NTNU
Norwegian University of
Science and Technology

Developments and prospects of visualization methods in fluid flow systems

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Outline

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Introduction and Background

Evolution and Classification

Thermal Visualization

Particle-tracking Visualization

Flow-surface Visualization

Visualization by Refractive Index Variation

Prospects

Outline

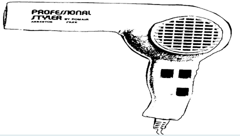
Introduction

Flow visualization

The technique of making flow patterns visible.

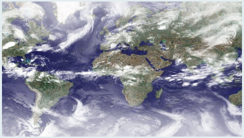
Why visualization techniques

- Too transparent.
- Too vast.
- Too small.
- Too fast.
- . . .



Transparent flow

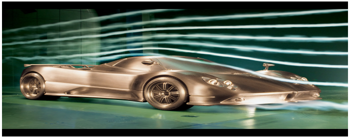
Tiny bubbles



Vast cloud

Fast-moving droplets

Purpose and need for flow visualization



Aerodynamic

Phase separation

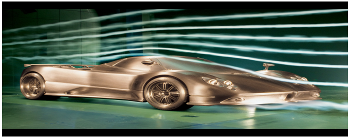
Fluid transportation

Spray process

Purpose and need for flow visualization

In general

- To gain and improve the understanding of fluid-mechanical problems, which are critical in different applications.
- To develop and verify numerical models.



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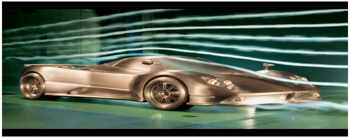

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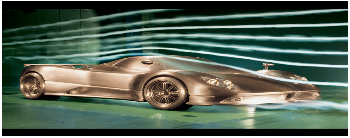

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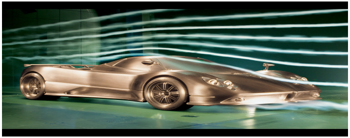

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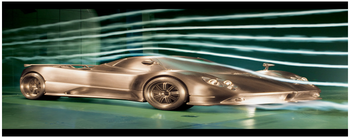

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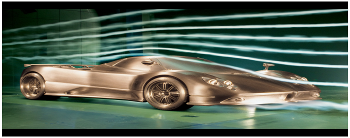

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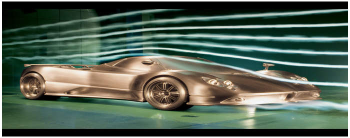

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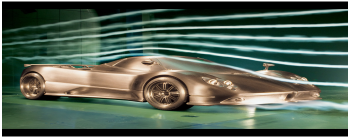

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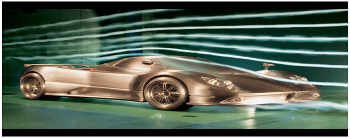

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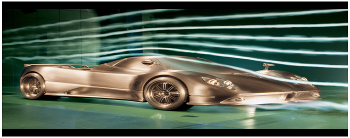

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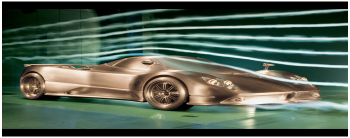

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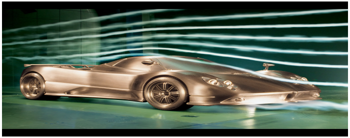

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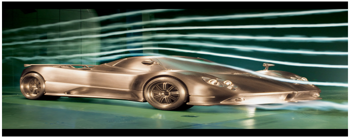

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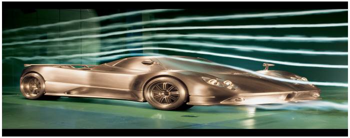

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Advantages of visualization techniques

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Compared with probes· · ·

- For some visualization techniques: Information on complete flow field.
- For most of the visualization techniques: Non-intrusive and non-disturbing.

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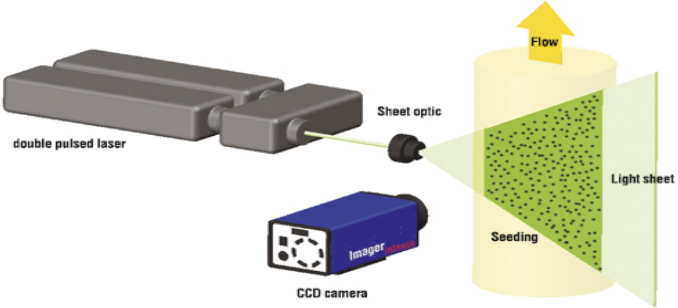

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Light → Flow → Detector

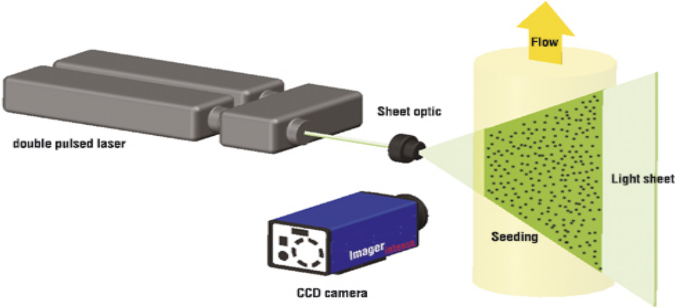

Illustration of a visualization experiment.

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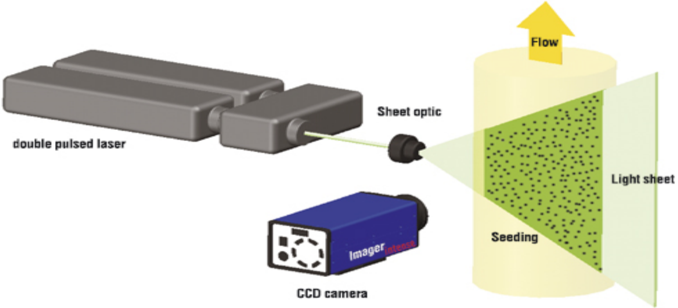

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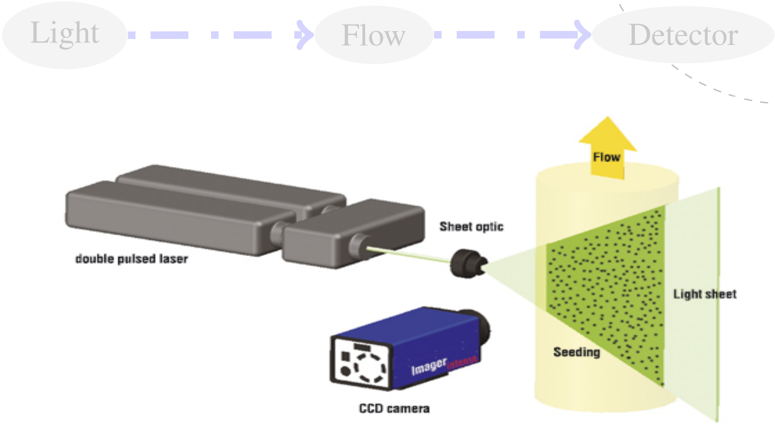

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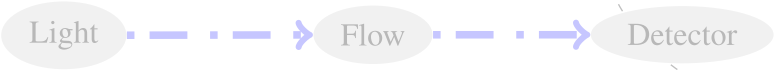

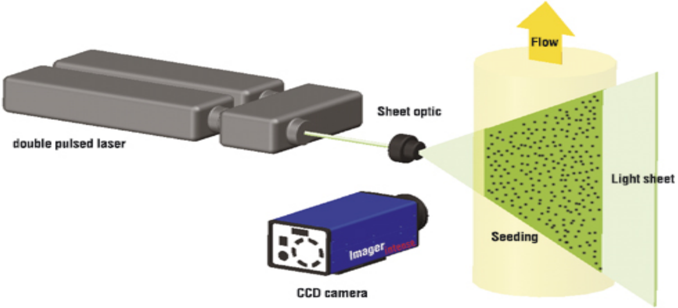

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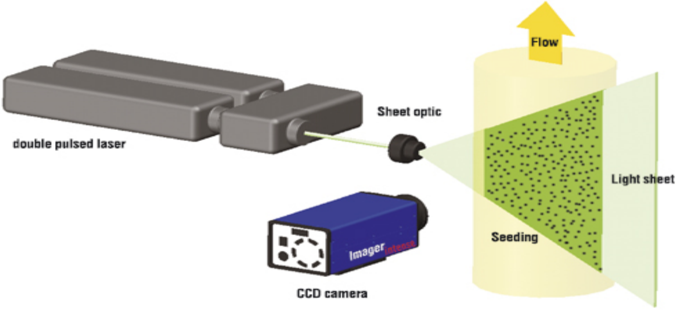

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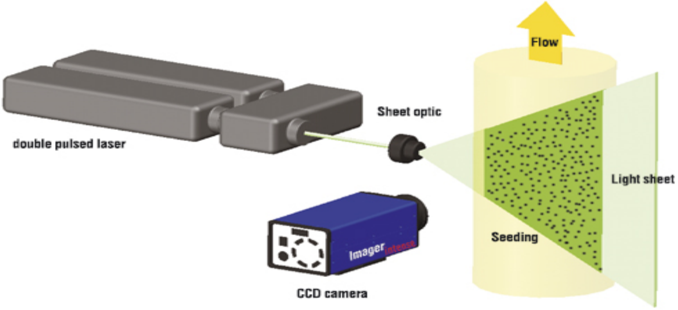

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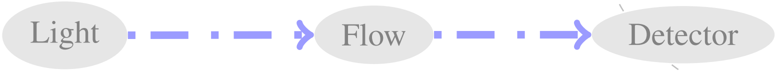

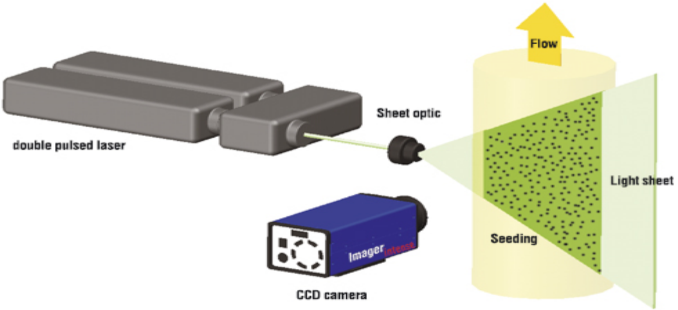

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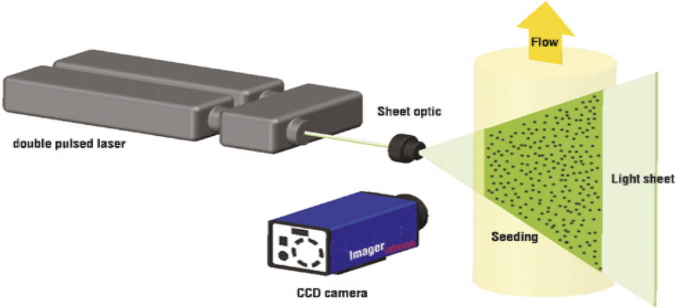

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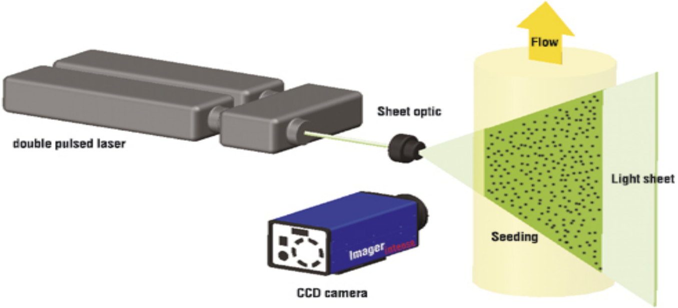

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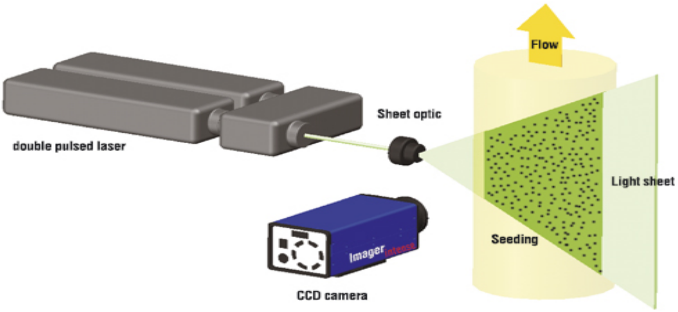

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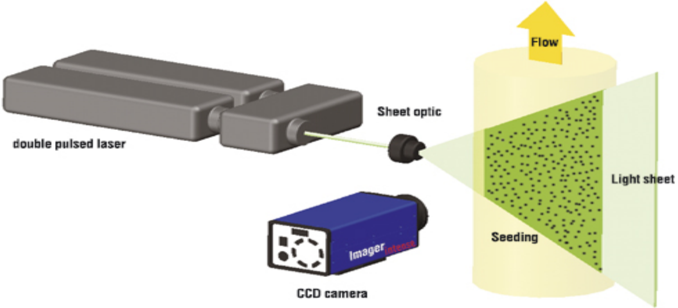

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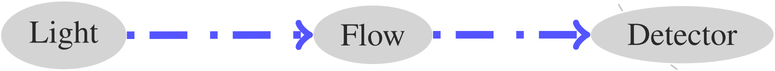

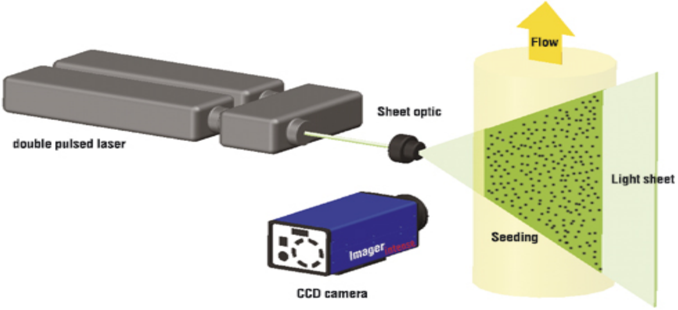

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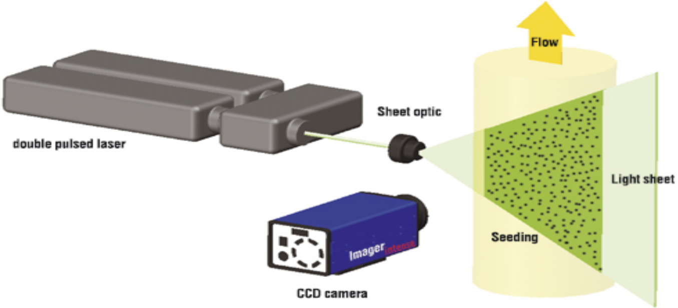

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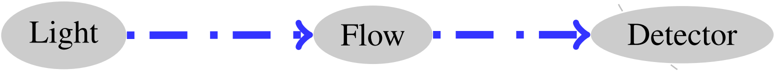


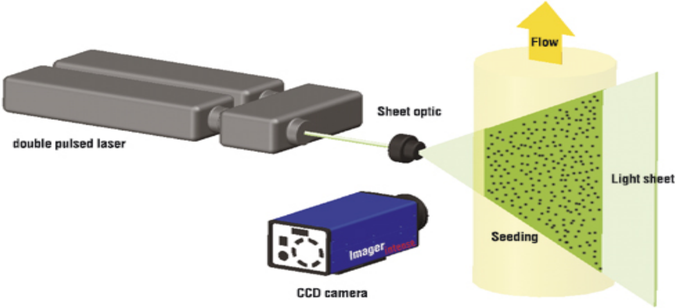


Illustration of a visualization experiment.

Evolution of light source

Earlier than 1800s

- Pros: Easy access, cheap, safe.
- Cons: divergence, low controllability.

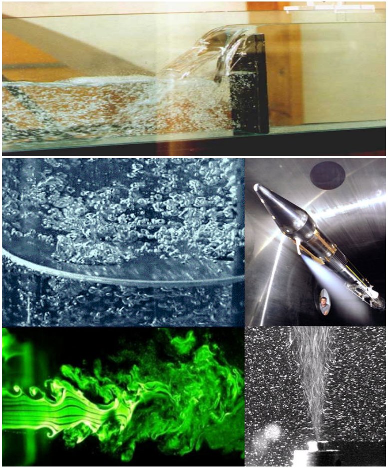
Late 1800s and earlier 1900s

- Pros: Easy access, cheap, safe.
- Cons: divergence, low controllability.

Nowadays

- Pros: high intensity, high controllability.
- Cons: Dangerous, relatively pricey (for laser).

Evolution of flow



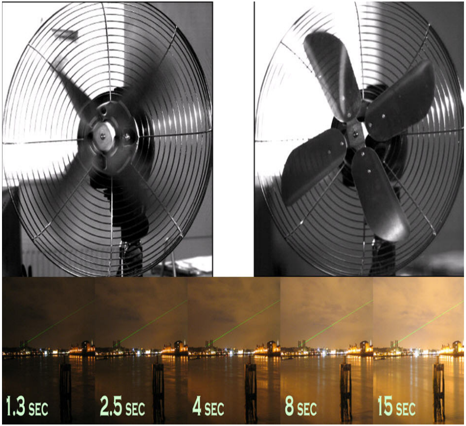
Earlier than 1900s: simple flows

- Characteristics: Mono-phase, low-speed, laminar, macro.
- Focus: Qualitative steady-state flow pattern.

From 1900s till nowadays: Complex flows

- Characteristics: Multi-phase, high-speed, turbulent, macro and micro.
- Focus: Quantitative and qualitative, steady- and unsteady-state flow.

Evolution of detector - terminology

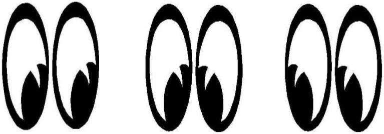


- Resolution.
- Bit depth (gray level).
- Color or monochrome.
- Camera interface.
- Physical size.

Crucial - How fast is the camera?

- Frame speed: fps - the higher the more continuous/fluent.
- Shutter speed: μs (10^{-6}) or pico (10^{-12}) second.

Evolution of detector



Earlier than 1900s: naked eyes

- Characteristics: Smooth but blurry observation, instant-memory.
- Focus: Steady-state macro flow.

Earlier 1900s: old camera

- Characteristics: Non-continuous (single-shot) and blurry.
- Focus: Steady-state macro flow.

Late 1900s till nowadays: digital camera and photodetector/sensor

- Characteristics: High-speed (up to more than 150, 000 fps), fast-shutter (80 pico second), high-resolution, sensitive and accurate.
- Focus: Fast-evolving complex flows both macro and micro.

Classification of visualization principles

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Thermal radiation

Particle light scattering

Tracer particles/seeds

Fluid molecules

Flow-surface interaction

Refractive index variation

Light interference

Light deflection

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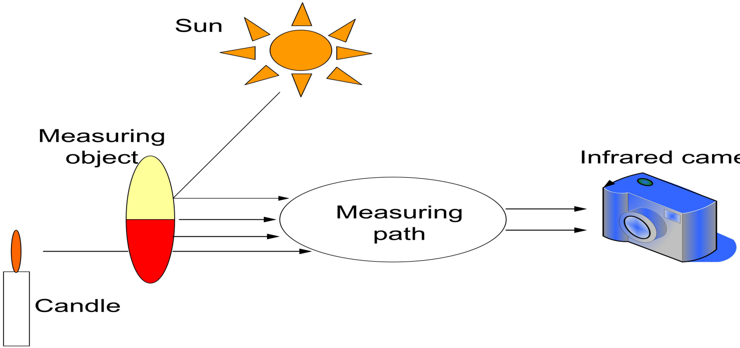
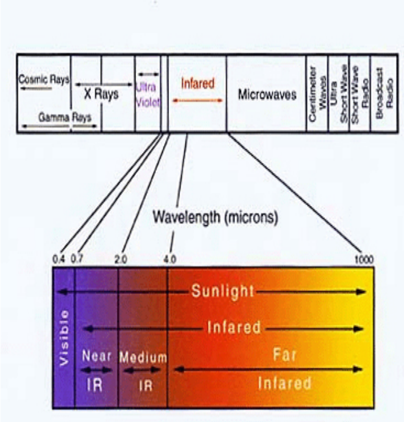
The principle of infrared thermography

General principle

Objects with a temperature above absolute zero (-273.15° C) emit electromagnetic radiation (thermal radiation). Determining its intensity, the temperature of the emitting object can be calculated without contact.



Measuring theory



Electromagnetic radiation spectrum.

theory

Wien's displacement law:

$$\lambda_{max} T = 2898 \, [\mu\text{m} \cdot \text{K}]$$

The maximum emitted radiation wavelength is a function of only temperature.

Stefan-Boltzmann law:

$$M = \sigma_e T^4 \, [\text{W}/\text{cm}^2]$$

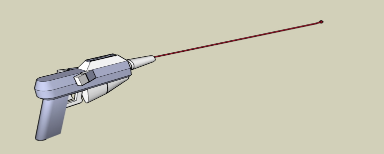
The total amount of energy radiated is directly related to the fourth power of the temperature (in Kelvin).

Example: human skin

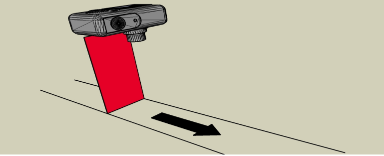
$$\lambda_{max} = \frac{2898}{305} \approx 9.5 \, \mu\text{m}$$

Thermal imaging devices oriented for human are most sensitive to wavelength 7–14 μm.

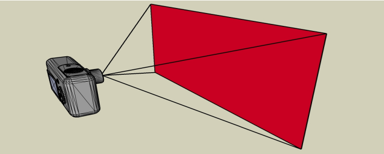
Measuring-system layouts



- Point-measuring system: pyrometer.

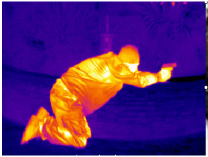


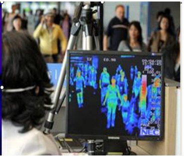
- Line-scanning system: Infrared line-scanner.

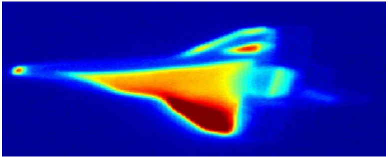


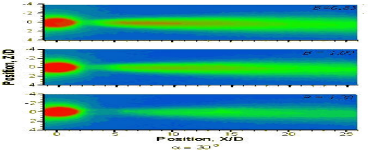
- Surface-measuring system: Infrared camera.

Application of the thermography









Non-intrusive temperature measurement in flow system. Except the applications in human-locating:

- Aerodynamic studies.
- Combustion process.
- Boundary layer studies.

Outline

The principle of particle-tracking visualization

General principle

Utilize the particles in the fluid to visualize the flow.

Ludwig Prandtl in front of his water tunnel for flow visualization in 1904.
Mica particles were used as tracer particles.

Two application groups

Flow/velocity field tracking

Particle Image Velocimetry (PIV)

Laser Doppler Anemometry (LDA)

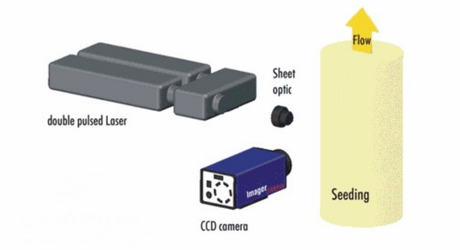
...

Flow pattern tracking

Characteristics of the two application groups

- Flow/velocity field tracking: Detailed velocity information with very high spatial and temporal resolution, while difficult to see what the flow looks like.
- Flow-pattern tracking: Whole picture of the flow (regimes) with high temporal resolution (high-speed camera), while not-so-detailed local velocity field information.

PIV - working principle



Procedures:

- Photograph-taking
  1. Seeding
  2. Two laser pulses
  3. Two frames
- Frame-analysis
  1. Interrogation areas/windows
  2. Statistical methods
  3. $V = \dfrac{\Delta L}{\Delta t}$
  4. Repetition$\cdots$

PIV - tracer/seeding particles

Theory

Stokes' drag law on gravity-induced velocity:

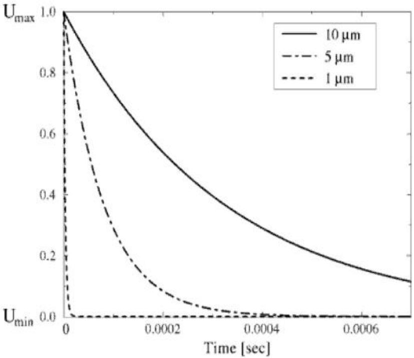
$$U_g = d_p \frac{\rho_p - \rho}{18\mu} g$$

Analogy equation on velocity-lag:

$$U_s = U_p - U = d_p \frac{\rho_p - \rho}{18\mu} a$$

$$U_p(t) = U \left[1 - exp(-\frac{t}{\tau_s}) \right]$$

$$\tau_s = d_p \frac{\rho_p}{18\mu}$$



Time response of oil particles with different diameters in a decelerating air flow.

PIV - selection of particles

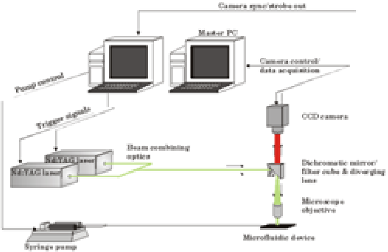
Criteria

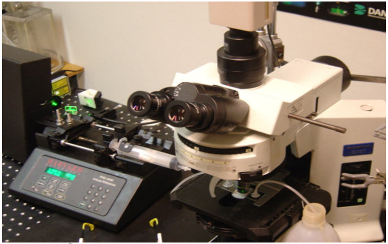
- Small enough to track the flow.
- Not too small to be imaged.

Type	Material	Mean D (μm)
Solid	Polystyrene	10–100
	Aluminum flakes	2–7
	Hollow glass spheres	10–100
	Granules for synthetic coatings	10–500
Liquid	Different oils	50–500
Gaseous	Oxygen bubbles	50–1000

Type	Material	Mean D (μm)
Solid	Polystyrene	0.5–10
	Alumina Al_2O_3	0.2–5
	Titania TiO_2	0.1–5
	Glass micro-spheres	0.2–3
	Glass micro-balloons	30–100
	Granules for synthetic coatings	10–50
	Dioctylphathalate	1–10
	Smoke	< 1
Liquid	Different oils	0.5–10
	DEHS	0.5–1.5
	Helium-filled soap bubbles	1000–3000

PIV - Micro PIV (μPIV)





μPIV and characteristics

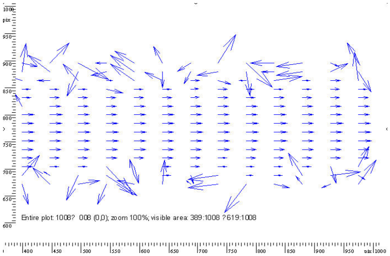
Extensive application of PIV.

- Applications: Micro-structures such as bio-cells and lab-on-a-chip etc.
- Seeding challenges: Traditional seeding particles are too LARGE.
  - Small.
  - Not too small.

Experiment description

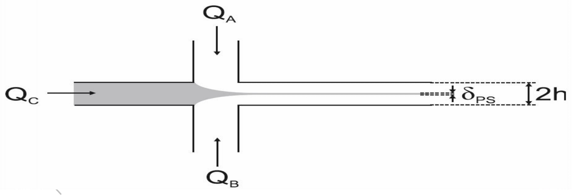
- Flow: $100 \times 100\ \mu$m channel.
- Material: De-ionized water seeded with 0.08 Vol% fluorescent polymer micro-spheres of 1 μm.

μPIV - results and indications



Flowrate (μl/min)	*Re*	Theo. mean (m/s)	Exp. mean (m/s)	Rel. dev. ((%))
1	0.19	0.0017	0.0076	335
10	1.86	0.017	0.020	20
50	9.32	0.083	0.091	9.2
100	18.65	0.167	0.186	11.6
Flowrate	*Re*	Theo. max	Exp. max	Rel. dev.
1	0.19	0.0035	0.013	271
10	1.86	0.035	0.036	2.9
50	9.32	0.175	0.175	0
100	18.65	0.351	0.32	8.8

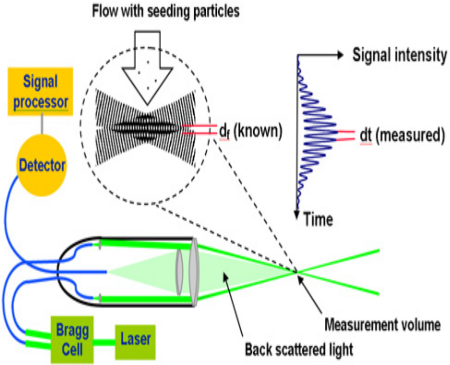
- Error sources: wall reflection, depth of channel (3D-flow), laser intensities.
- Amending: use max-velocity, hydrodynamic focusing.



LDA - working principle

Principle

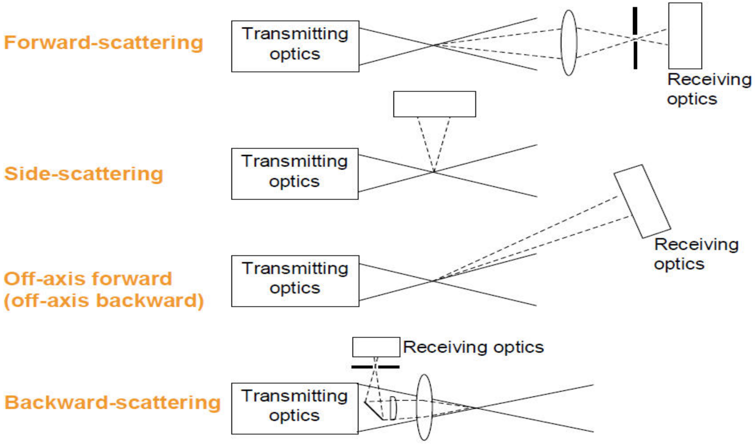
Laser doppler effect: The change in frequency of a wave for an observer moving relative to the source of the wave.



- Particle-tracking
  1. Seeding
  2. Light scattering
  3. Photodetector

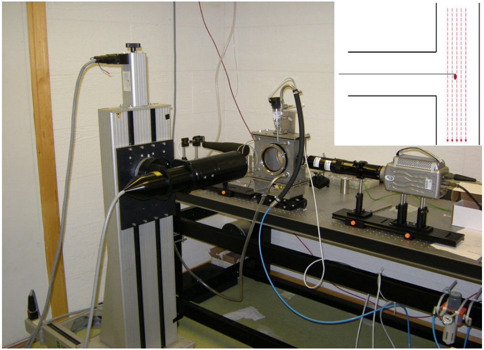
- Information-analysis
  - From calibration: $D_f = \dfrac{\lambda}{2sin\theta/2}$
  - From photodetector: $\Delta t = \dfrac{1}{f}$
  - $V = \dfrac{D_f}{\Delta t}$

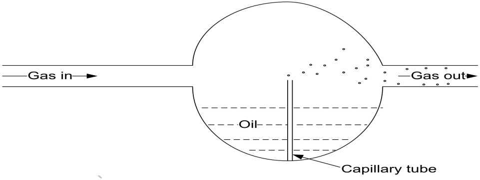
LDA - system layouts



Four layouts for LDA systems.

LDA - experiment





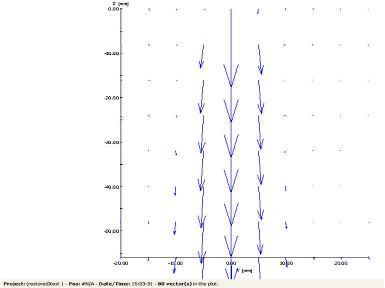
LDA and characteristics

- Point measurement: small control-volume, scan to obtain the whole-field.
- Seeding challenges: small-not enough light, large-not match fringe-width.

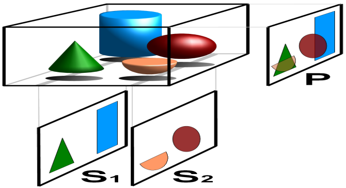
Experiment description

- Flow: Continuous air-flow out of a pipe of 10 mm-diameter.
- Plane: cross the pipe-diameter.
- Seeder: coupling to the gas flow using olive oil.

LDA - results and 3D measurement



Flow field from LDA.



Tomography.

Results

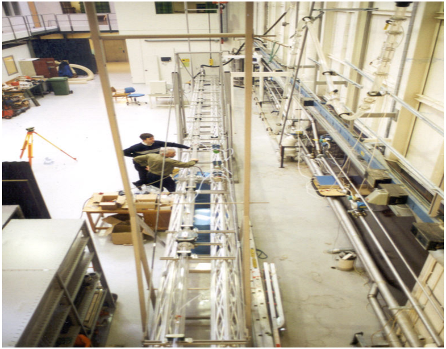
- Velocity field within downstream $50mm$: quite centralized with little divergence, vortex is small.
- Divergence of air-flow became more obvious at further downstream.

Tomography for both LDA and PIV

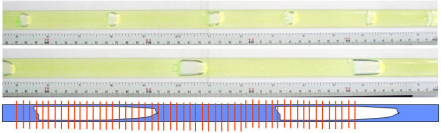
A method for reconstructing the 3D-flow.

- Scanning the flow field of different planes/slices.
- Superposing the flow-fields.

Flow regime characterization



Multiphase flow lab.



Experiment-simulation coupling strategy.

Flow regimes investigation under different hydrodynamic conditions.

Characteristics of the photography technique

- Transparent along the whole pipe enables photographing from different points and angles.
- Camera mounted on the rail with possibility of remote control can be used for online-tracking of the flow evolution.
- Fluorescent dye is used as the fluid tracer.

Outline

Flow-surface visualization

General principle

Use colored fluid, e.g. colored oil, onto a solid surface to reveal the flow streamlines in the limit as the surface is approached.

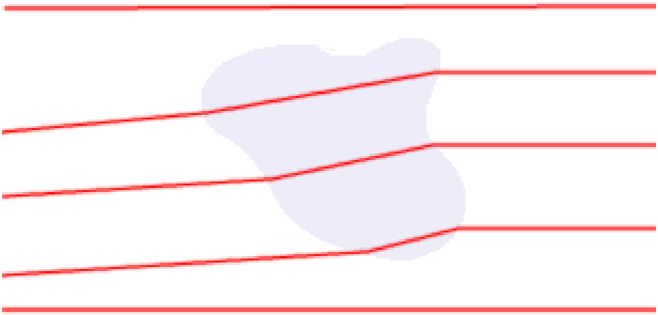
Examples of flow-surface visualization.

Outline

The working principle Refractive-ind. visualization

General principle

Depend on the light distortions when passing through an object of a changed refractive index.



Light distortion passing through an object of different refractive index.

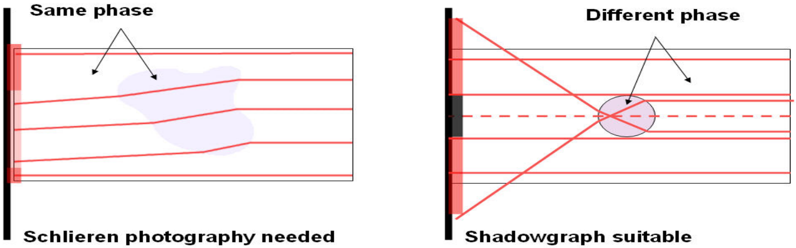
Schlieren photography and Shadowgraph

In common

Utilizing the refractive index variation; Light source; camera· · ·

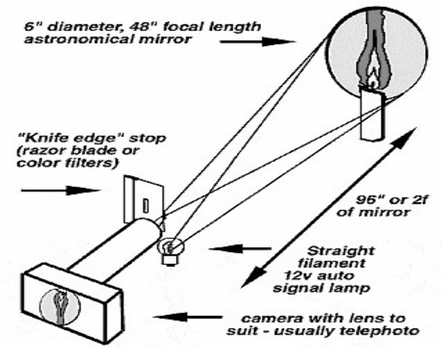
Difference

Due to different levels of refractive index variation, different *system-setups* must be used to make the flow *visible*.



Comparison between Schlieren photography and shadowgraph.

Schlieren photography



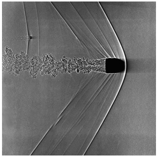
Schlieren-system setup.

Component and principle

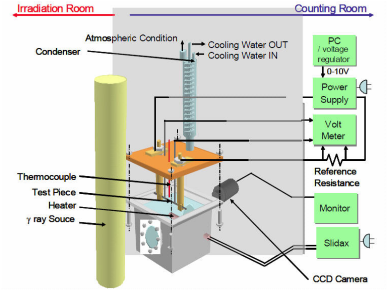
- Collimated light beam.
- Concave mirror to focus the light.
- “Knife-edge” to cut the focused beam and enhance the intensity-variation.
- Camera.

Applications

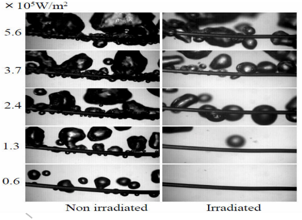
- Shock wave visualization.



Shadowgraph



Shadowgraph setup.



Experiment-simulation coupling strategy.

Component and principle

- Collimated light beam (Halogen lamp 250 w in the left study).
- Camera.

Applications

- Detailed multiphase flow phenomena.
- A more specific example in this afternoon· · · .

Outline

Prospects of the visualization techniques

Hardwares

Faster, Higher, Stronger!

- Fast-gated: already pico-second level.
- High-frequency: computer, camera, as well as laser-pulse.
- High resolution and large capacity.
- Strong function: e.g. combination of fast-gated and high-frequency· · · .

Fluid flow

Complex, More complex

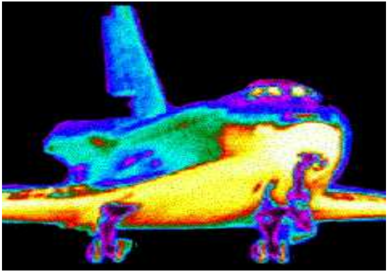
- Hypesonic
- Multiphase
- Micro and Nano
- Multidisciplinary

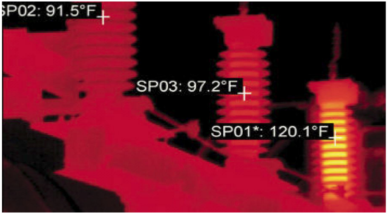
Measuring system

Simpler and more automatic

- Calibration
- System setup
- Small and portable
- Multi-function

Future of the thermography





The technology limitation

- Surface measurement.
- Low speed.

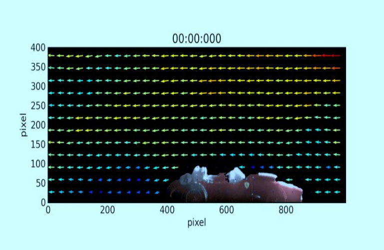
The future applications

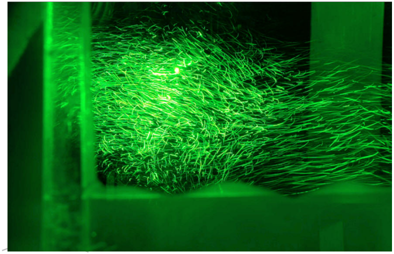
- Flow distribution: in hemofilter, heat exchangers.
- Quick fault-identification: macro as well as micro.
- Transient thermal change in flows.

The future of thermography relies on sensor

- More sensitive.
- More accurate.
- Higher speed.

Future of the particle tracking photography





The technology development

- Tracer particles: applicability and safety.
- Spatial resolution, which you cannot see from the left picture.
- Temporal resolution.

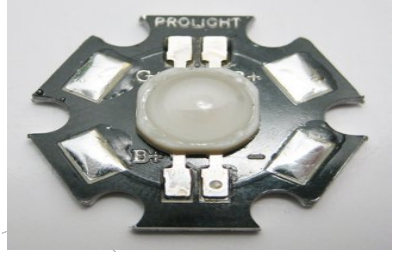
The future applications

- High temperature flow: e.g. exhaust gas, high temperature air flow $\cdots$
- Super- and hyper-sonic flow: with extremely high spatial and temporal resolution.
- Micro- and nano- flow.

The future of particle tracking photography relies on multidisciplinary science

- Tiny and inert (“healthy”) particles.
- Fast-gated and high-speed camera.
- High quality light source: high-frequency pulsing and short duration of illumination.

Future of the photography by refractive-variation



The technology development

- High quality LED.
- Picture resolution: high with less decrease in speed.
- Temporal resolution: needs to be higher.

The future applications

- Physical: Detailed and fast-evolving multiphase flow phenomena.
- Numerical: Model development and verification from the detailed experiments.

The future of photography by refractive-variation relies on camera mainly

- High picture resolution
- High-speed
- Fast-gated (for continuous-wave light)

Thank you for your attention!