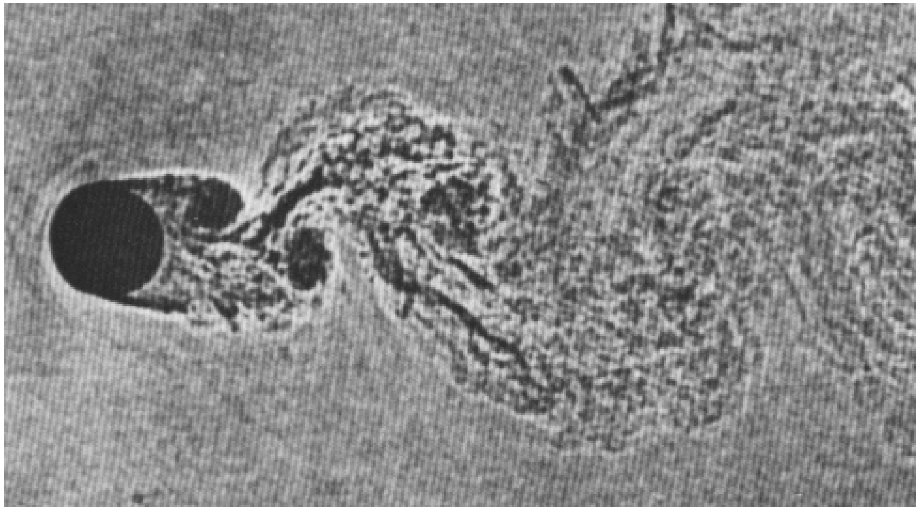
- **The Shadowgraph is based on the relation:** $$\frac{\partial \theta}{\partial y} \approx \frac{\partial^2 \rho}{\partial^2 y}$$
- **It yields sharper images with higher contrast than Schlieren method since all incident light is utilized in the image.**

Shadowgraph (I)

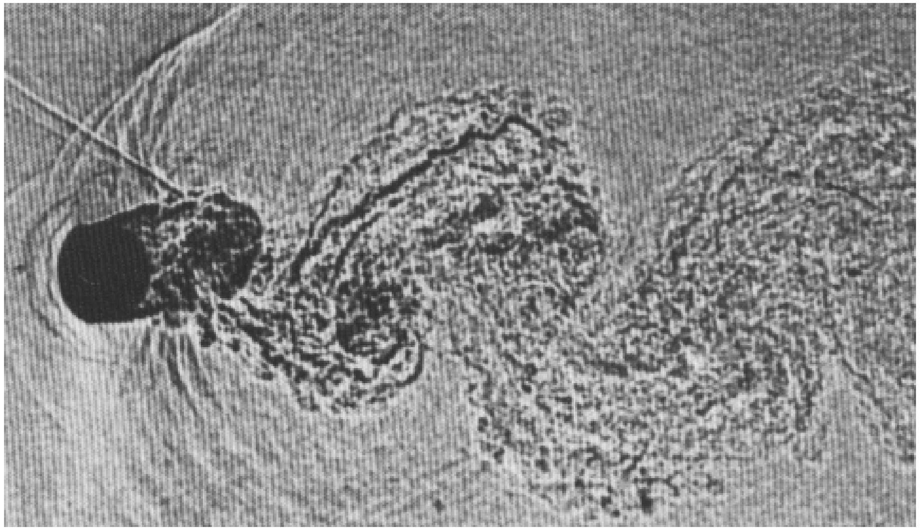


laminar helium jet into air (0.26 cm nozzle)
85kHz weak shock wave along 60° cone
from Chan & Lee (1972)

Shadowgraph (I)



M = 0.45,
Re = 110,000

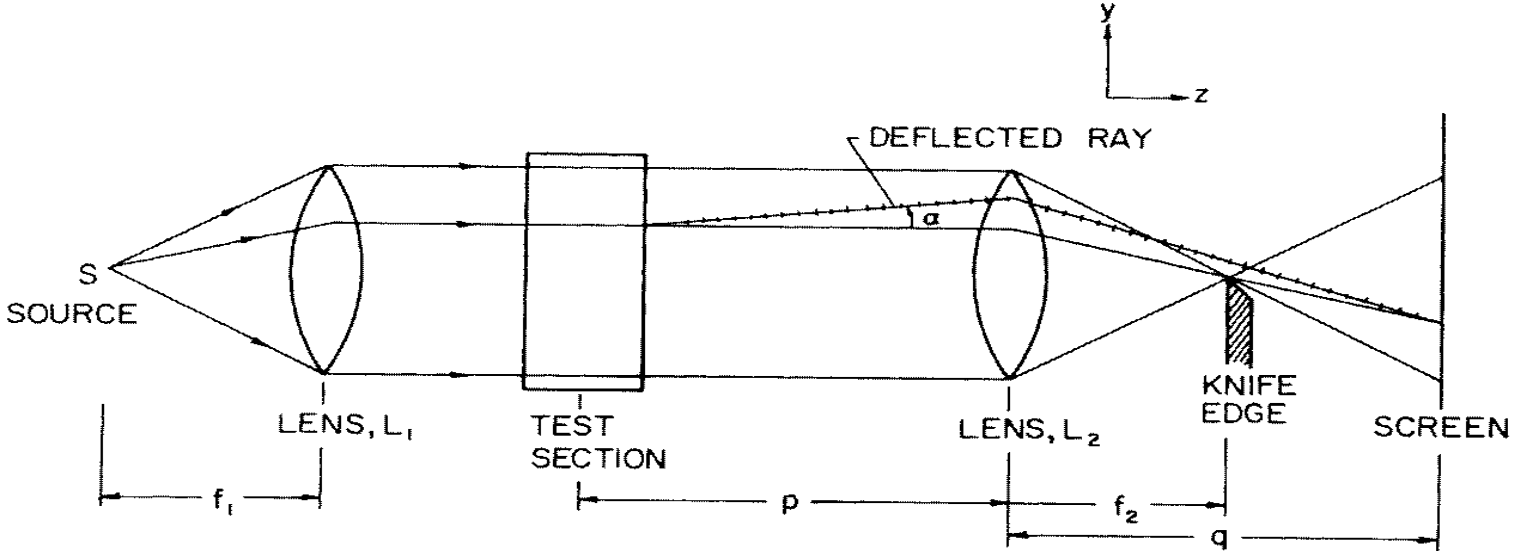


M = 0.64,
Re = 1,350,000

By Dyment et al.(1980)

Schlieren Method

- ***Configuration:***

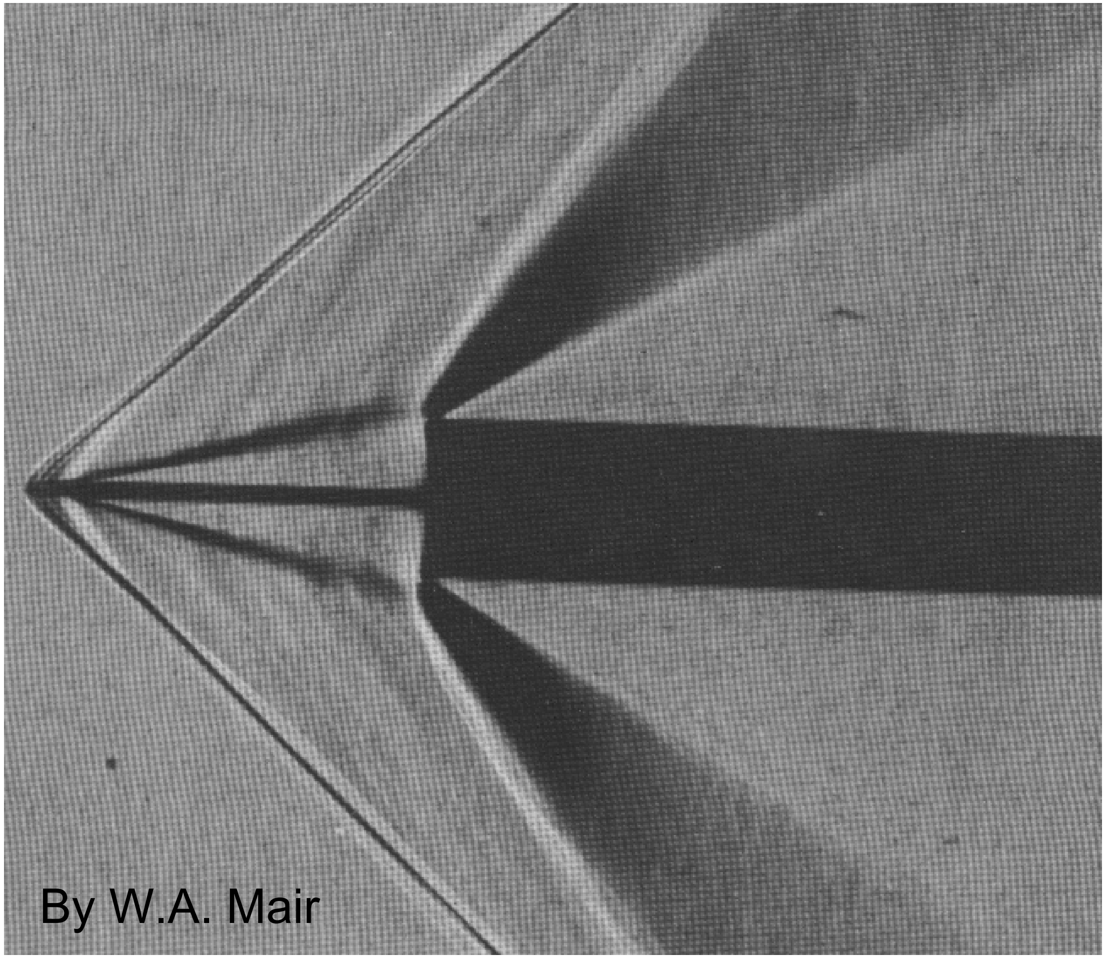


- ***The change of light intensity on the screen***

$$I/I = \alpha = (L/n)(dn/dy) \propto (L/n)(d\rho/dy)$$

- ***negative density gradient : dark***
- ***positive density gradient : light***

Schlieren photo

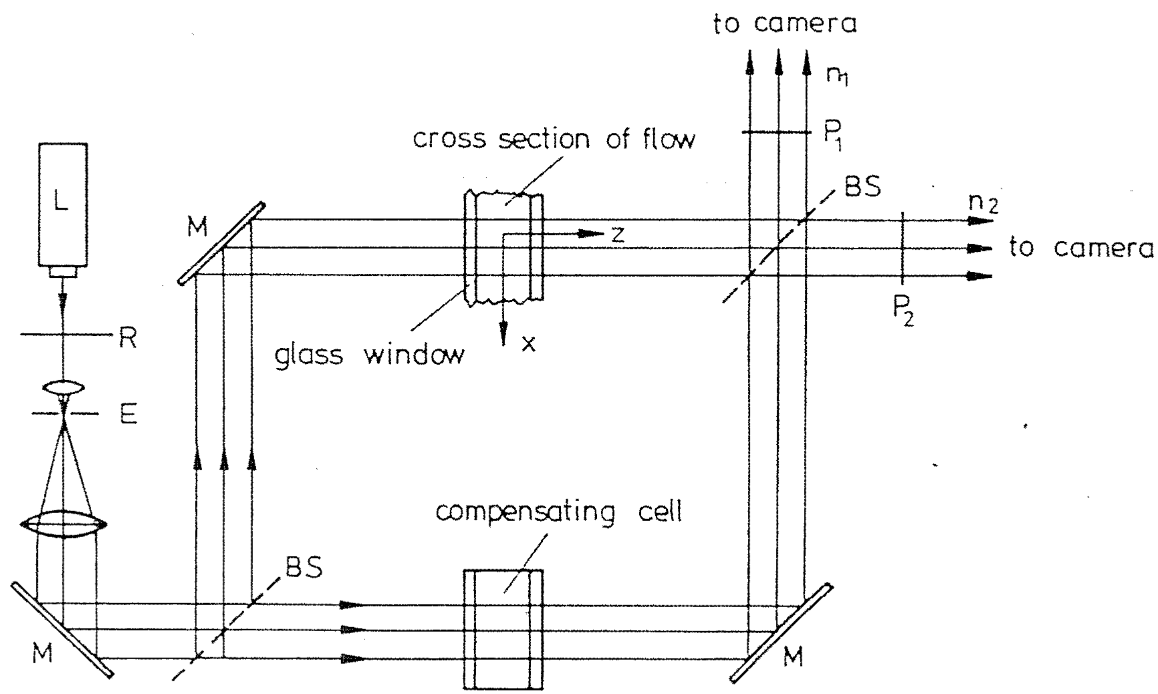


M = 1.96

Interferometry Method

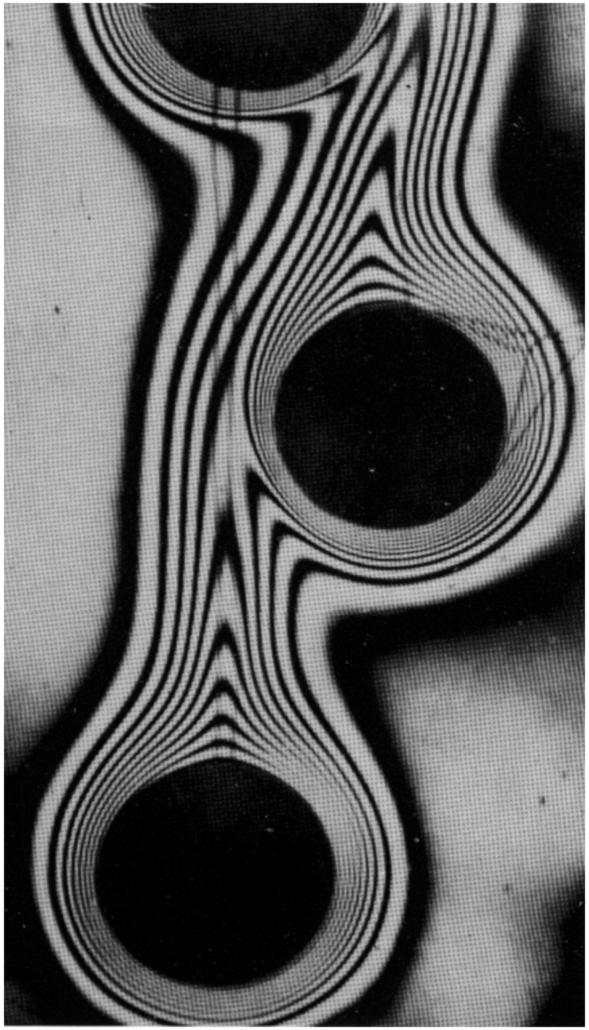
- **Configuration:**

  Mach-Zehnder Interferometer



- **If density variation are present, then phase differences between the object path and reference path result, which lead to interference patterns after recombination.**

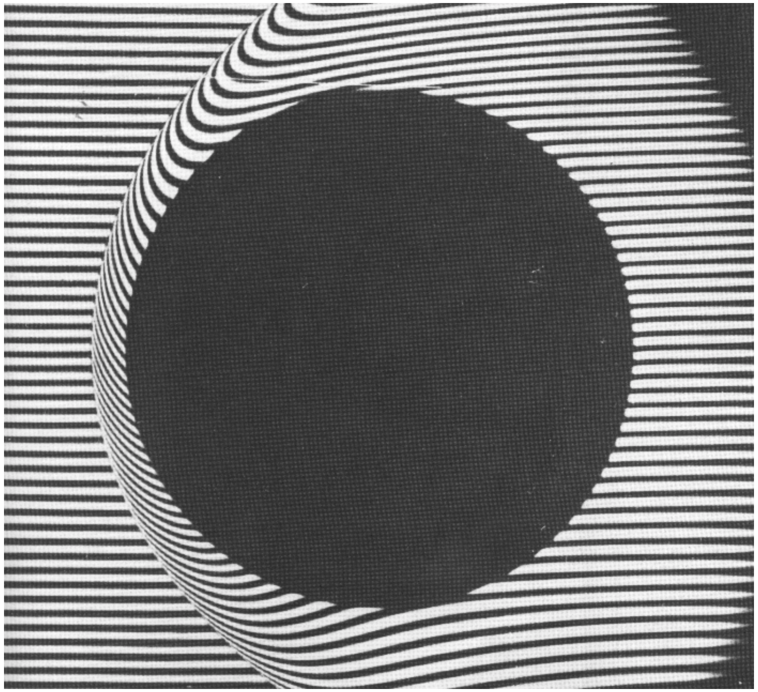
Interferogram



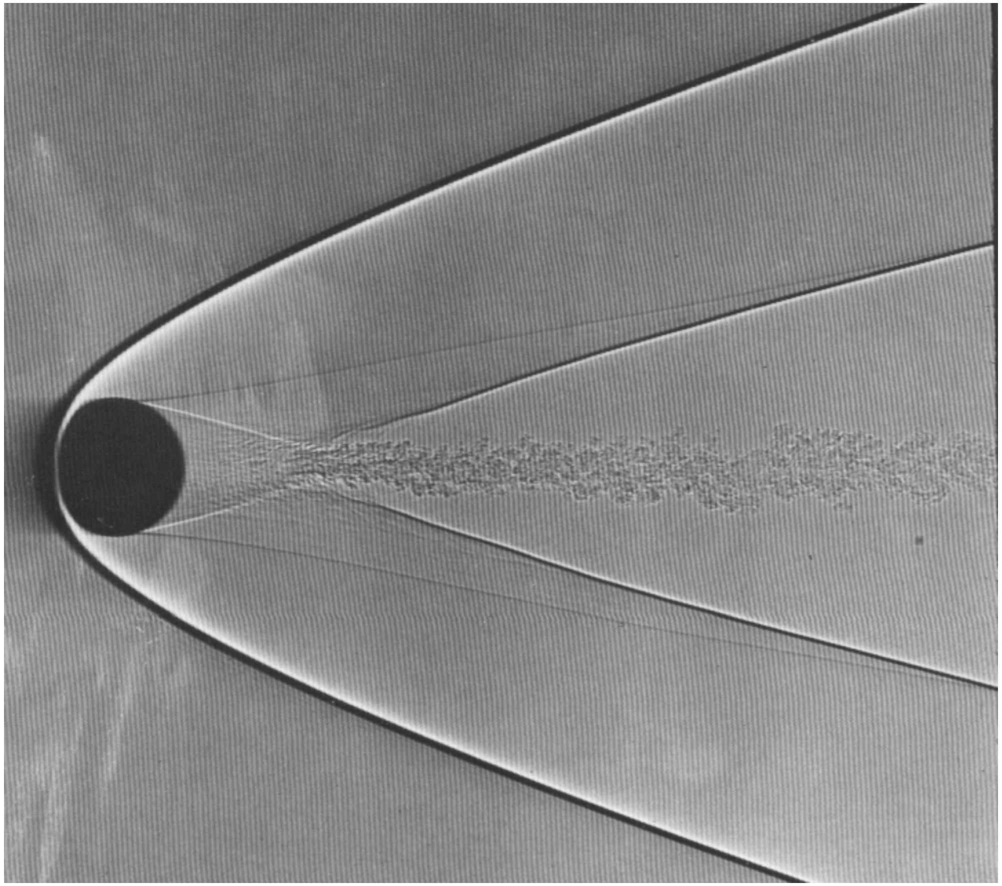
Eckert & Soehngen (1948)

Interferogram & Shadowgraph

1/2” sphere M = 5.7



M = 4.01

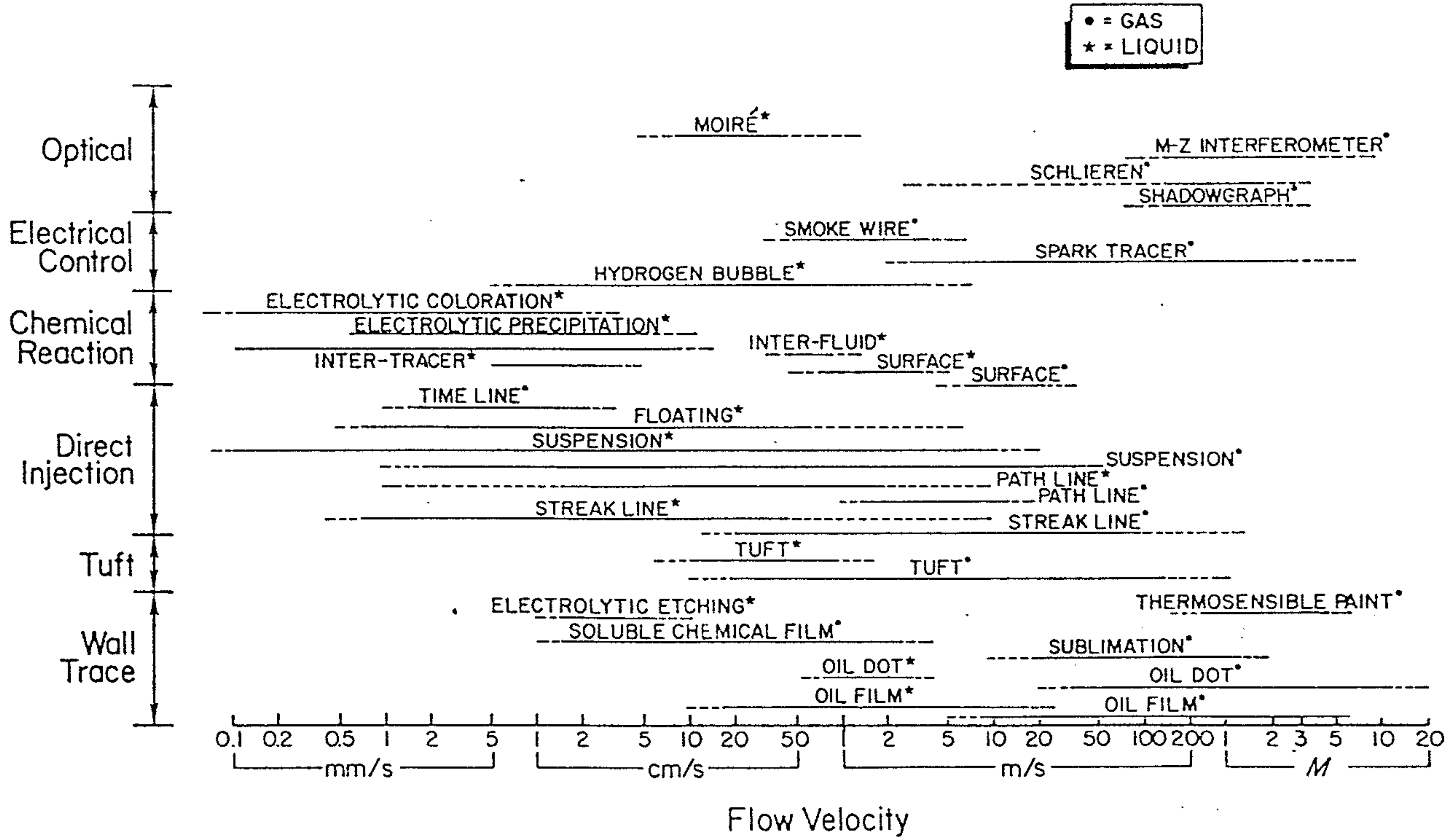


By A.C. Charters

Interferometry & Schlieren

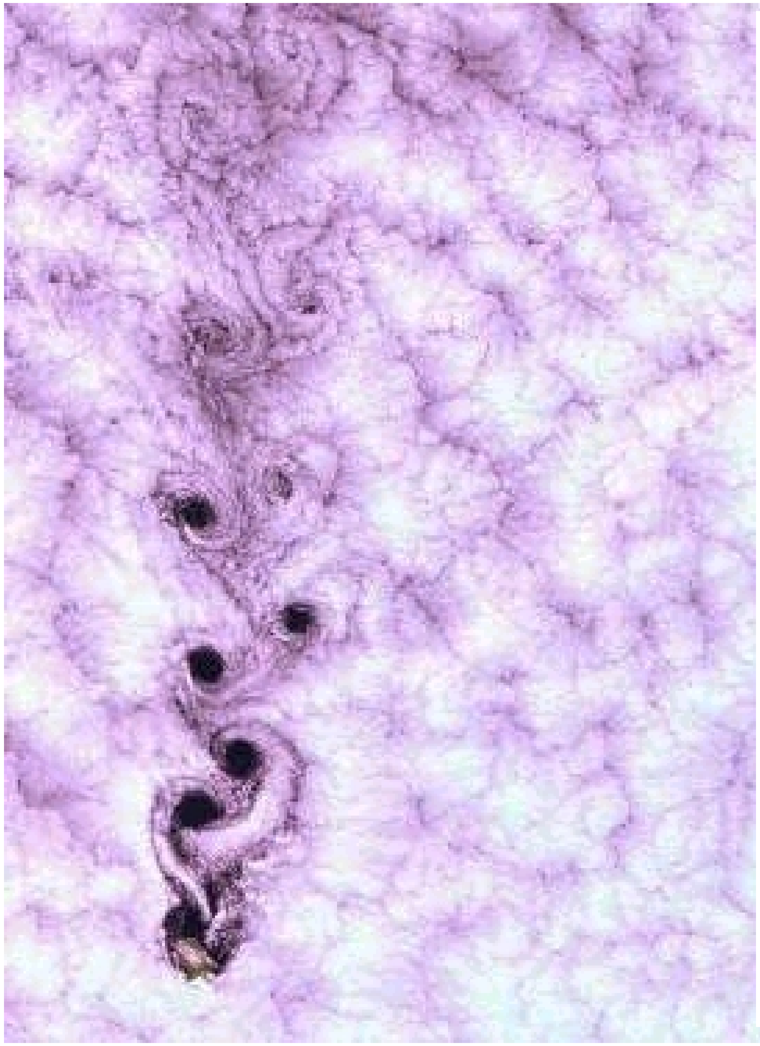
Blast waves
By Klein & Takayama
(2001)

Applicable range for Flow Visualization Methods



Yang (1989)

Von Karman Vortex Street in nature



A rare meteorological phenomenon caught by LANDSAT 7 on 9/15/1999. In the southwest of the scene is Alejandro Selkirk Island, a squarish island that rises almost vertically 1 mile above the southern pacific. A boundary layer that sandwiches a saturated, unstable layer of clouds
between two more stable layers is broken by the island, causing
a formation of vortices known as a Karman Vortex Street.

Kelvin-Helmholtz roll-ups in a cloud formation

Kelvin-Helmholtz roll-ups as seen in a cloud formation.
The picture is from the National Center for Atmospheric Research.

Surface wave

This spectacular picture of a B1 bomber flying over a lake (sea?) appears to show the wake generated by the wave field emanating from the airframe. What is wrong with this picture?
(by Jan-Olov Newborg , from Stockholm).

Scock wave by F-4 fighter

TMAA SCAN

F-4 Phantom II Caught Breaking the Sound Barrier.

Using a 35mm camera, a telephoto lens and ASA 400 film, Pat Maloney, an engineering planner, photographed an F-4 Phantom II at the moment it broke the sound barrier at the Annual Point Magu Naval Air Station Air Show. "The photograph of the visible shock wave is rare." stated Maloney. "It required a humid day, split second timing and no small measure of luck." Maloney frequently practices photography at the many air shows he attends.

Formation of trailing vortices in the wake of a C-130 Hercules

1993 Aviation Week & Space Technology by James E. Hobbs, from Lockheed Aircraft service Co., Ontario, California.
The plane is ejecting flares during a test of an infrared missile warning and self-protection system installed on a C-130 Hercules.
The trailing vortices formed in the wake are clearly visible.

Vortex ring formation